Calorimetry in HEP
From concepts to experiments

J.-B. Sauvan
LLR CNRS / École polytechnique

ESIPAP 2020 – 03/02/2020

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

Calorimetry and Machine Learning

Examples of calorimeters Present and future

Reference

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

A few words about myself

- Physicist at the Laboratoire Leprince-Ringuet
  - Located at the Ecole polytechnique, close to Paris
- PhD thesis in ATLAS, starting roughly at the same time as the LHC
  - Jet energy calibration
  - Z+jets cross section measurements
- On CMS since 2012
  - Higgs measurements ($H \rightarrow ZZ^* \rightarrow 4$ leptons, $H \rightarrow \tau\tau$)
  - Electron energy corrections
  - Phase 1 calorimeter trigger upgrade
  - High Granularity Calorimeter (CMS endcap calorimeter Phase 2 upgrade)

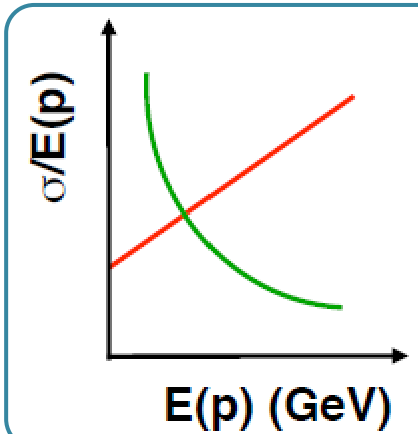
Lecture plan

- 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
- Calorimetry and Machine Learning
- Examples of calorimeters Present and future

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

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

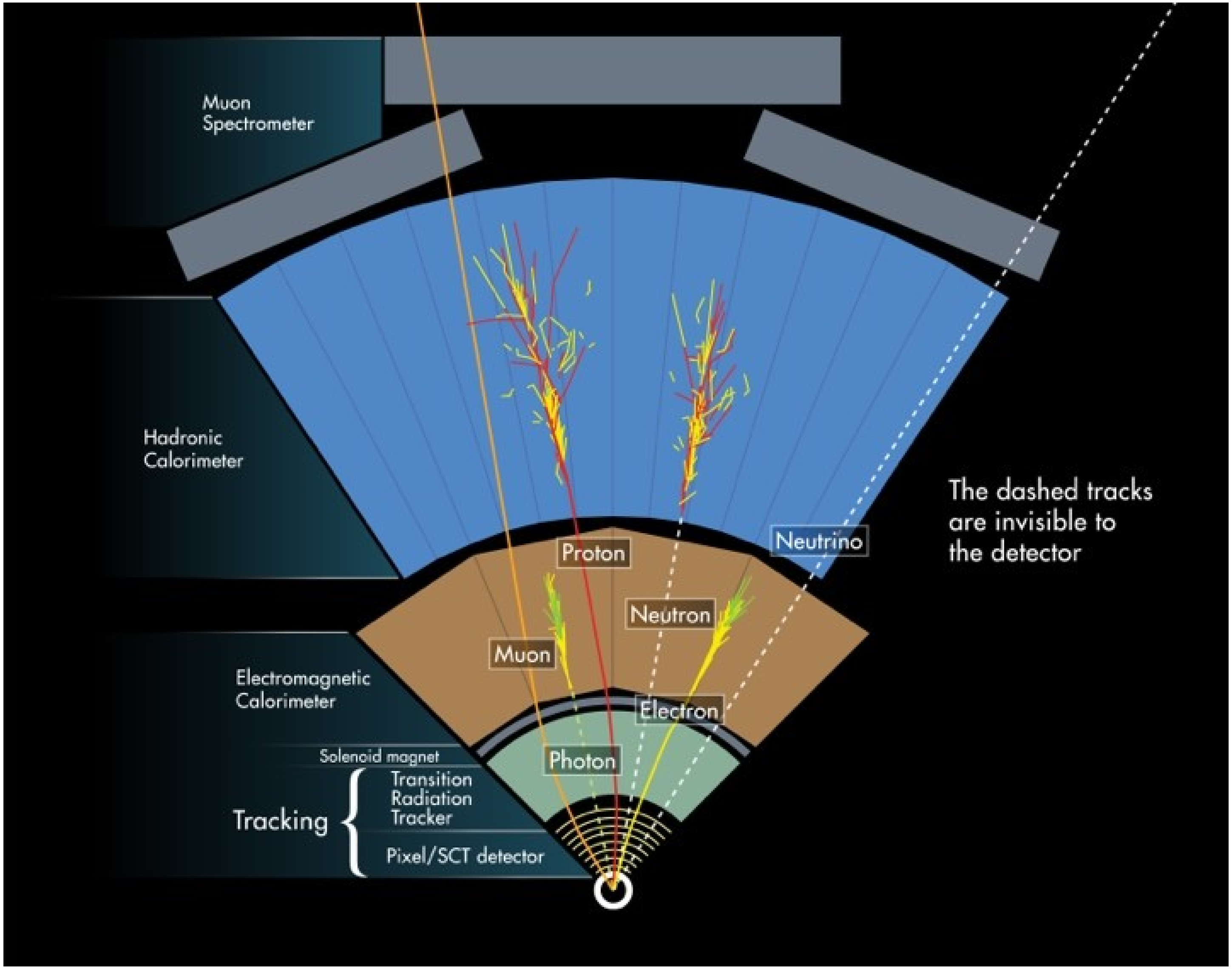
- Calorimeters can measure both charged and neutrals

Working together with other detectors

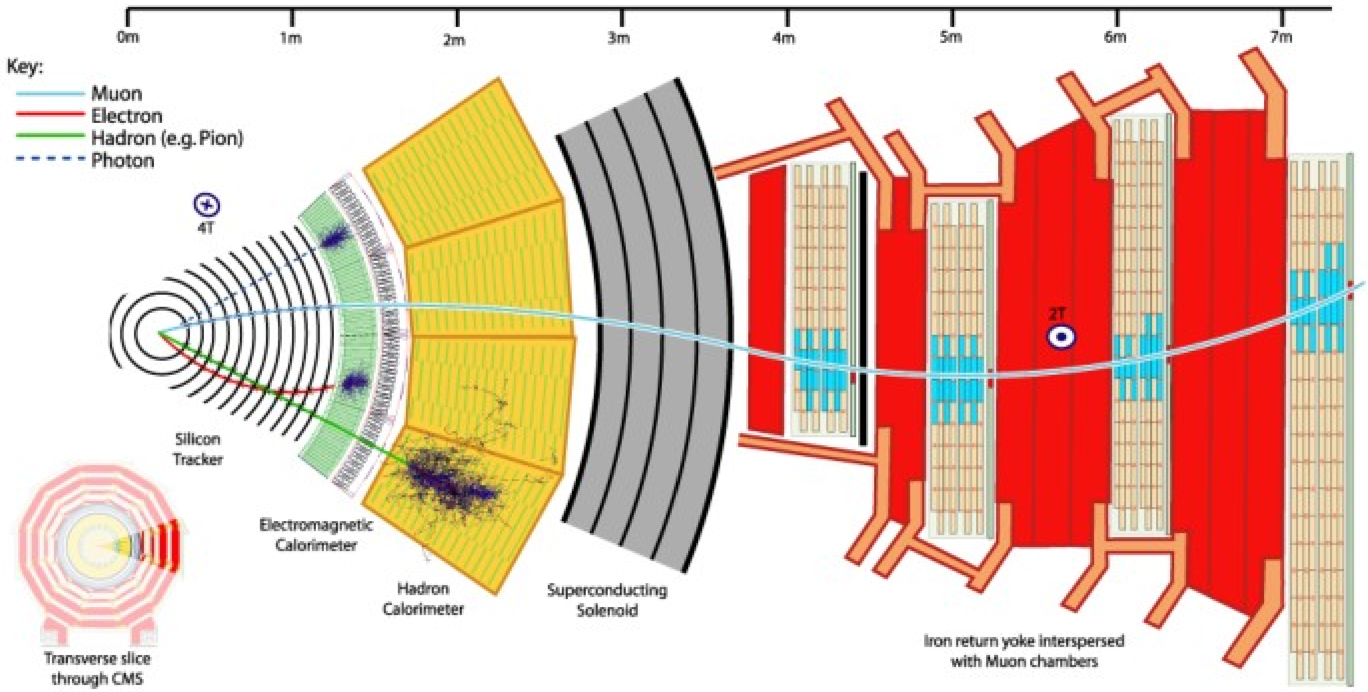
Muon spectrometer

Calorimeters

Trackers

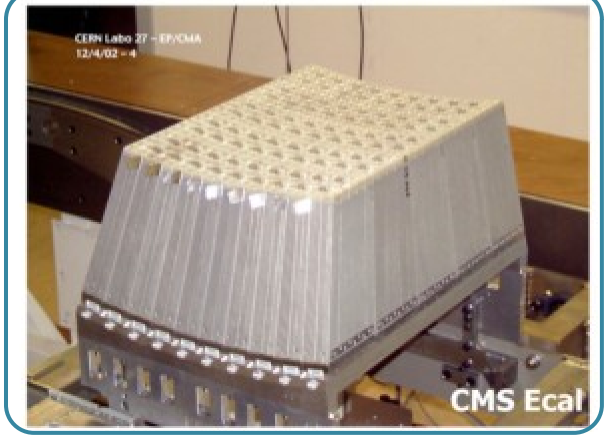


CMS ECAL



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

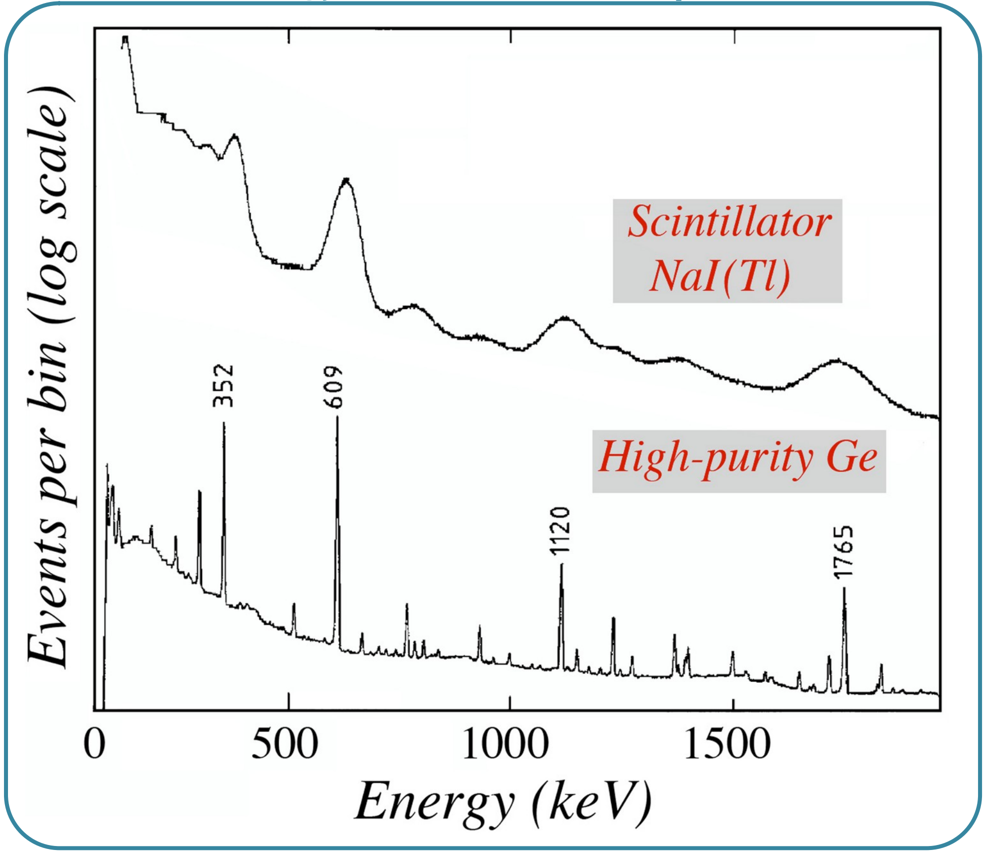
CMS ECAL module



Back to the origins: Nuclear radiation detectors

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

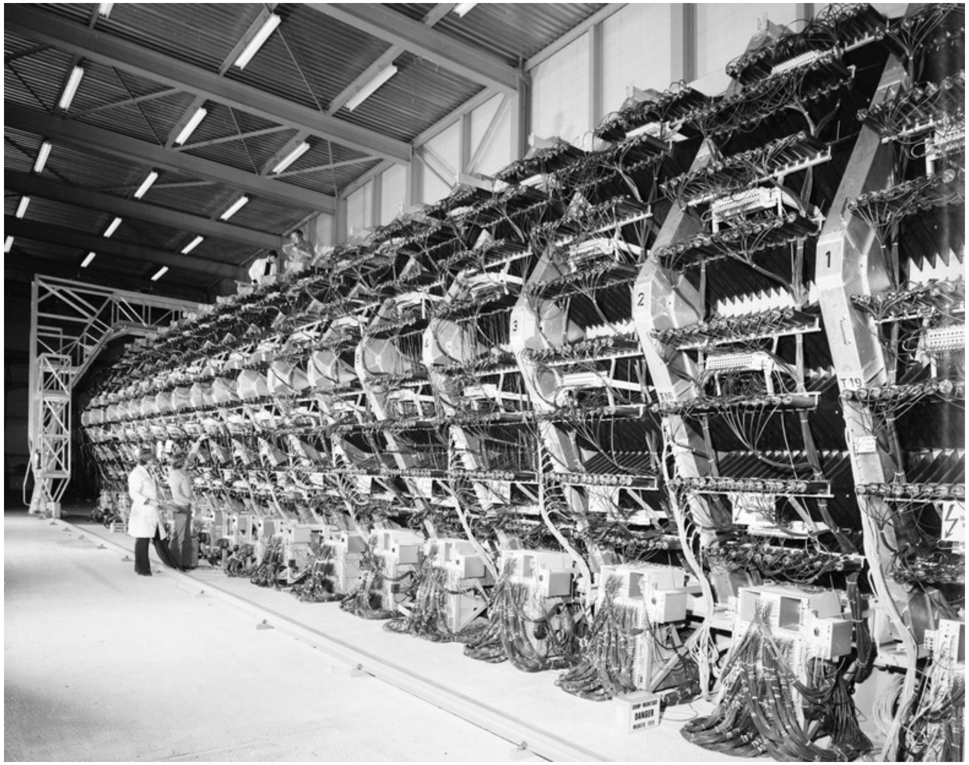
Energy resolution is important



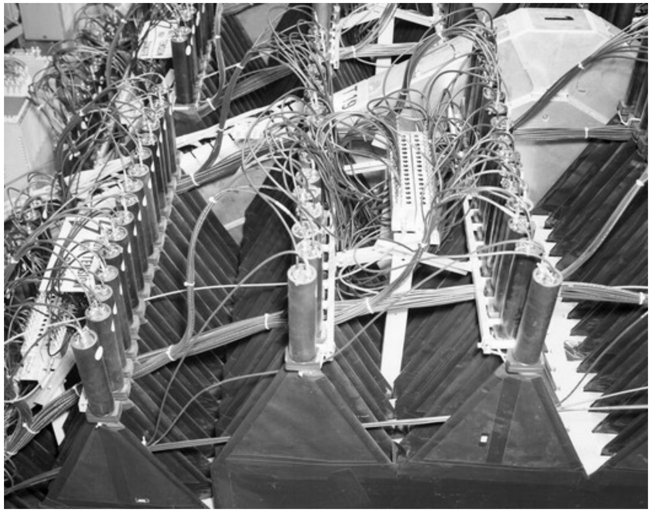
Neutrino experiments at SPS (CERN)

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

WA1 experiment



Scintillators + PMT

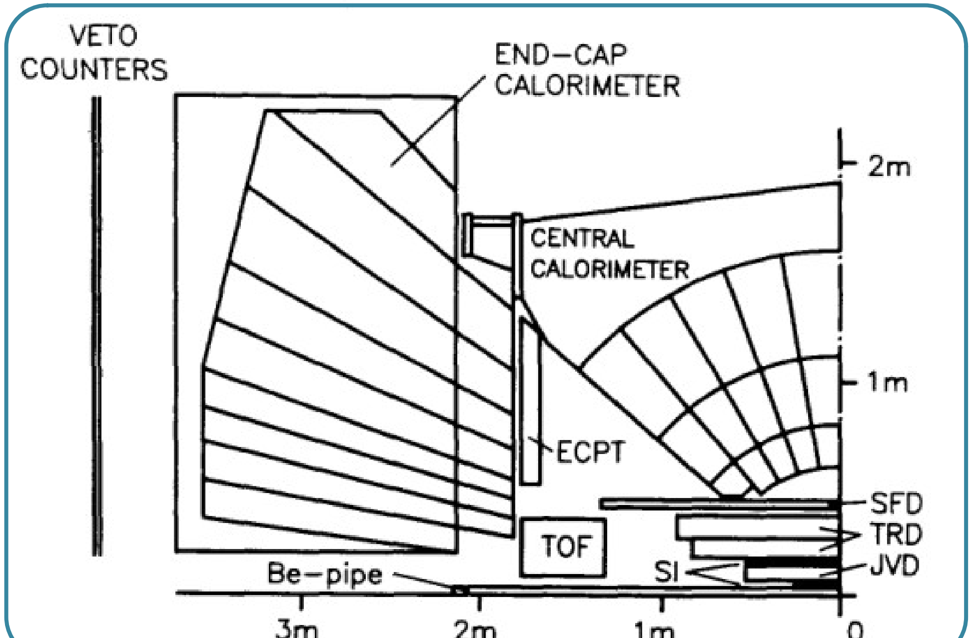


UA1 and UA2

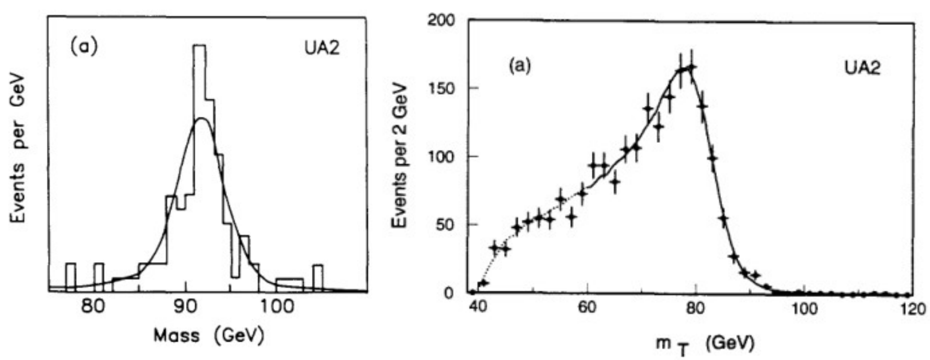
- UA1 & UA2 = Experiments at the SppS (CERN)
- UA2 (1981-1990)
  - More focused on calorimetry
  - Lead (or Iron) + scintillator
- Discovery of the W and Z bosons

UA2 detector

UA2 cross-section

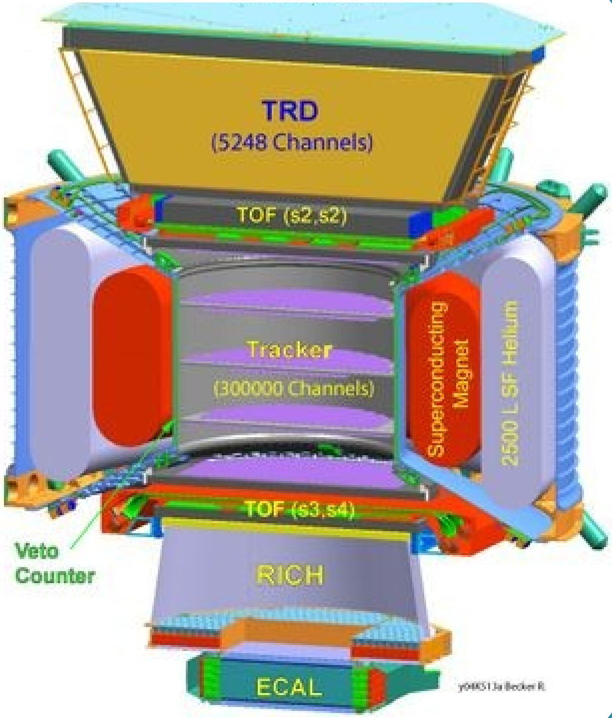


Z mass & W transverse mass

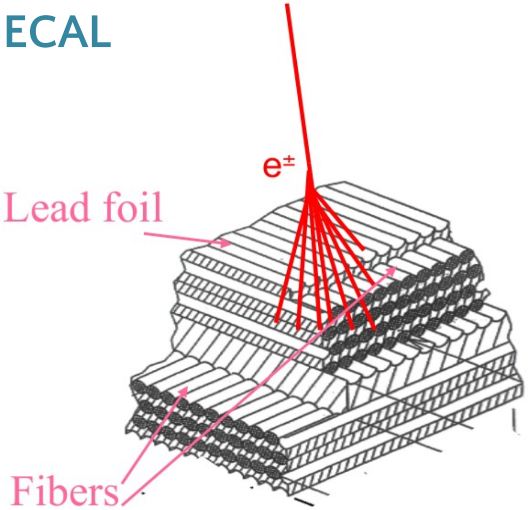


AMS

AMS cross-section



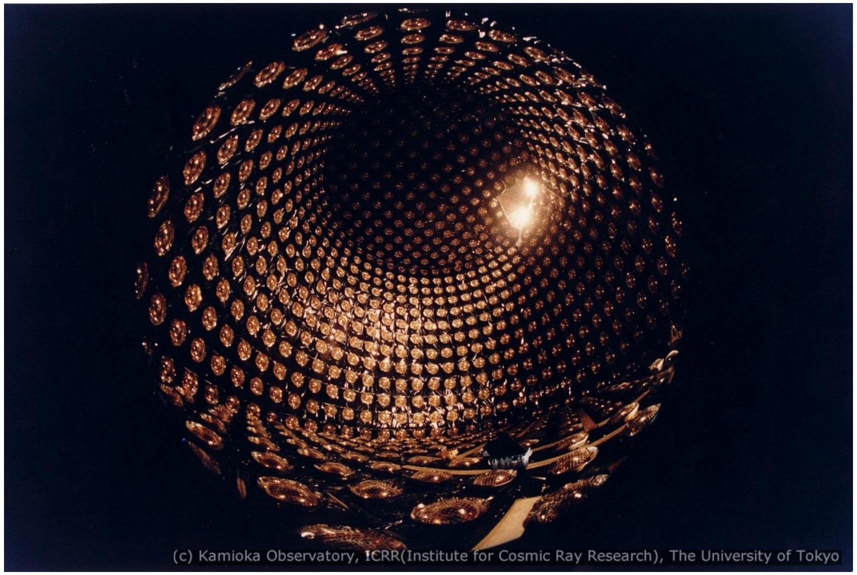
ECAL

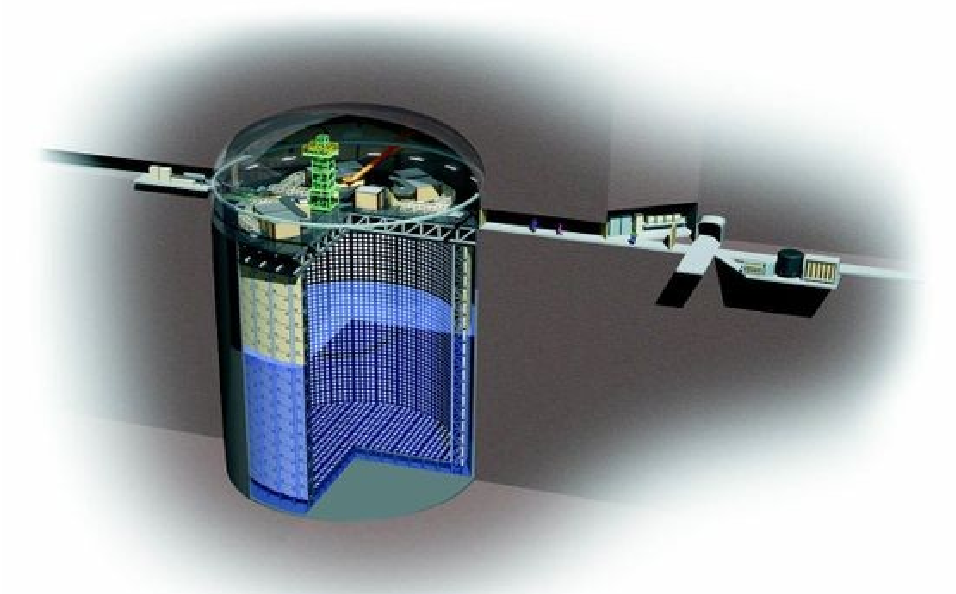


- AMS: experiment on the International Space Station
- Search presence of anti-matter in cosmic rays
- Electromagnetic calorimeter
  - Measure high energy electrons/positrons
  - Discriminate against protons

Kamiokande

Super-Kamiokande





- Water tank placed in underground mine (> 2140 t)
- 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

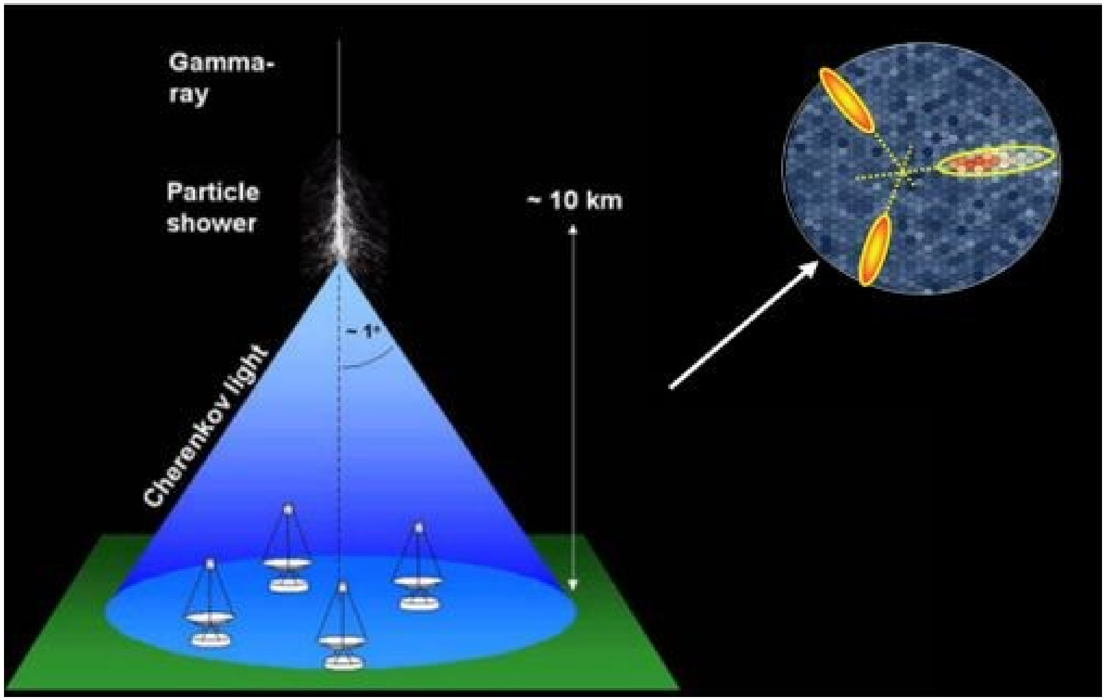
Large PMT

HESS

The 5 HESS telescopes

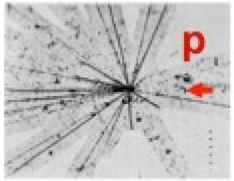
- Explore cosmic gamma rays
  - Interaction with the atmosphere
  - Emission of Cerenkov light
- Telescopes record this Cerenkov light on the ground

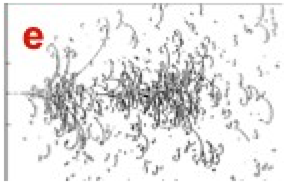
Detection principles



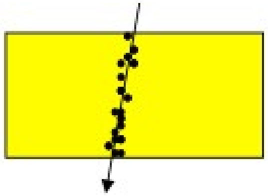
Calorimeter: principles

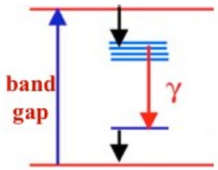
Particles interact with matter
Depends on particle and material

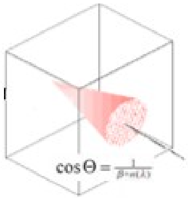




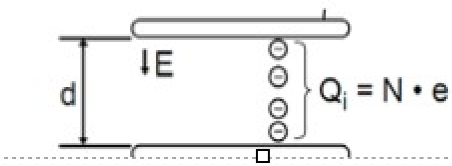
Energy lost transferred to detectable signal
Light, electric signal, etc.

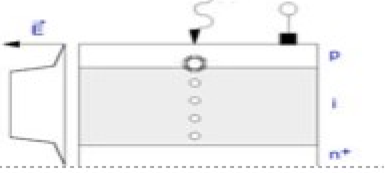




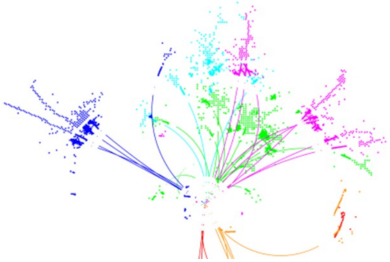


Signal collected and acquired
In the end: digitized signal





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?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter
response & resolution

Electronics readout and trigger

Energy
reconstruction & calibration

Beyond calorimetry: Particle Flow

Calorimetry and Machine Learning

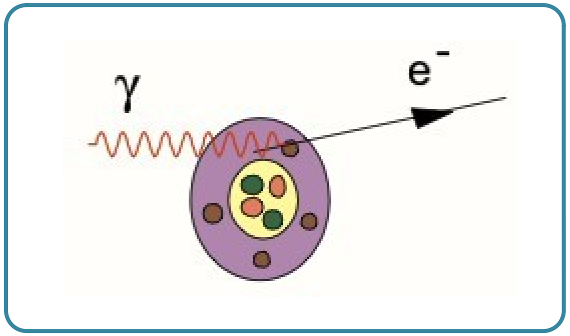
Examples of calorimeters
Present and future

