Calorimeters in Particle Hunting

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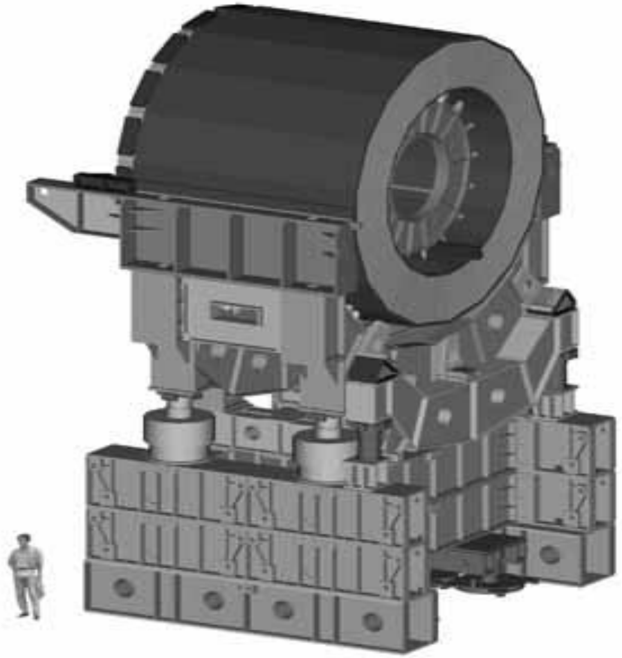
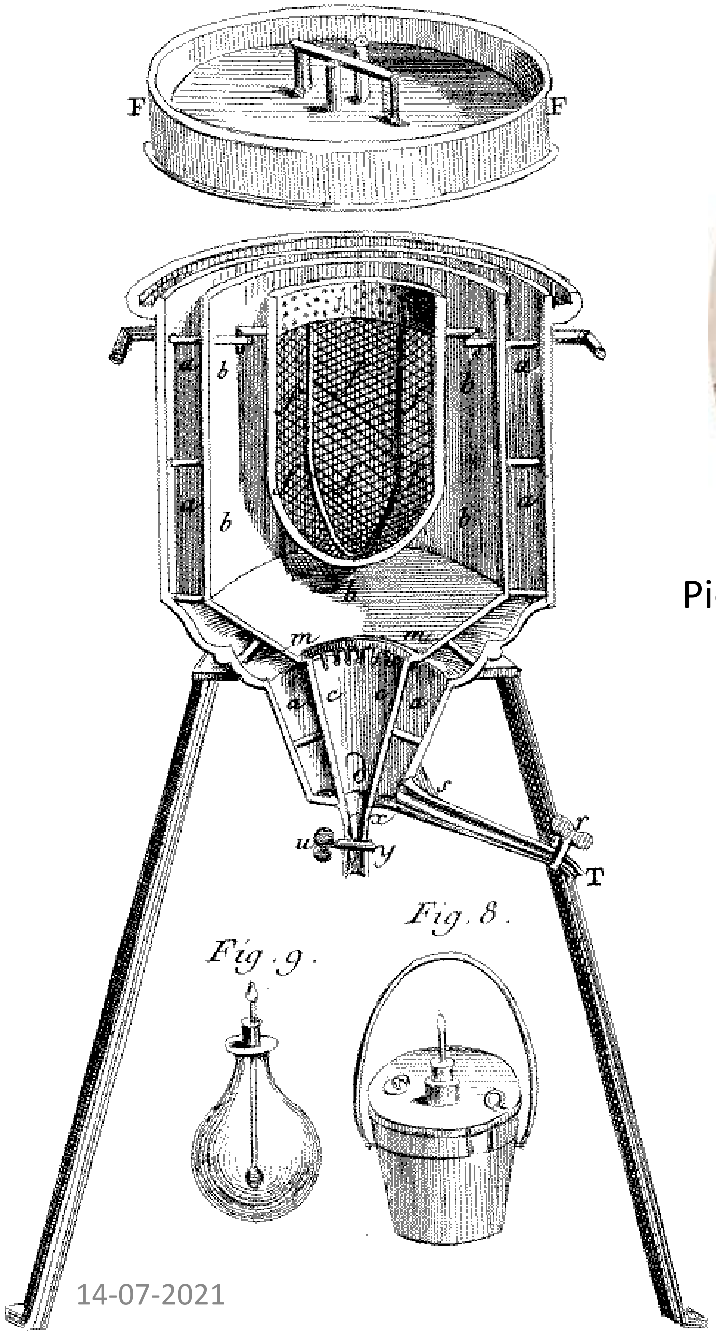
1780

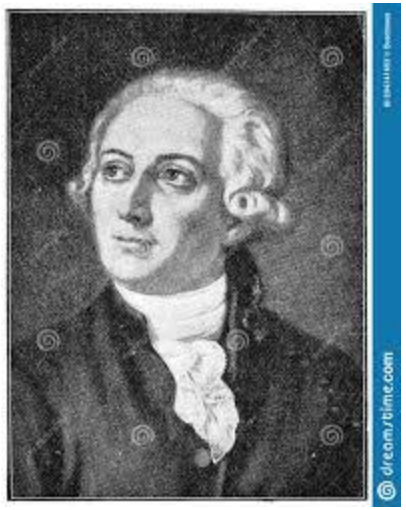


2000

The Lavoisier-Laplace Ice Calorimeter



Pierre Simon Laplace
1749-1827

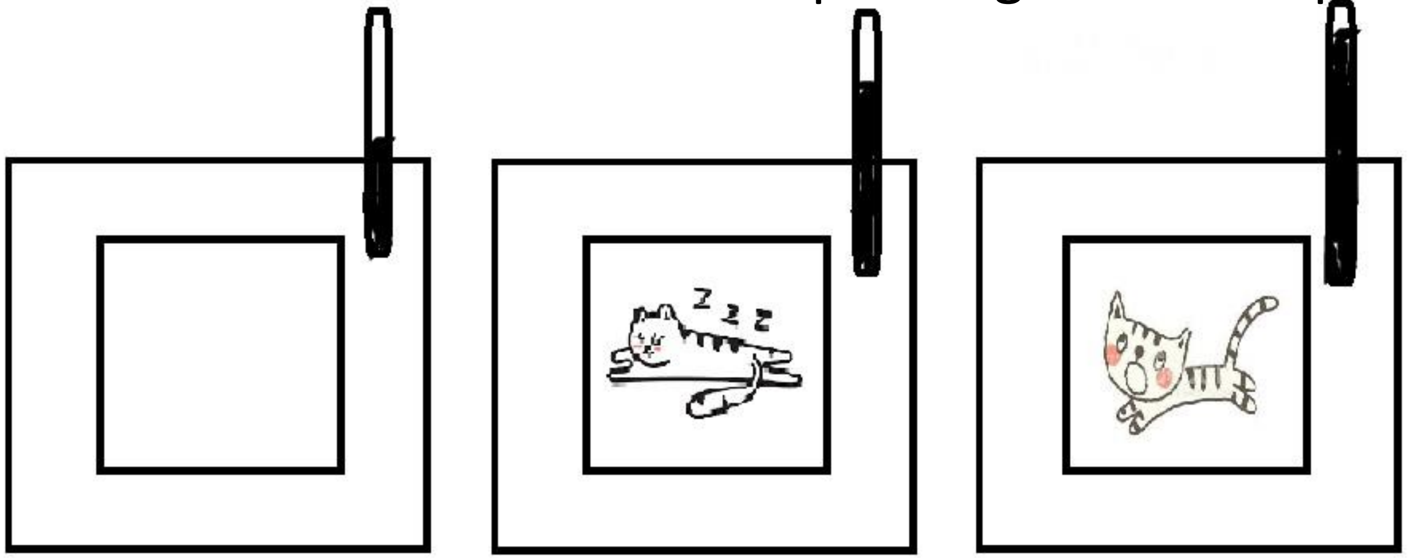


Antoine Lavoisier
1743 - 1794

In 1782-84 this device was used by Lavoisier and Laplace to measure the content of the "element" caloric in a sample of combustible oil. The oil was burned in a lamp held in a bucket held in a wire mesh cage (*f*) surrounded by ice in spaces *b* and *a* of the double walled container a foot in diameter. The lid (*F*) was topped with ice, Heat produced was measured indirectly, by assessing the amount of water that collected at the bottom of the chamber, which is the impact of the heated oil on the ice in the outer chamber.