Electromagnetic interactions with matter

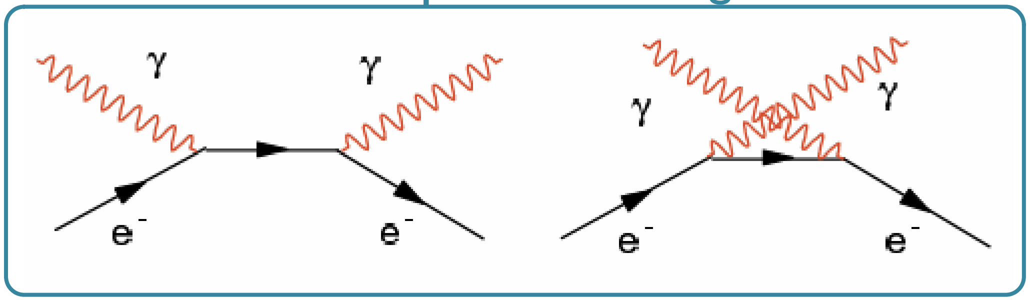
Photons | Electrons

Low energy

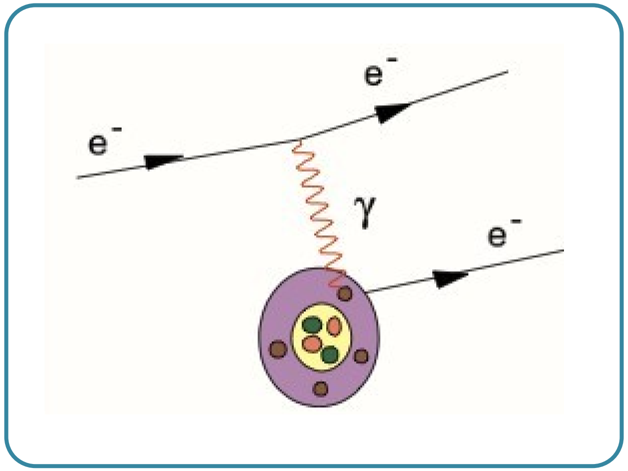
Photoelectric effect



Compton scattering

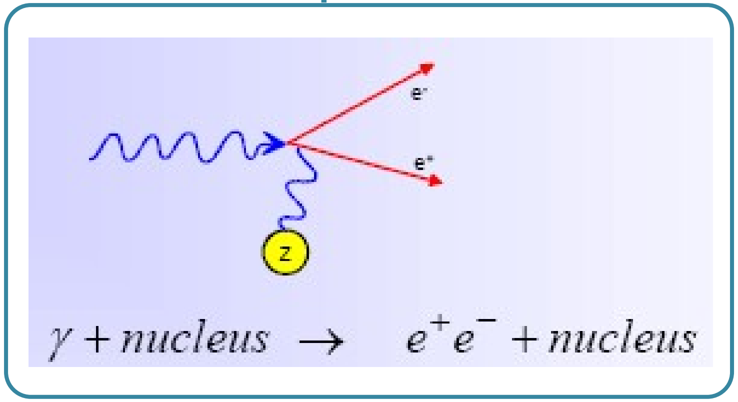


Ionisation

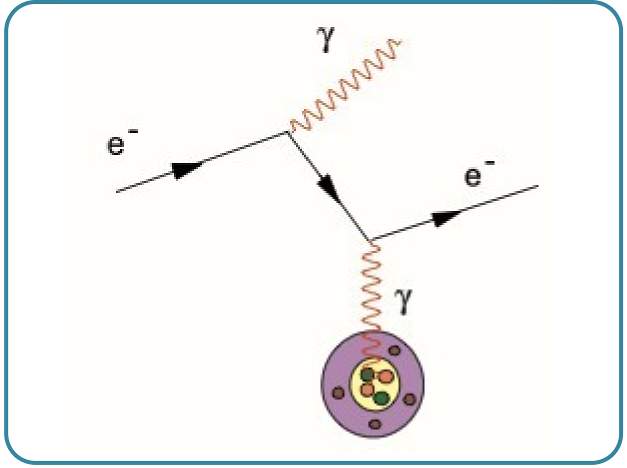


High energy

Pair production

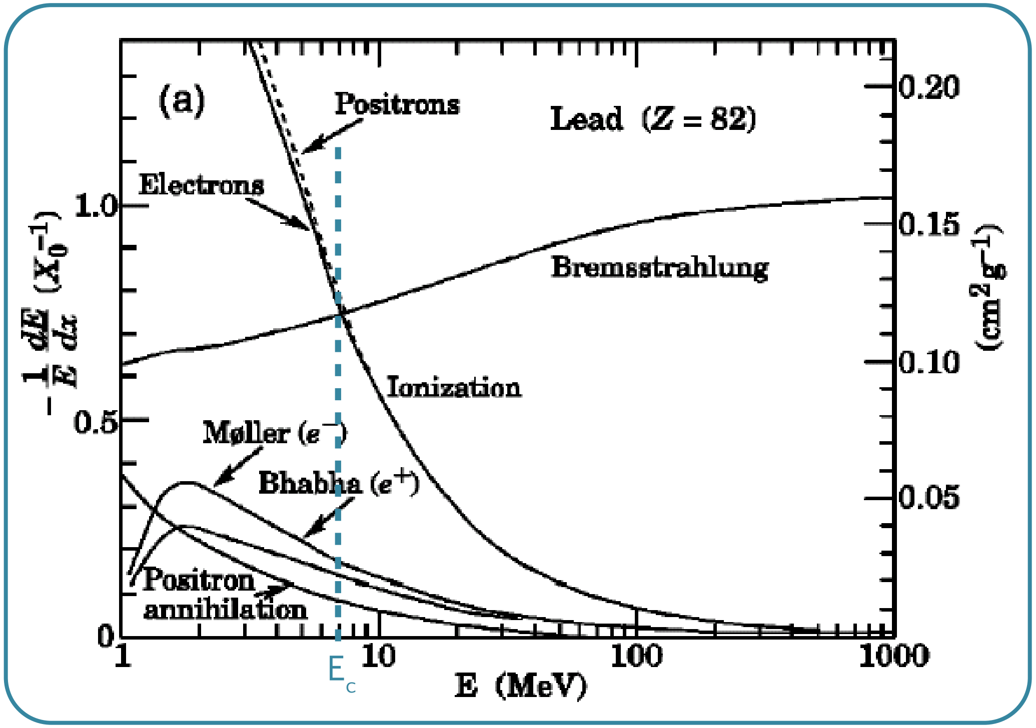


Bremsstrahlung

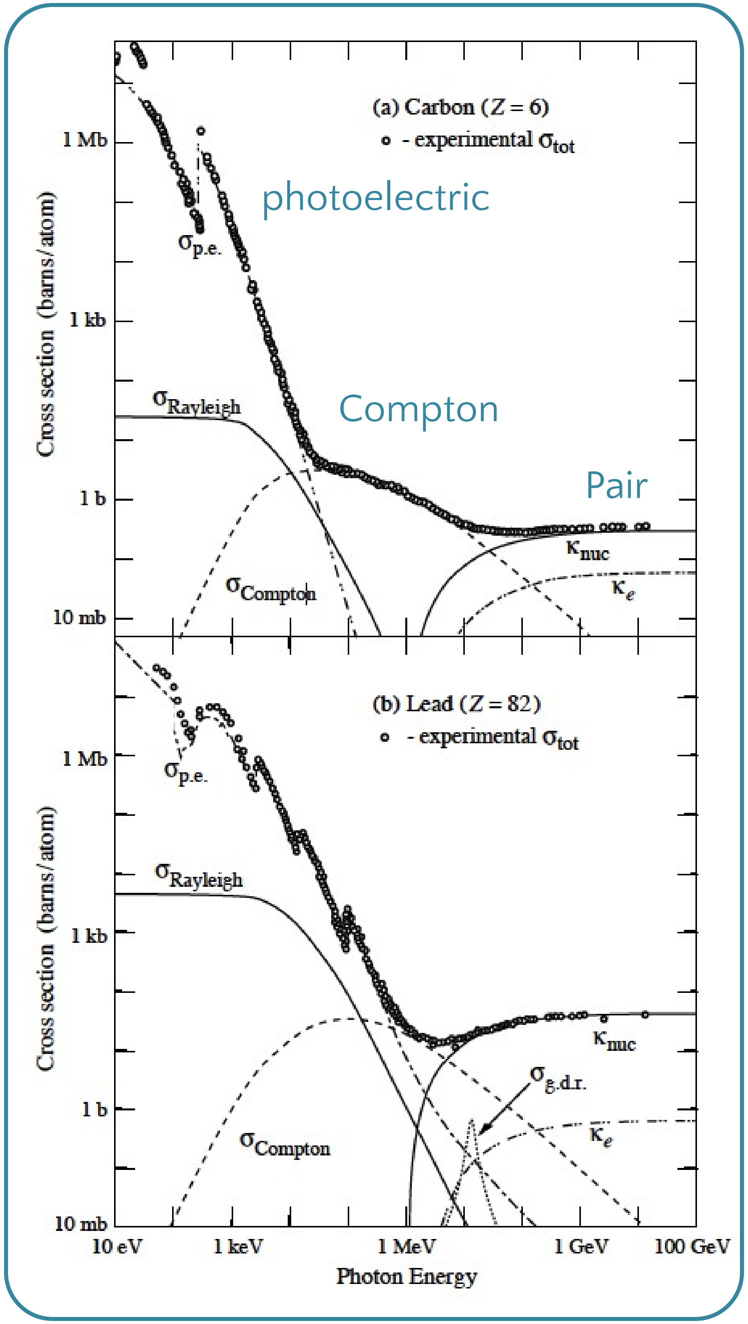


Dominant processes

Electrons



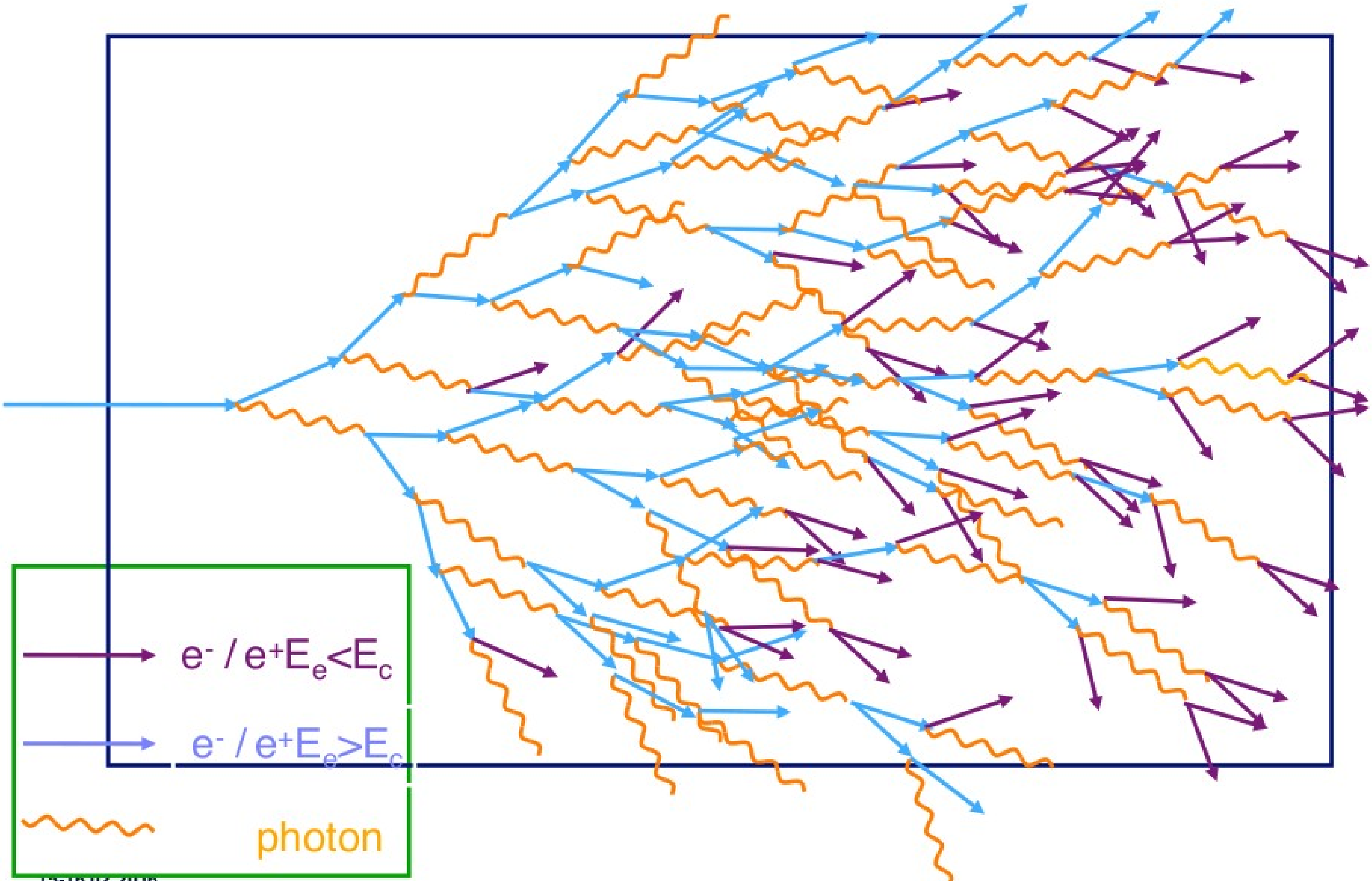
Photons



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

Shower development

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



Energy loss and mean free path

Two dominant processes: Bremsstrahlung and pair production

Electron energy loss

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

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

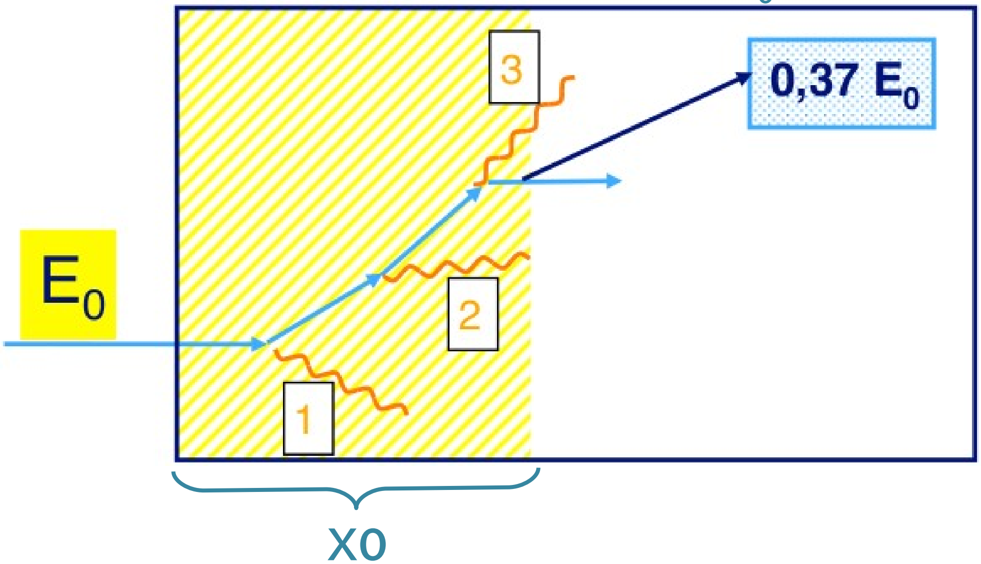
$$x(E_0/2) = X_0 \ln(2)$$

Pair prod. probability

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

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

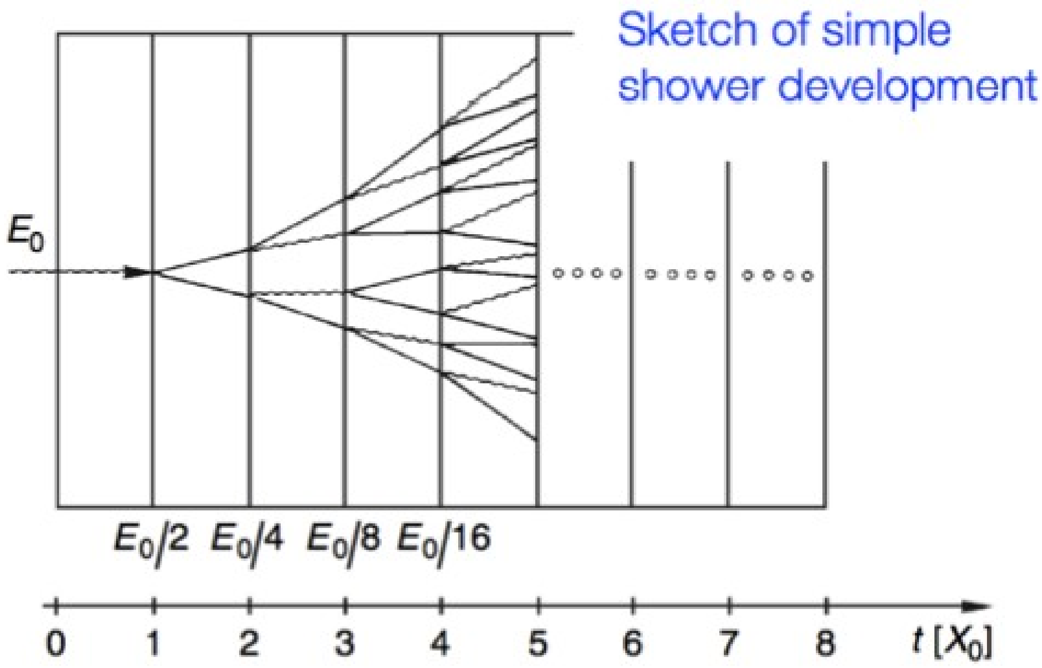
Radiation length X_0



- $X_0 \approx \frac{180\,A}{Z^2}\, g.cm^{-2}$
- Electrons loose half of their energy in about $2/3 \times X_0$
- Photons convert in about $9/7 \times X_0$

Simple shower model

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



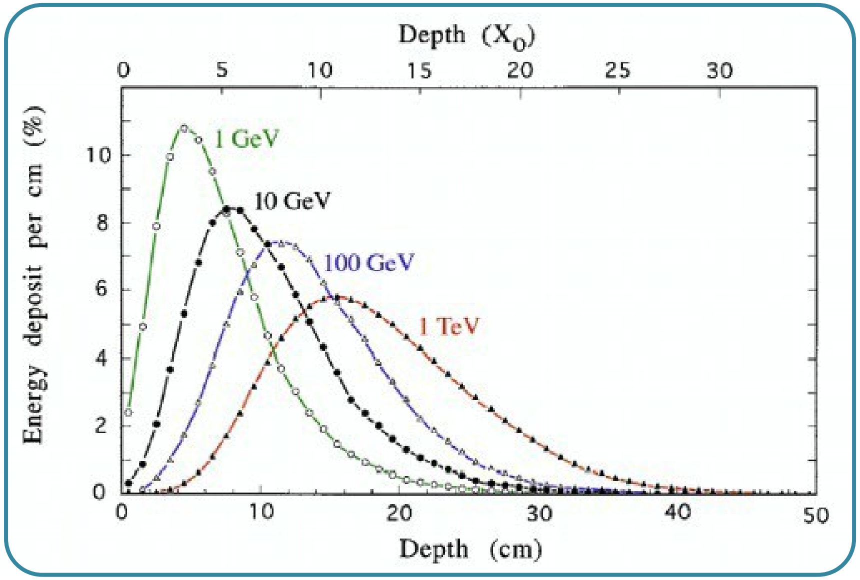
$t = x / X_0$

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

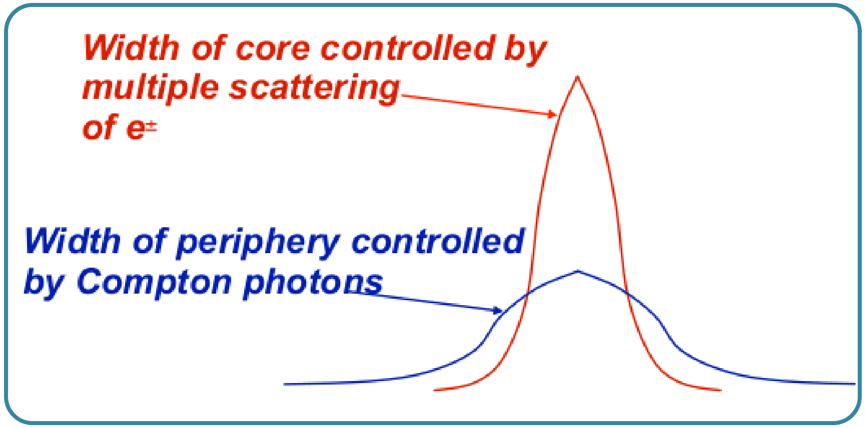
$$R_M = \frac{21\, MeV \times X_0}{E_c} \approx \frac{7\, A}{Z} g.cm^{-2}$$

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

Longitudinal profile



Lateral profile

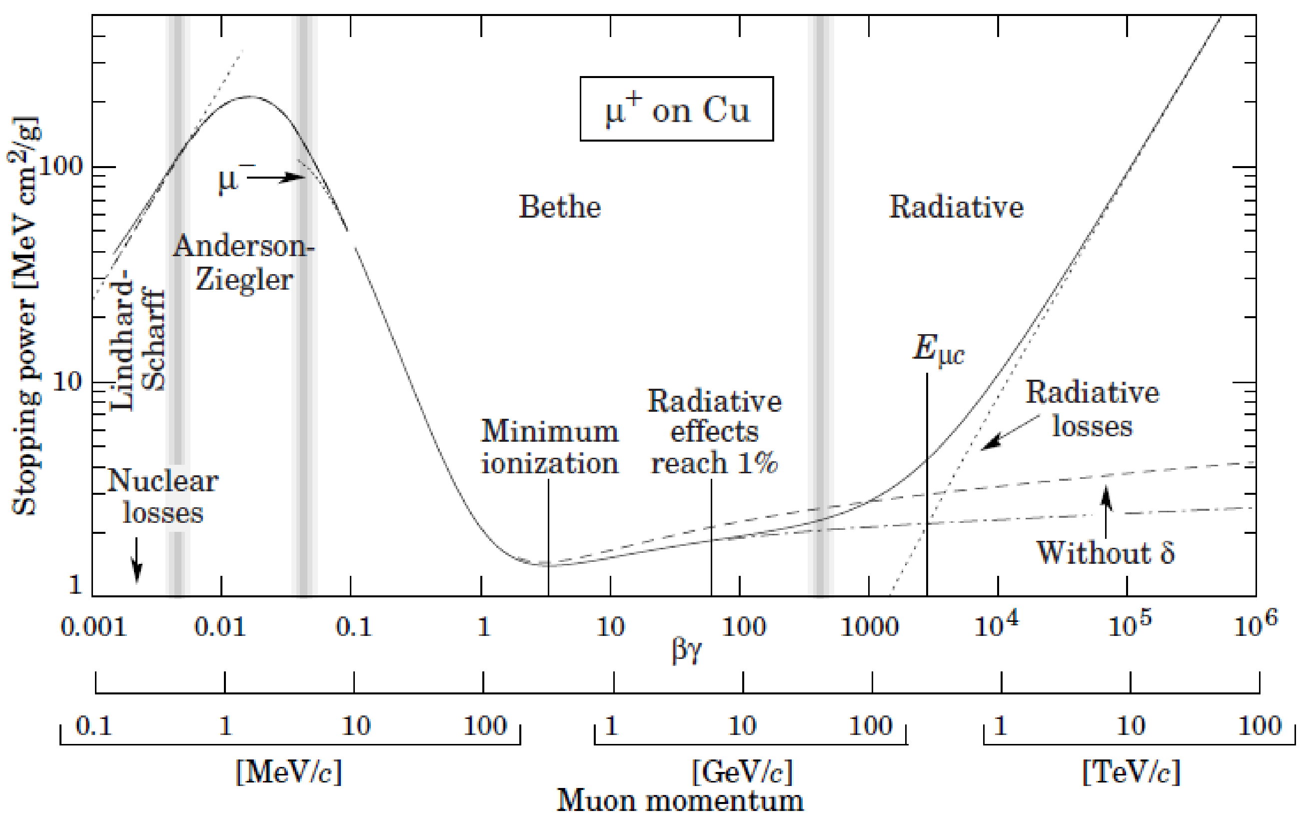


Useful quantities

- Radiation length $$X_0 \approx \frac{180\,A}{Z^2}\,g.cm^{-2}$$ Compound: $$\frac{1}{X_0} = \sum \frac{w_j}{X_j}$$ w_j = fraction of material
- Critical energy $$E_c = \frac{610\,MeV}{Z+1.24}$$
- Moliere radius $$R_M = \frac{21\,MeV \times X_0}{E_c} \approx \frac{7\,A}{Z}\,g.cm^{-2}$$ Compound: $$\frac{1}{R_M} = \sum \frac{w_j}{R_{Mj}}$$
- Shower maximum $$t_{max} = \ln(E_0/E_c) - \begin{matrix} 1 & \text{(electrons)} \\ 0.5 & \text{(photons)} \end{matrix}$$
- Longitudinal containment $$L(95\%)/X_0 = t_{max} + 0.08\,Z + 9.6$$
- Lateral containment $$R(95\%) = 2\,R_M$$

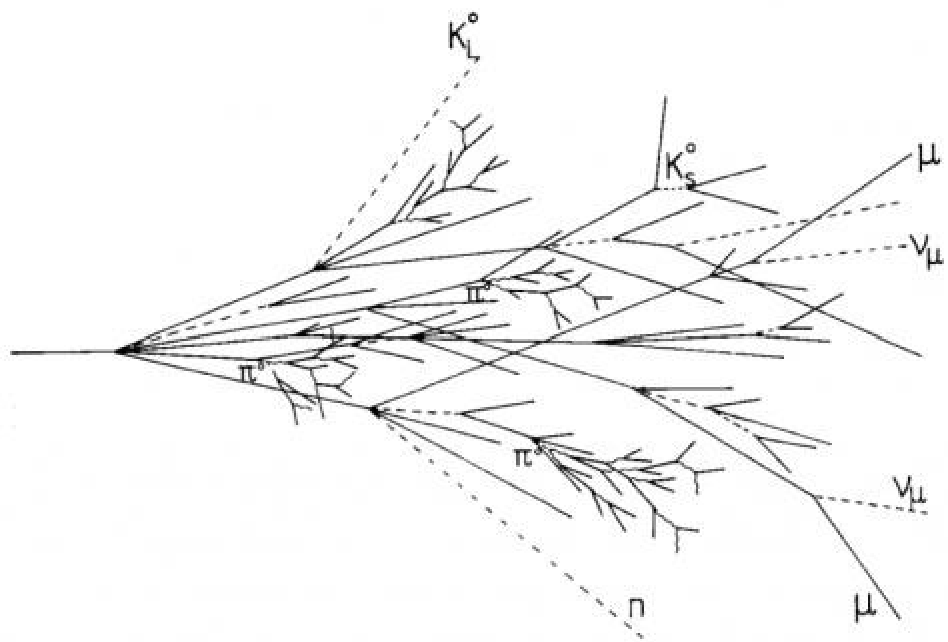
The case of the muon

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



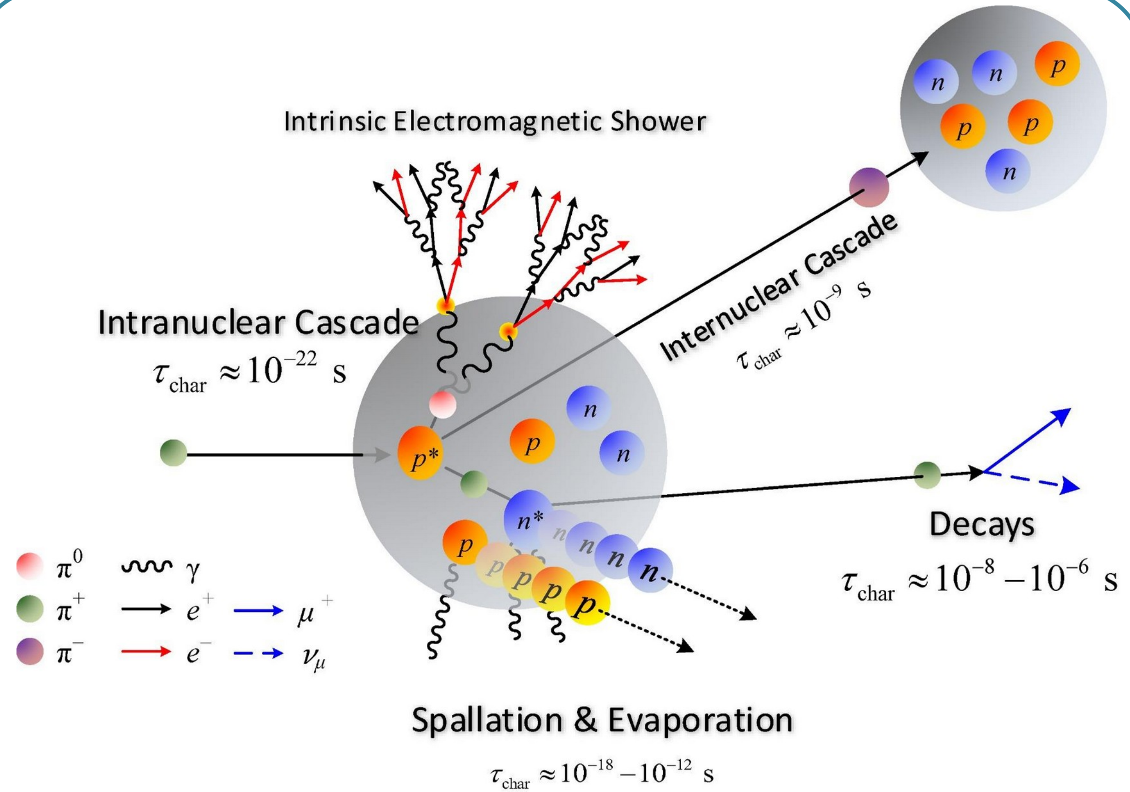
Hadronic showers

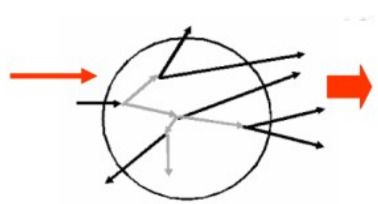
- Cascade of particles initiated by a hadron
  - Strong interaction in addition to EM interaction
- Many processes involved
  - Ionisation
  - Hadron production (fragmentation, etc.)
  - Charge exchange
    - $\pi\ n \rightarrow \pi^0\ p$
  - Spallation, fission
  - Nuclear de-excitation
  - Pion decay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



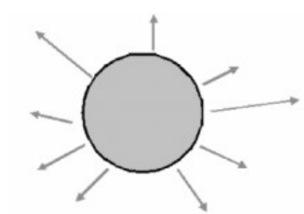
Hadronic interactions

Hadronic shower evolution





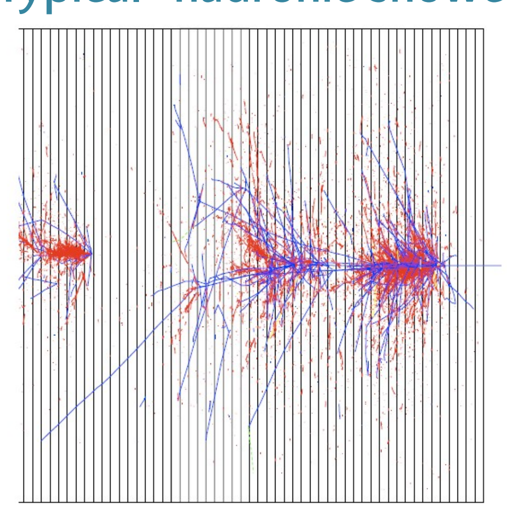
Intranuclear cascade
Incoming direction
Fast



Evaporation
Isotropic
Slow

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

"Typical" hadronic shower

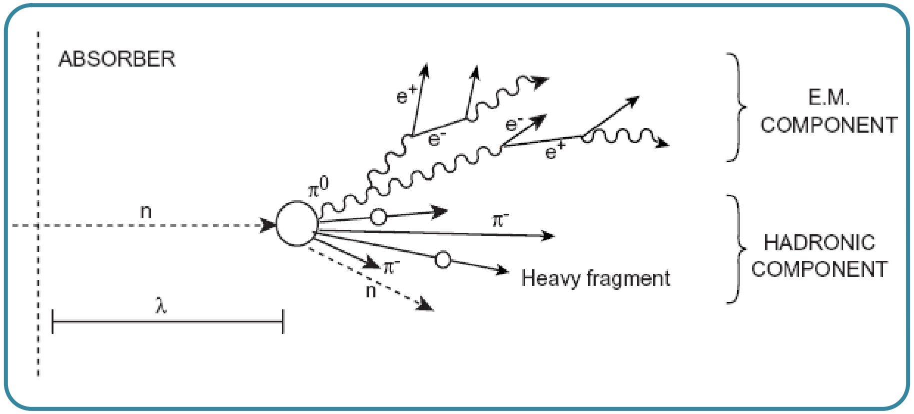


Electromagnetic component

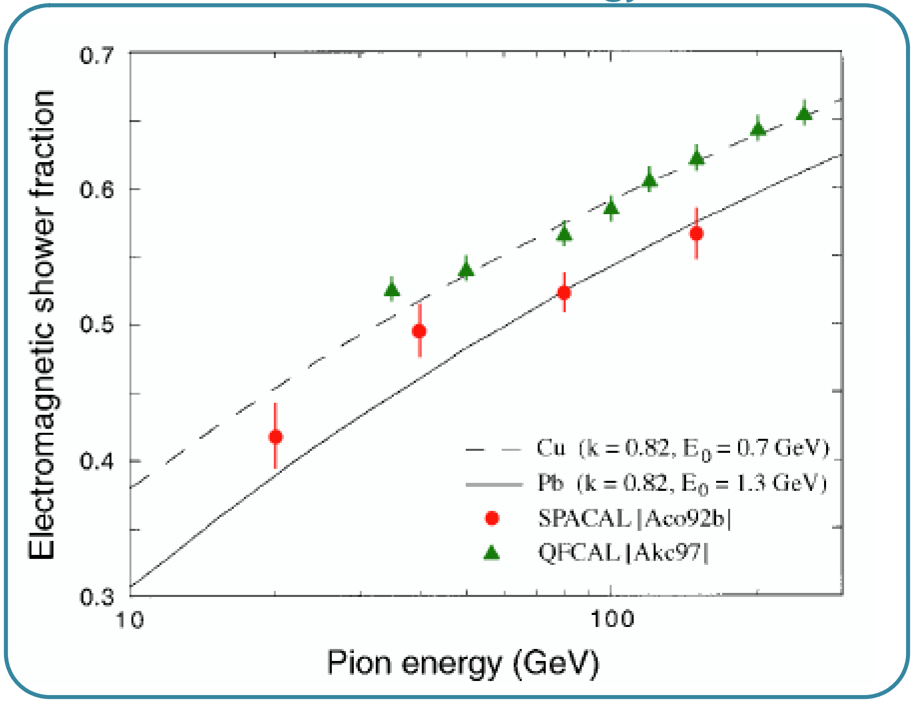
- Contributions
  - Electrons & photons from excitation, radiation, etc.
  - Neutral pions (e.g. $\pi^0 \to \gamma\gamma$)
- First interaction → about 1/3 of π_0
  - Remaining hadrons may undergo neutral pions too
- On average, EM fraction increases with energy

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

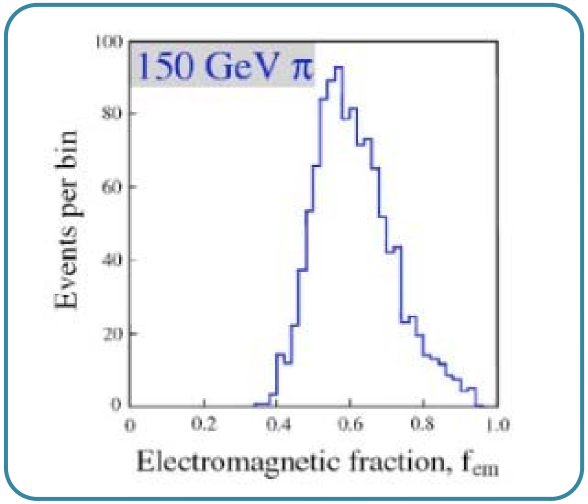
First hadronic interaction



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%

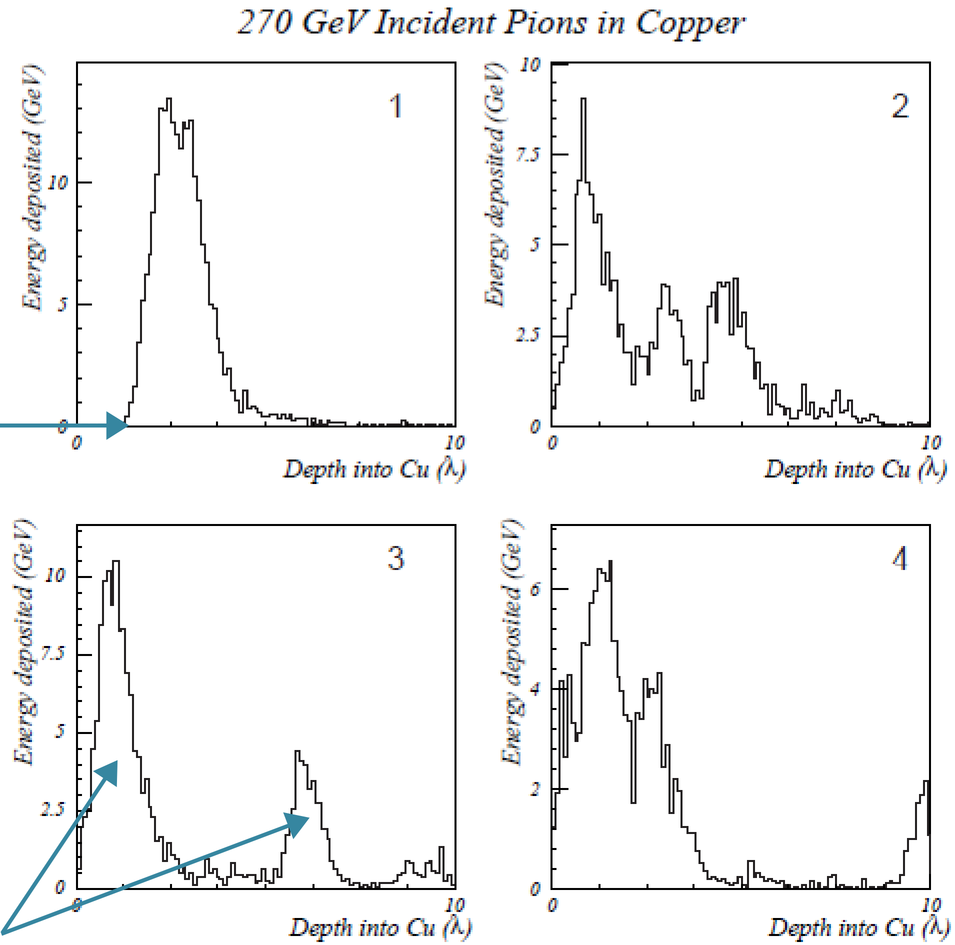
- A large part of energy losses is invisible
  - Energy used to release protons and neutrons from nuclei
  - Kinetic energy carried by recoil nuclei
- Also significant fraction in evaporation neutrons
  - Elastic scattering (large energy transfer for small nuclei, e.g. Hydrogen)
  - Neutron capture (sizeable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

Shower development

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

Examples of longitudinal development

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



π_0 production in consecutive hadronic interactions

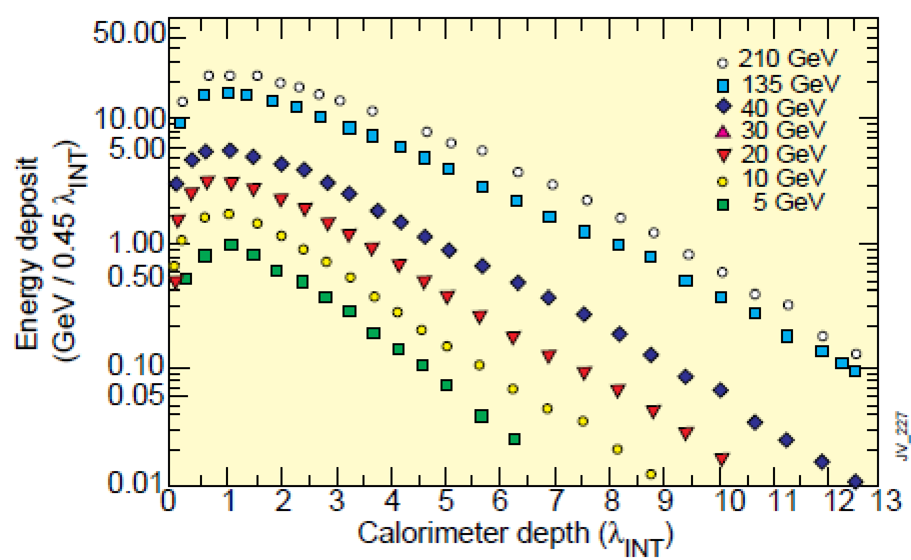
Longitudinal profile

- Hadronic shower governed by the interaction length $\lambda_{\rm int} \propto A^{1/3}$
  - 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

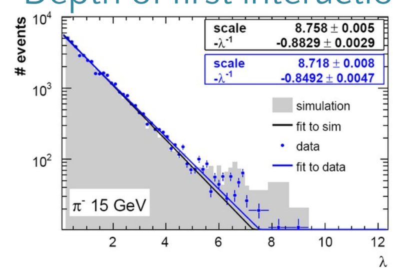
Examples of radiation and interaction length

	Z	ρ (g.cm^{-3})	E_c (MeV)	X_0 (cm)	$\lambda_{\rm int}$ (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

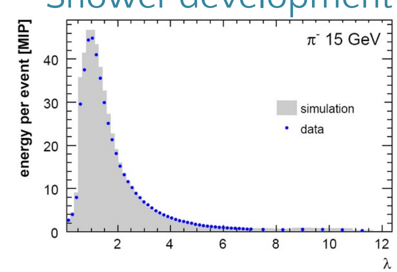
Longitudinal profile



Depth of first interaction



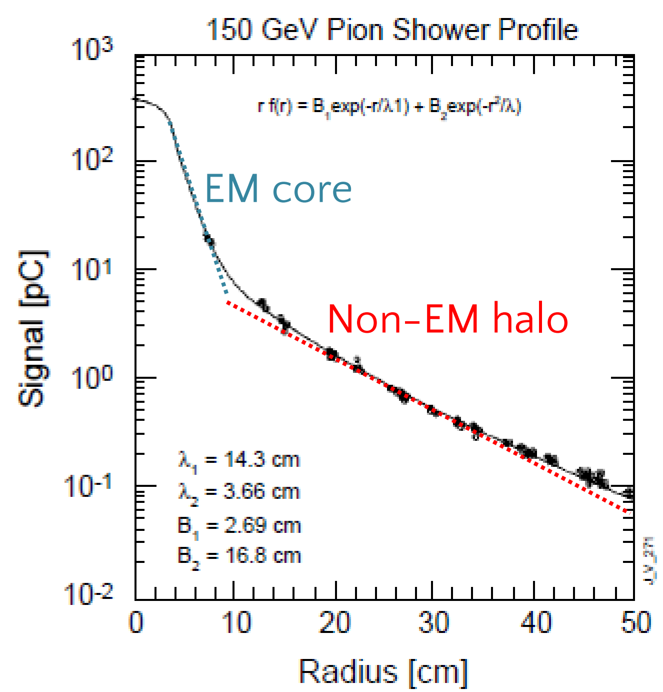
Shower development



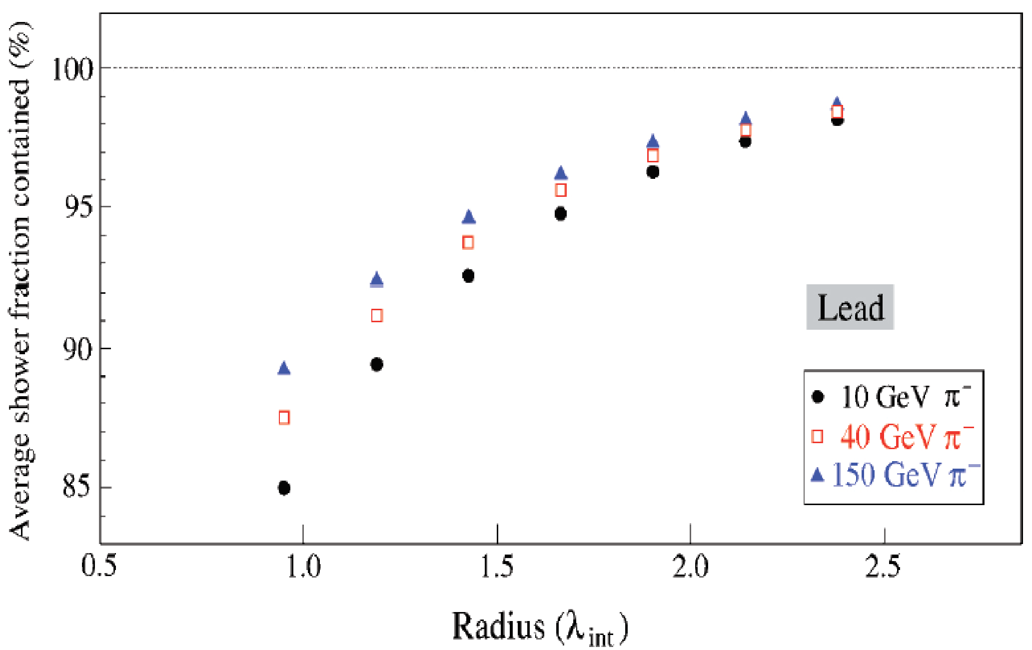
Lateral profile

- Lateral shower development has two components
  - Electromagnetic core
  - Non-EM halo (mainly non-relativistic shower particles)
- Mean transverse momentum from interactions (~300 MeV) about the same magnitude as energy lost in 1 λ
  - Lateral containment well characterized by λ

Lateral profile



Lateral containement



Lecture plan

What is a calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Electronics readout and trigger

Energy reconstruction & calibration

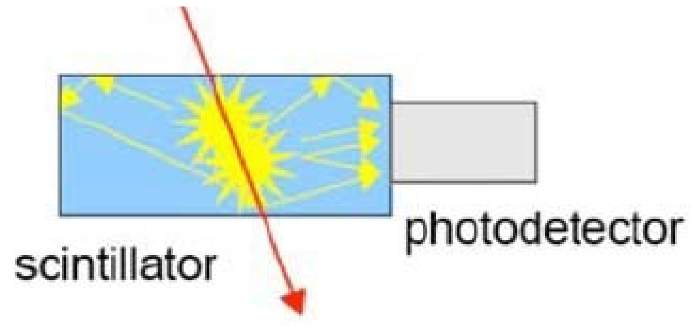
Beyond calorimetry: Particle Flow

Calorimetry and Machine Learning

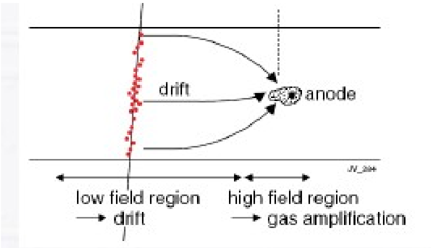
Examples of calorimeters Present and future

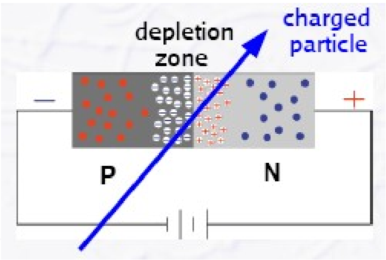
Measurement principles

- 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



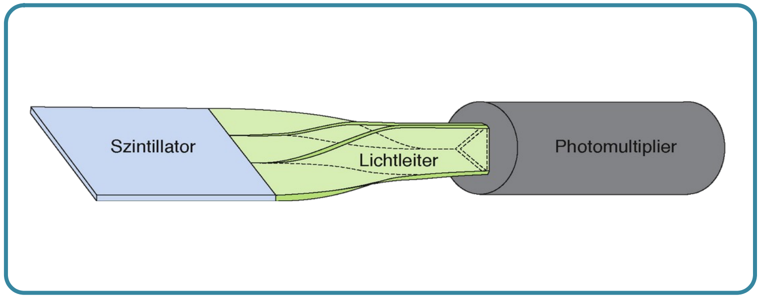


- One can also measure (very small) temperature increase
  - e.g. Bolometers
  - Not presented in this lecture

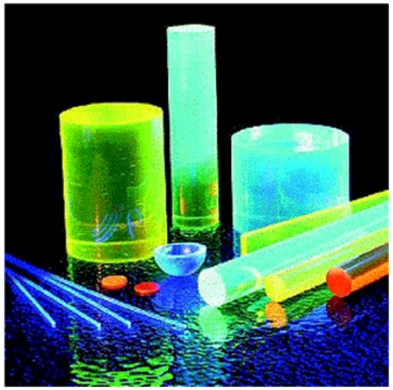
Scintillators

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

Light production and collection



Various scintillators



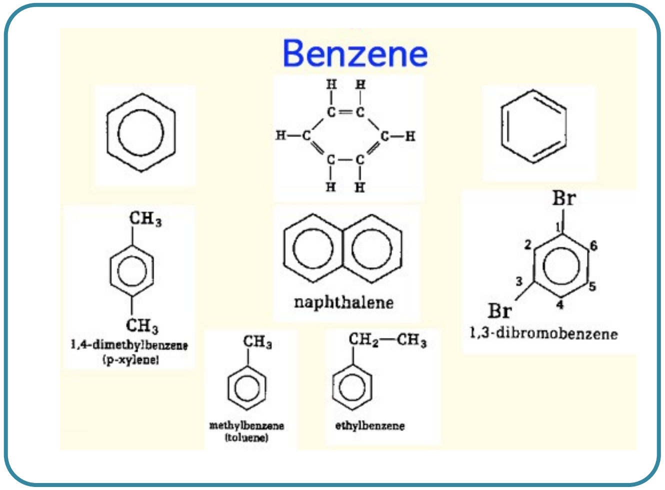
- 2 types of scintillating material
  - Organic (plastics or liquids)
  - Inorganic (crystals)
- 2 types of light emission
  - Fluorescence: prompt (ns → µs)
  - Phosphorescence: emission over long period (us → ms)

CMS PbWO4 crystal

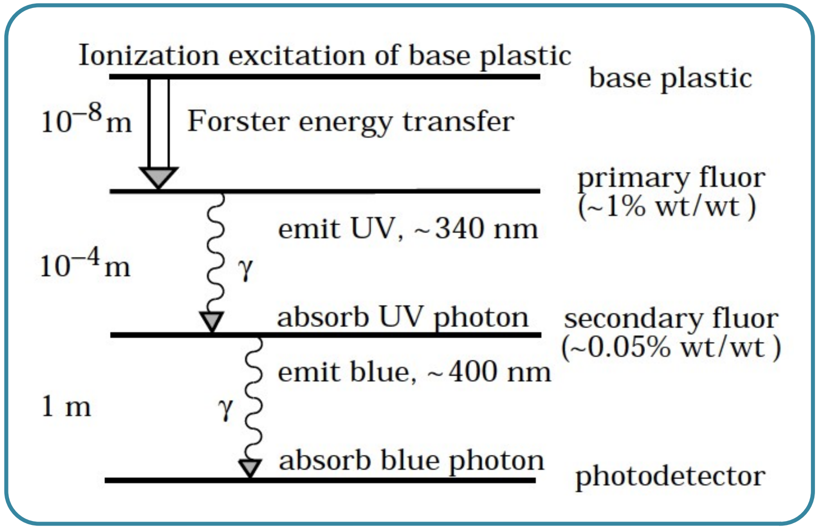
Organic scintillators

- Organic crystals, organic liquids, plastic scintillators
  - Aromatic hydrocarbon compounds (containing rings)
  - Typical solvent+scintillator
- 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



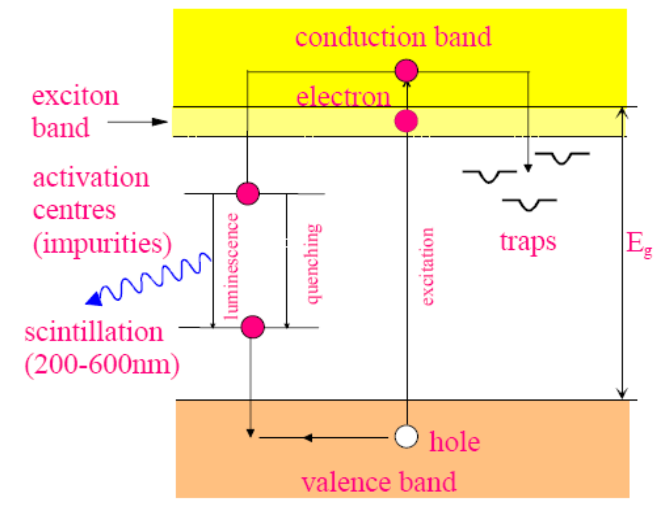
Inorganic scintillator

- 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

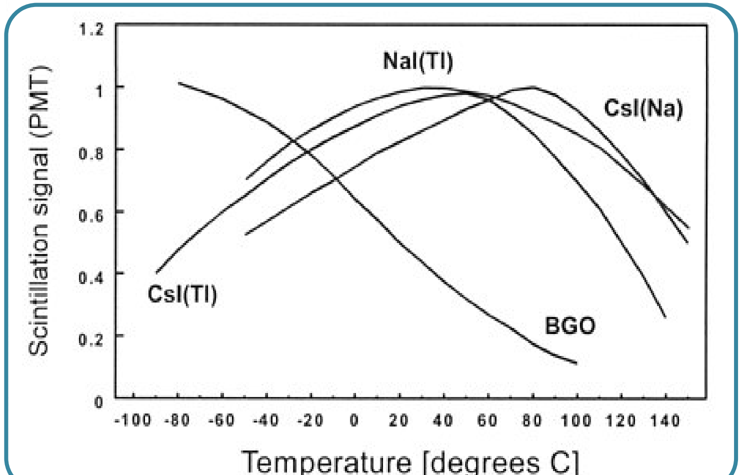
Material	Form	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	crystal	415	230	3.67	38,000
pure NaI (-196°C)	crystal	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	crystal	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	crystal	480	2000	7.13	24,000
CsI(Na)	crystal	420	630	4.51	39,000
CsI(Tl)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

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

Light emission process



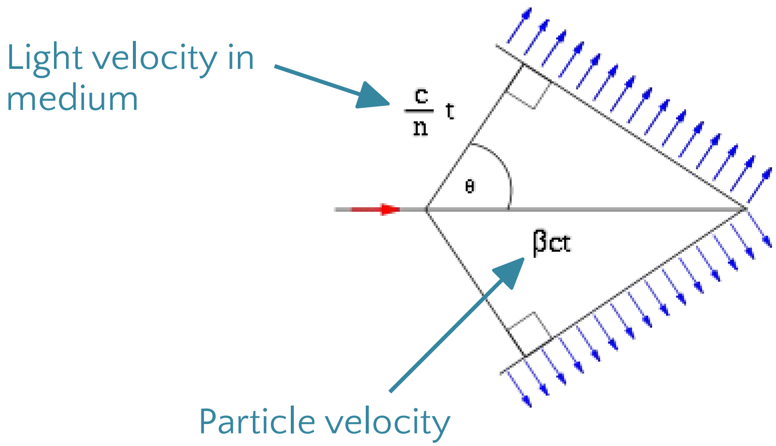
Light yield vs temperature

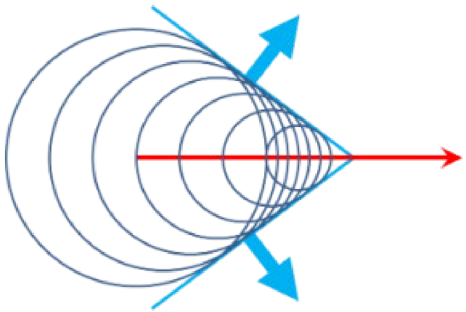


One word on Cherenkov effect

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

Principle



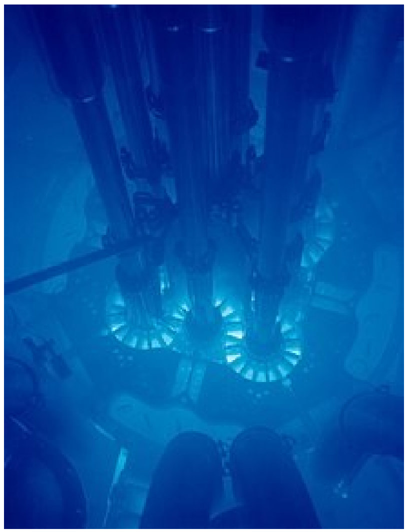


- Propagation angle $$\cos(\theta) = \frac{1}{n\beta}$$

Medium refractive index

$\beta = v_p / c$

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



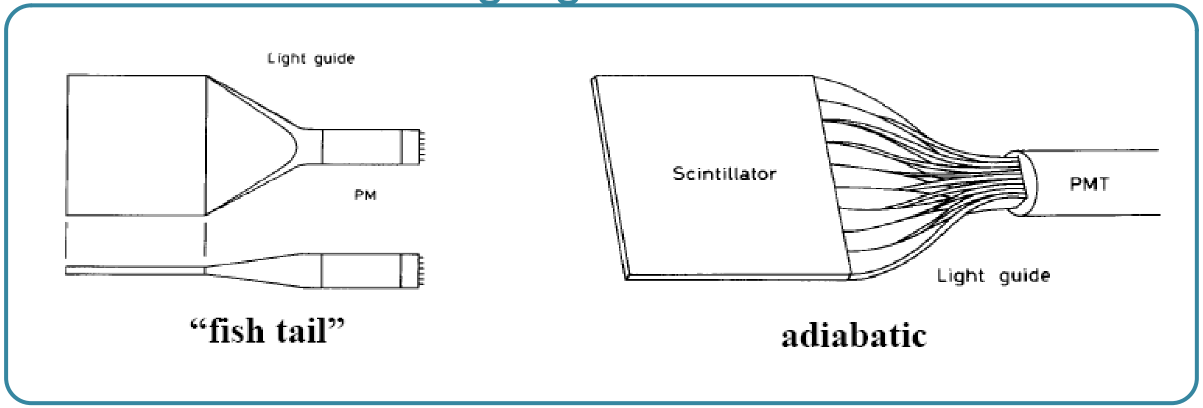
Spectrum in $1/\lambda^2$

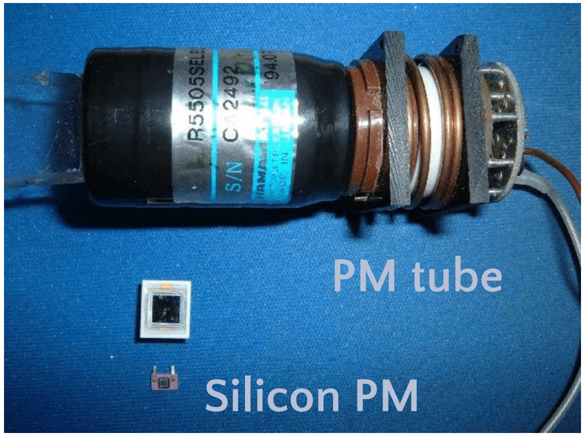
→ appears blue/violet in the visible spectrum

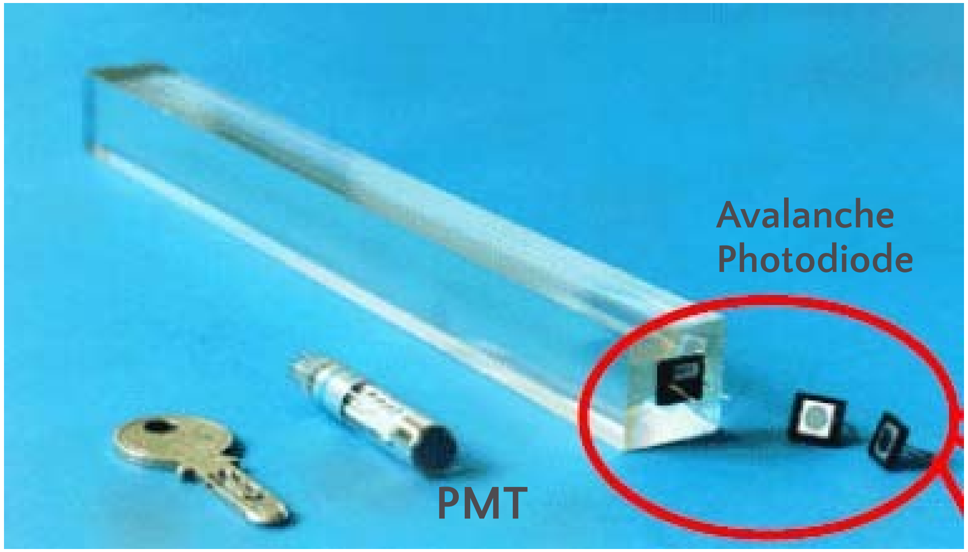
Photodetectors

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

Light guides





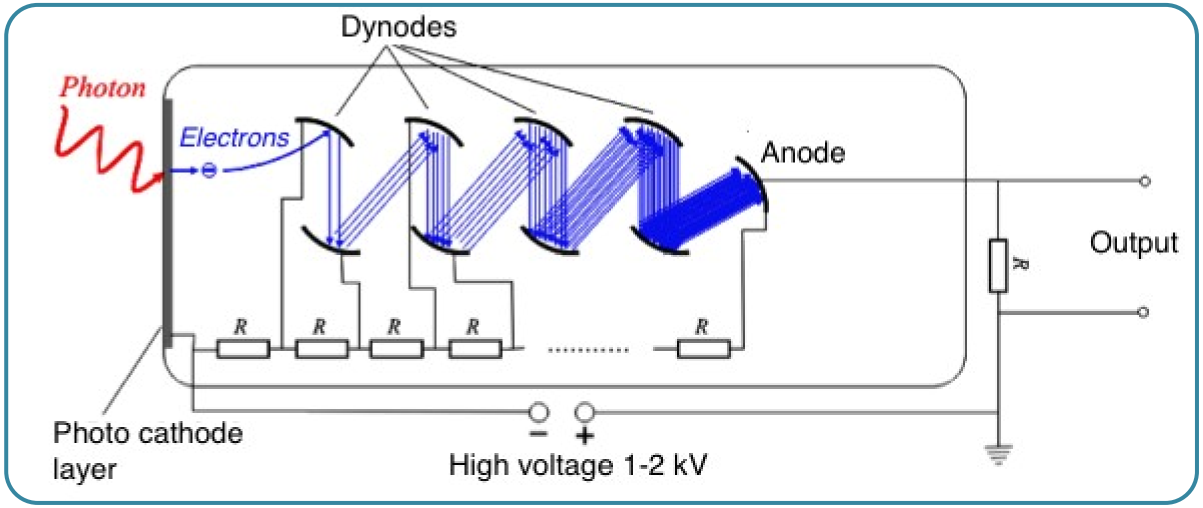


Large PMT

Photomultipliers

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

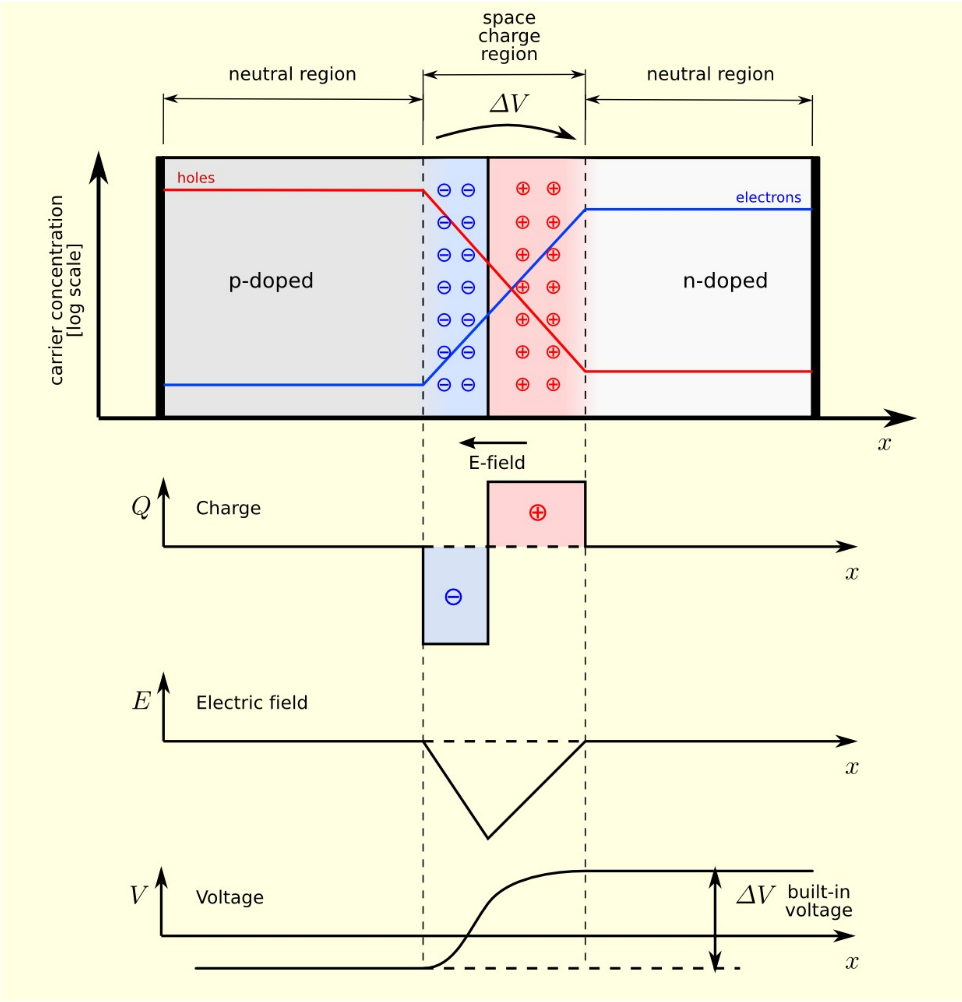
Varieties of PMT



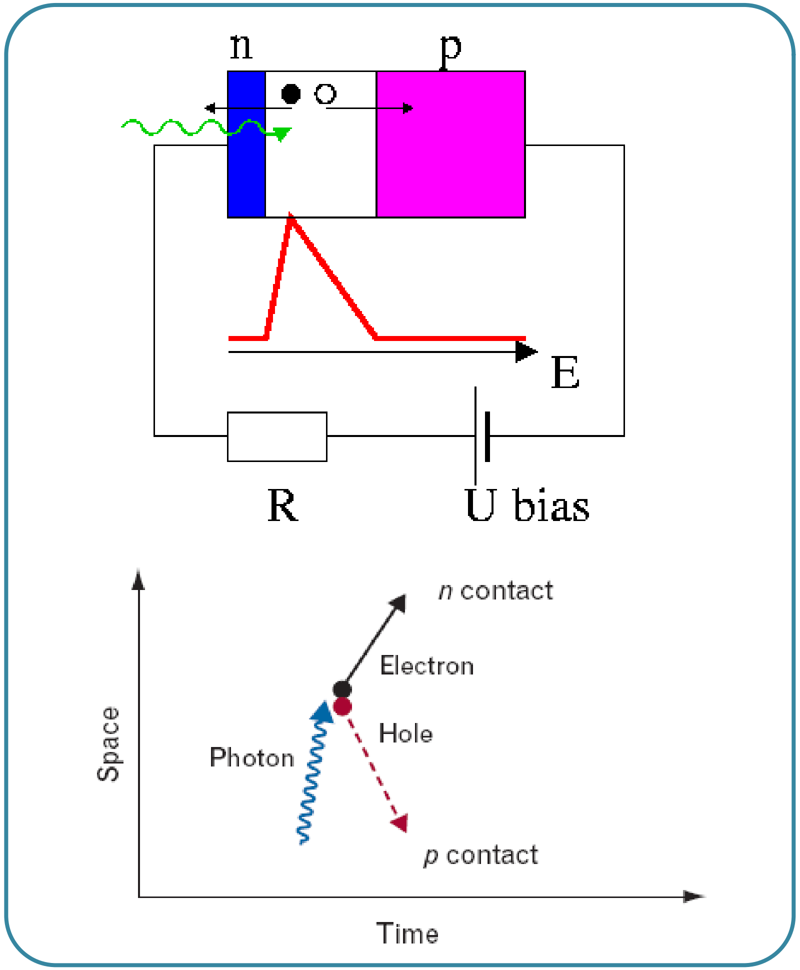
Signal amplification

PN diodes

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



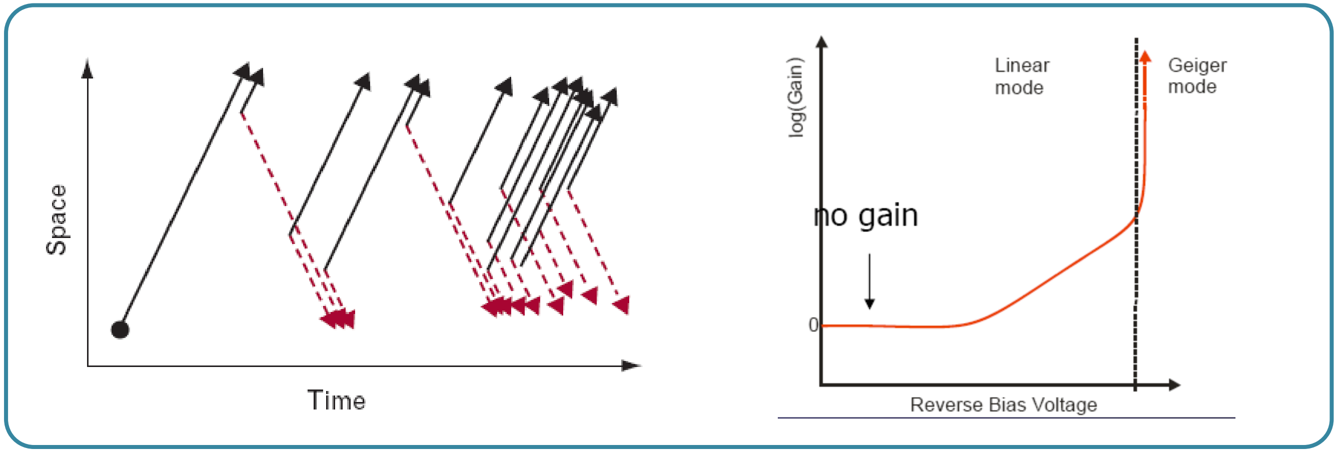
Photodetector based on PN diode



Silicon PM, Avalanche Photo Diodes

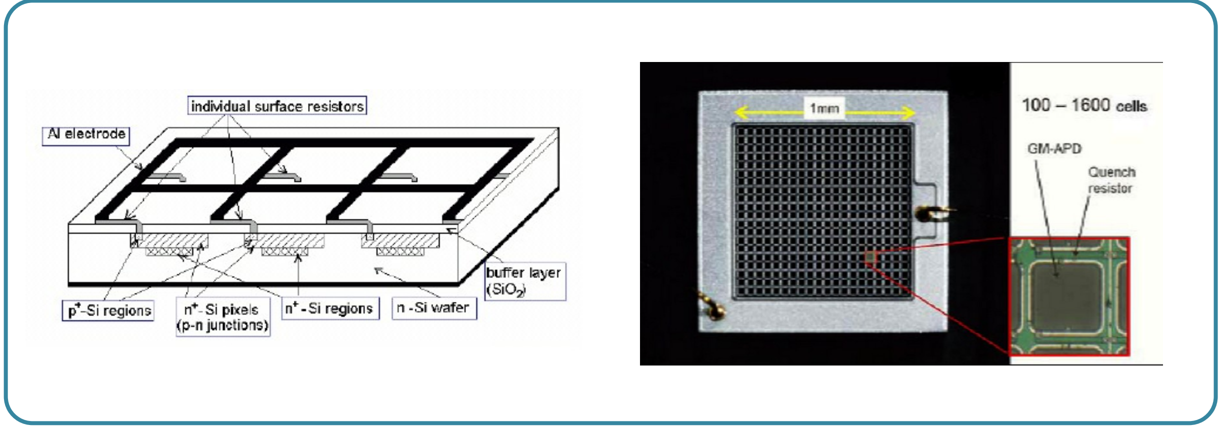
- Applying a reverse voltage above breakdown
  - Creates electron-hole multiplication

PN diode in breakdown mode



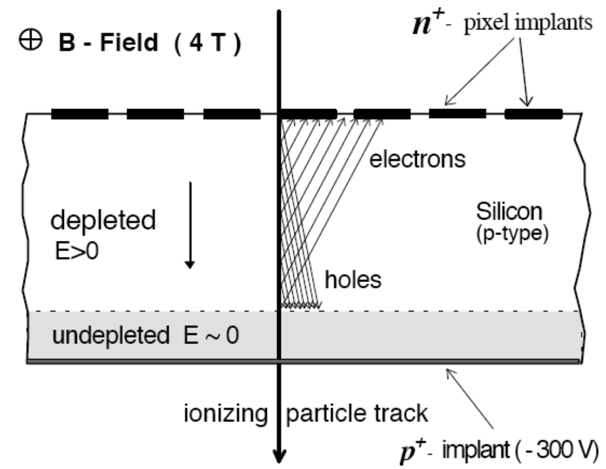
- Linear mode = Avalanche Photo Diode (APD)
- Geiger mode APD
  - Binary mode
  - → Silicon PM
  - Arrays of G-APD

Array of Geiger mode APD

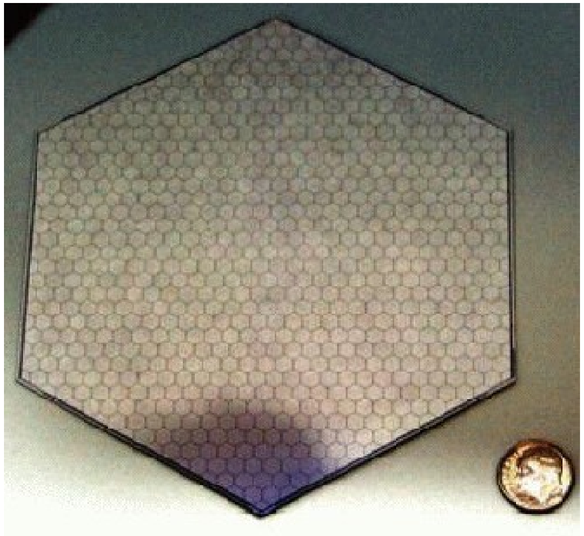


Direct charge collection with semiconductor detectors

- 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 thickness: few 100 microns
- High bias voltage: few 100V

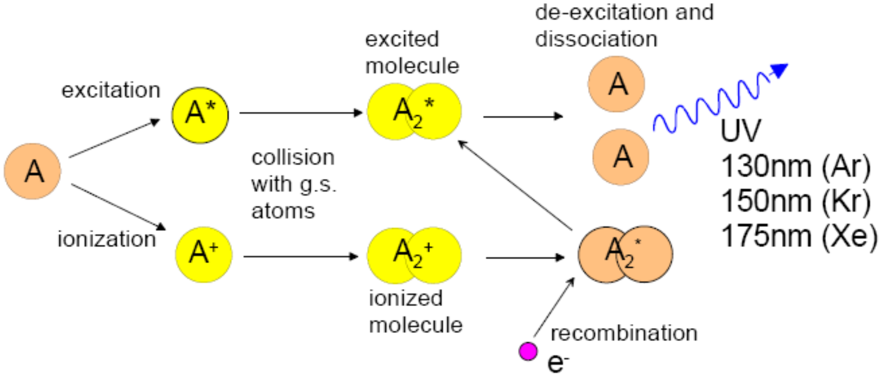


Silicon sensors with hexagonal cells

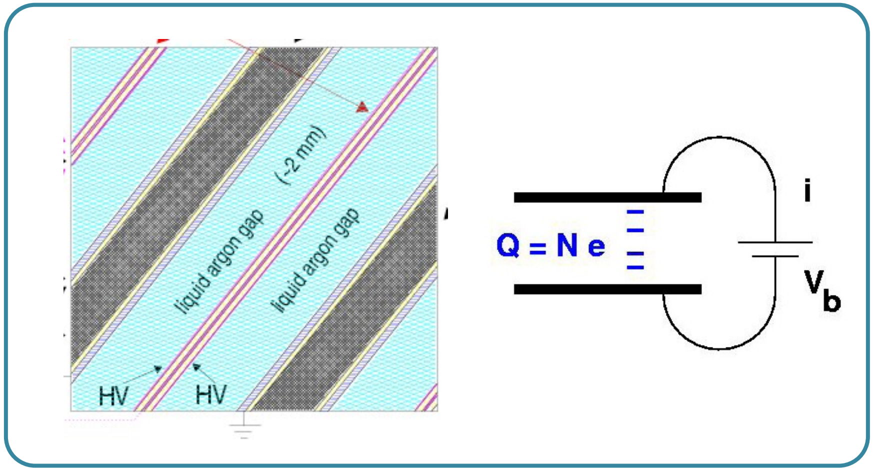


Direct charge collection with noble liquids

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



Charge collection



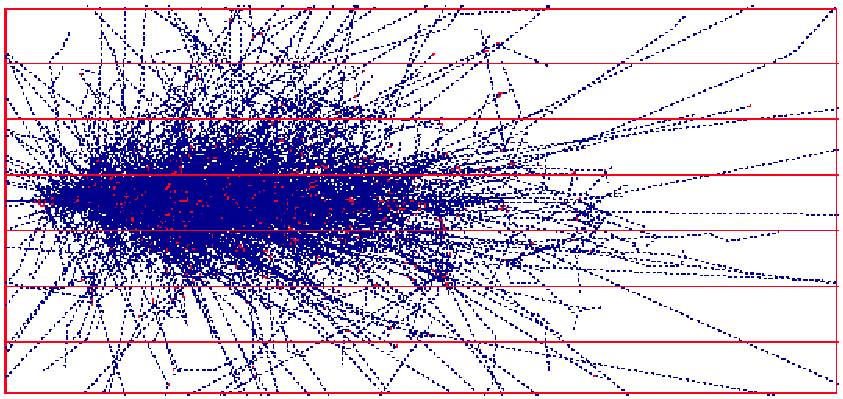
Noble liquids characteristics

	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

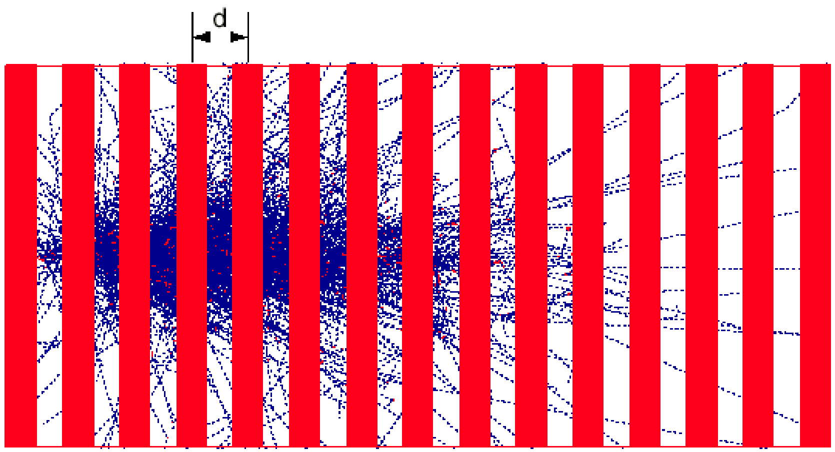
- Similar principles can also be used in gas detectors
  - But low density, so amplification needed → less stable
  - Larger detectors