Calor → Heat

Amount of heat absorbed = corresponding rise in temperature



However, calorimetry in particle physics does not correspond to measurements of ΔT

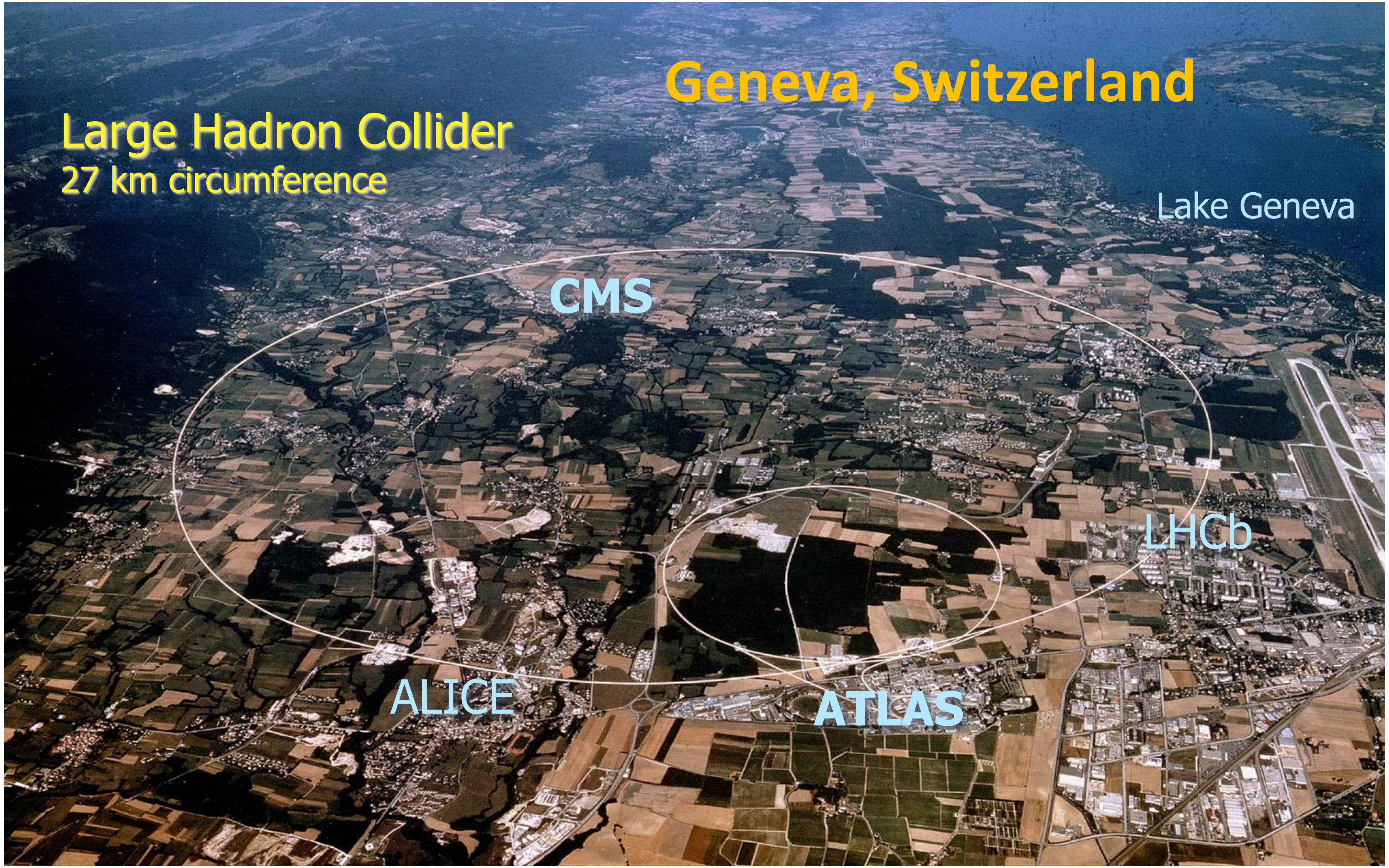
The temperature change of 1 liter water at 20 °C by the energy deposition of a 1 GeV particle is 3.8 10^{-14} K !

LHC: total stored beam energy E = 10^{14} protons 14 TeV ~ 10^{8} J

If transferred to heat, this energy would only suffice to heat a mass of 239 kg water from 0° to 100°C

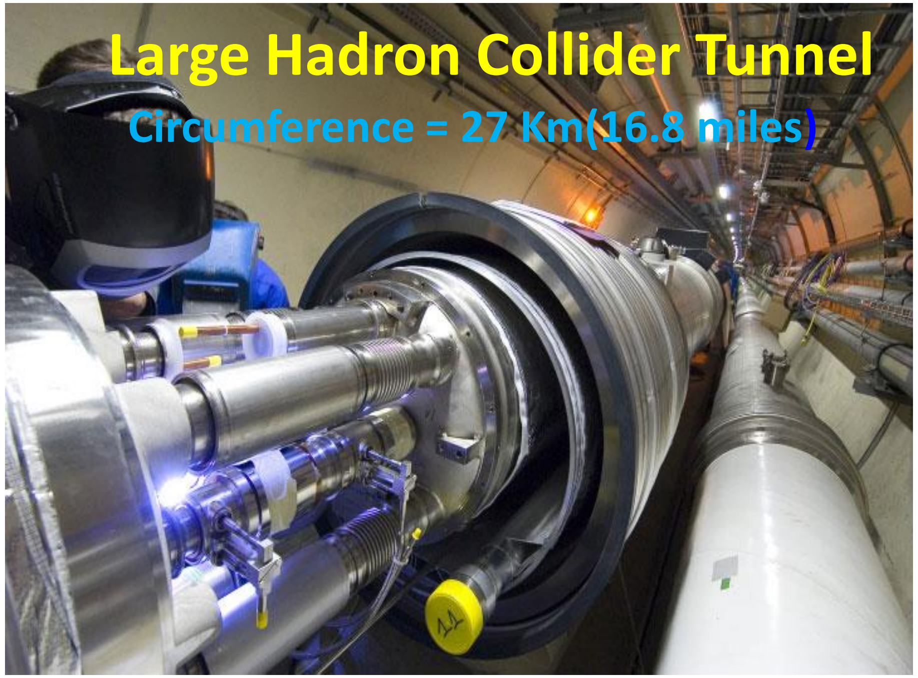
Calorimeters are used to measure the energy of a particle