Two calorimeter types

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



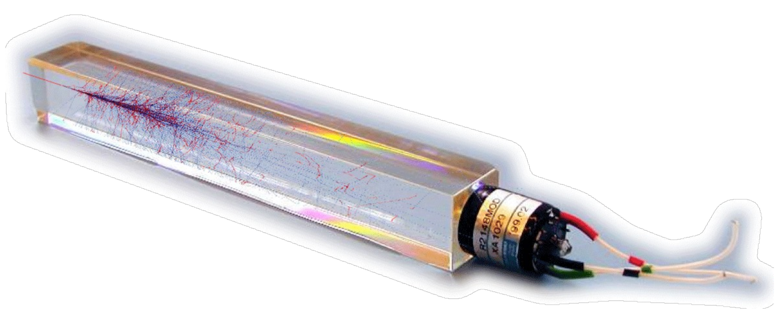
- Sampling calorimeter
  - Two materials
    - One for shower development (absorber)
    - One for signal collection (detectors / active material)
  - Only energy deposited in active material is collected
    - The shower is sampled

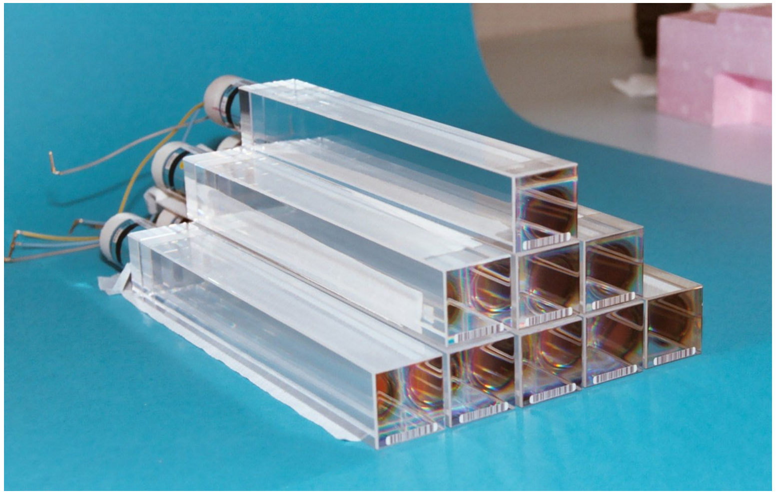


Homogeneous calorimeters

- 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 $PbWO_4$ crystals





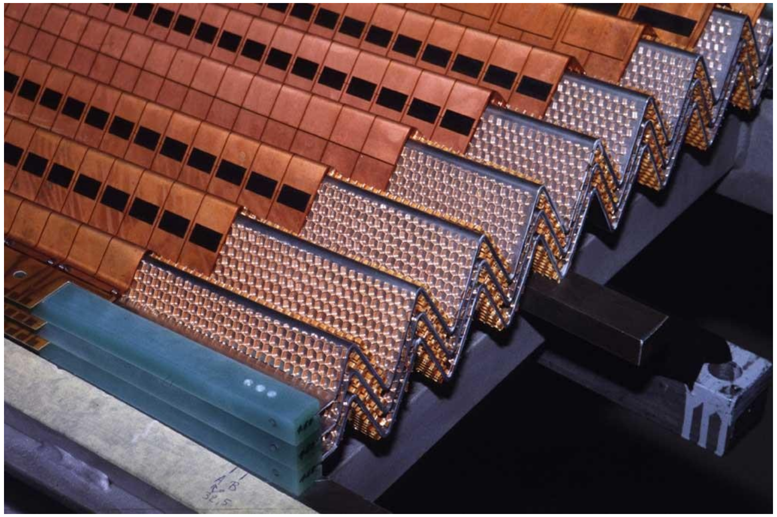
Sampling calorimeter

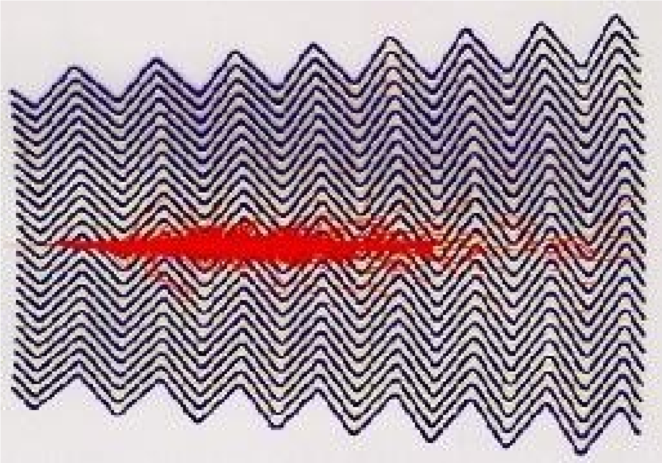
- Absorber with high-density material
- Interleaved with active readout devices
- Lower cost than homogeneous calorimeters
- And can have longitudinal segmentation
- But
  - Only part of the shower energy is collected
  - Fluctuation of energy deposited in active layers
    - Proportional to number of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

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

    - And less charges deposited compared to homogeneous calorimeters

ATLAS Liquid Argon ECAL

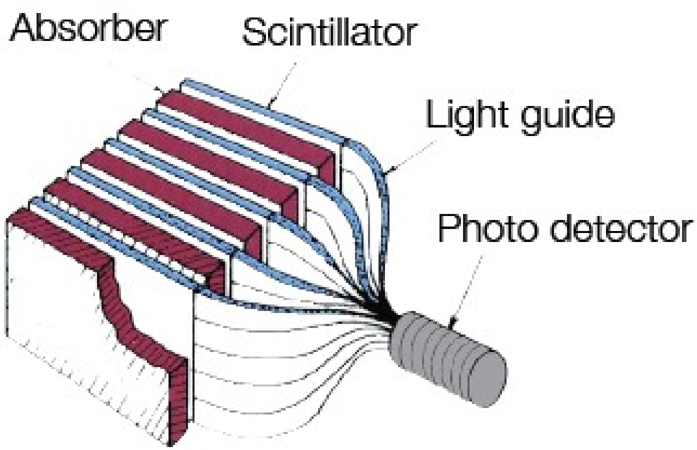




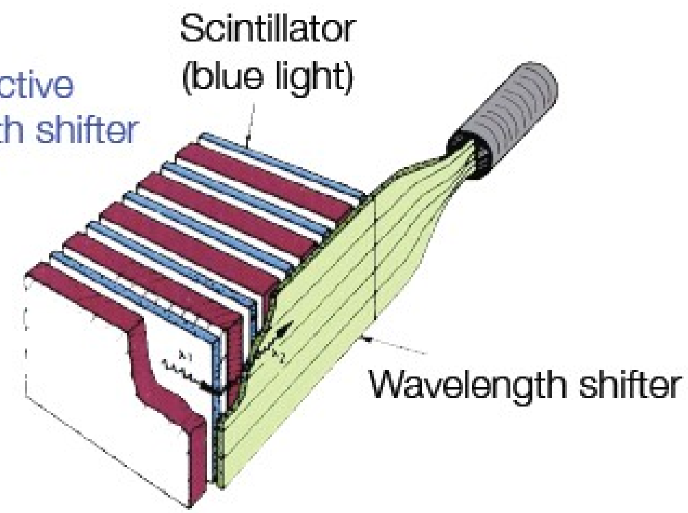
Some types of sampling calorimeters

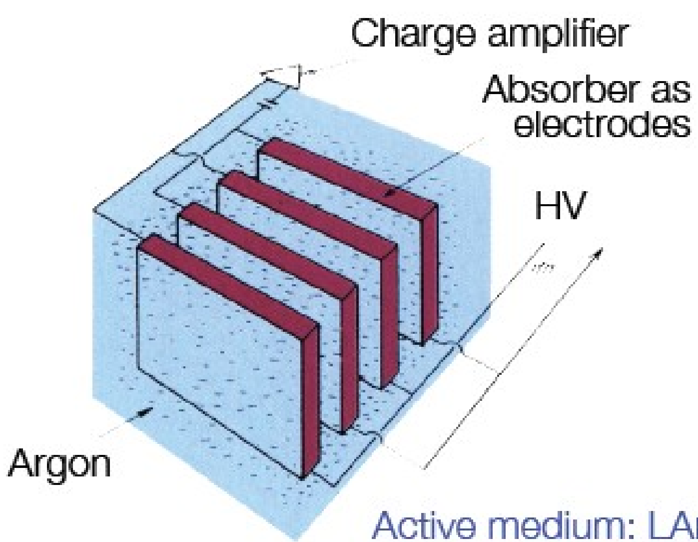
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



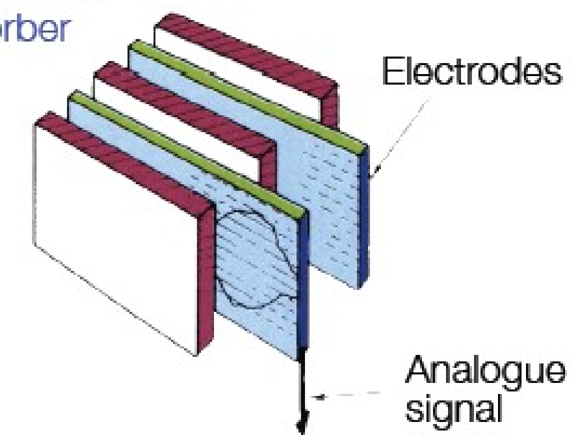
Scintillators as active layer; wave length shifter to convert light





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

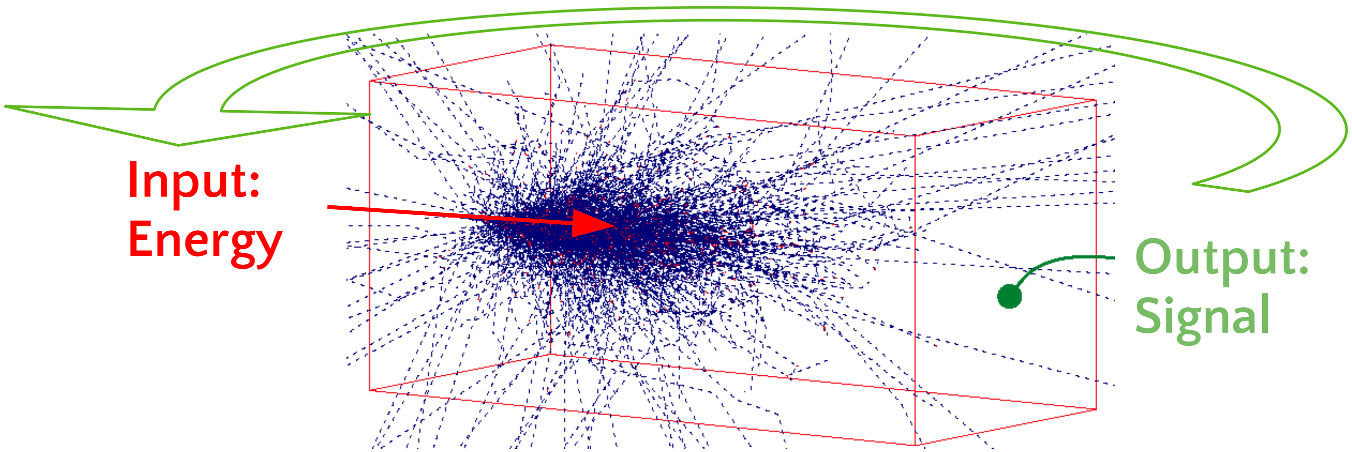
Beyond calorimetry: Particle Flow

Calorimetry and Machine Learning

Examples of calorimeters Present and future

Measurement of showers

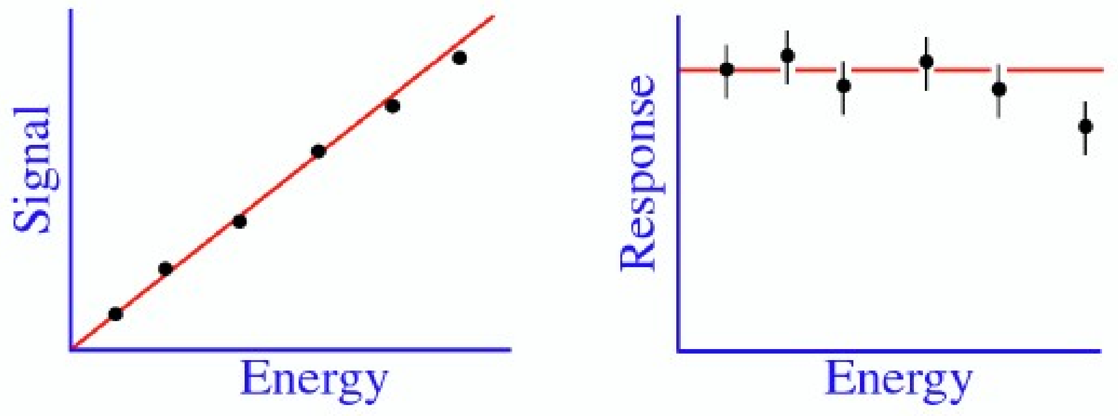
- From collected signal back to the energy of the particle



- 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

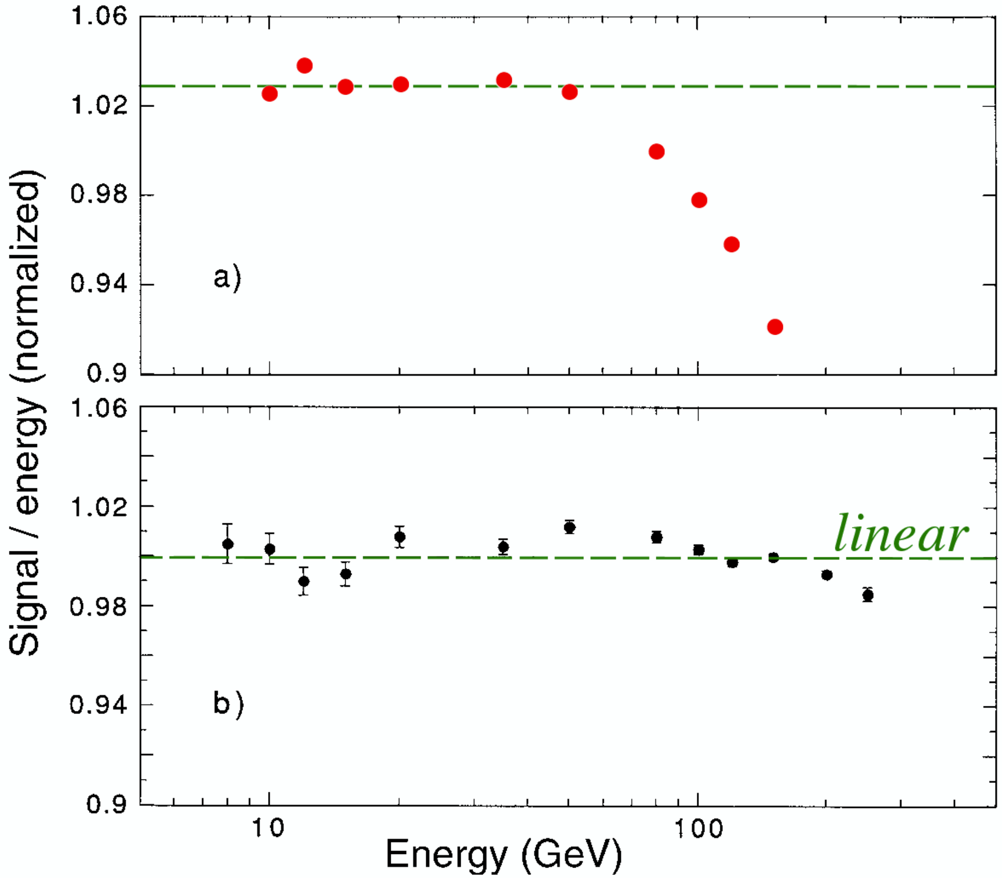
- Response: average signal per unit of deposited energy
- A linear calorimeter has a constant response
  - The signal is proportional to the deposited energy



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

Instrumental sources of non-linearity

- Instrumental effects
  - Saturation of scintillators, photo-detectors, electronics



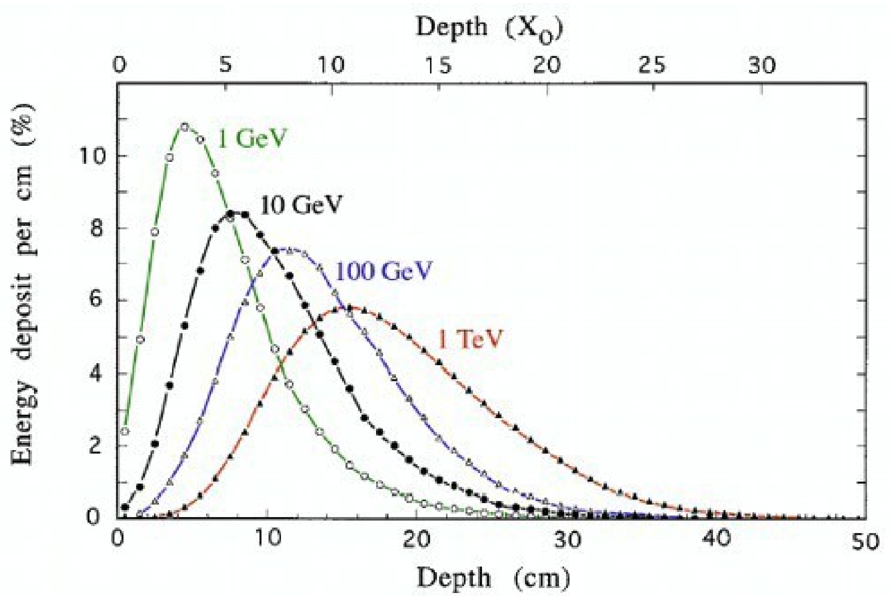
PMT saturation in QFCAL calorimeter

After correction of this saturation

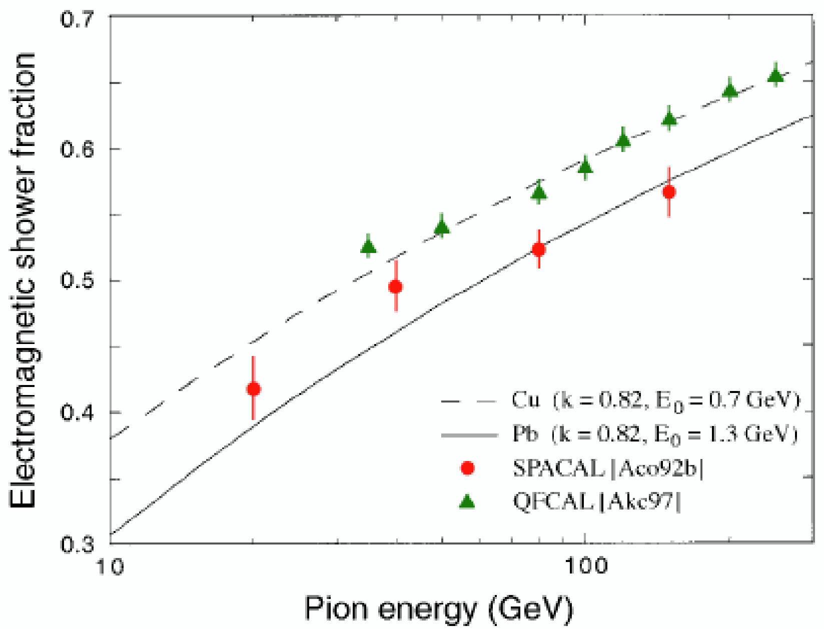
Sources of non-linearity

- Non-linearity appears if response varies with something that varies with energy
  - Deposited energy counts differently depending on depth
    - And depth increases with energy
  - Electromagnetic and hadronic energies count differently
    - And EM fraction increases with energy
- Energy leakage`

Longitudinal profile vs energy



EM fraction vs energy

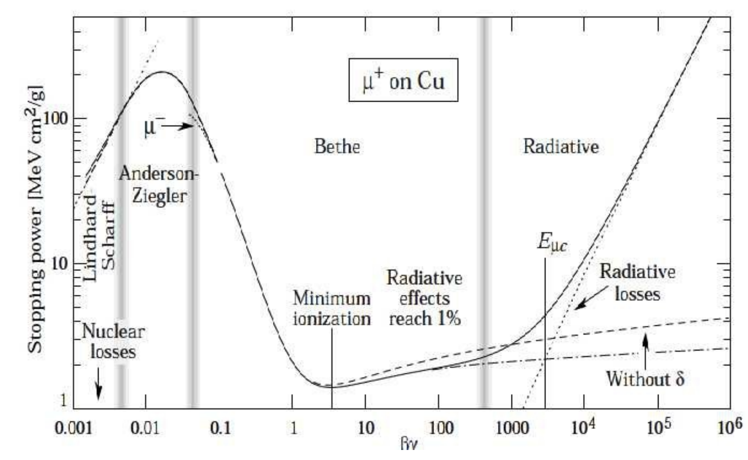


Sampling: EM vs mip response

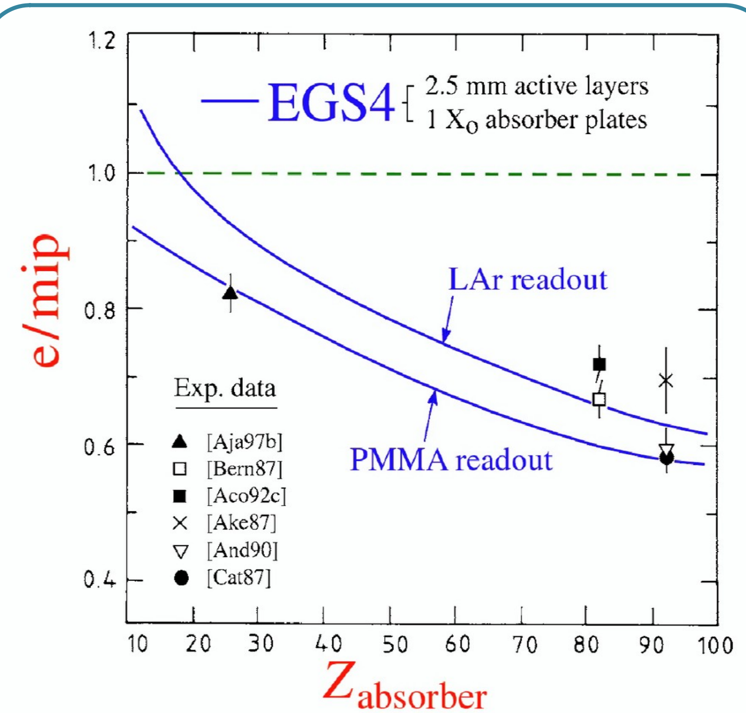
- Homogeneous calorimeters
  - Same response for EM showers and mips (e/m=1)
- Sampling fractions defined for a minimum ionizing particle (mip)

$$f_{samp} = \frac{(dE/dx)_{mip}^{active}}{(dE/dx)_{mip}^{total}}$$

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

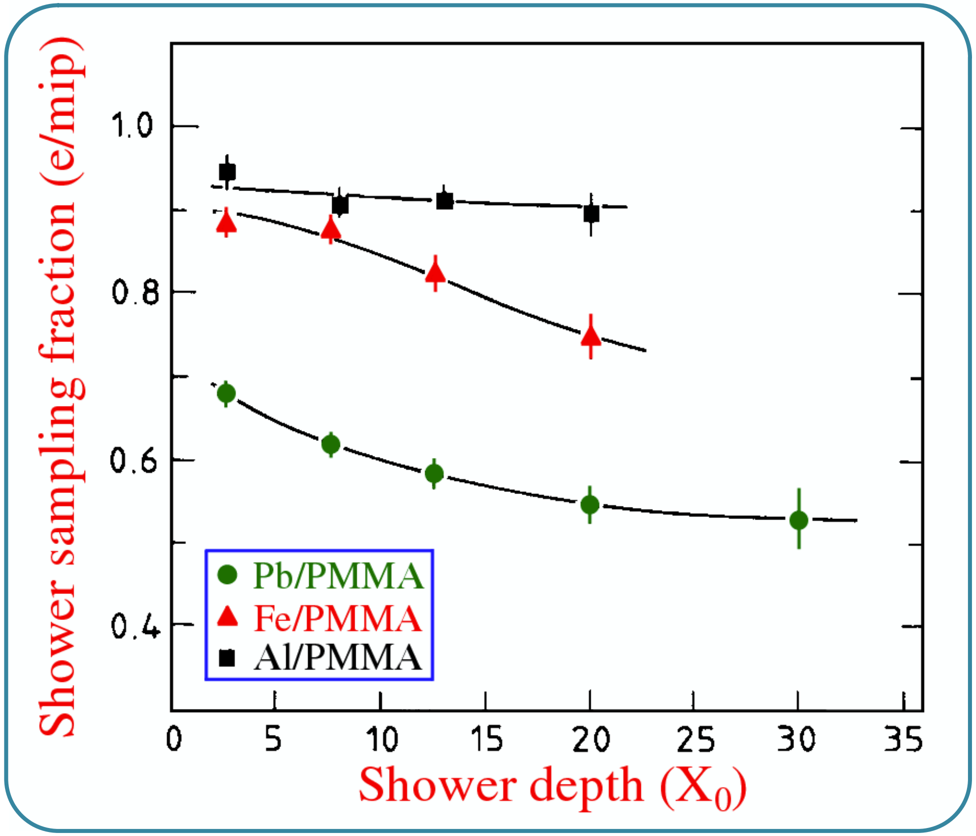


e/m vs absorber Z



Sampling: e/m dependence with shower depth

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



e/m vs shower depth

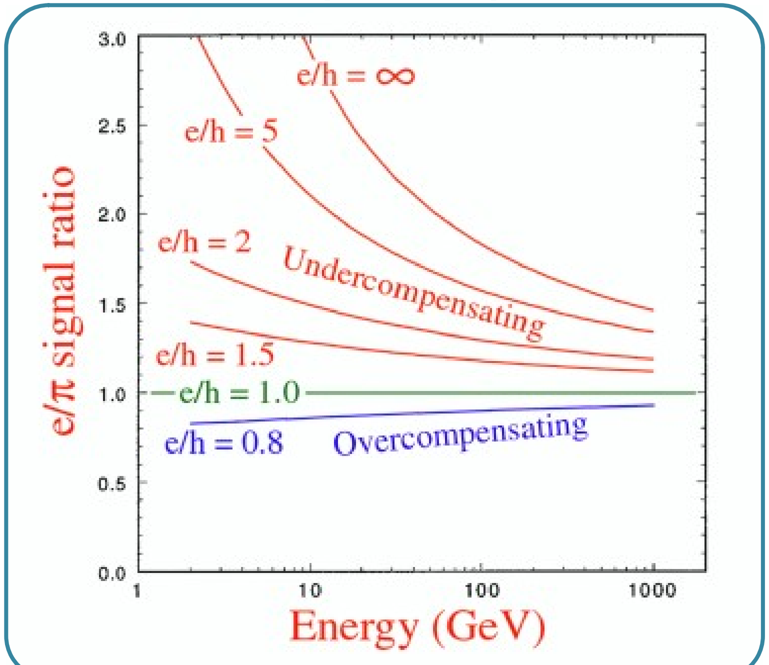
Hadronic response and compensation

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

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

- EM fraction increases with E → non linearity

Non-compensation effect on electron vs pion responses



Non-linearity and e/h

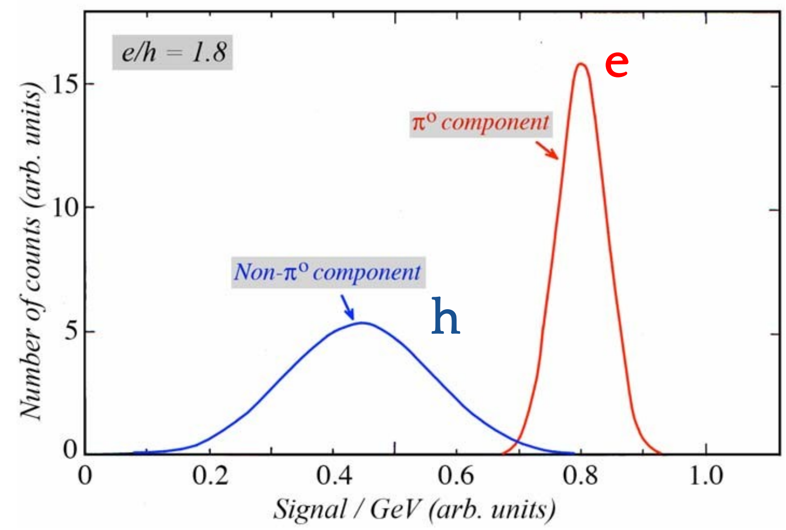
- Non-linearity determined by e/h

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

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

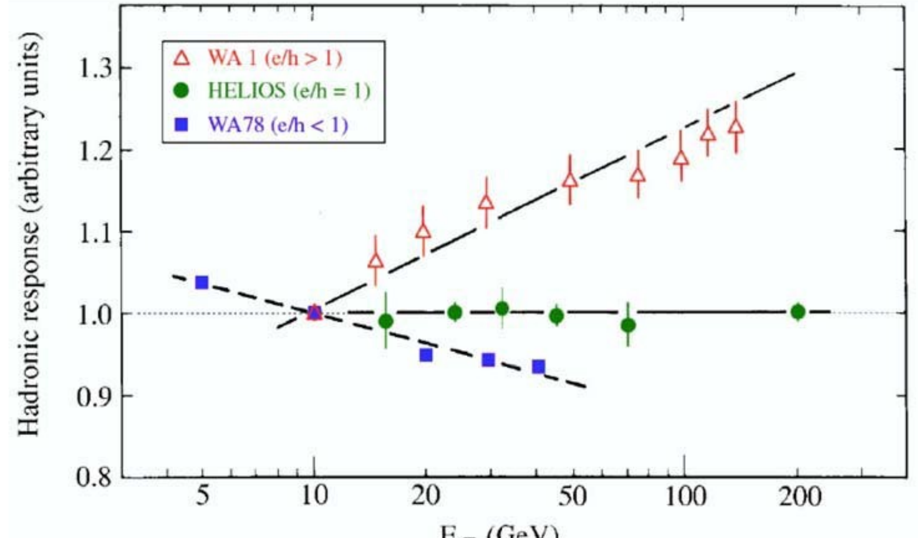
$$e/h=1\Rightarrow\frac{\pi(E1)}{\pi(E2)}=1$$

The origin of non linearity



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

Pion responses vs energy



- Non-electromagnetic shower energy split
  - 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}

< 1

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

= 0

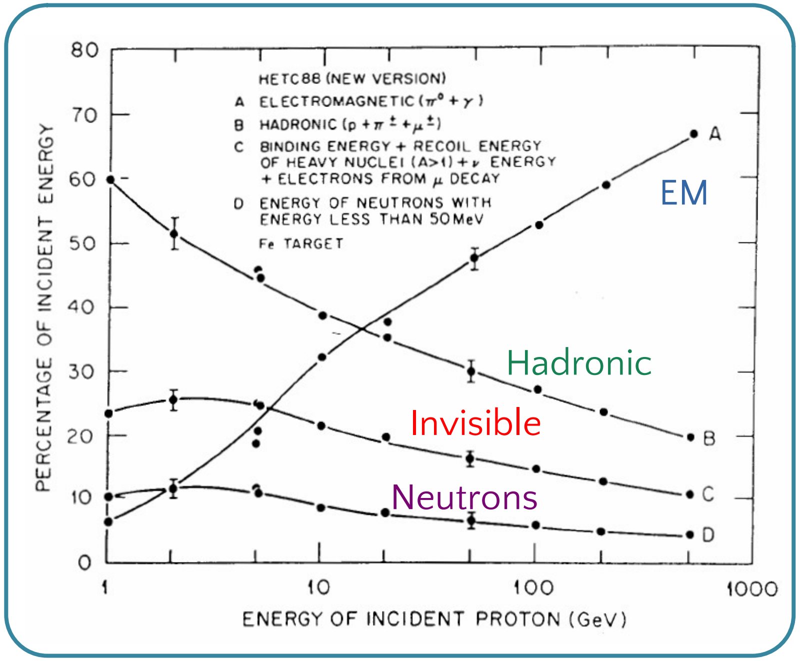
= 1 (similar to mip in their ionization loss)

> 1 (more efficient sampling)
But saturates

> 1 (through elastic scattering)

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

Sharing of energy between components



Increasing neutron response

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

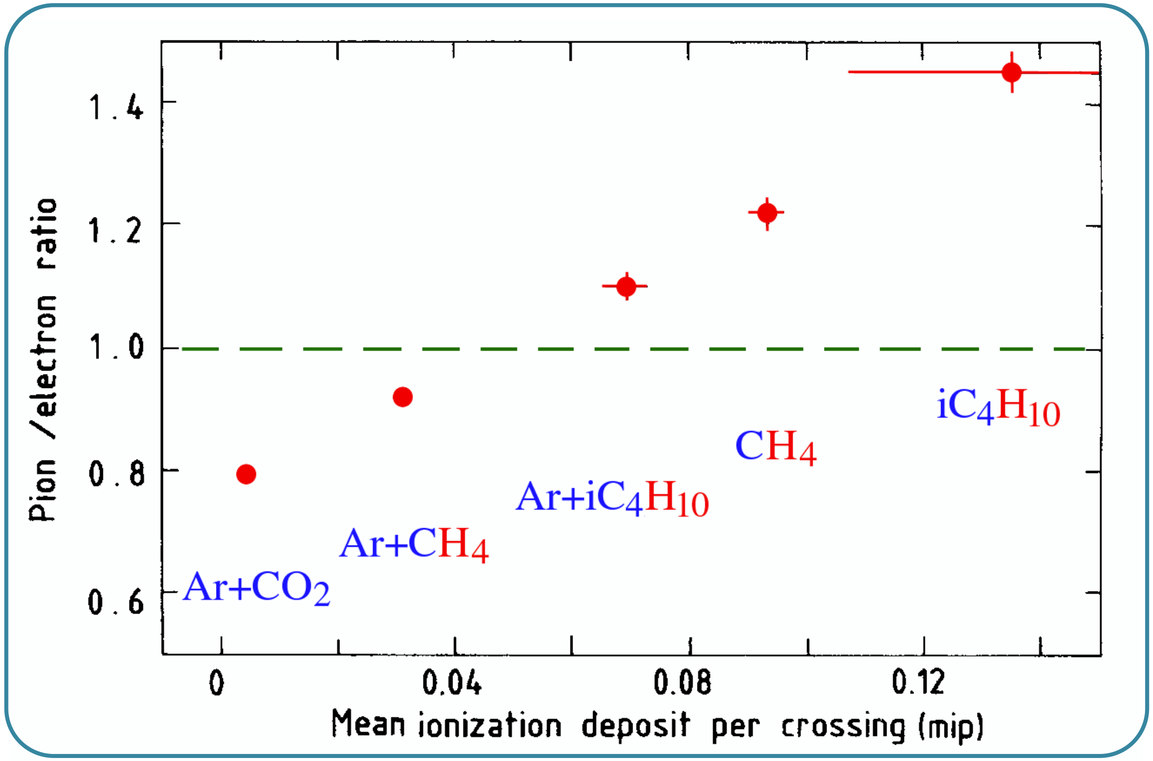
  n/mip = 45
- Pb / H_2 calorimeter structure with 90/10 sharing
  - 1 MeV neutron deposits 87% in H_2
  - mip deposits 0.25% in H_2

  n/mip = 350

Tuning neutron response with active material

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

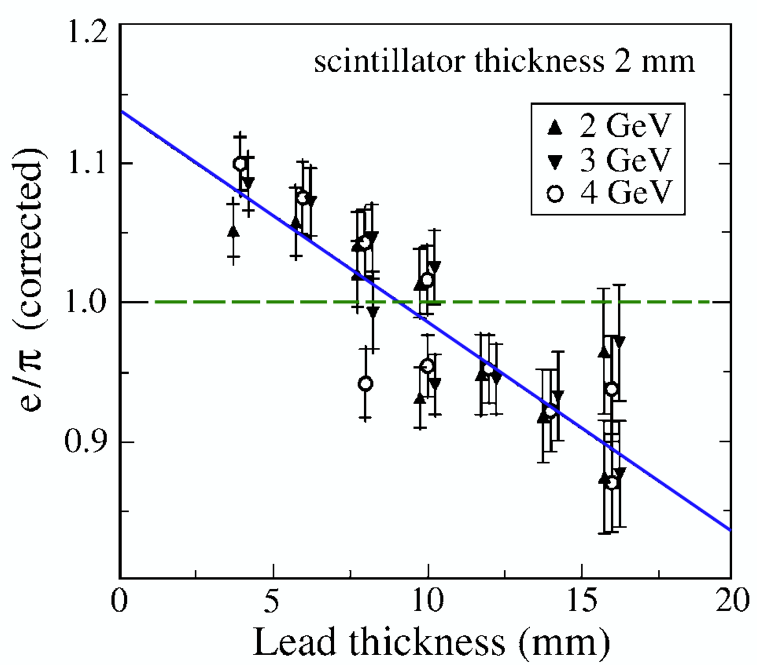
π/e for several materials, with different energy deposits by slow neutrons (Uranium / gas calorimeter with different gas mixtures)



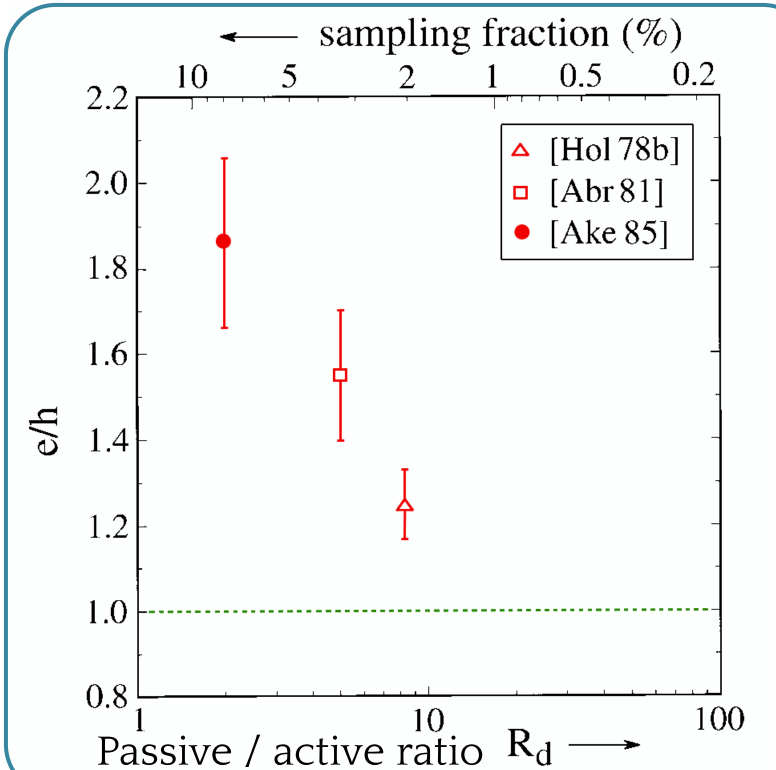
Tuning neutron response with sampling fraction

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

e/π for Pb / Scint calorimeters



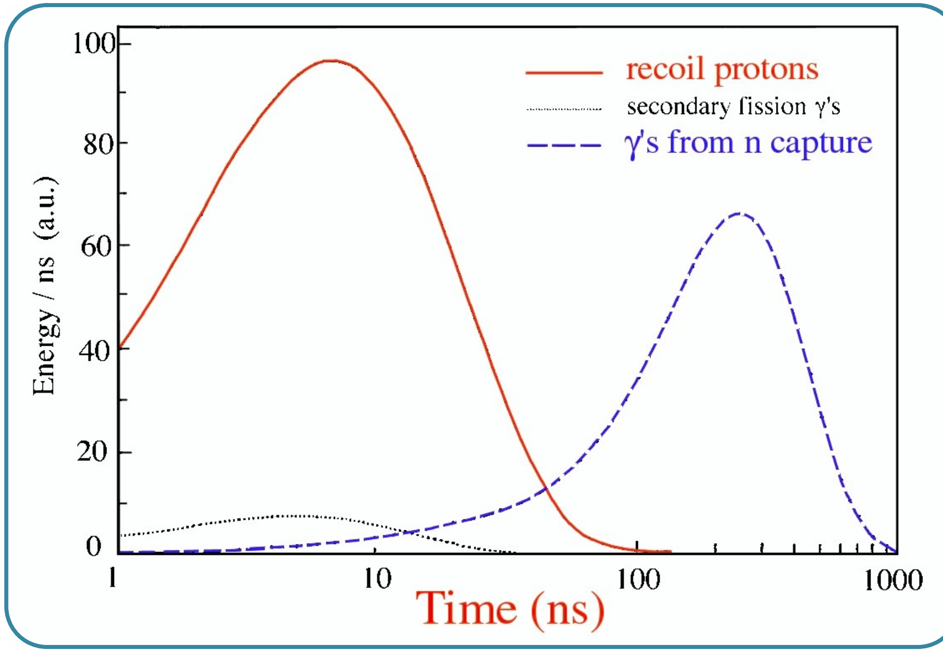
e/h for Fe / Scint calorimeters



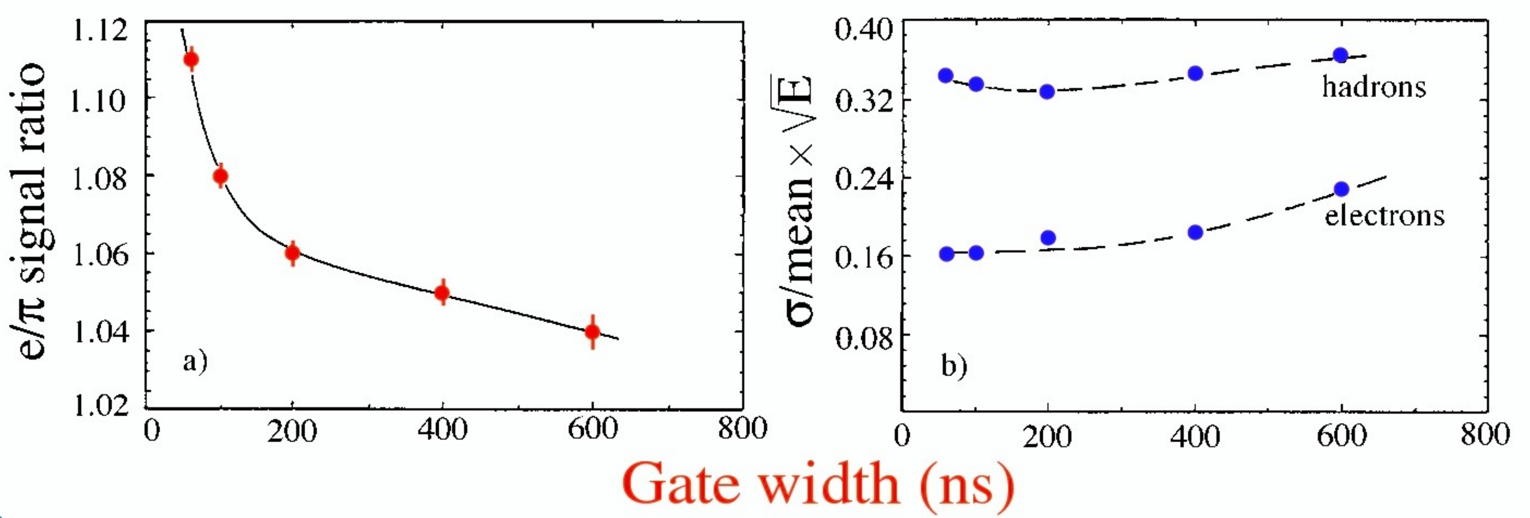
Energy released by slow neutrons

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

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



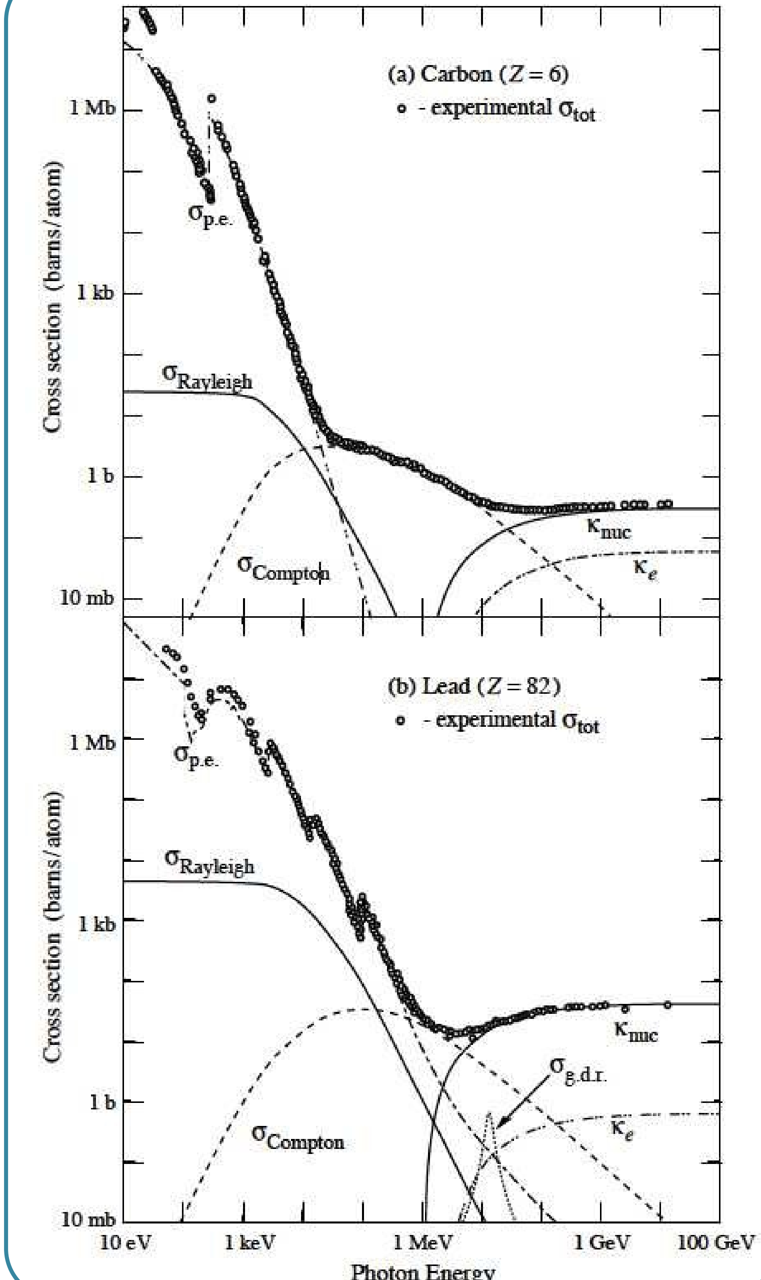
Impact of charge integration time on compensation and resolution



Decreasing EM response

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

Cross sections in Carbon and Lead



Pros & cons of compensating calorimeters

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

Energy resolution

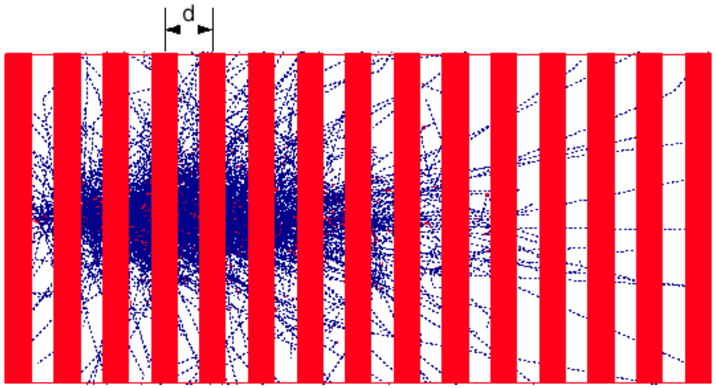
- Calorimeter's energy resolution is determined by fluctuations
- Input energy E $\propto$ N number of secondary particles
  - Poisson distribution of N → $\sigma(E)/E \propto \sqrt{N}/N \propto 1/\sqrt{E}$
  - Although in reality only a fraction can be detected (threshold effects)
- Other types of fluctuations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

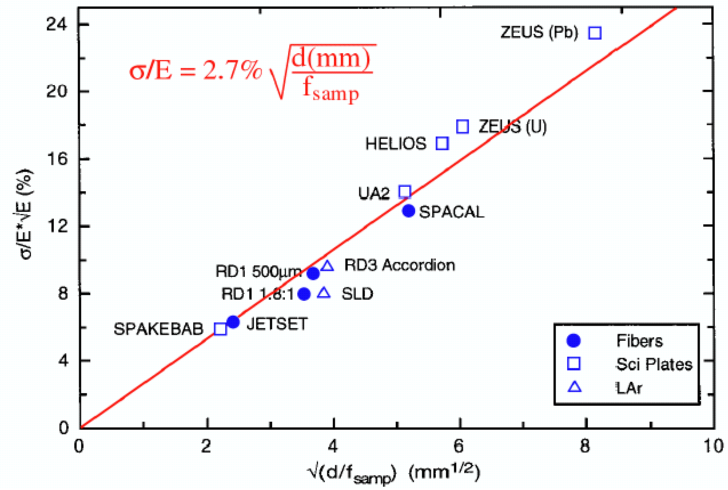
$$f_{samp} = \frac{(dE/dx)^{active}_{mip}}{(dE/dx)^{total}_{mip}}$$

  - 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



Thicker active layer → worse resolution
Lower sampling → worse resolution

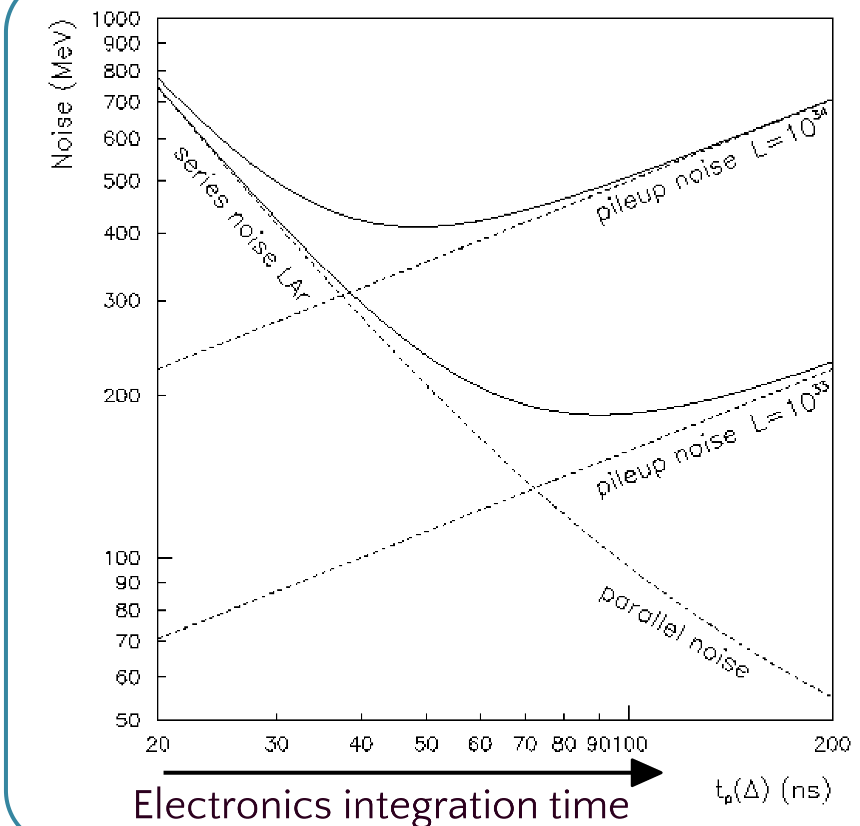
$$\frac{\sigma(E)}{E} \propto \sqrt{\frac{d}{f_{samp}}} \frac{1}{\sqrt{E}}$$



Noise

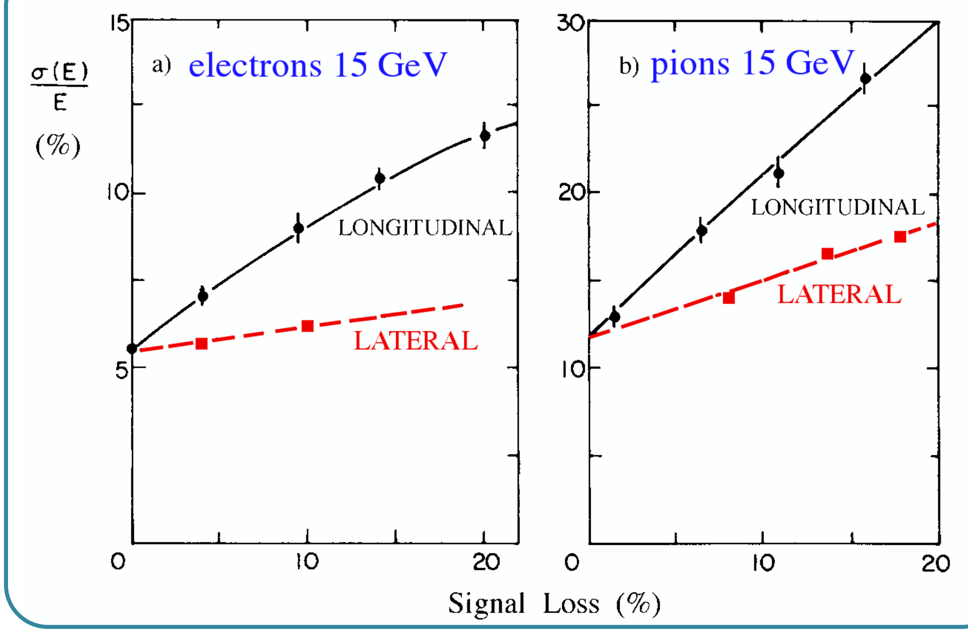
- Noise fluctuations are constant in energy
  - → Impact resolution in 1/E (mainly low energy)
- Usually comes from the electronics readout system
- But at hadron colliders
  - Contributions from pile-up interactions
  - = fluctuations due to multiple low energy collisions

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 ln(E)
  - Alleviated if calorimeter "sufficiently" deep
- Lateral leakage
  - One tends to limit the lateral size over which the signal is integrated
  - Need to limit integration of channels with low S/N
  - Need to limit integration of nearby showers



Contribution of leakage fluctuations to energy resolution

Energy resolution: parametrization

Stochastic   Constant

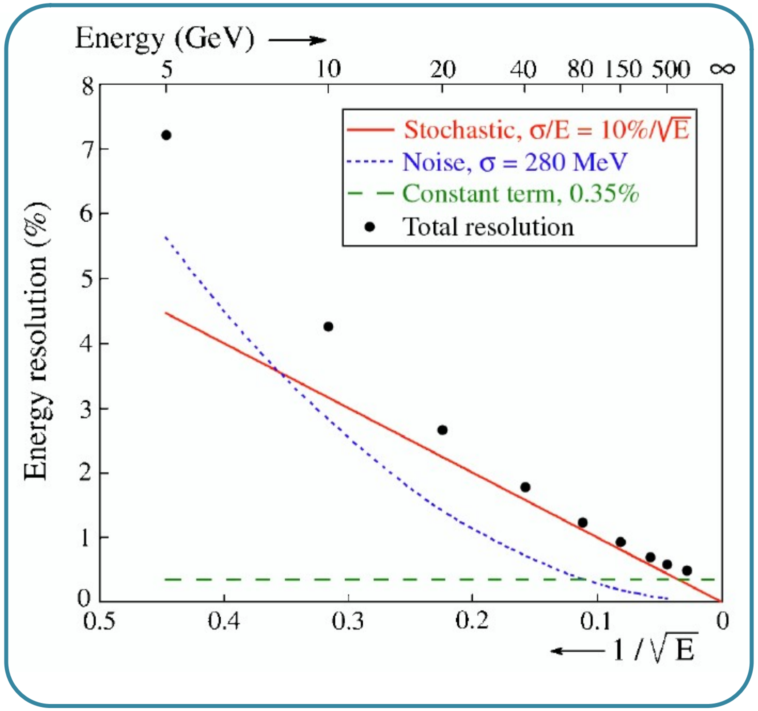
$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

Noise

$\oplus$ = quadratic sum

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

Energy resolution in EM ATLAS barrel calorimeter



Homogeneous vs sampling calorimeters

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

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

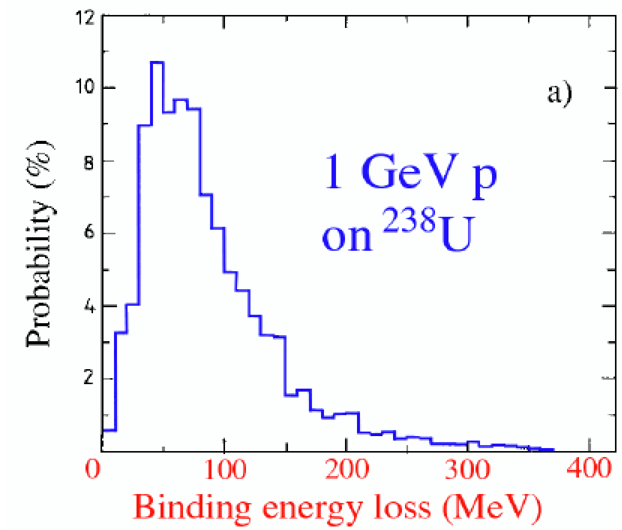
Homogeneous

Sampling

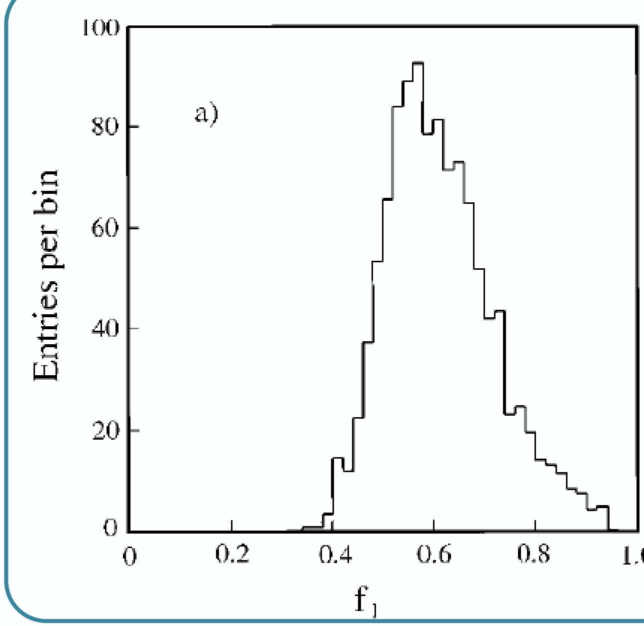
Fluctuations in hadron showers

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

Binding energy loss for 1 GeV proton in Uranium



EM fraction of 150GeV π showers in SPACAL



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

Calorimetry and Machine Learning

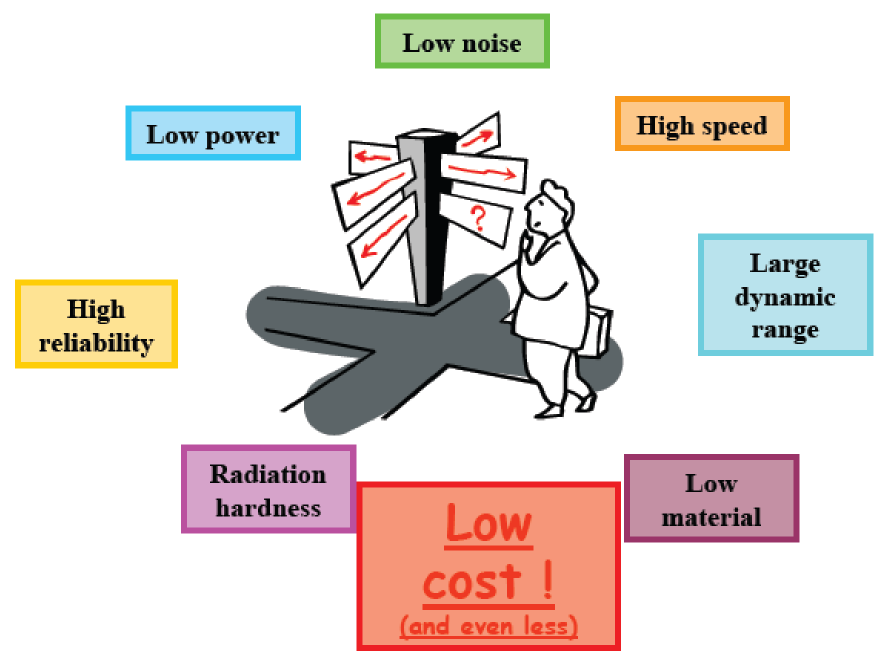
Examples of calorimeters Present and future

Signal acquisition

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

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

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



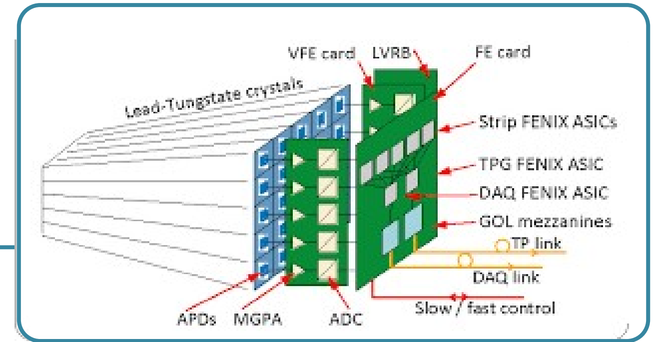
Data acquisition

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

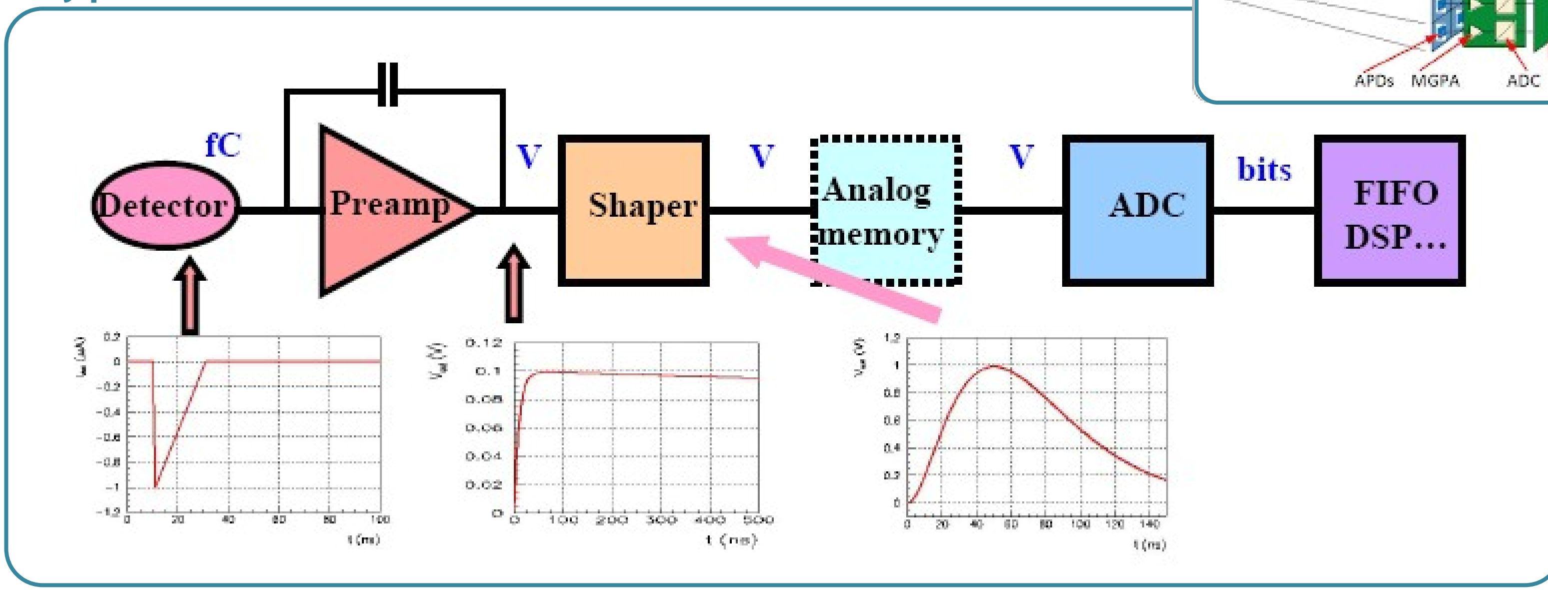
Readout electronics

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

CMS ECAL FE electronics



Typical front-end electronics chain

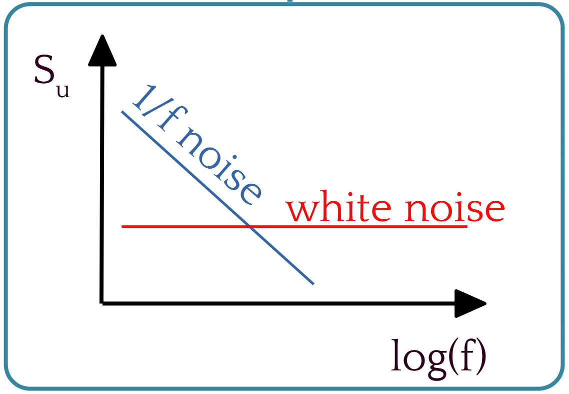


- Very small signals (fC)
  - Amplification needed
  - Optimisation of S/N (shaper)
- Need time to decide to keep the event or not → memory
- Conversion from analogue signal to digital values (ADC pulse sampling)

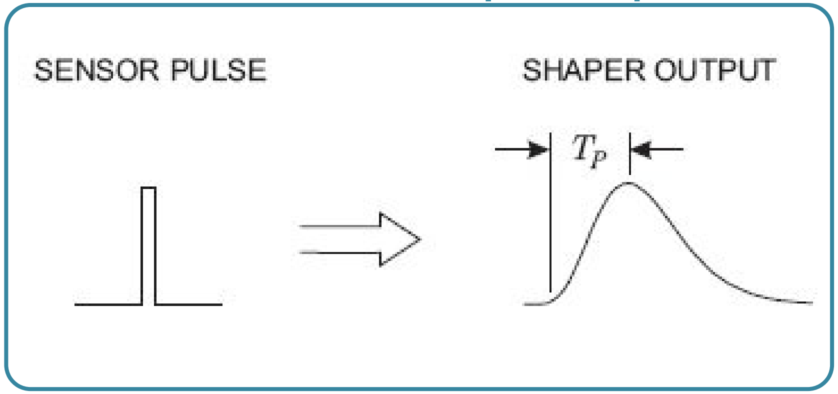
Pulse shaping

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

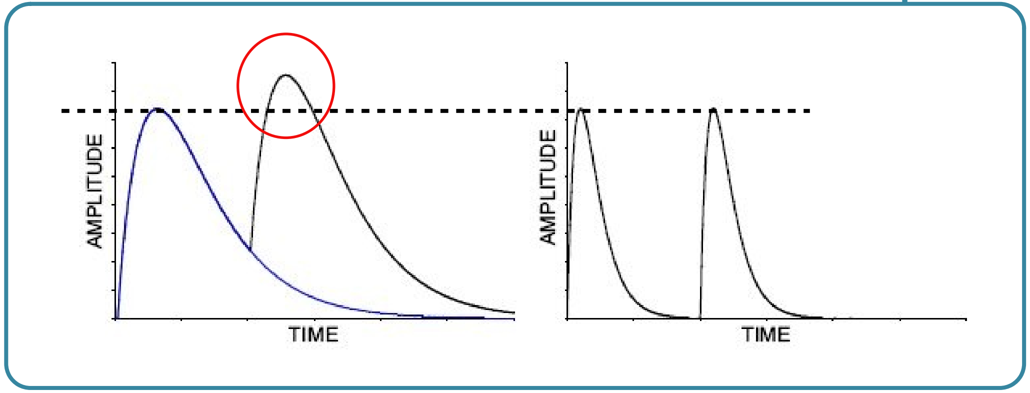
Noise spectrum



Shaper output



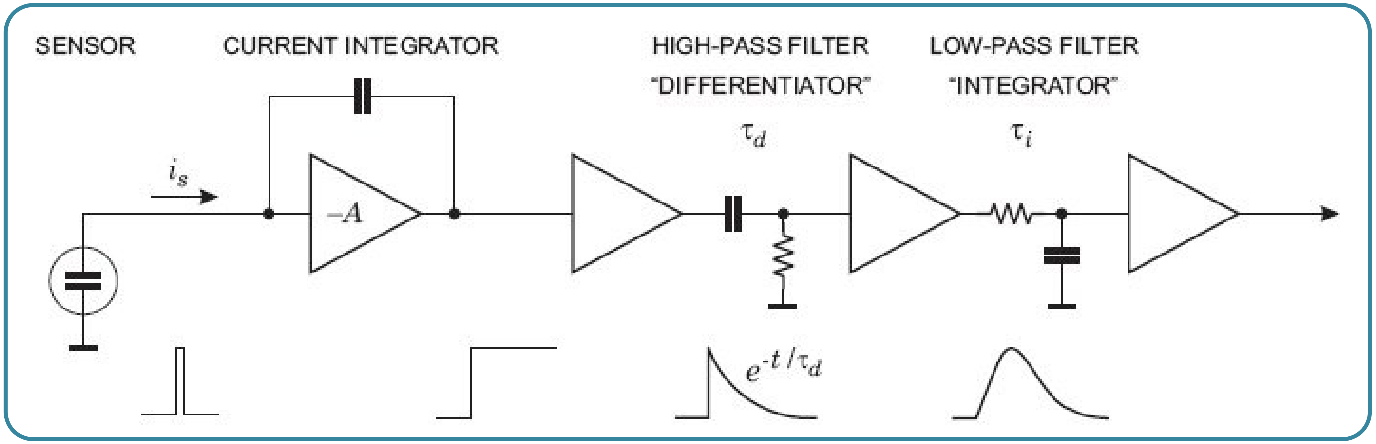
Pulse overlap



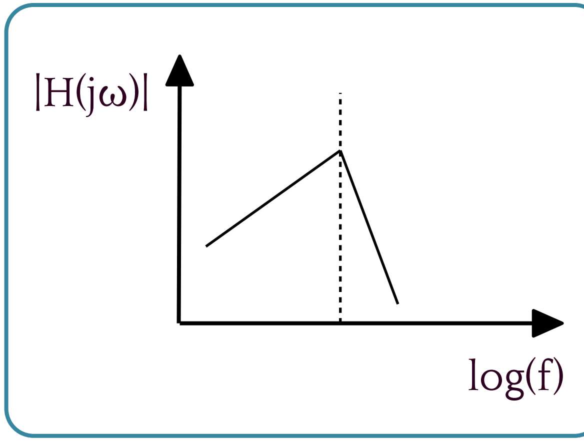
CR–RC shaper

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

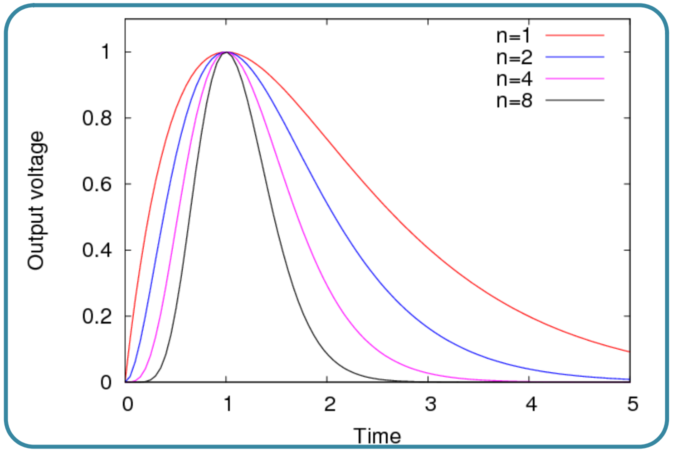
Integrator + RC–RC chain



RC–(RC)^n transfer function



Impact of filter order

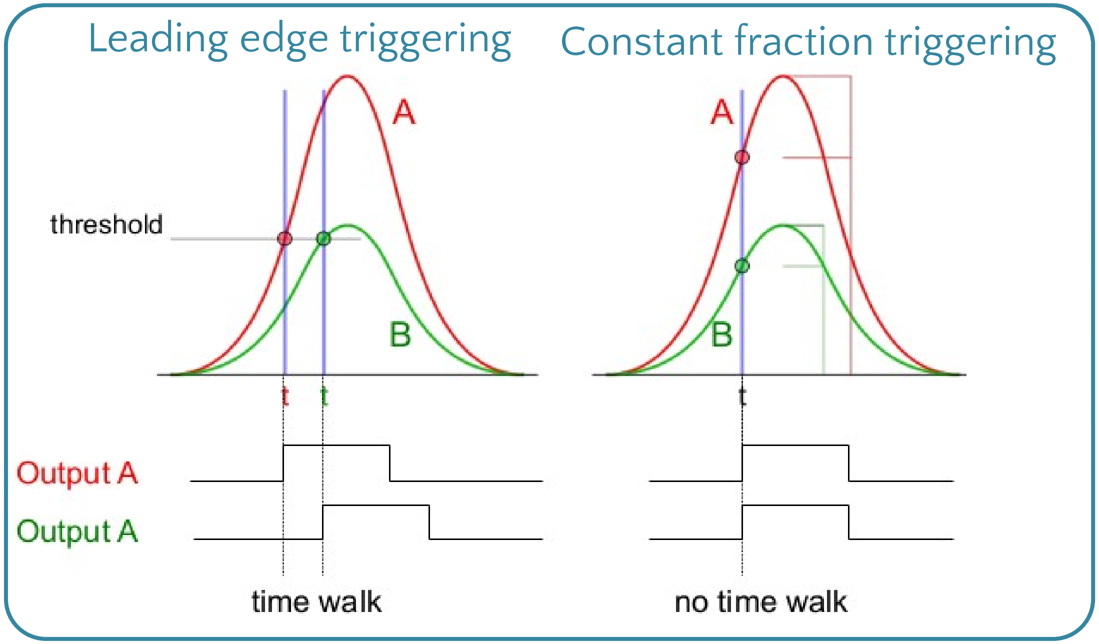


- Can also have additional RC or CR steps
  - e.g. CR–(RC)^2
  - CR–(RC)^n approximates Gaussian shape