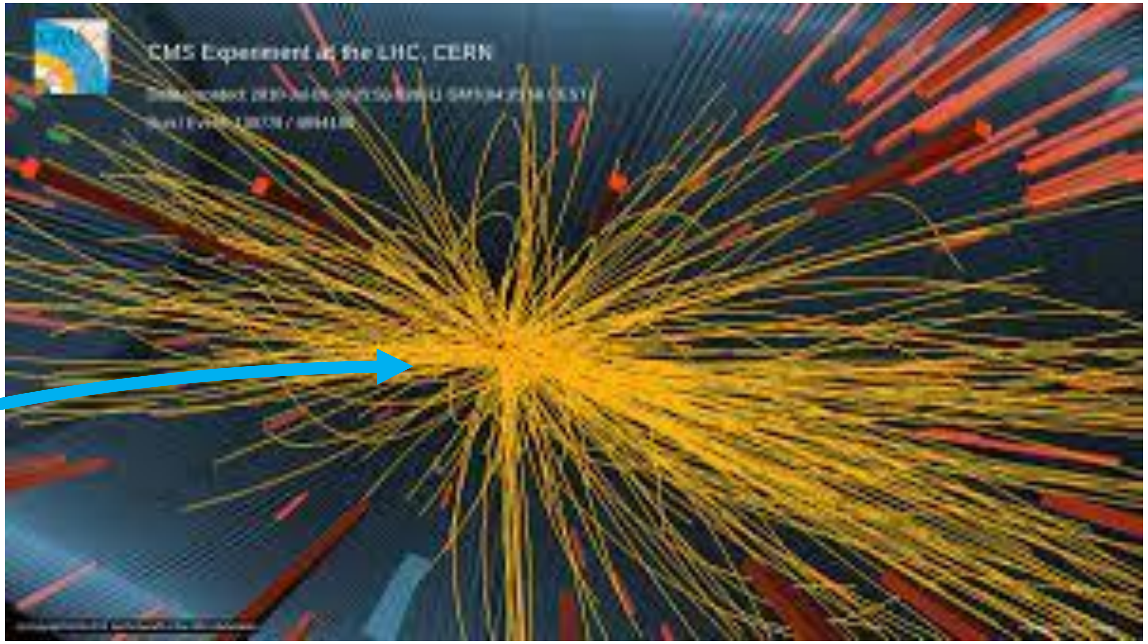
CERN Site

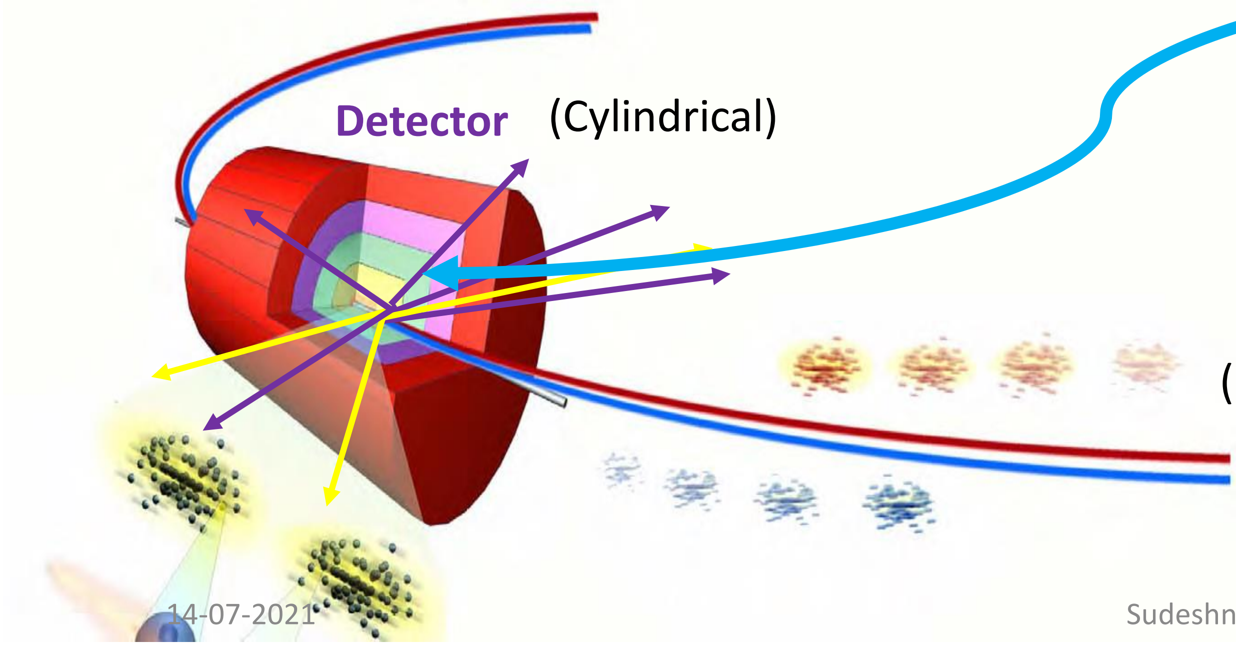


Ring is 1 Km under the surface

http://www.cern.ch


Large Hadron Collider Tunnel
Circumference = 27 Km(16.8 miles)


CMS Experiment at the LHC, CERN


Detector
(Cylindrical)
(particle beam in bunches)

Reconstructing Physics

Energy momentum

Particle ID Missing Energy

difficult

Electron Muon Photon

Missing Energy
(neutral particles)

pion kaon Lambda ....

All other particles decay ~instantly, or in flight, usually within a few hundred microns from the collision, into one or more of the particles above

J/psi D^0 $D^{\pm}$...........

Mass

B^0 $B^{\pm}$......................

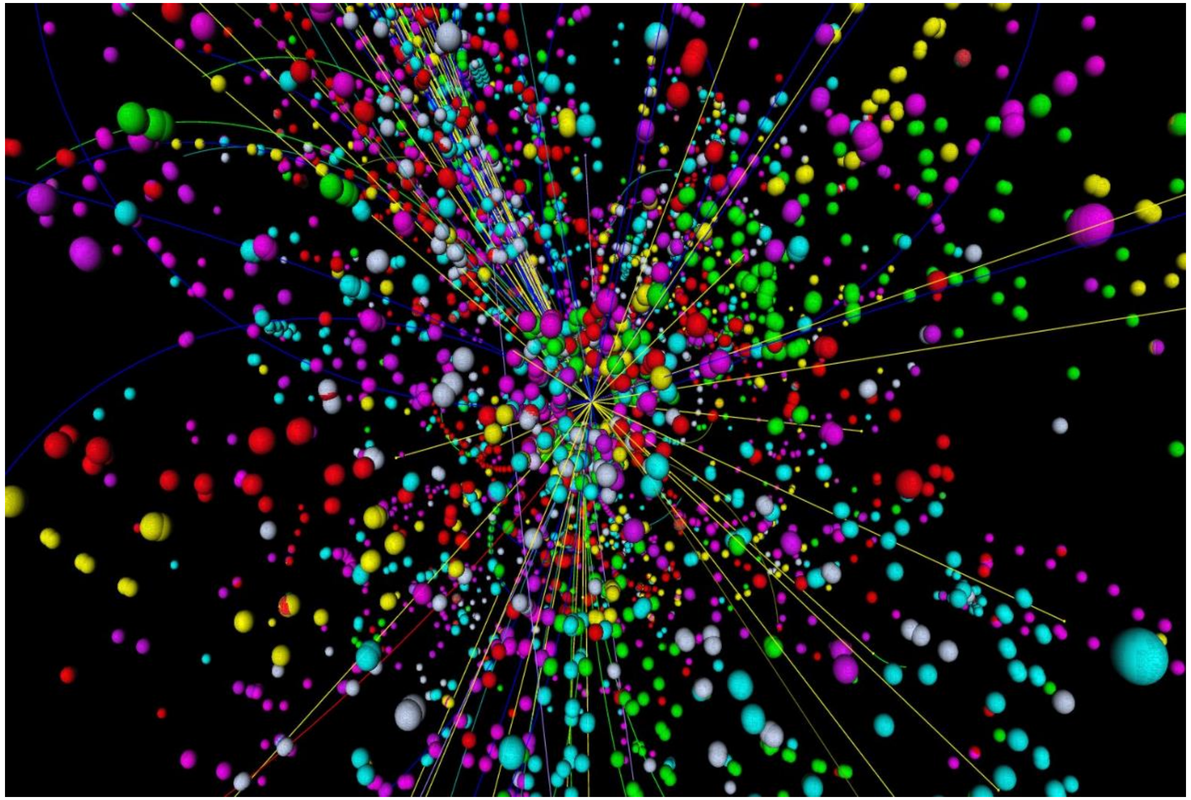
t $\bar{t}$

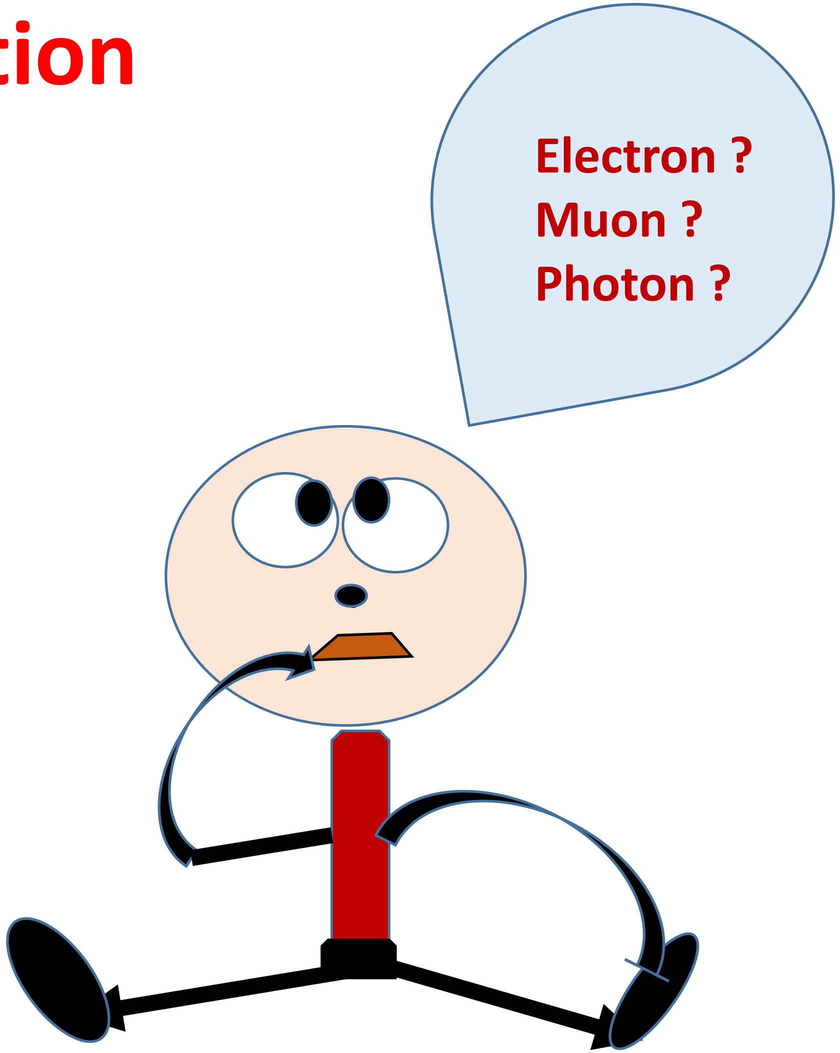
Supersymmetric particles (SUSY) Higgs

Same particles make signal and background

Particle Identification

Why is it important in High Energy Physics Experiments ??

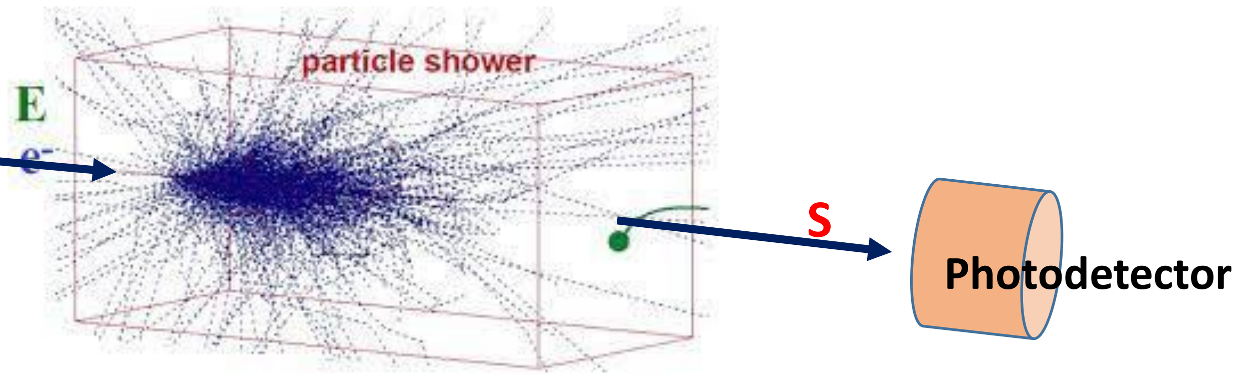




Need many clues

Calorimetry: basic mechanism

Incoming particle
(can be at O(TeV) at LHC)



- Energy lost by the formation of **electromagnetic** **or** **hadronic** cascades /showers in the material of the calorimeter **(different phenomena → different devices)**
- Calorimeters are designed to stop and fully contain the incoming particle (end of the road)
- **Measure –** energy of incoming particle by total absorption
- - direction of the incoming particle
- Convert E of the incident particle into detector response S
- S is generally light quanta (photons)
- **Photo-detectors then detect these "quanta"**

Shower Properties

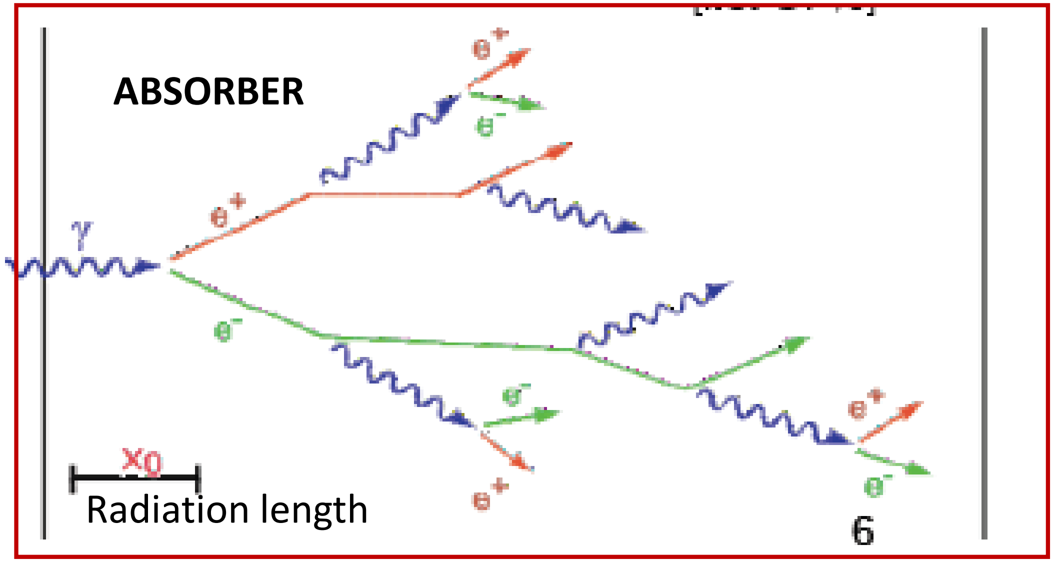
- Logitudinal development - in the direction of the primary particle
- Lateral development – in the transverse direction
- Different shapes for different particles

Particle Showers

Calorimeters measure energy of charged secondary particles created by the interaction of the incoming particle with a block of material

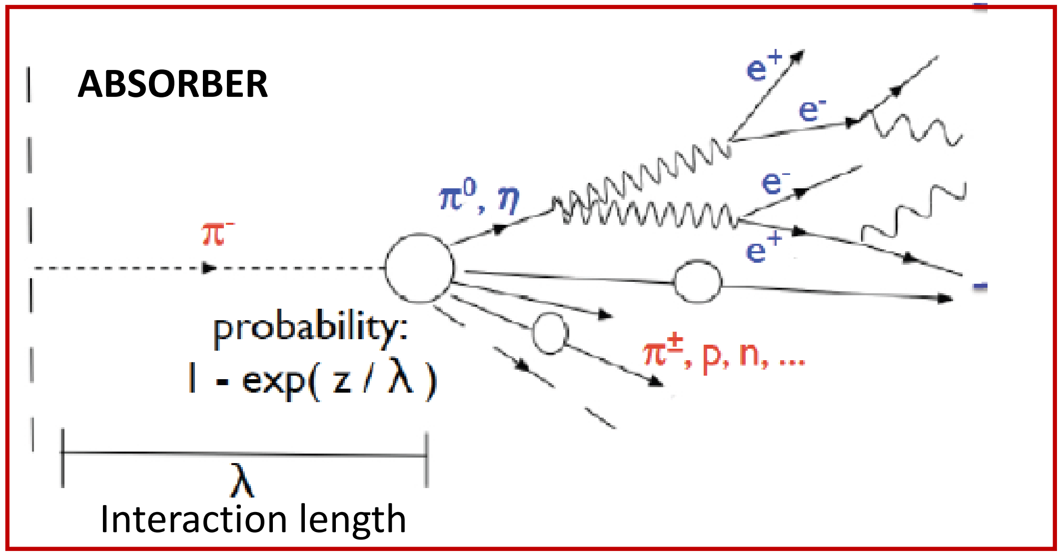
Electromagnetic Calorimeter

- EM shower initiated by e, γ
- Shower development based on two processes
  - * Bremsstrahlung
  - * Pair creation
- e+, e- and γ are the sole components of the shower