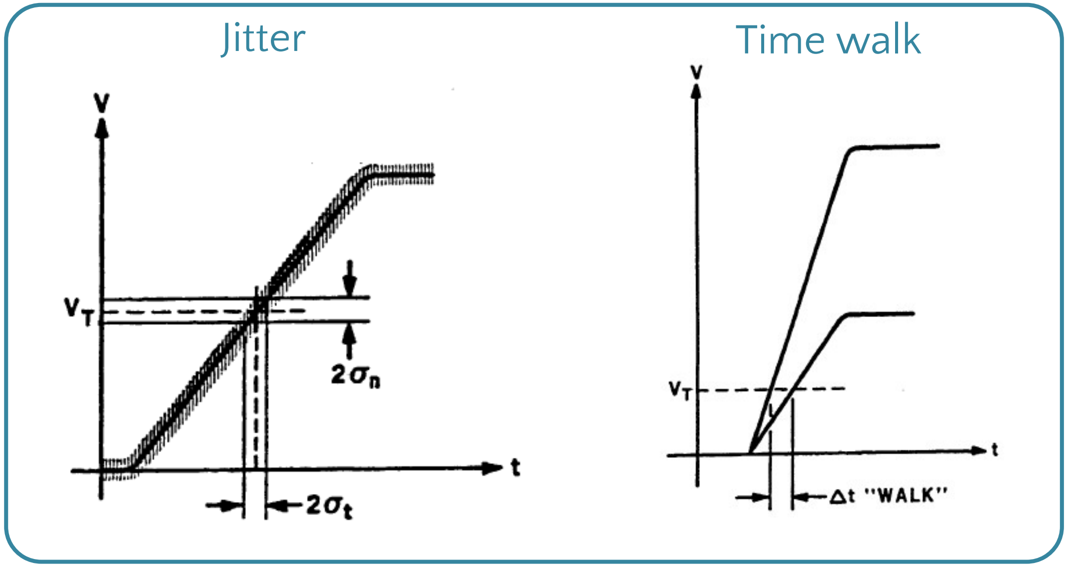
Time measurement

- 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

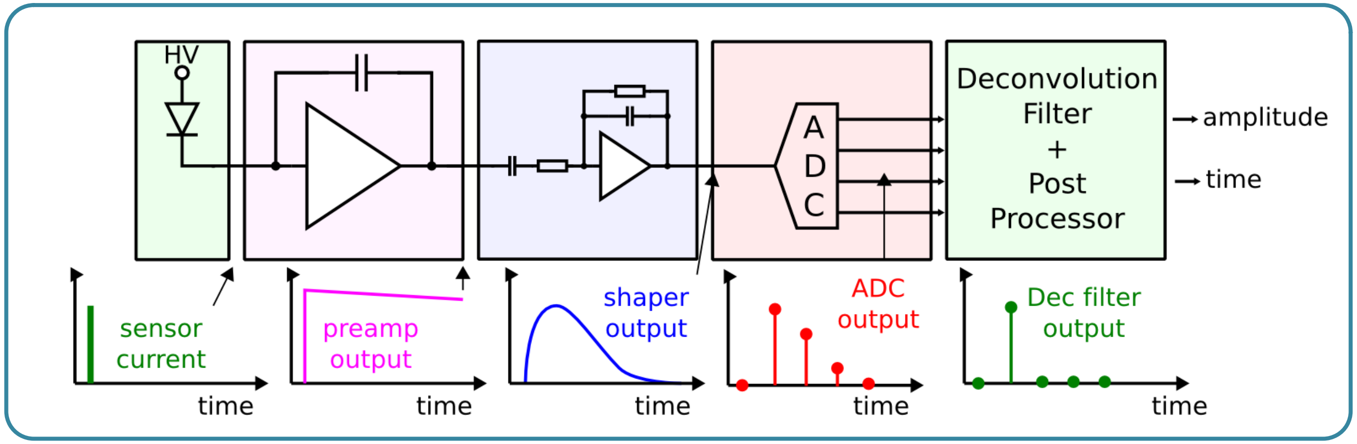


Measurement degraded by



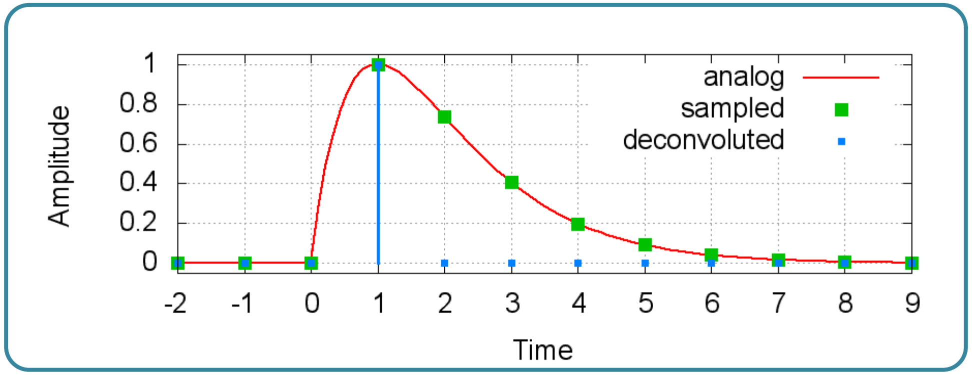
Amplitude measurement

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

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

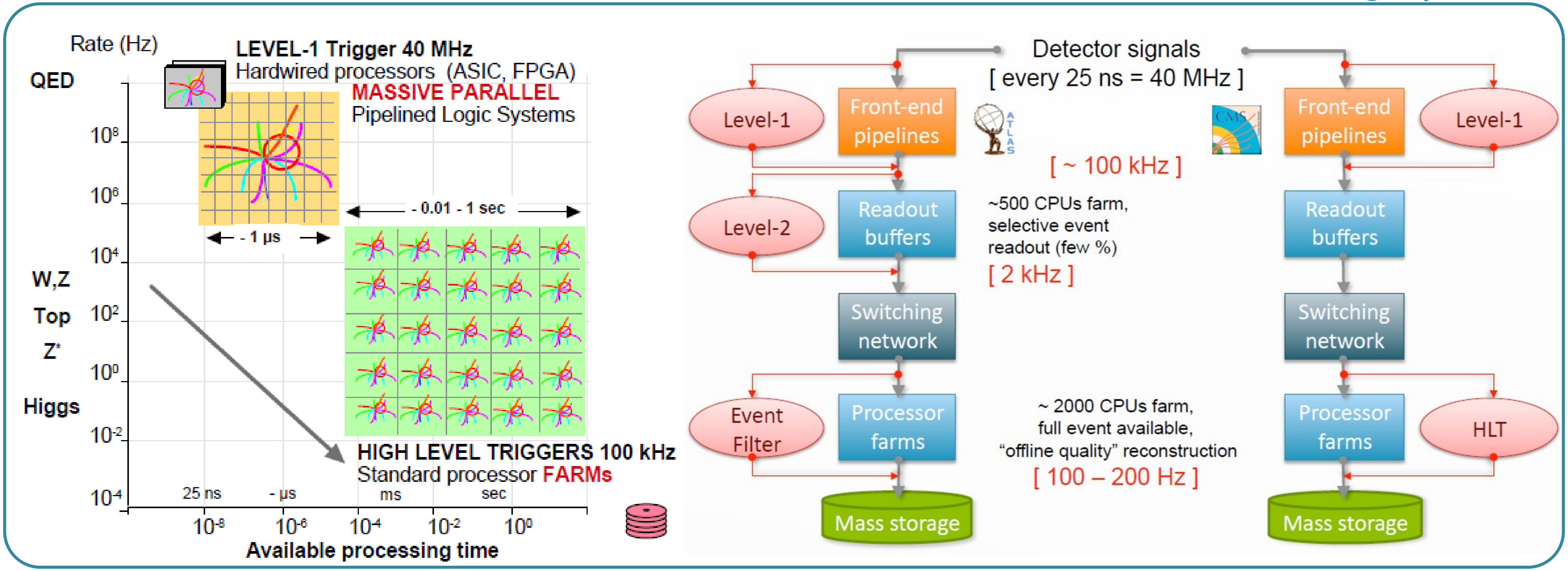


    - Weights w_i can be optimized with various techniques
    - Takes into account noise characteristics and known pulse shape
  - Peak finder to find maximum

Trigger

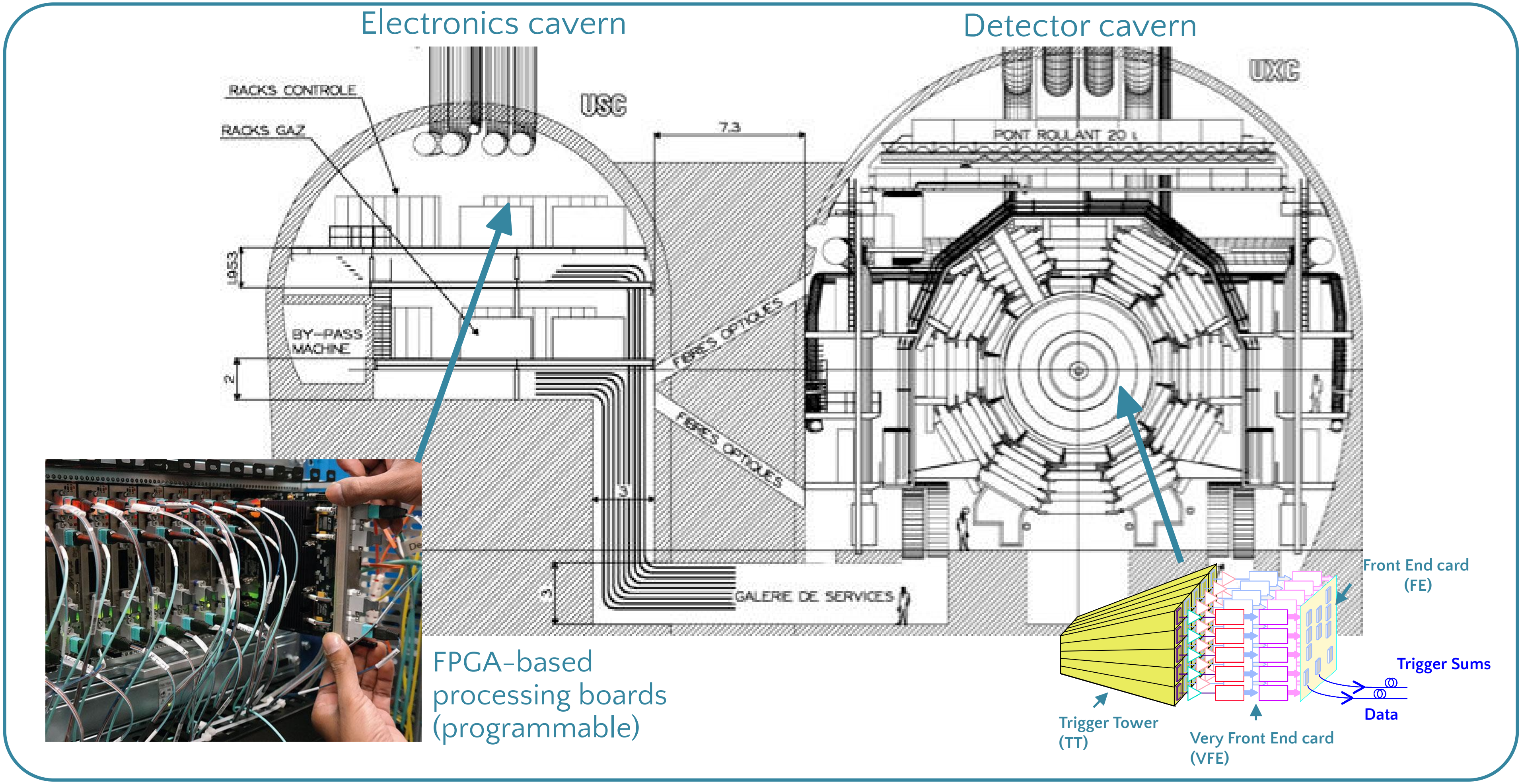
- In many cases it is impossible to store or transfer all the data from a calorimeter
  - e.g. at the LHC
- Need fast trigger system to eliminate uninteresting events
  - Trade-off between high performance (signal efficiency / background rejection)
  - And fast decision / low latency
- One solution: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

Rate reduction in multi-stage systems



Off-detector electronics

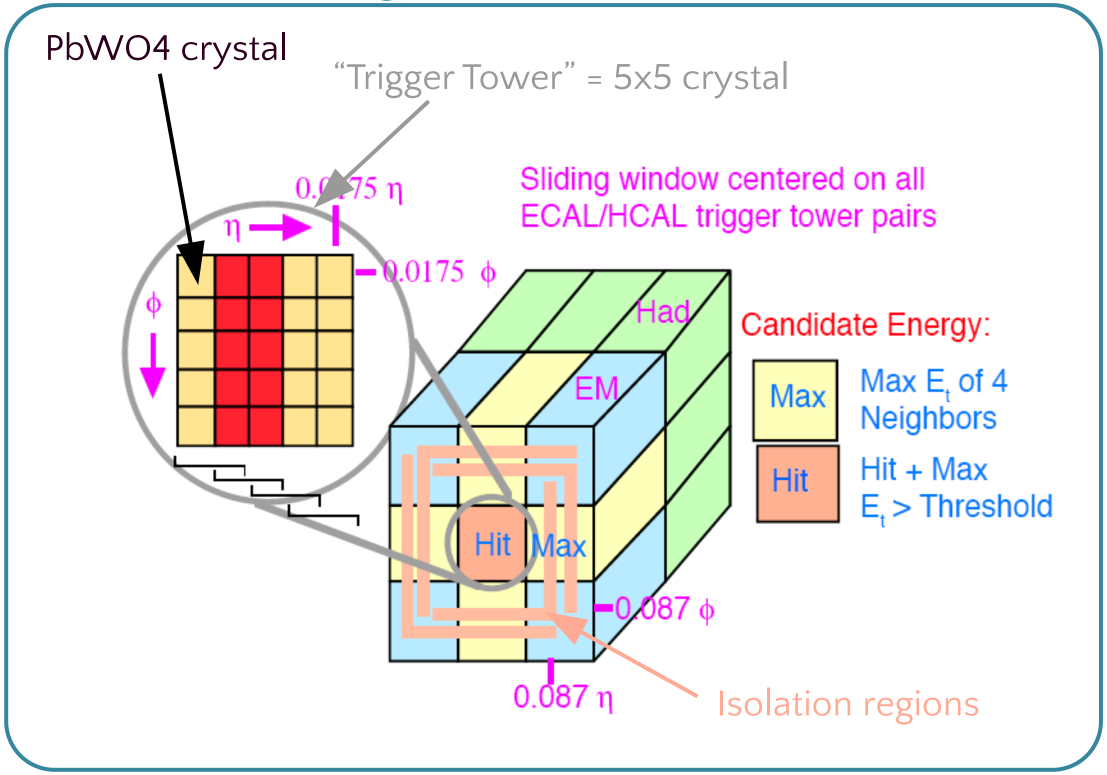
- First trigger level (L1) processing : hardware based (ASIC, FPGA)
  - Data simplification / coarsification on-detector (in front-end electronics)
  - Reconstruction and decision making off-detector (in back-end electronics)
  - Linked with optical fibers



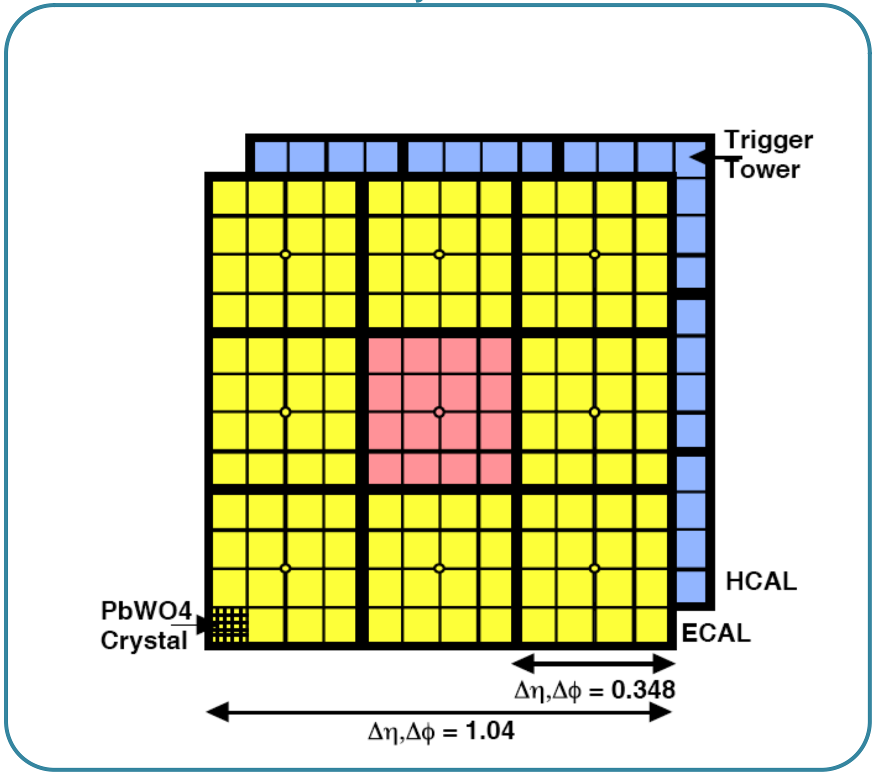
Calorimeter trigger objects, examples (CMS, Run 1)

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

Electromagnetic shower reconstruction



Hadronic shower (jet) reconstruction



Lecture plan

What is a calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Electronics readout and trigger

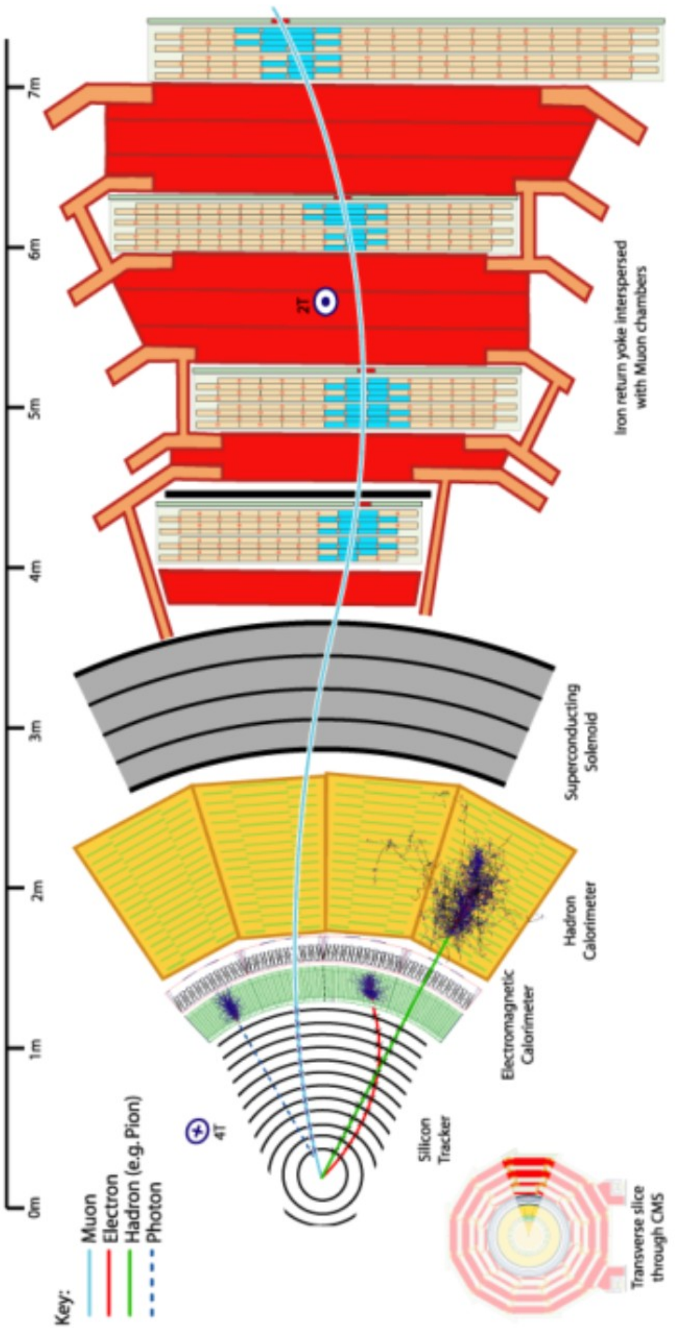
Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

Calorimetry and Machine Learning

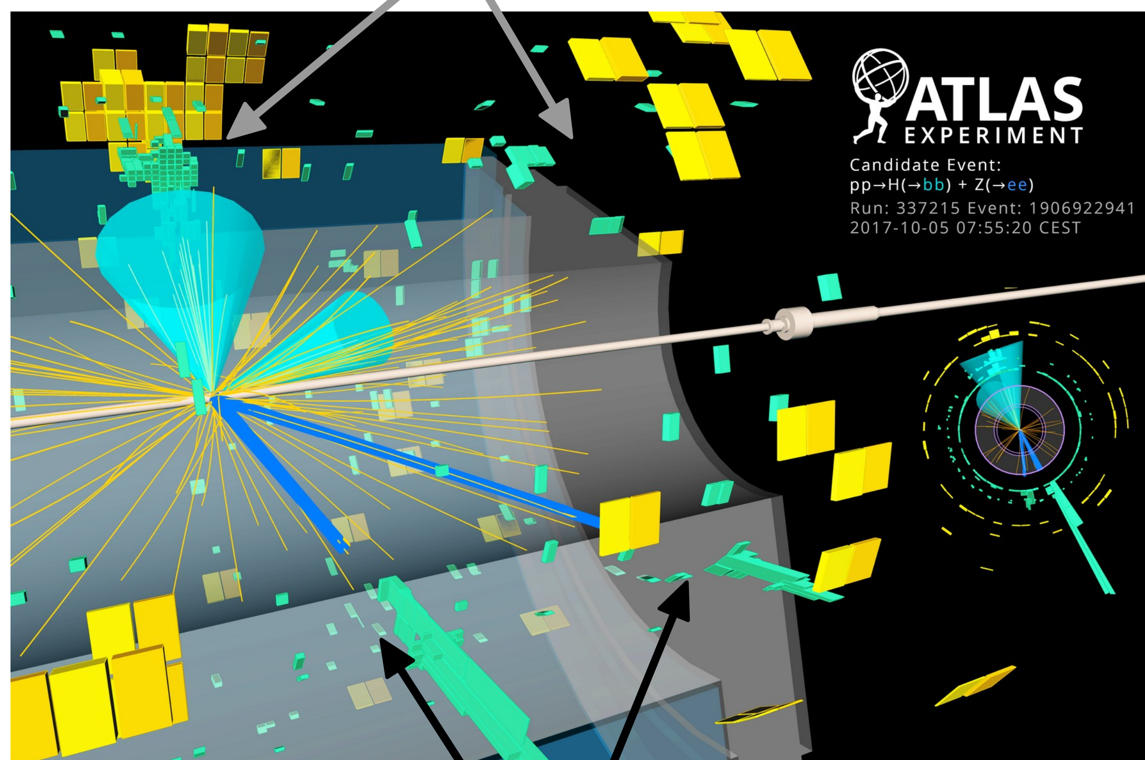
Examples of calorimeters
Present and future

Reconstructing particles in calorimeters



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

Reconstructed jets

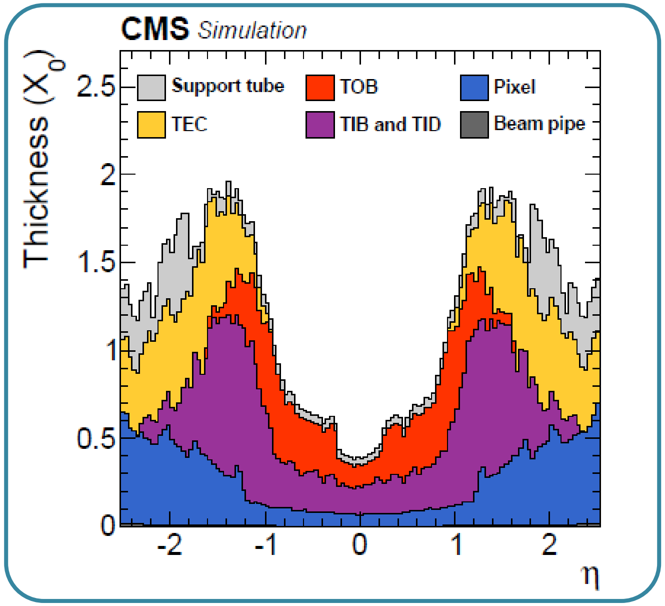


Reconstructed electrons

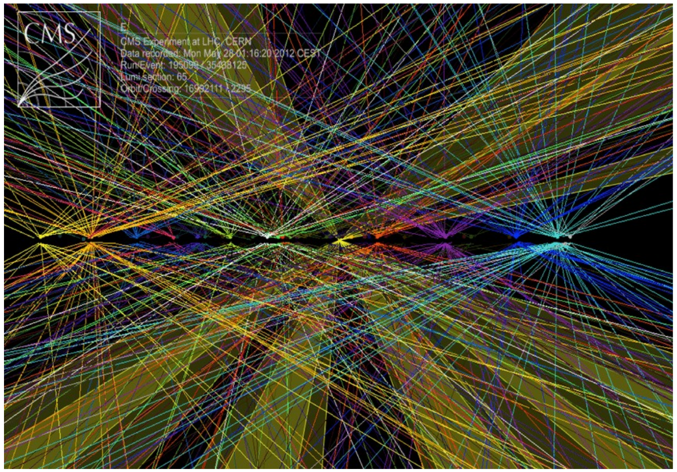
Real-life conditions

- 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

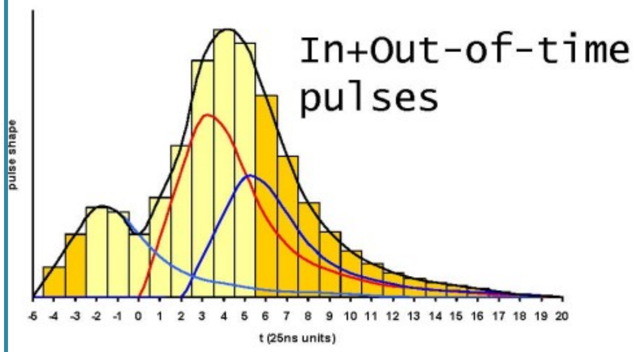
Material in front of the CMS calorimeters



Tracks from multiple simultaneous interactions

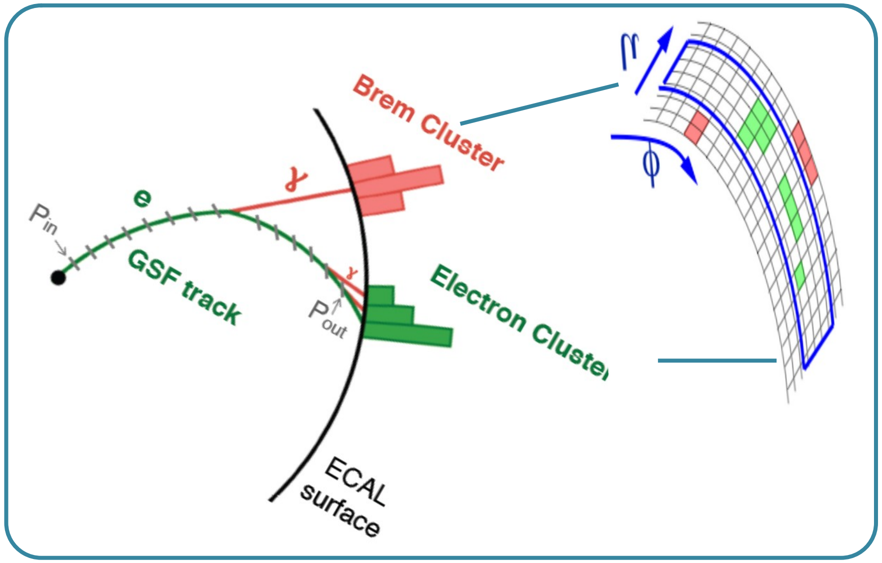


Energy deposited from consecutive interactions

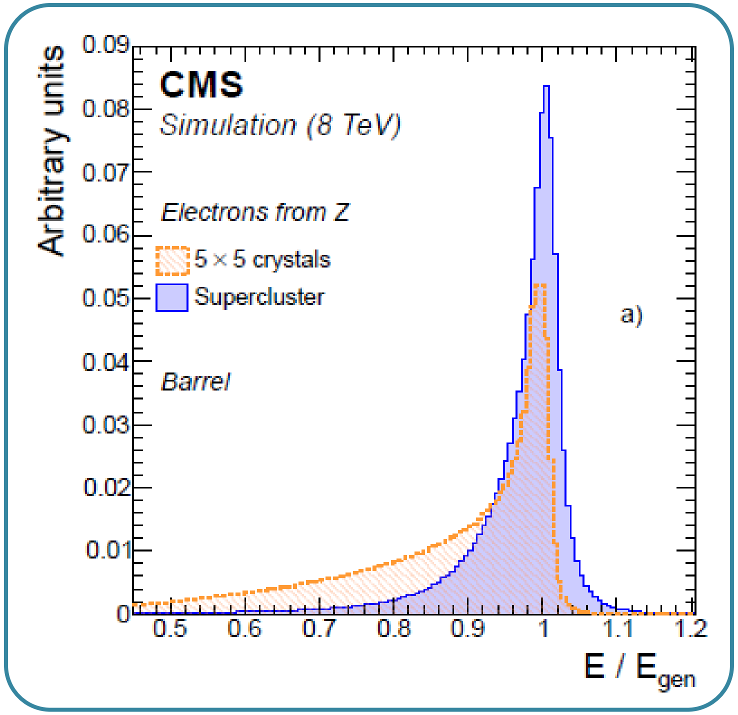


Electrons and photons reconstruction

- 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

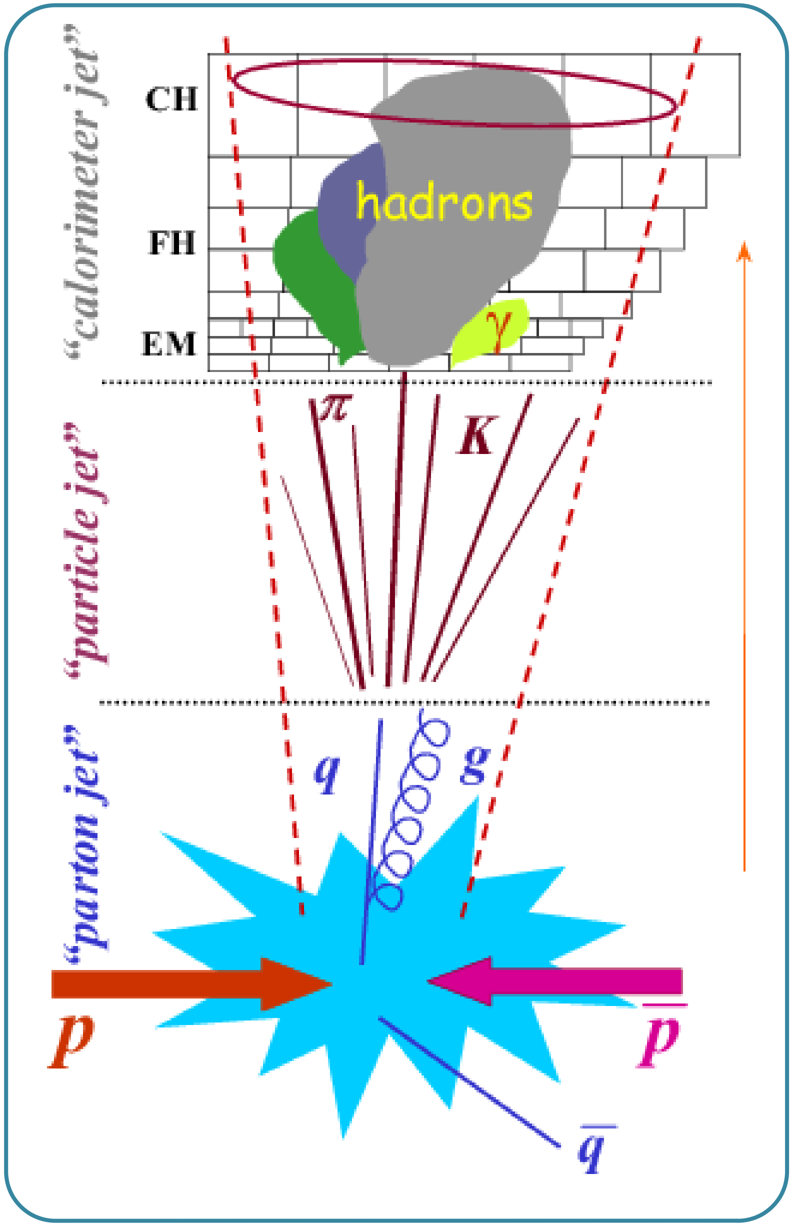


Impact of grouping distant clusters



- 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 overlapping showers
- Jets are reconstructed in two steps
  - Clustering of topologically connected deposits
  - Grouping clusters together with distance-based association (creates cone-like objects)

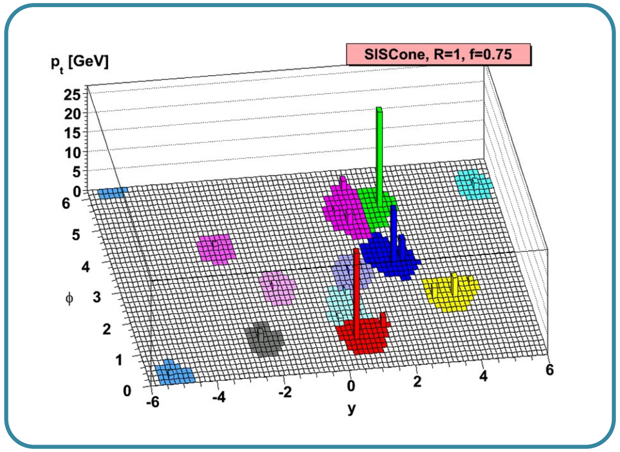
Jet algorithms

- 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

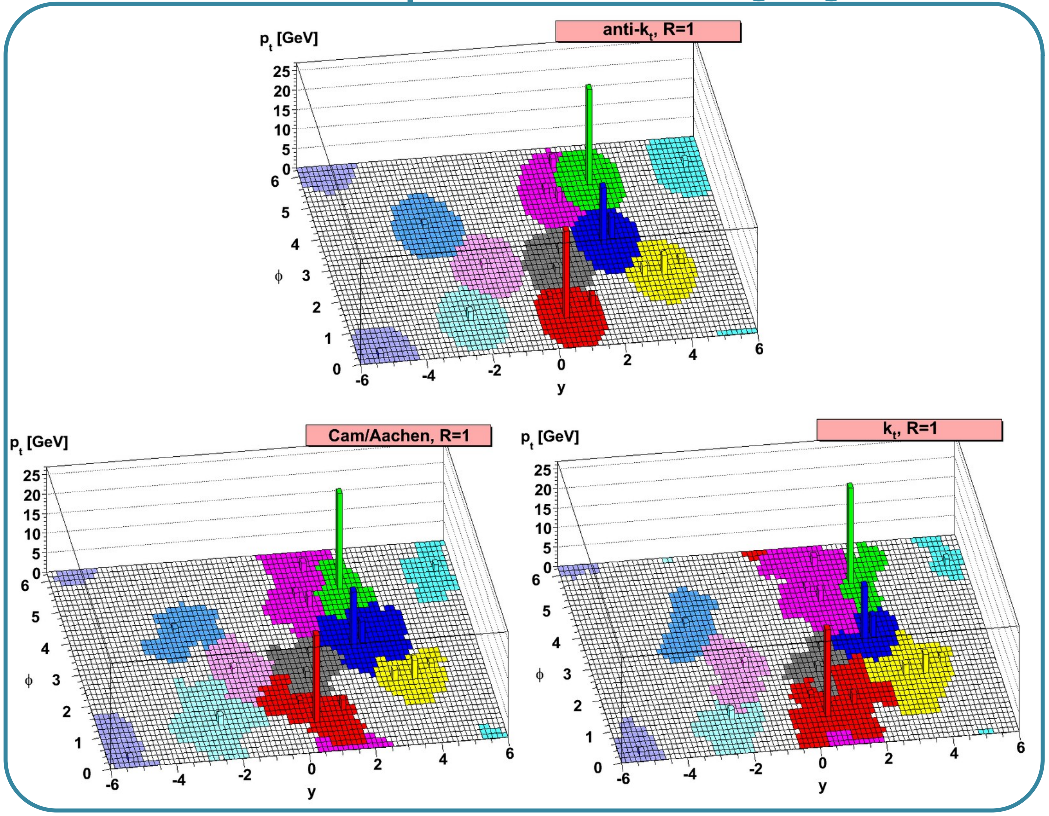
$$d_{ij} = min\left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2}\right) \times \frac{R_{ij}^2}{R}$$