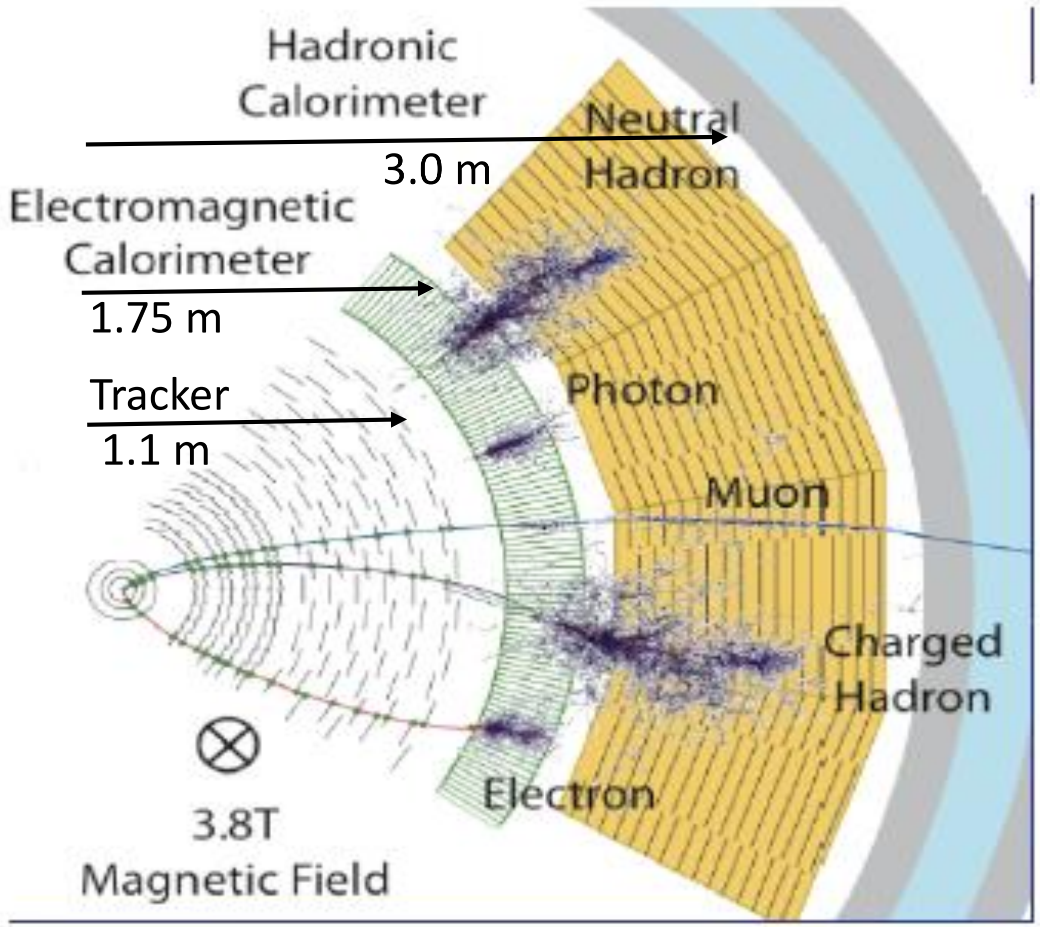


Hadronic Calorimeter

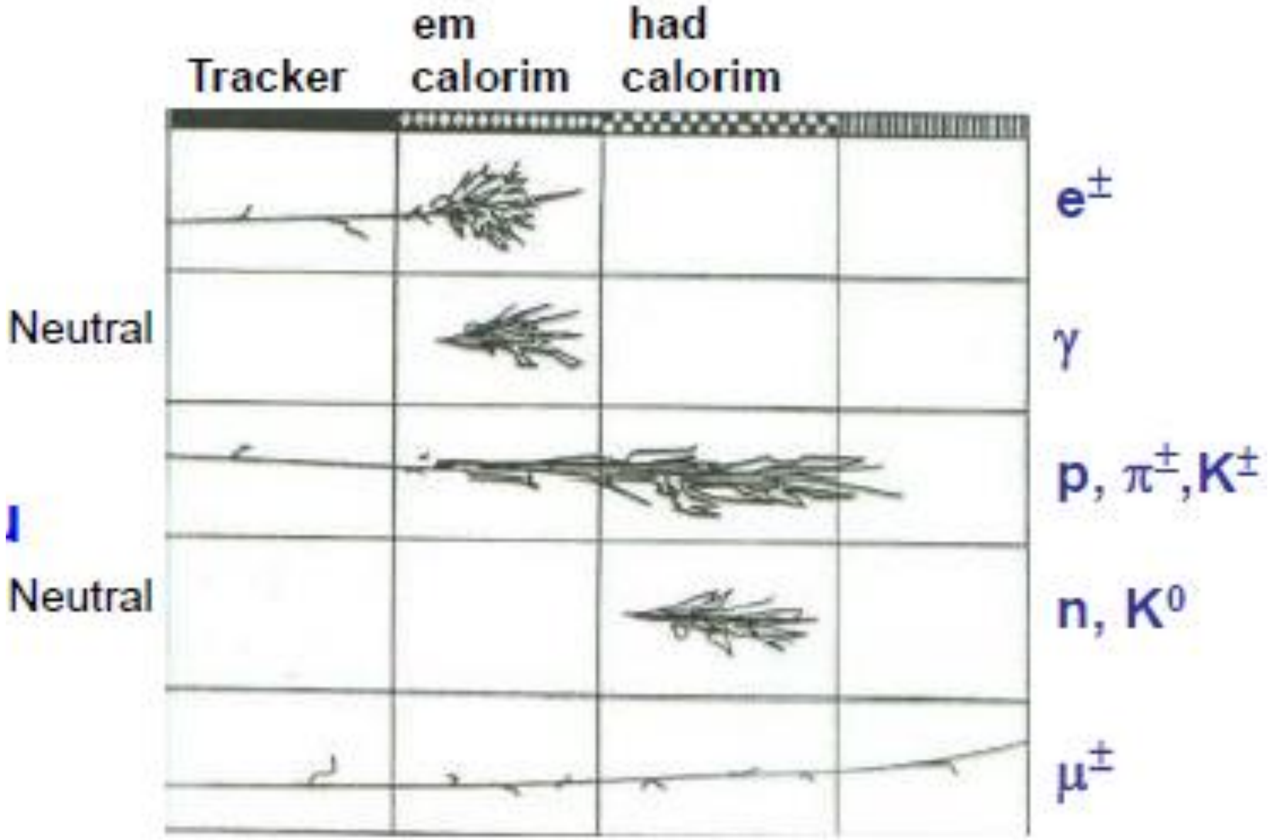
- Hadronic shower initiated by the hadrons (p, n, π)
- Hadronic showers also always have a EM component
- Shower development based on hadronic and EM interactions
- Large variety of particle components



Where you stop is what you are



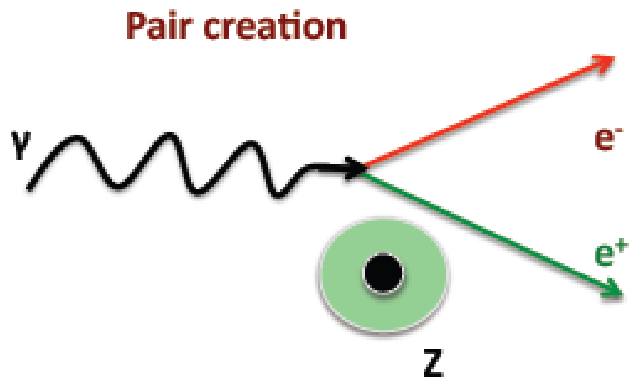
A wedge end view of the CMS detector

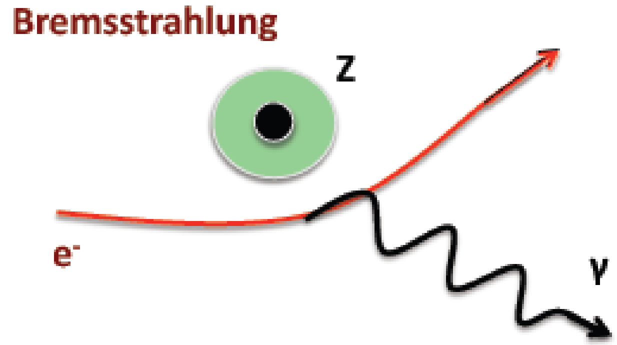


Get the sign of the charged particle from the tracker

Electromagnetic showers – basic concepts

- Above ~1GeV energy loss by e/γ is dominated by radiative processes $\rightarrow$ We focus on these





- At lower energy other processes contribute
  - Ionization for electrons
  - Compton scattering, photoelectric effect for photons

EM Shower – basic concepts

- **EM showers develop longitudinally and transversely**
- **A Few parameters can describe the development**

Radiation length

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

Dividing by density gives the length in cm

- After passage through 1 X_0 of material an electron has $(1/e)^{th}$ of its original energy, i.e. 37%
- In 1 X_0 1 electron loses ~2/3 by emitting a photon (bremsstrahlung in the presence of an atom)
- In 1 X_0 1 photon has a probability of ~7/9 to undergo conversion by pair production

X_0 can be (approximately) assumed as generation length: at each generation (step) the number of particles in the shower doubles and the energy of the particles halves

Critical energy $$E_c \approx \frac{610 MeV}{Z + 1.24}$$

E > E_C : no energy loss by ionization/excitation
E < E_C : energy loss only by ionization/excitation

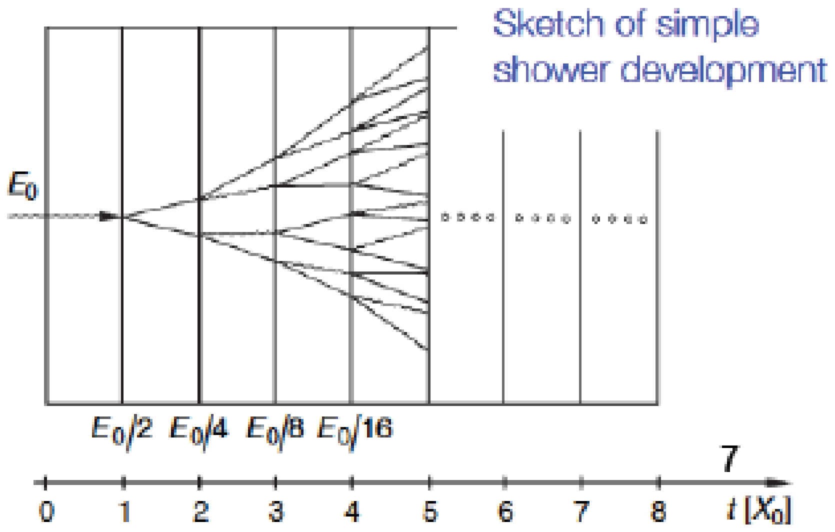
Moliere radius $$R_M = \frac{21 MeV}{E_c} X_0 \propto \frac{A}{Z}$$

Measures the transverse shower size: average lateral deflection of electron with E = E_C after 1 X_0

Shower Model

Simplified model: shower development governed by X_0 [Heitler]

- **2^t particles after t [X_0]**
- **Each with energy $E/2^t$**
- **Stops if E < critical energy E_C**
- **Number of particles $N = E/E_C$**
- **Maximum at $t_{max} \propto \ln (E_0/E_C)$**



Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle, i.e. Calorimeters can be compact

A few typical numbers: $E_C \approx 10$ MeV, $E_0 = 1$ GeV → $t_{max} = \ln (100) \approx 4.5$; $N_{max} = 100$

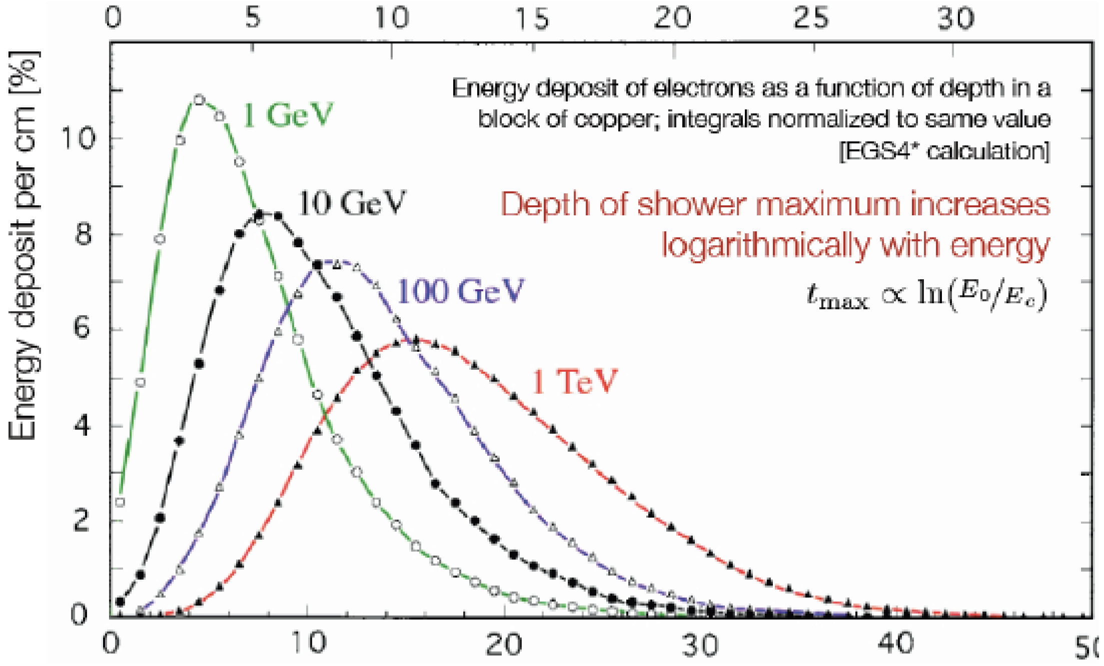
$E_0 = 100$ GeV → $t_{max} = \ln (10000) \approx 9.2$; $N_{max} = 10000$

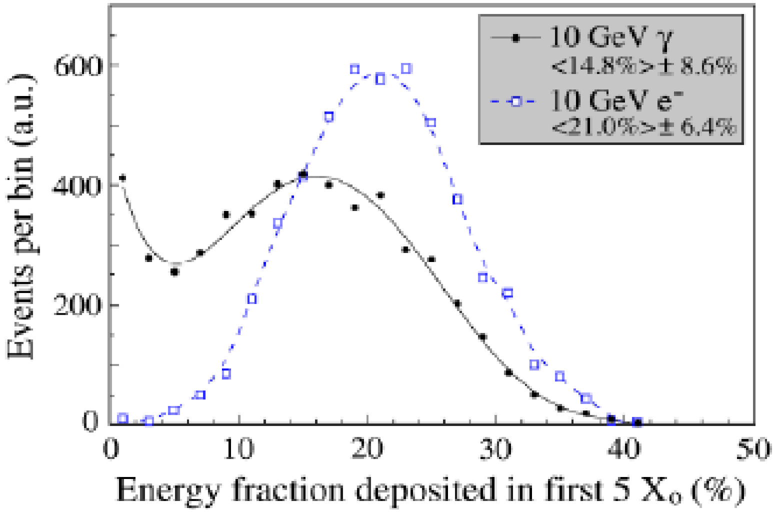
	Szint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

→ 100 GeV electron will be contained in 16 cm of Fe or 5 cm of Pb

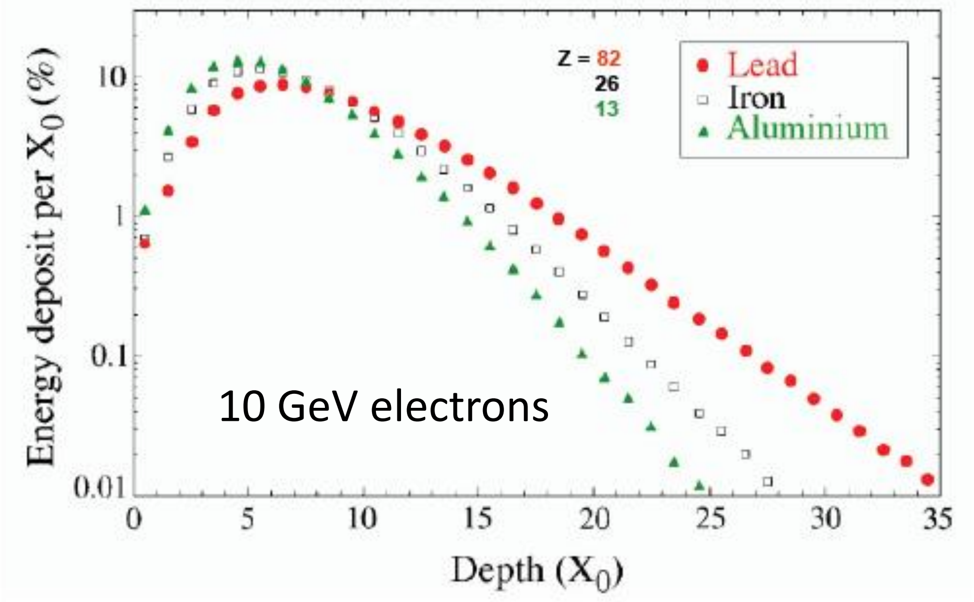
Longitudinal Development of EM Shower

Longitudinal profile





Material effect



EM showers are contained (>99%) in 20 X_0 regardless of the material (X_0 depends on ρ)

Important differences between showers initiated by **e** and γ

$$t_{max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

with:

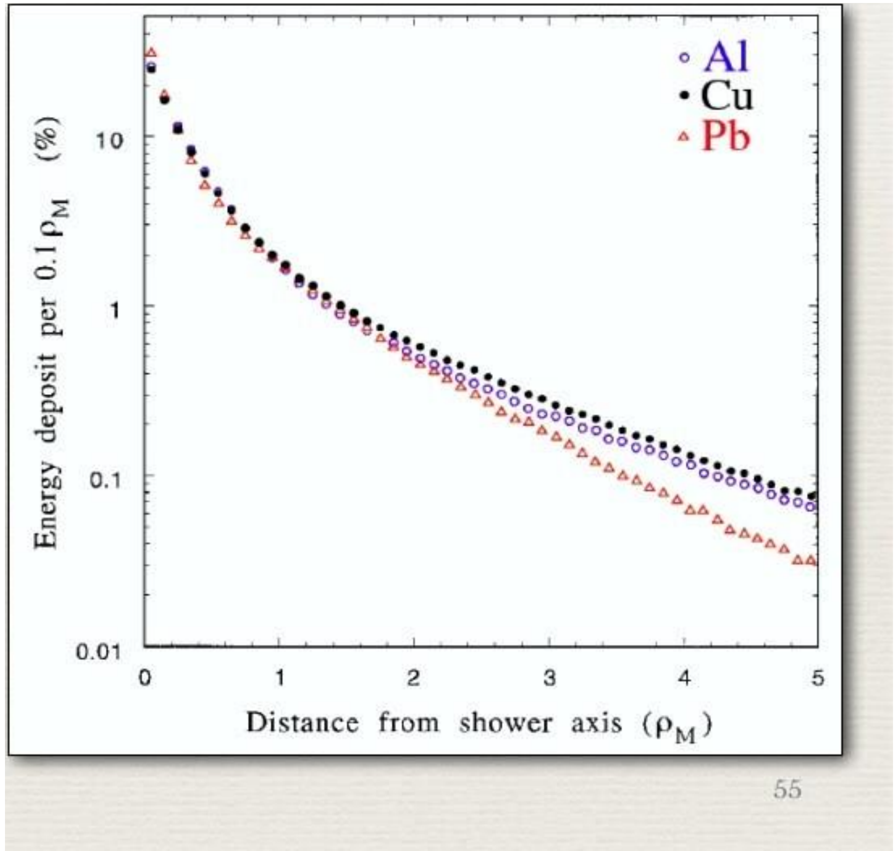
$C_{e\gamma} = -0.5$ [γ-induced]

$C_{e\gamma} = -1.0$ [e-induced]

Development of EM Shower

Lateral Shower Development

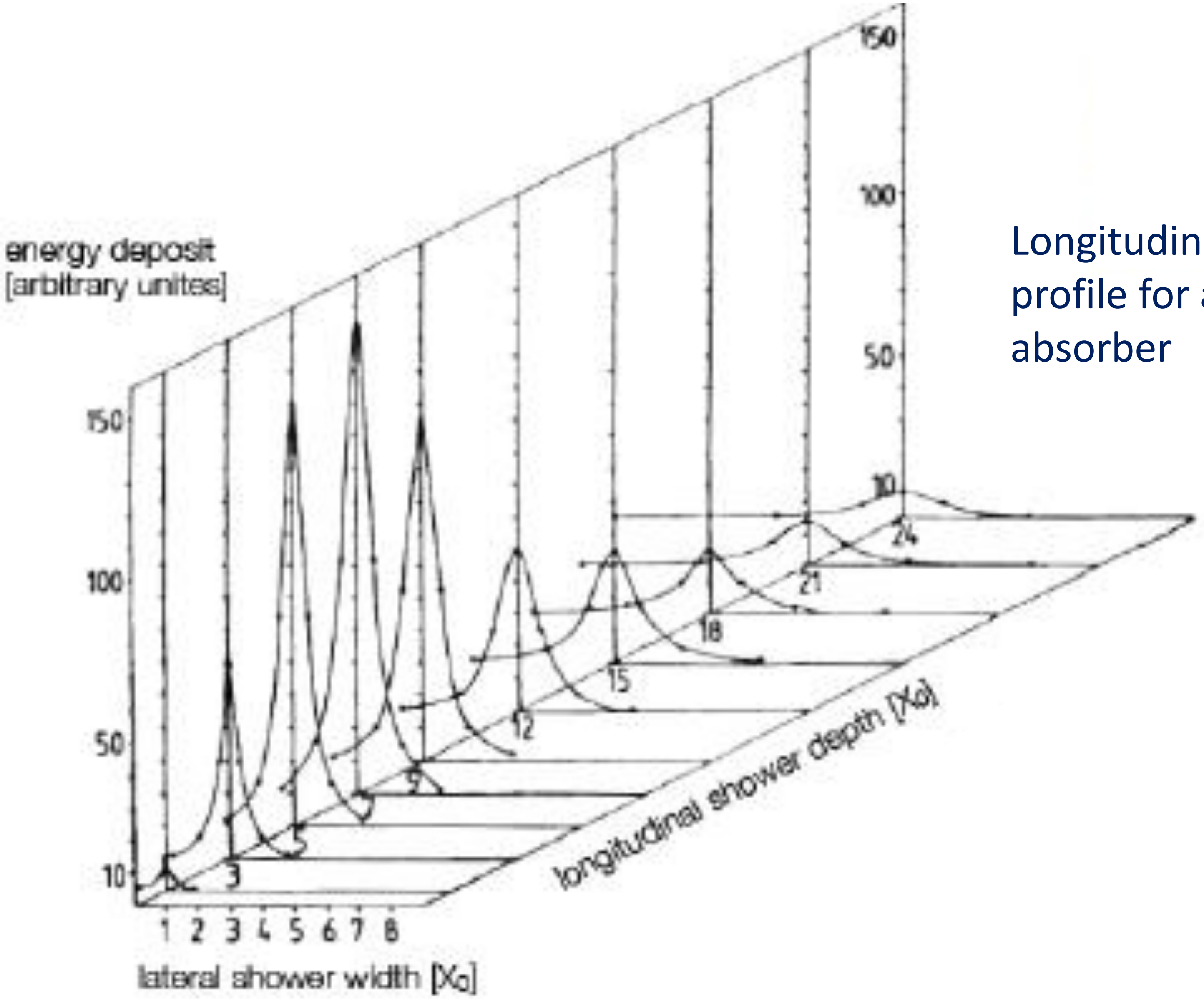
Lateral shower developmen:
EM showers contained in
1 RM: ~87%
2 RM: ~96%
5 RM: >99%



Shower decay:

After the shower reaches maximum number of particles, it decays slowly through ionization and Compton scattering ➡ **Not proportional to X_0**

3D Shower Development

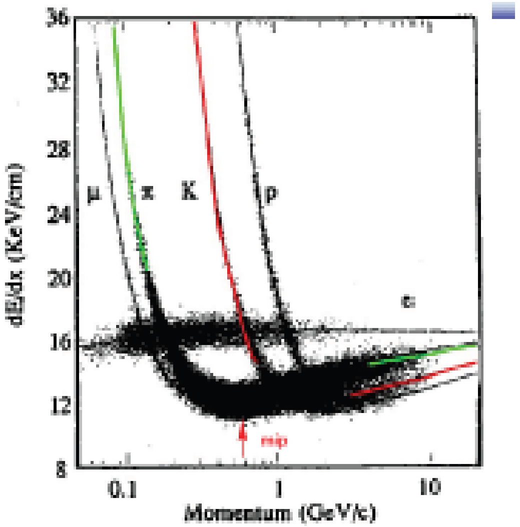


Longitudinal and Transverse shower profile for a 6 GeV electron in a lead absorber

Muons ???

Heavy Particles: M >> m_e

➡ **Bethe-Bloch**

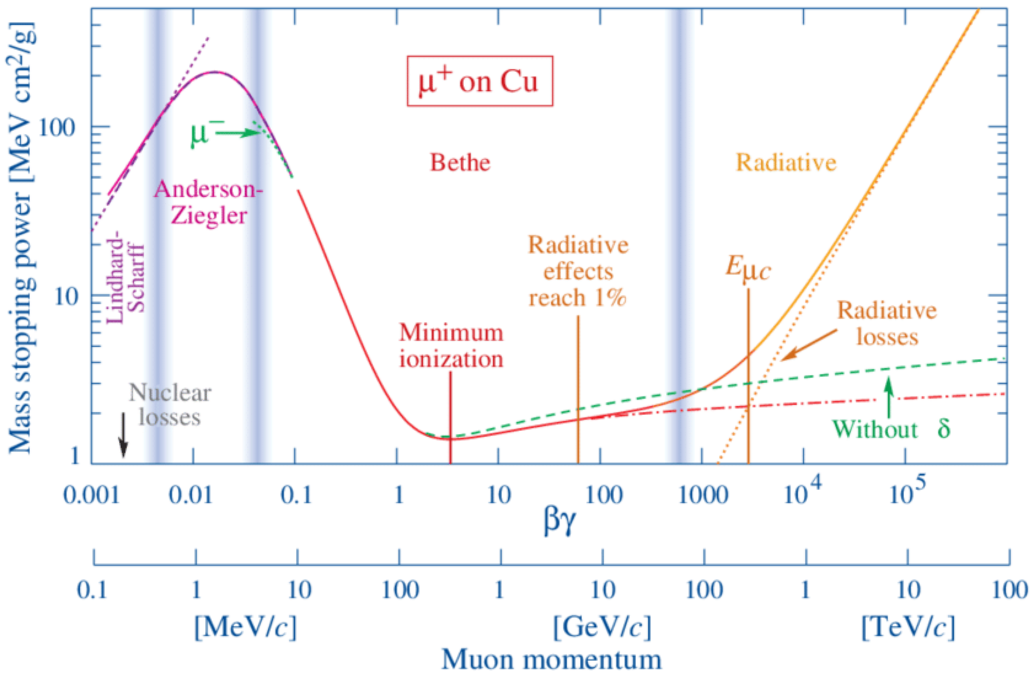


Minimum Ionizing Particle
dE/dx = minimum

$$E_c^{\mu} = E_c^{e}\left(\frac{m_{\mu}}{m_e}\right)^2 \approx 4 \cdot 10^4 E_c^{e}$$