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

Example of cone algorithm



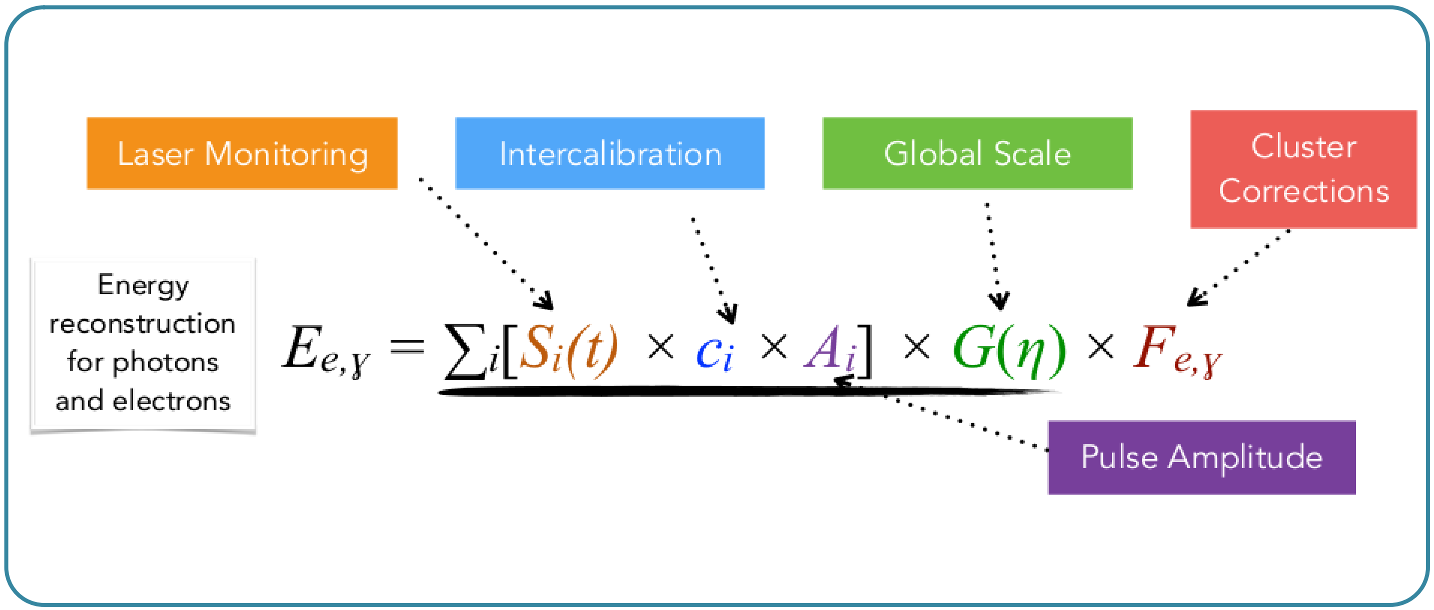
Most common sequential clustering algorithms



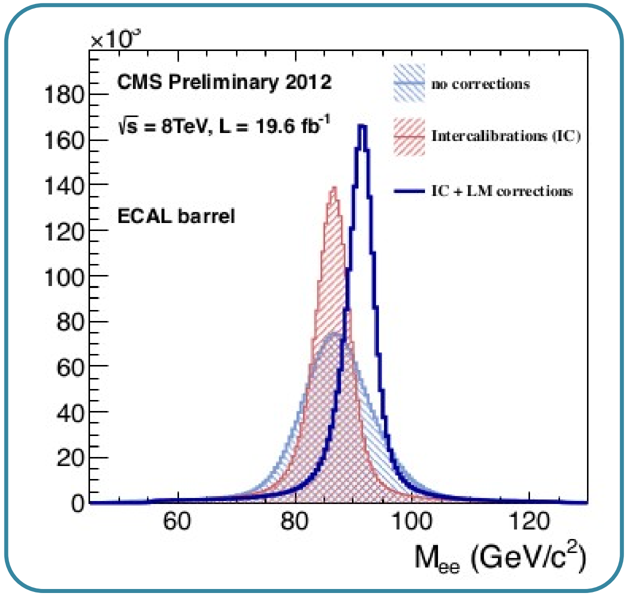
Calorimeter calibration / energy reconstruction

- 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



Impact of intercalibration and laser monitoring



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

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

P pedestal

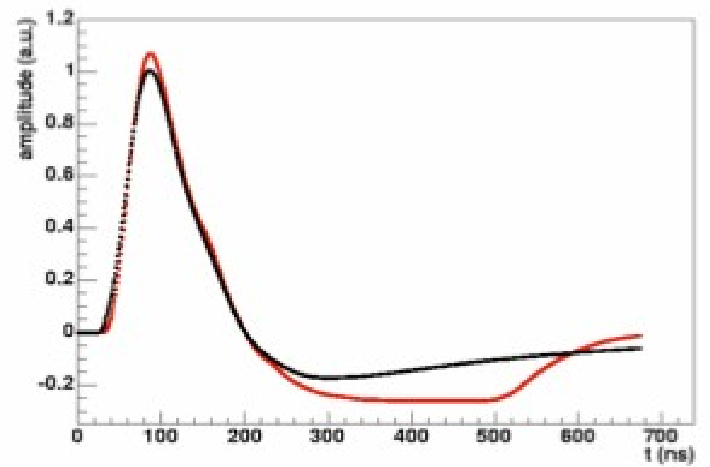
$$E_{cell} = F_{\mu A \rightarrow MeV} \, . \, M_{cal}/M_{phys} \, . \, R \, . \, \Sigma \, a_i \, (ADC_i - P)$$

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

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

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

P pedestal

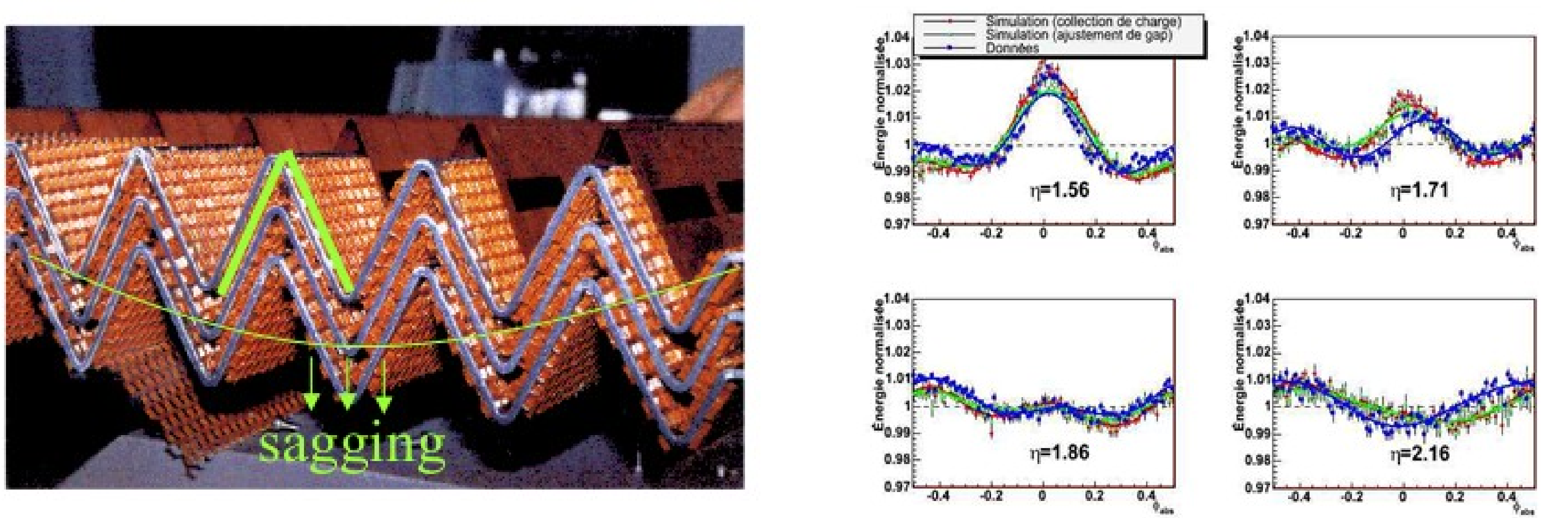
$$E_{cell} = F_{\mu A \rightarrow MeV} \,.\, M_{cal}/M_{phys} \,.\, R \,.\, \Sigma\, a_i\, (ADC_i - P)$$

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

a_i : Optimal Filter Coefficient to estimate pulse amplitude

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

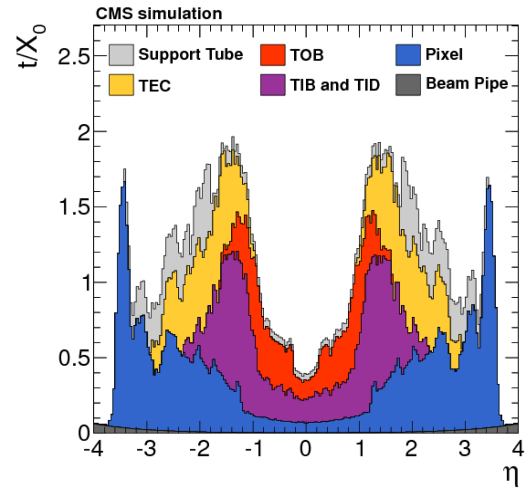
Gravity effects impact sampling fraction

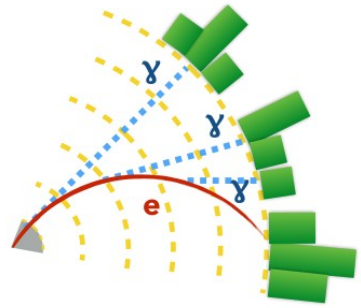


Cluster energy corrections

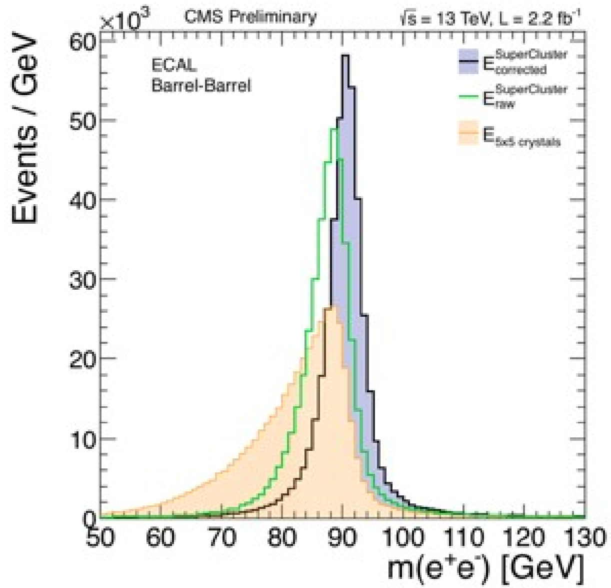
- Several sources of energy reconstruction inefficiencies
  - Threshold applied (e.g. to reduce noise impact)
  - Unclustered energy (linked to calorimeter depth, cluster size, interactions with material in front of the calorimeter)
- Remaining noise propagating to the final reconstructed cluster
- Requires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

Material in front of the CMS ECAL



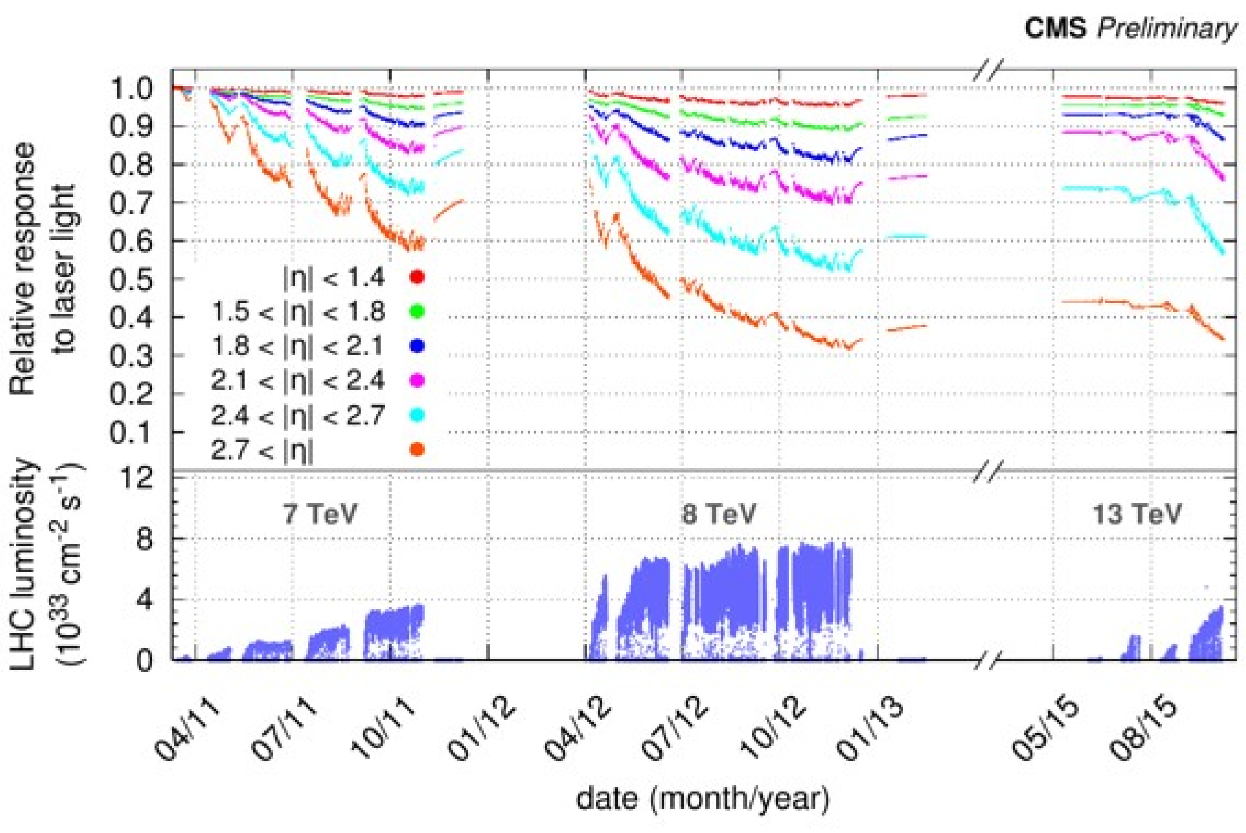


Impact of clustering and corrections on reconstructed Z mass

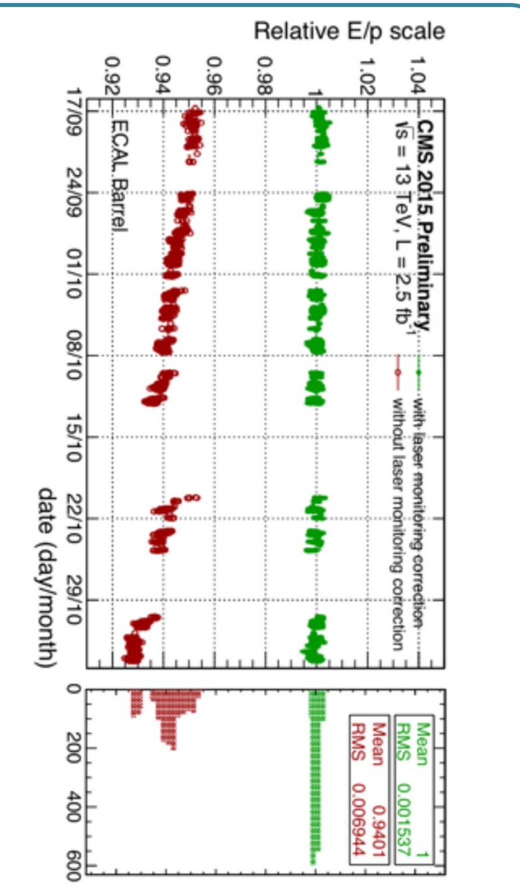


- Some parameters affecting the detector response change with time
  - Temperature, radiation effects (e.g. light attenuation), etc.
- These parameters are monitored and the response is corrected accordingly

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



Effect of monitored crystal response on reconstructed electron energy



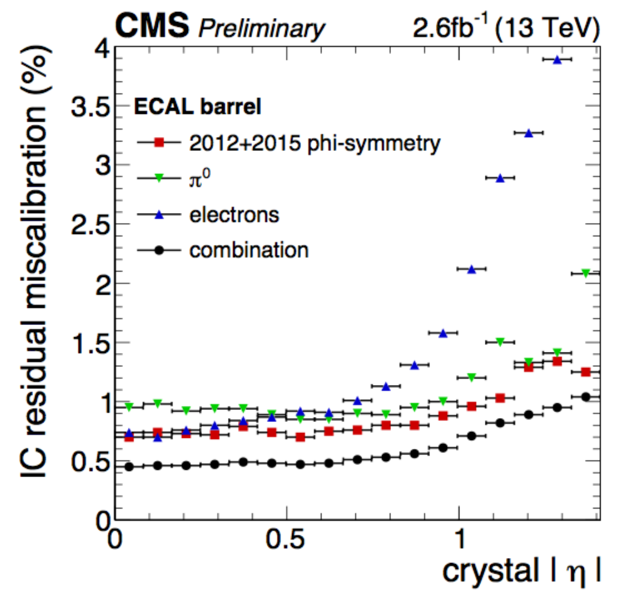
Intercalibration

- 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 detectors

Intercalibration methods used in CMS ECAL

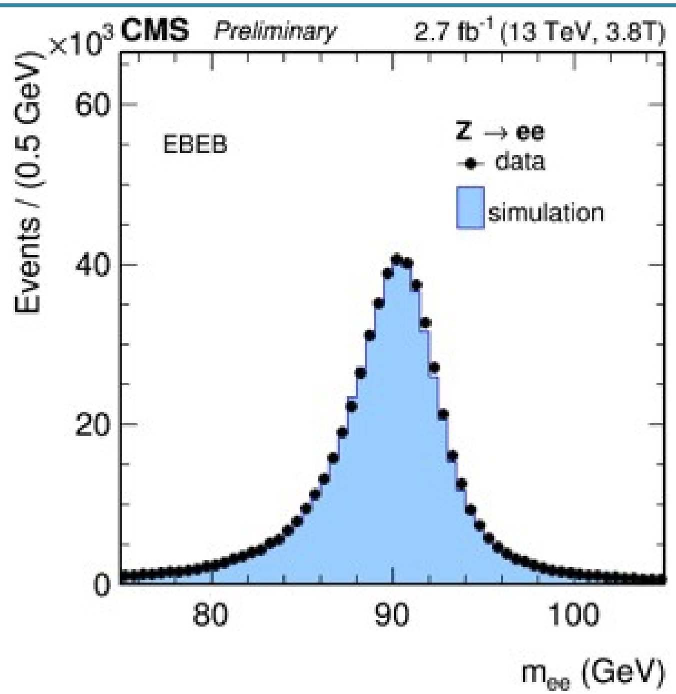
Method	Description	Timescale
ϕ-symmetry	Energy flux around ϕ rings (constant η) should be uniform - IC corrects for non-uniformity	~days
$\pi^0/\eta \to \gamma\gamma$	In a ϕ ring, use IC to improve $M(\gamma\gamma)$ resolution for π^0 and η resonances	~months
E/p	Compare isolated electron energy from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

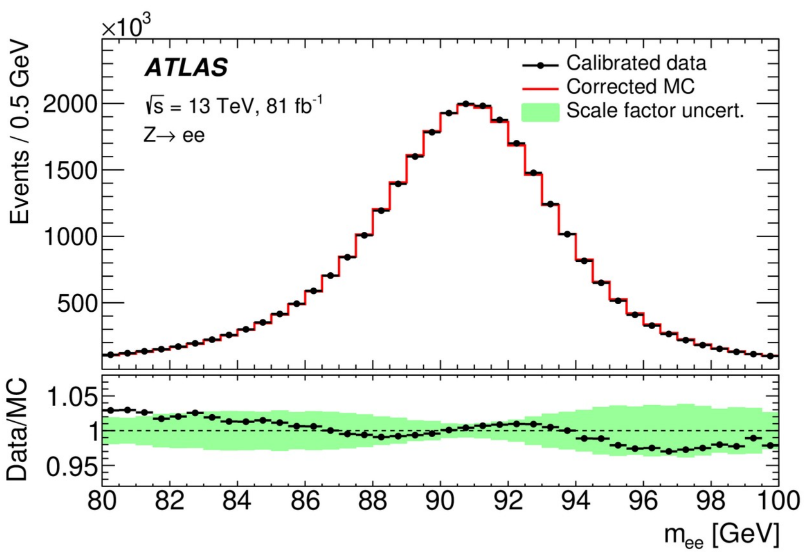
Precisions obtained with each intercalibration methods



Absolute calibration

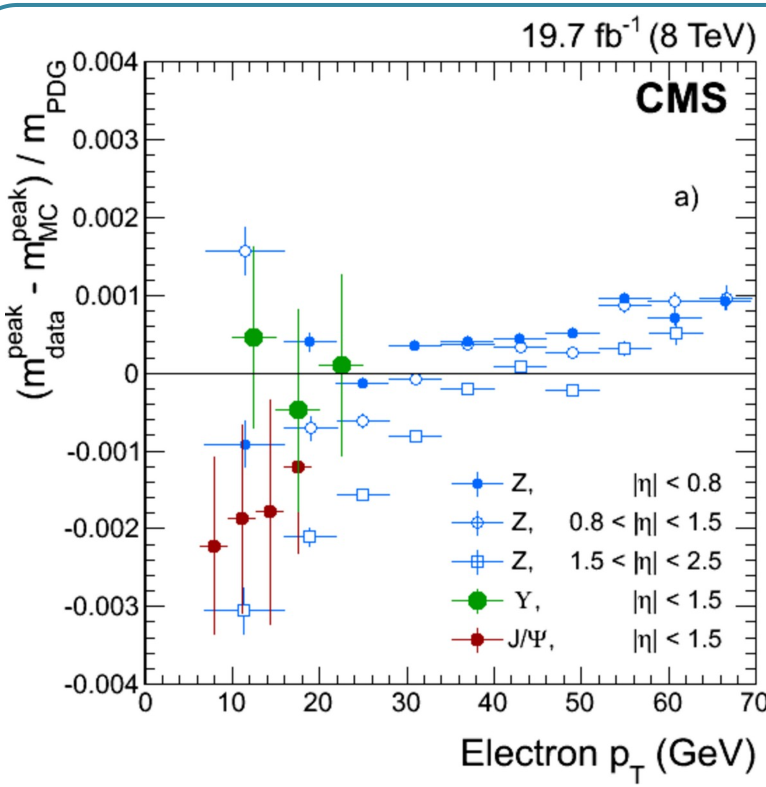
Comparisons of Z peak obtained in data and simulation (CMS and ATLAS)





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

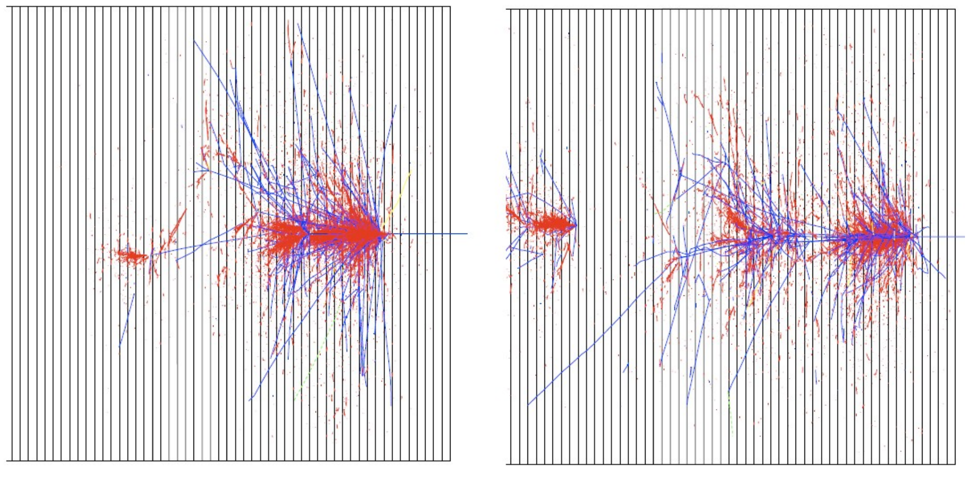
Linearity check with different resonances



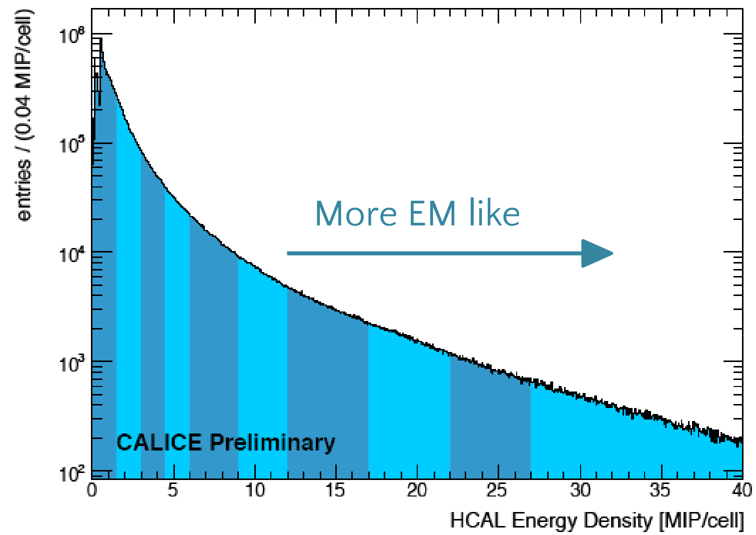
Jet energy measurement

- 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

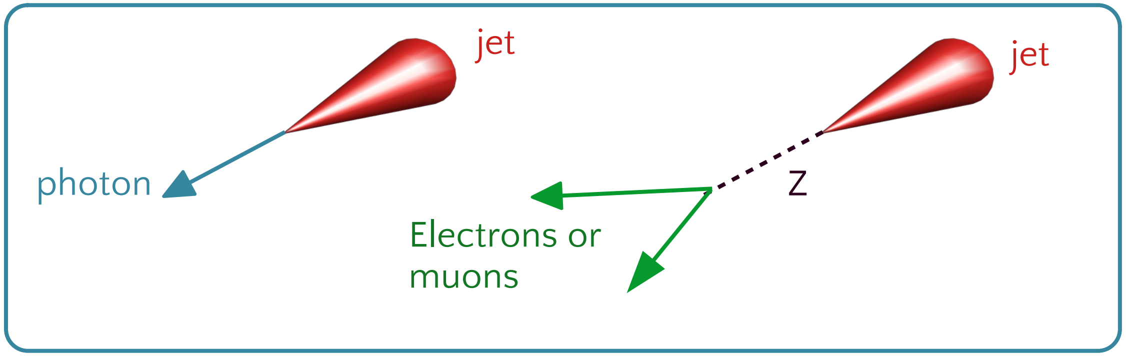


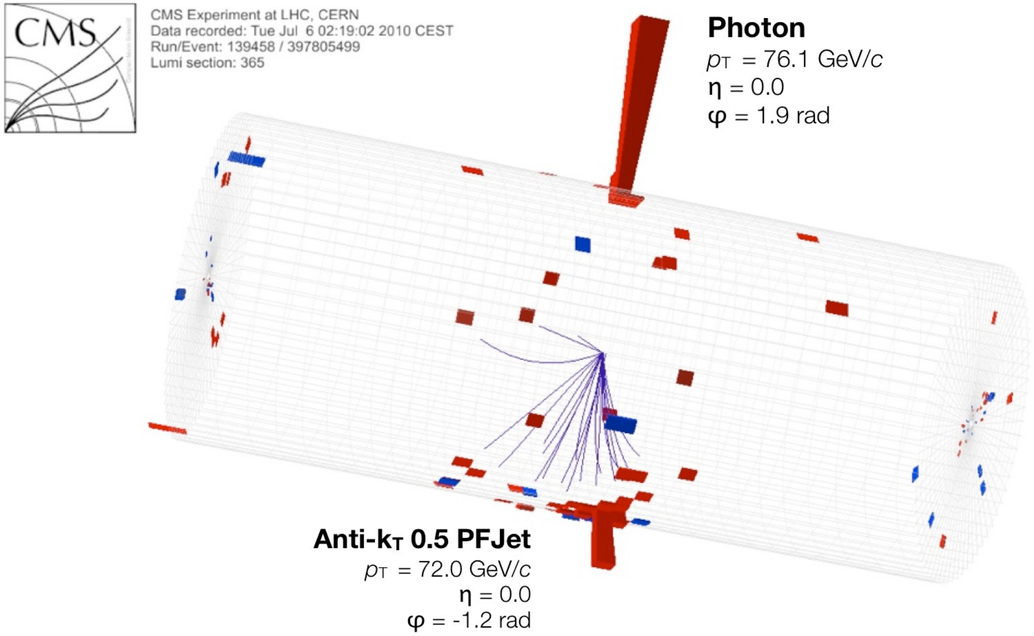
Cell energy density



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

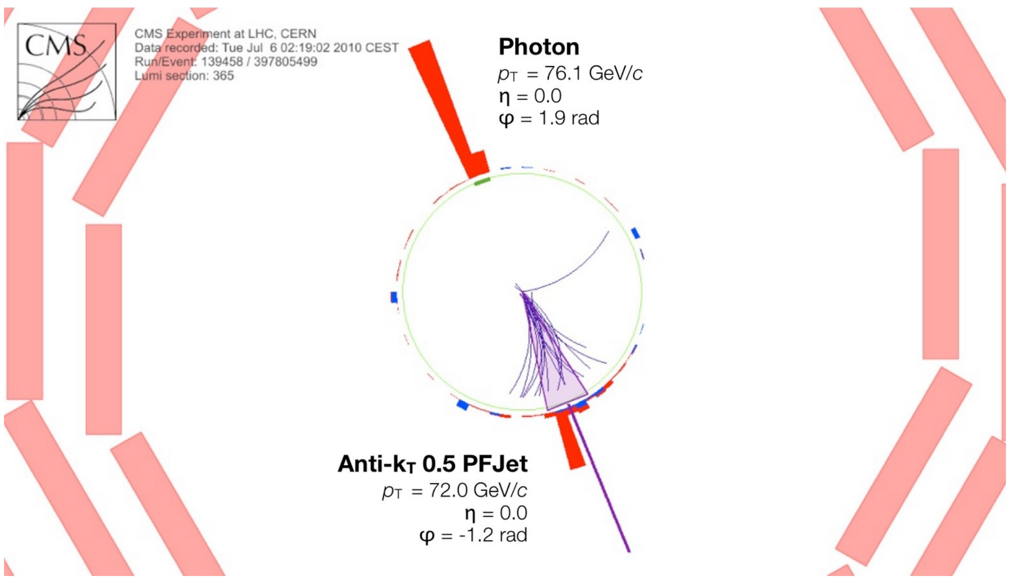




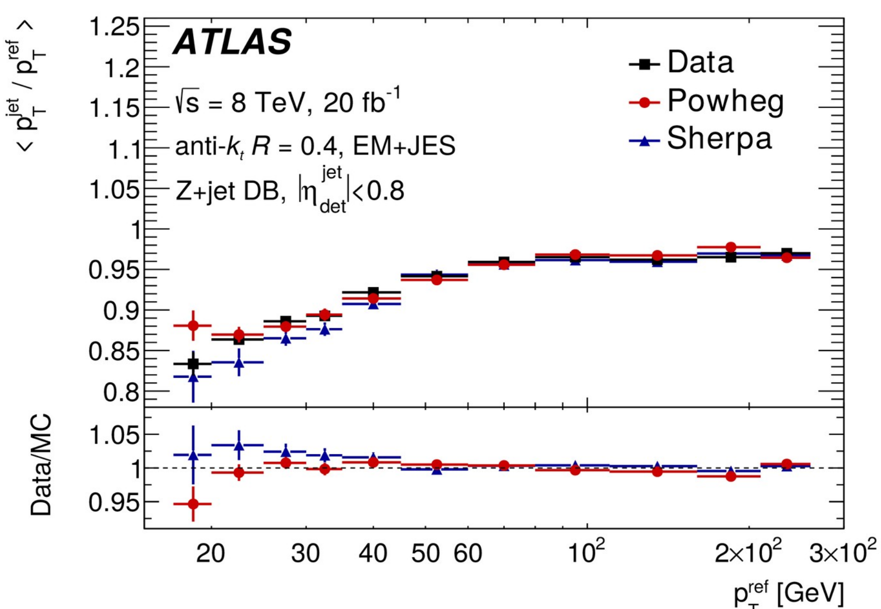
Jet in situ calibration

- 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?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Electronics readout and trigger

Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

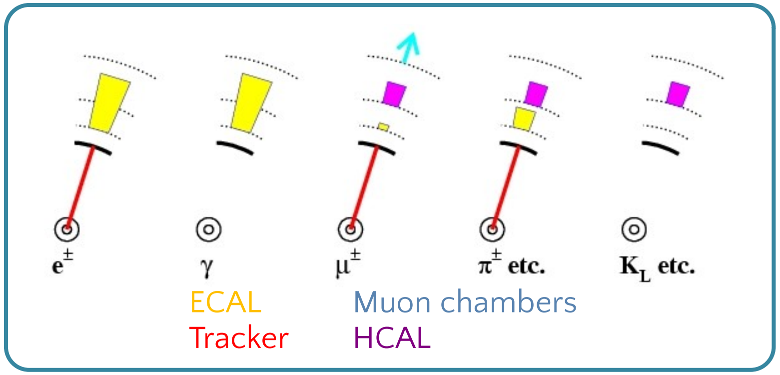
Calorimetry and Machine Learning

Examples of calorimeters
Present and future

Reconstruction beyond calorimeters

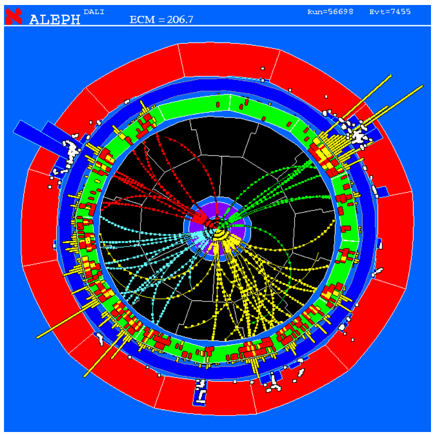
- Electrons, photons, hadrons, etc. produce different signatures in the different subdetectors
  - Photon: mainly ECAL
  - Electron: ECAL + tracker
  - Charged hadrons: all calorimeters + tracker
  - Neutral hadrons: all calorimeters
  - Muons: Mainly muon chambers + tracker

Signatures from different particles

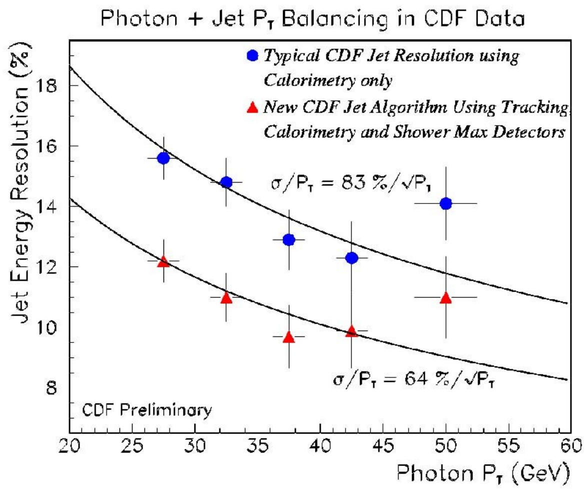


- The idea is to combine the information from all subdetectors
  - Can better identify objects and measure / calibrate their energy
- Pioneered in ALEPH at LEP (90's) and used later in other detectors

WW → 4q in ALEPH



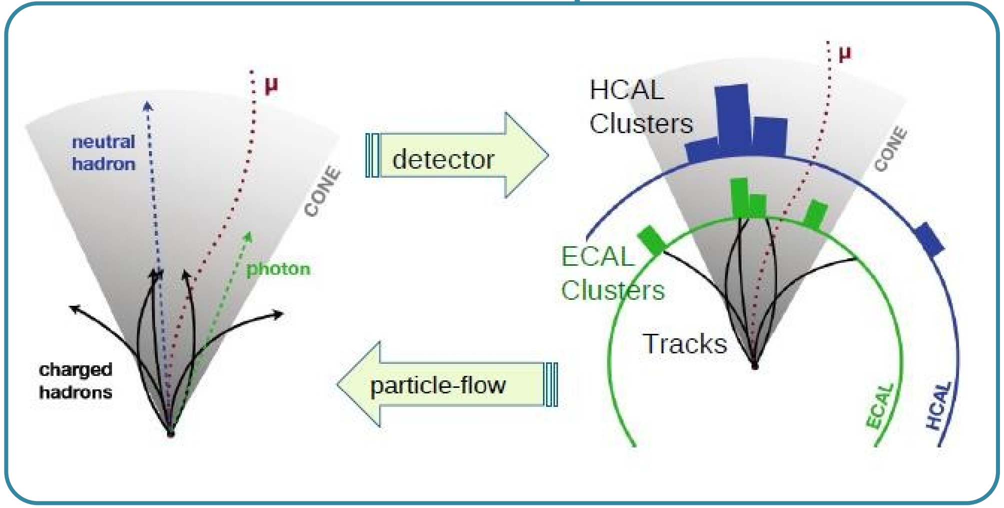
Improvement in jet energy resolution in CDF



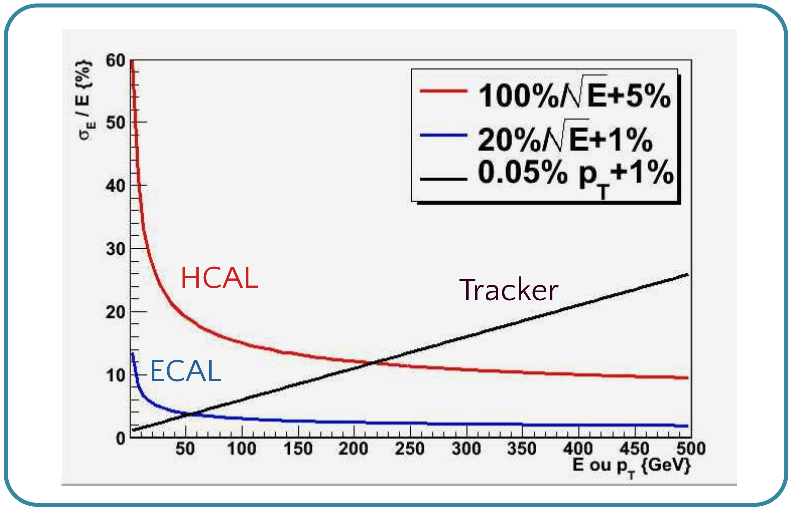
Particle Flow

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

From detector to particles



Typical resolutions



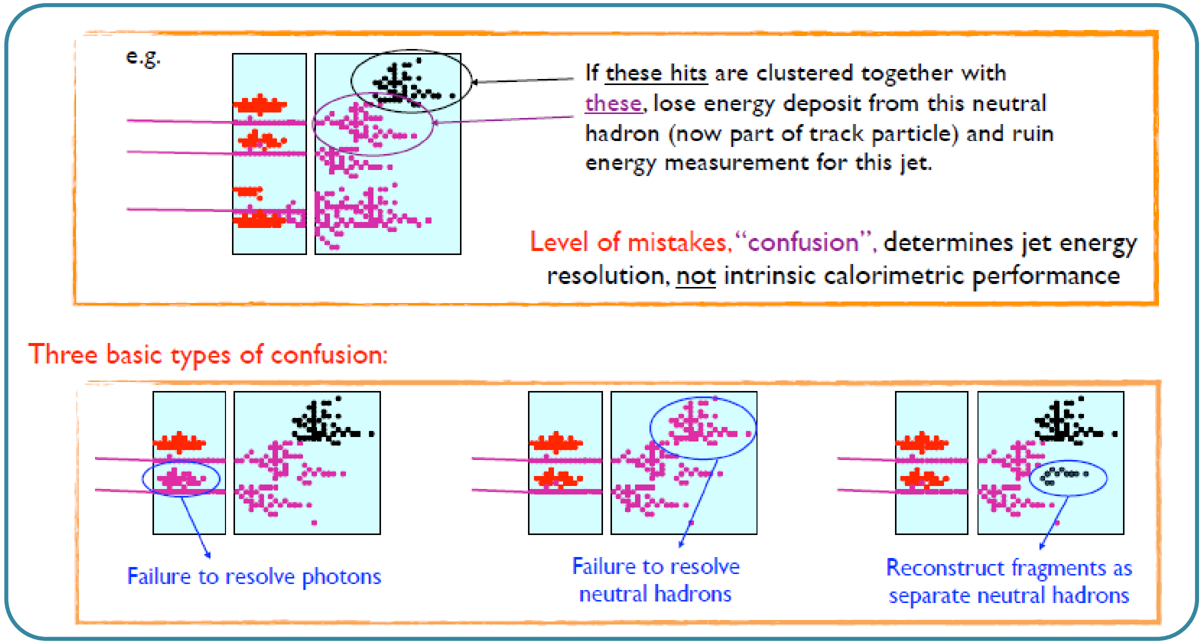
Particle Flow challenges

- Jet energy resolution (forgetting correlations):

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

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

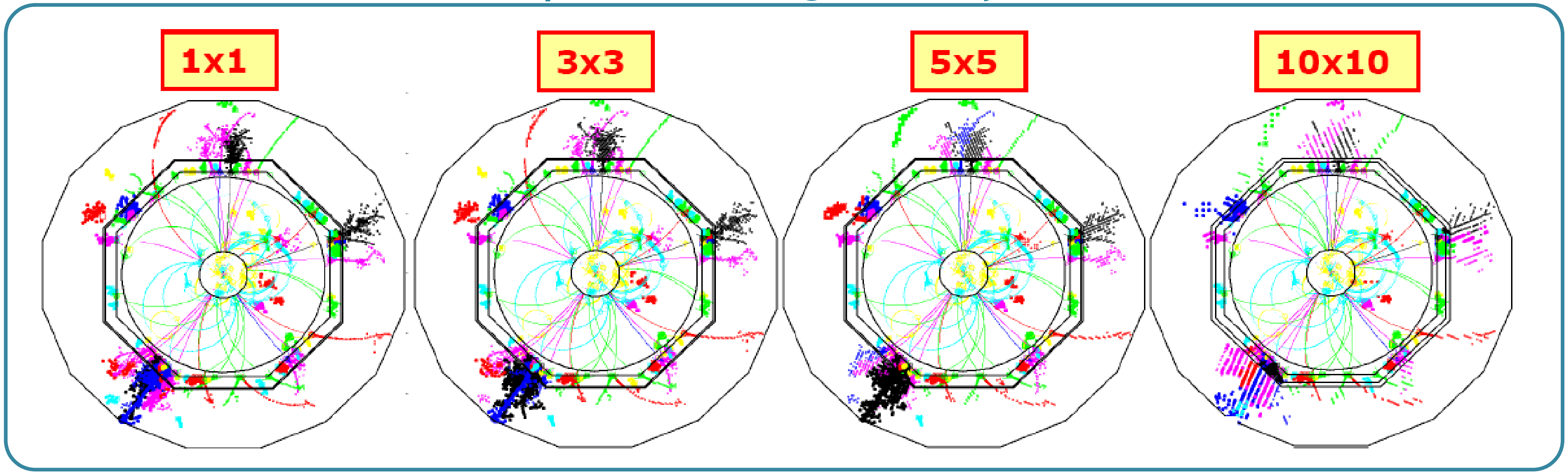
Confusion effects



Particle Flow ingredients

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

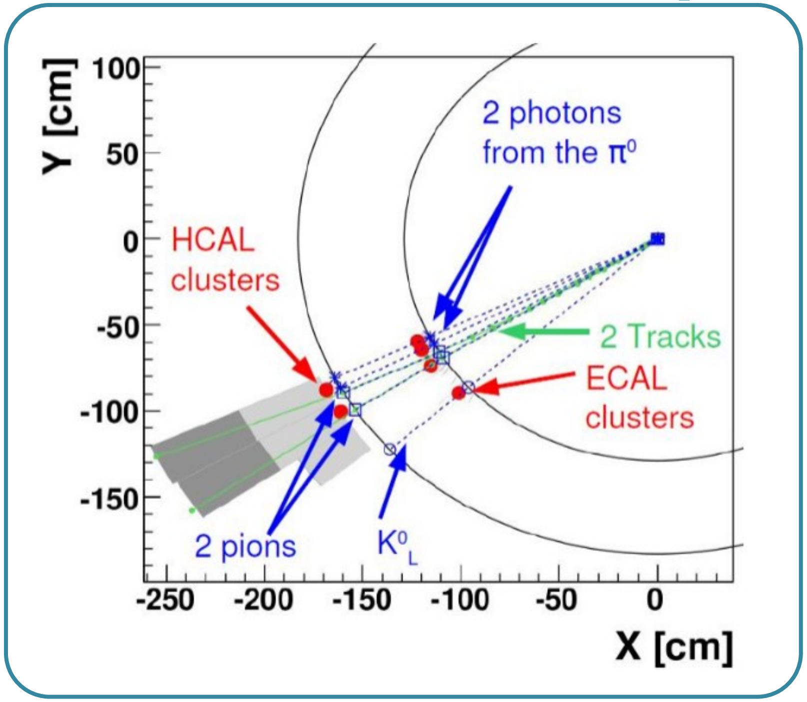
Impact of HCAL granularity



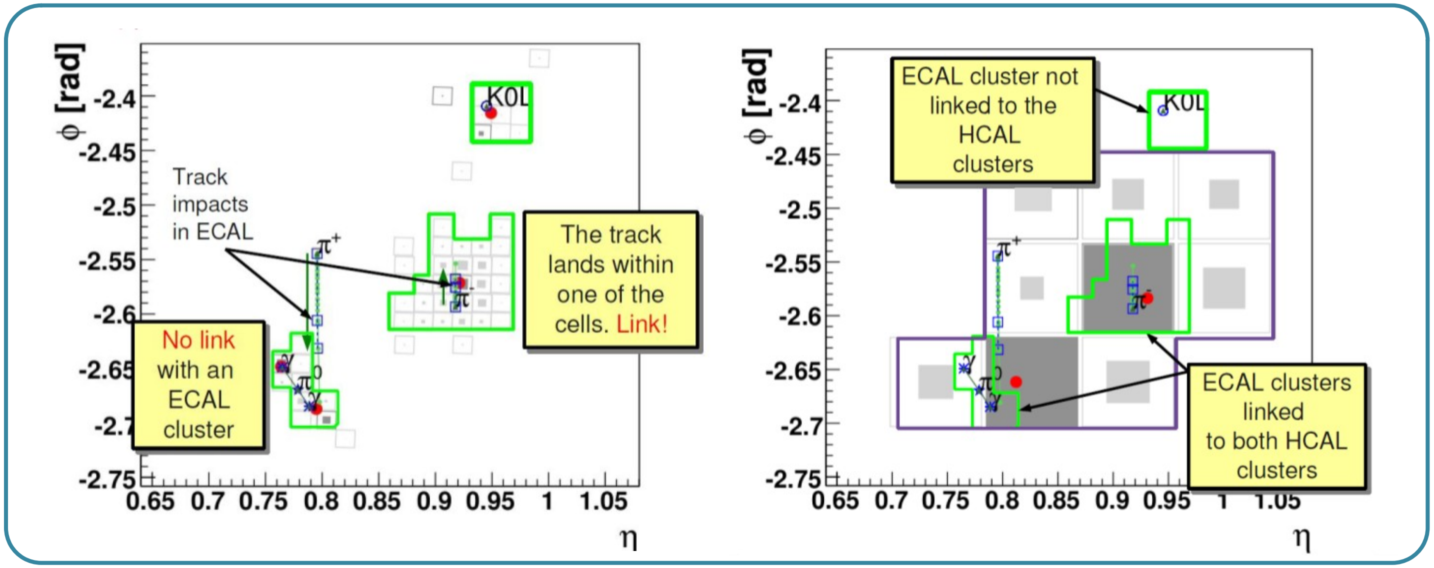
Particle Flow in CMS

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

A jet containing π^+, π^-, π^0, K_L^0



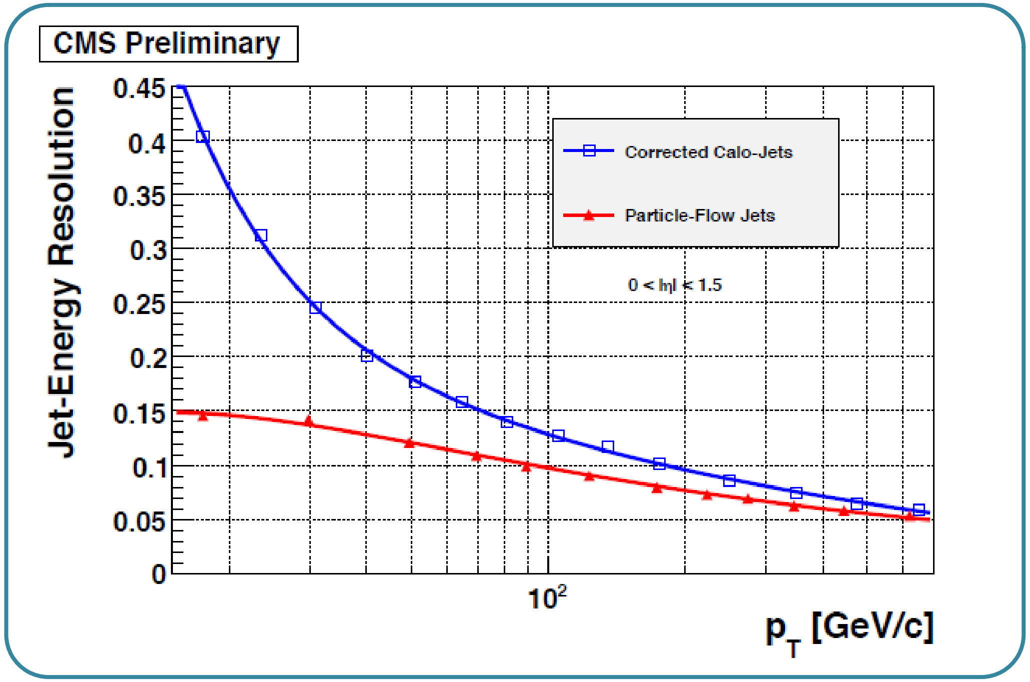
ECAL and HCAL surfaces



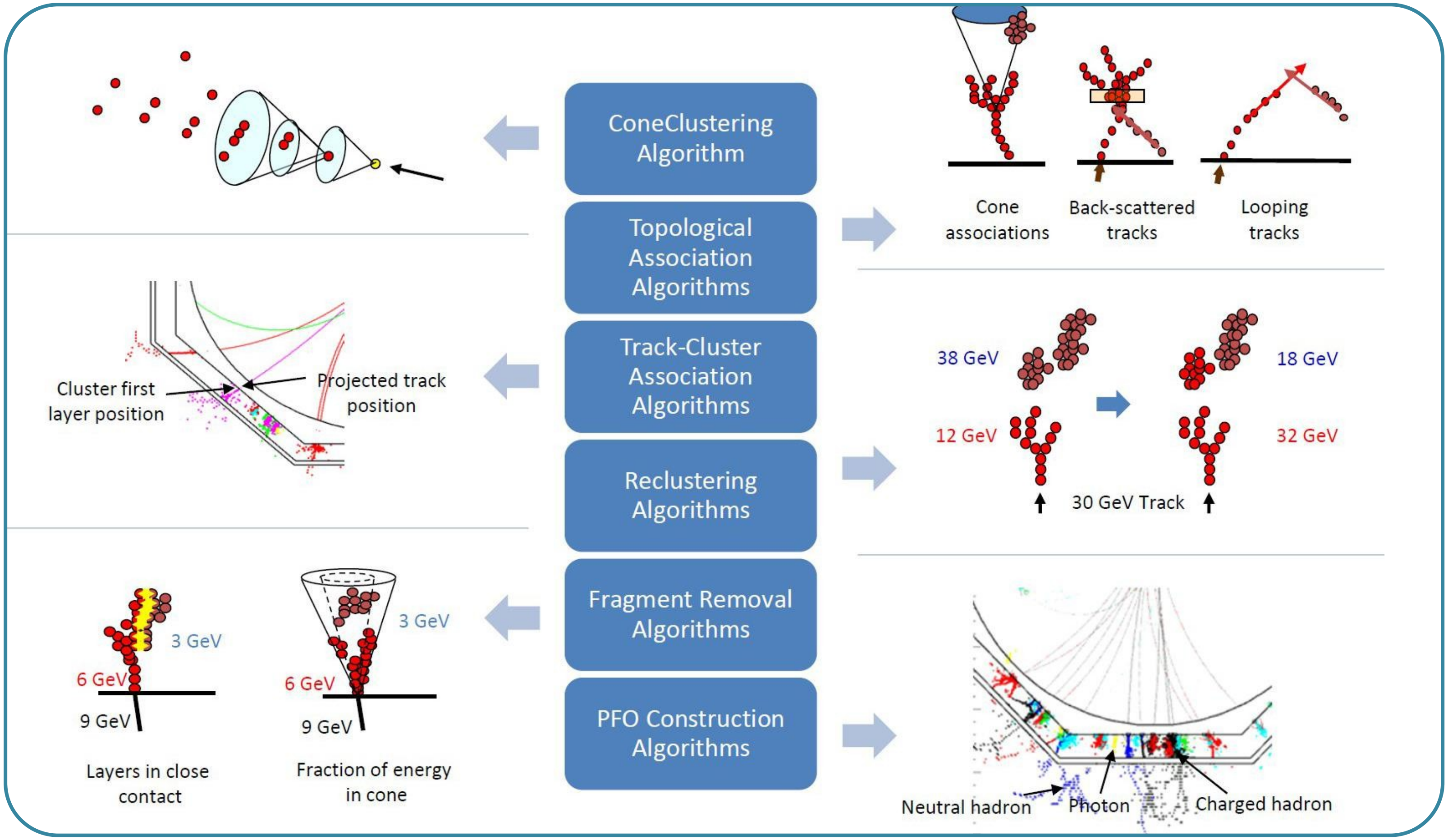
Particle Flow in CMS

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

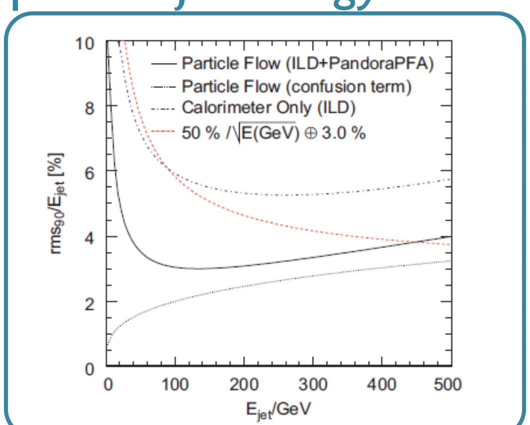
Improvement in jet energy resolution from PF



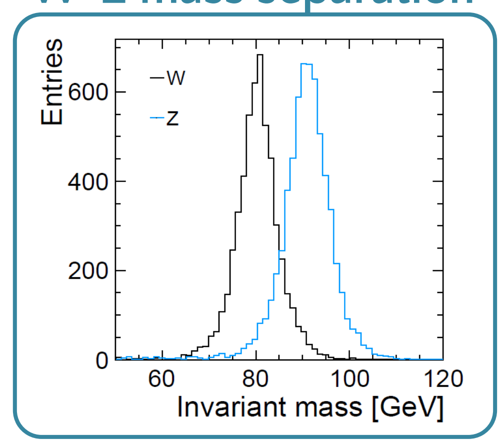
Particle Flow at the ILC



Impact on jet energy resolution



W-Z mass separation



Lecture plan

What is calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Electronics readout and trigger

Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

Calorimetry and Machine Learning

Examples of calorimeters Present and future

Calorimetry and machine learning

- Machine learning used since a long time in HEP (in particular for problems related to calorimetry)
  - 1987: Neural networks for tracking and calo clustering
  - 1993: JetNet package
- Used already at LEP and (much more) at TeVatron
  - Mostly small neural networks and trees
- Boosted Decision Trees widely used at LHC, e.g.
  - Cluster energy corrections
  - Cluster identification
  - Jet tagging
- The community is now moving to deep neural networks (as the rest of the world)
- A lot is being done with calorimeters
  - Probably due to their image-like data

Computer Physics Communications 49 (1988) 429–448
North-Holland, Amsterdam

NEURAL NETWORKS AND CELLULAR AUTOMATA IN EXPERIMENTAL HIGH ENERGY PHYSICS

B. DENBY

Laboratoire de l'Accélérateur Linéaire, Orsay, France

Received 20 September 1987; in revised form 28 December 1987

CERN LIBRARIES, GENEVA
P00021783

LU TP 93-29
CERN-TH.7135/94
December 1993

JETNET 3.0 – A Versatile Artificial Neural Network Package

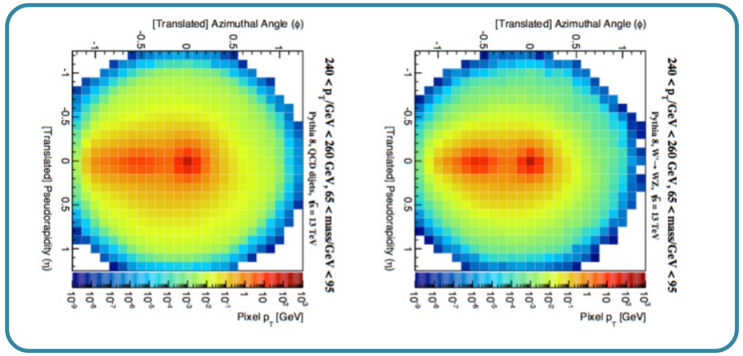
Carsten Peterson and Thorsteinn Rögnvaldsson

Department of Theoretical Physics, University of Lund, Sölvegatan 14 A, S-223 62 Lund, Sweden

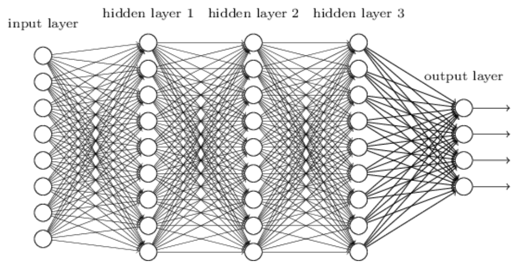
Leif Lönnblad

Theory Division, CERN, CH 1211 Geneva 23, Switzerland

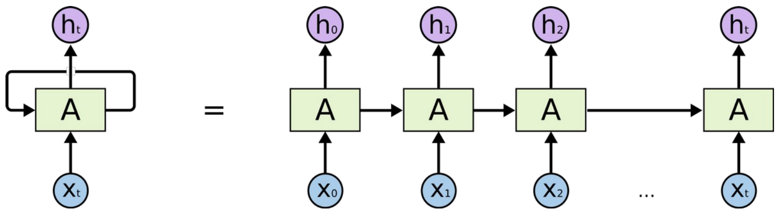
(average) QCD and boosted W jets



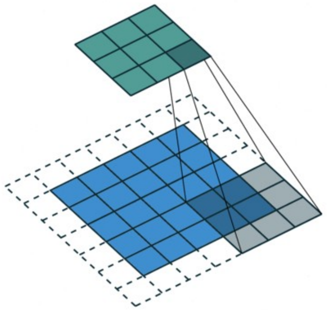
Impact of inputs on network architectures



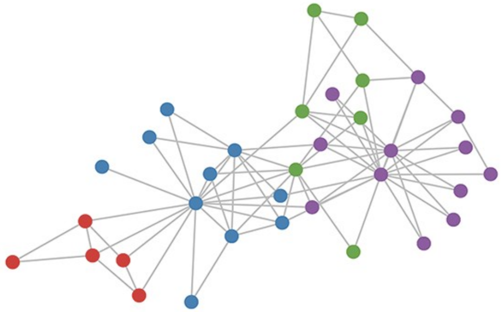
- Fully connected network
  - Low input dimensionality
  - e.g. cluster shape features



- Recurrent network
  - Sequential processing of inputs
  - Useful for variable number of inputs
  - e.g. constituents in a jet



- Convolutional network
  - Regular grid in Euclidian space
  - Best for images
  - e.g. regular calorimeter cells

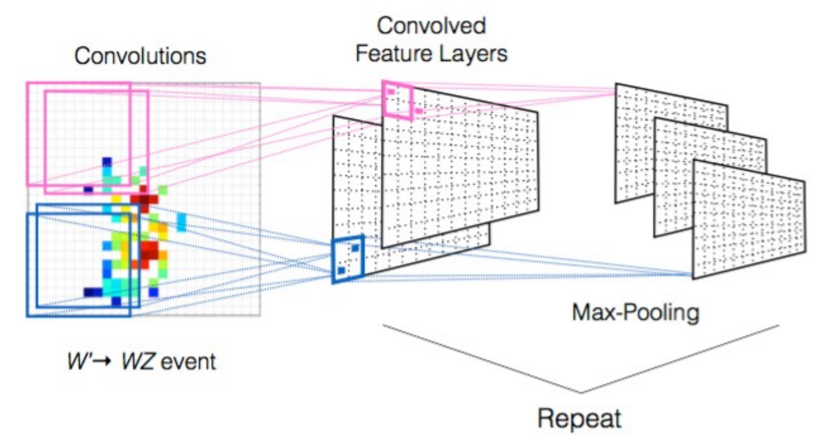


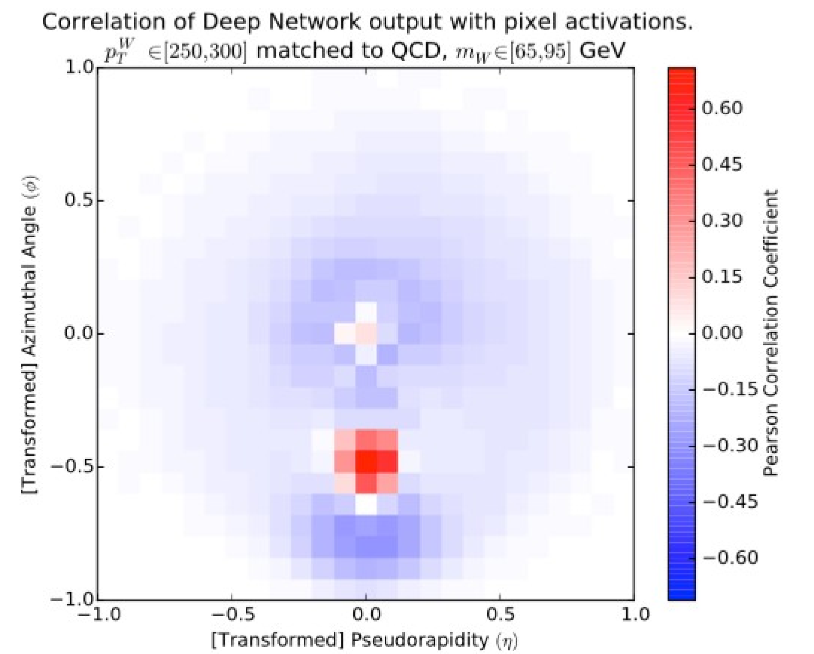
- Graph network
  - Data points with a sense of connection
  - e.g. irregular calorimeter cells

Jet images : convolutional NN

- Treat calorimeter energy deposits like an image
  - Can apply all methods developed for image processing
- Instead of "cat vs dog" we do "EM vs HAD showers" or "QCD jet vs boosted W"
- Let the network learn the shower features from raw energy deposits
- Better performance compared to handmade features

Extracting shower features with kernel convolutions

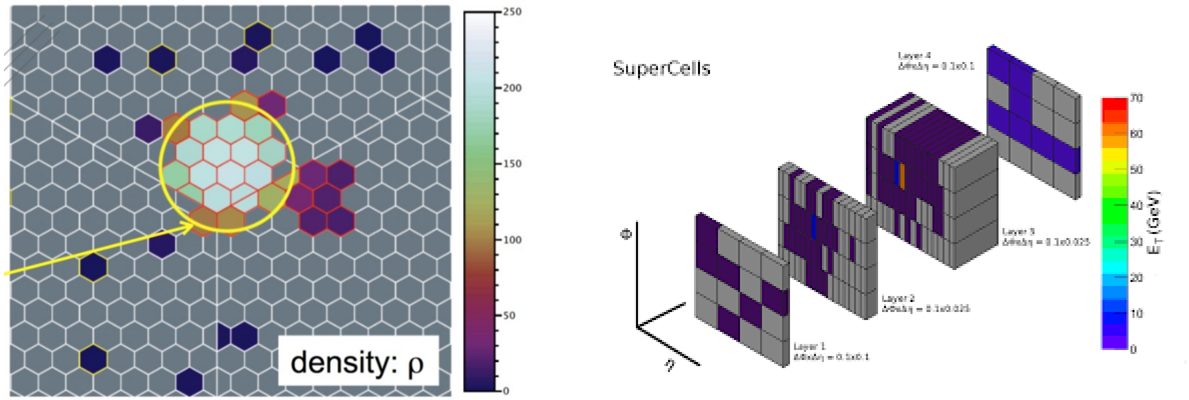




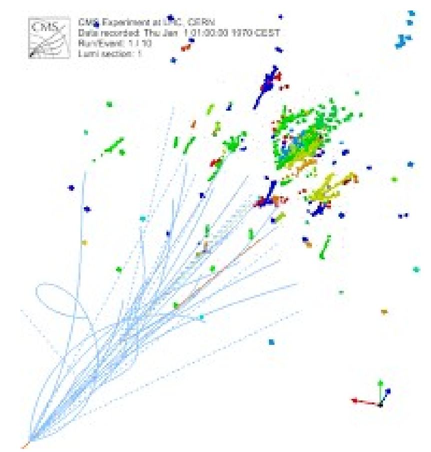
Correlation between network response and pixel activations = what the network "sees"

Calorimeters are irregular → graph networks

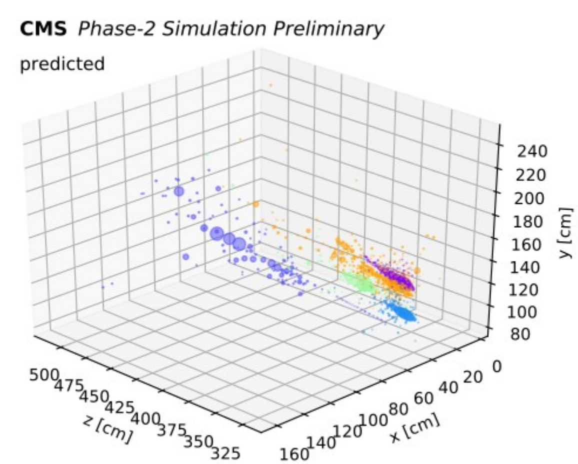
Most calorimeters have cell irregularities



Calorimeters are more and more granular and in 3D



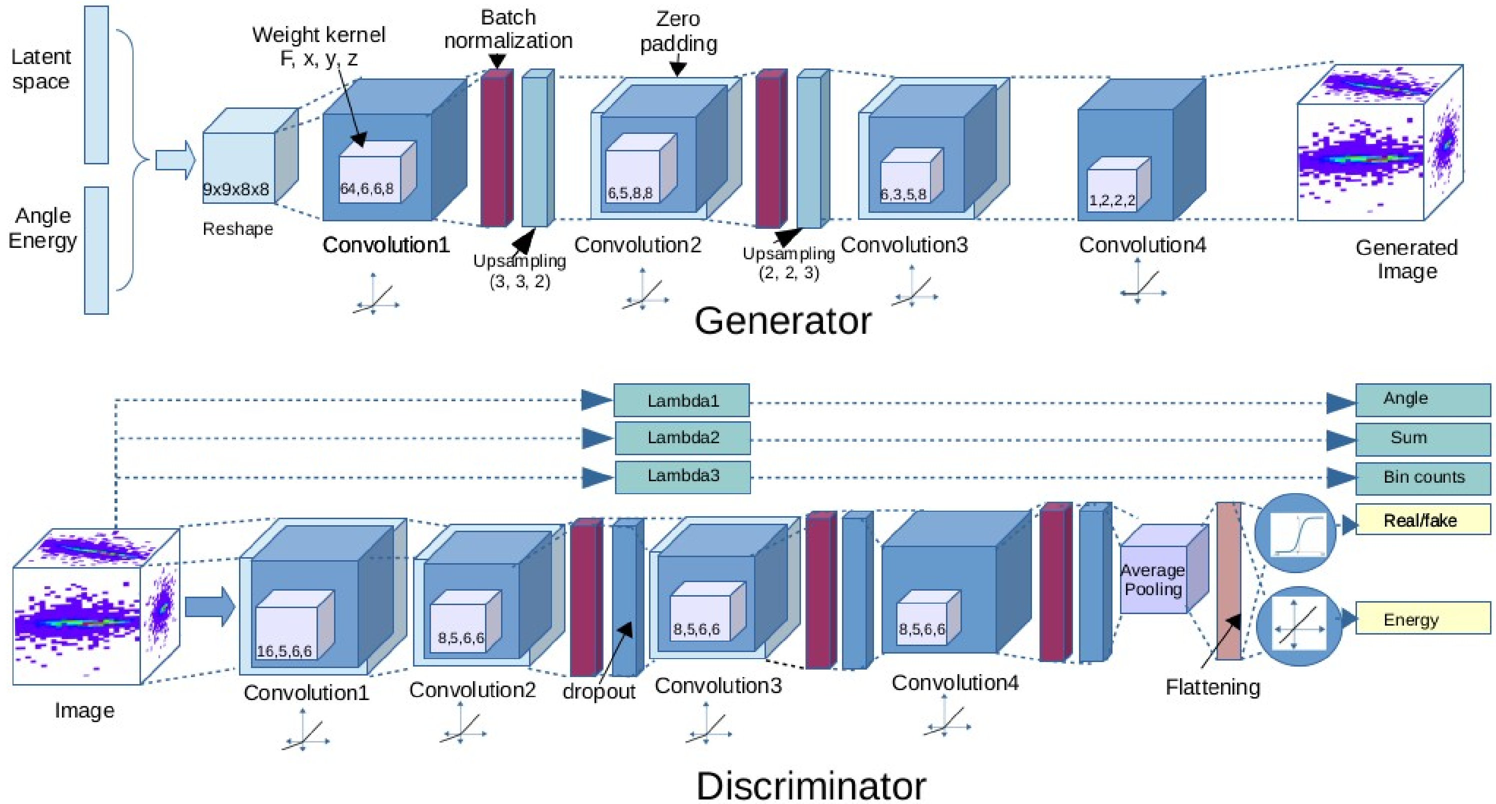
Showers segmentation with graph networks



- In these cases, graph networks are better suited
- Point-like sparse data with distance relationship between points
- Standard CNNs need a mapping to a regular grid
  - This step tend to deteriorate the information which can be extracted from showers

Generative adversarial networks (GAN)

- The simulation of the interaction of particles in a calorimeter is CPU consuming
  - In particular with highly granular calorimeters, and collision events with a lot of PU
- GANs can be used to perform fast simulation
- Based on a "Generator" network and a "Discriminator" network
  - The Generator is trained to fool the Discriminator
  - The Discriminator is trained to identify fake images produced by the Generator



- Very promising results but things can still be improved

EM shower shapes – GEANT4 vs 3DGAN