E_C (e^-) in Cu = 20 MeV
E_C (μ) in Cu = 1 TeV

Z_{Cu} = 29



Muon energy losses mainly via ionization ➡ "no shower"

Hadronic Showers

Strong Interaction with detector material

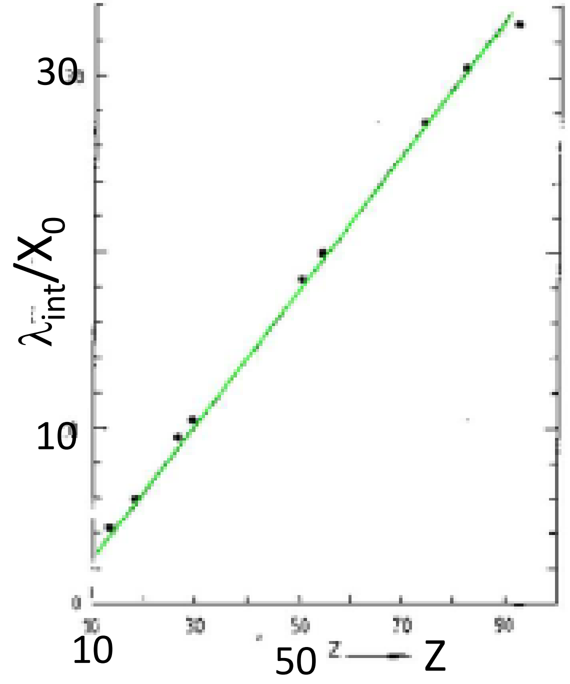
Importance:

- Charged hadrons: complementary to track measurement
- Neutral hadrons: the only way to measure their energy

Hadronic Interaction length (λ_{int}) ≈ 35 $A^{1/3}$ g/cm^2

(mean distance travelled by a hadronic particle before undergoing an inelastic nuclear interaction)

Electromagnetic Radiation length (X_0) ≈ 180 A/Z^2 g/cm^2



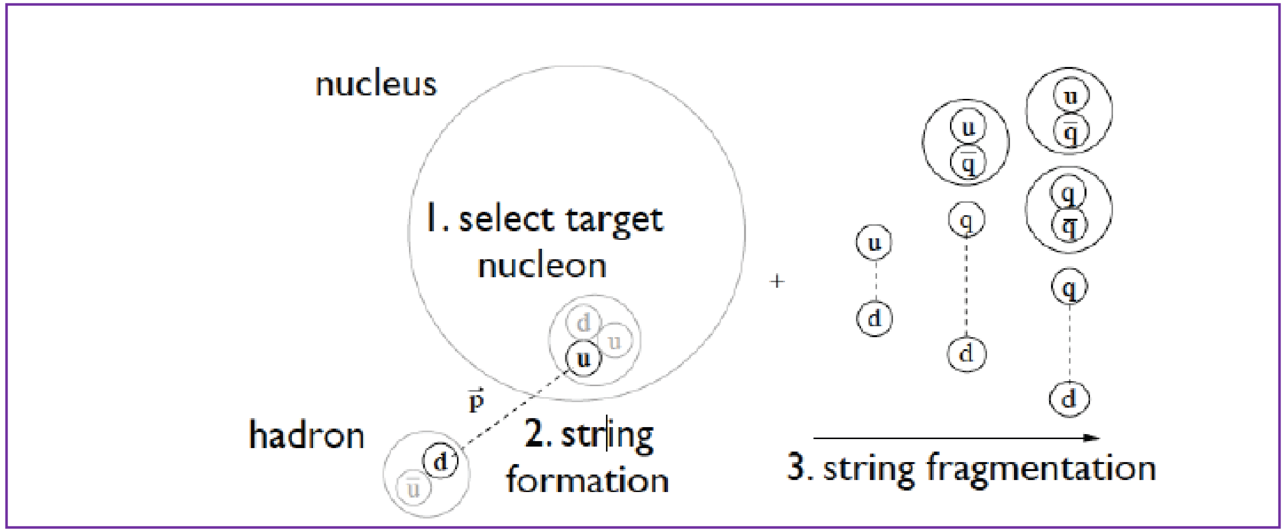
EM shower in PbWO4 23 cm deep x 2.19 cm radius
Hadron shower in Iron 80 cm deep x 16.7 cm radius

Hadronic showers are longer and wider than EM showers
Hadron calorimeters are much longer and broader than EM calorimeters

$$\left.\begin{array}{l} X_0 \sim \dfrac{A}{Z^2} \\ \lambda_{int} \sim A^{1/3} \end{array}\right] \rightarrow \frac{\lambda_{int}}{X_0} \sim A^{4/3} \qquad \lambda_{int} \gg X_0$$

Hadronic showers

- 1^{st} stage: the hard interaction – hadron energy > 10 GeV described by string models



- Projectile interacts with single nucleon (p, n)
- A string is formed between quarks from interacting nucleons
- String fragmentation generates hadrons

Hadron (p, π) + Nucleus $\rightarrow \pi^{+} + \pi^{-} + \pi^{0}$ + …. + Nucleus* (GeV scale)

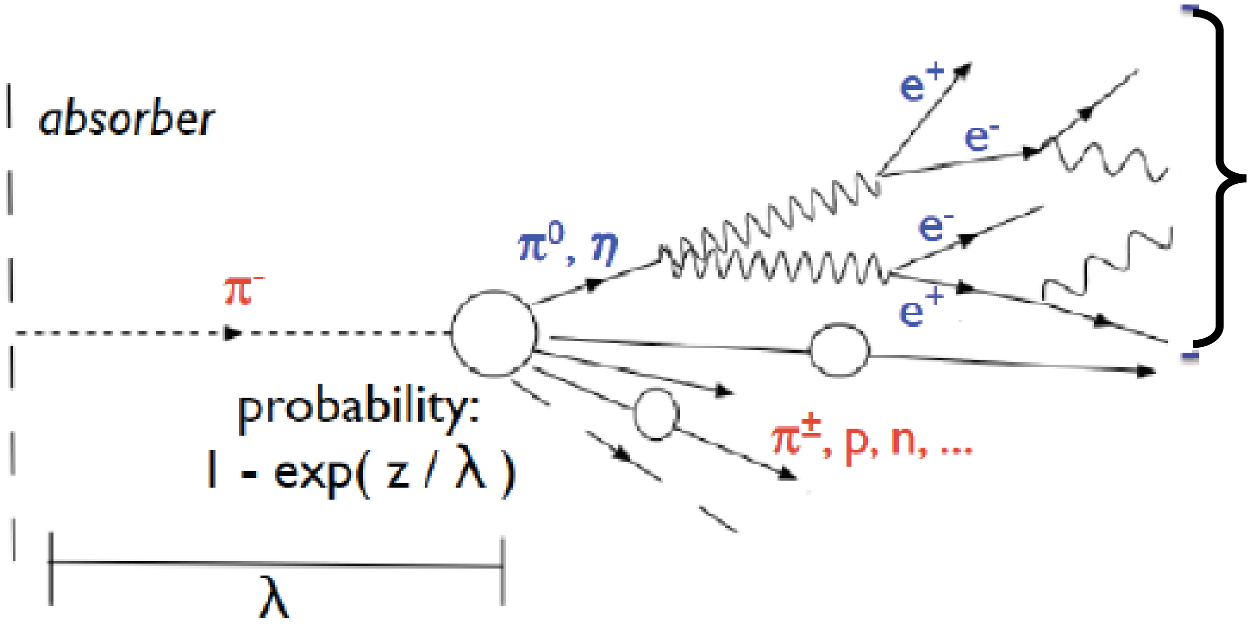
- 2^{nd} stage: hadron energy 10 MeV < E < 10 GeV via intra nuclear cascades

Nucleus* $\rightarrow$ Nucleus A + n, p, α,…. (low MeV scale)

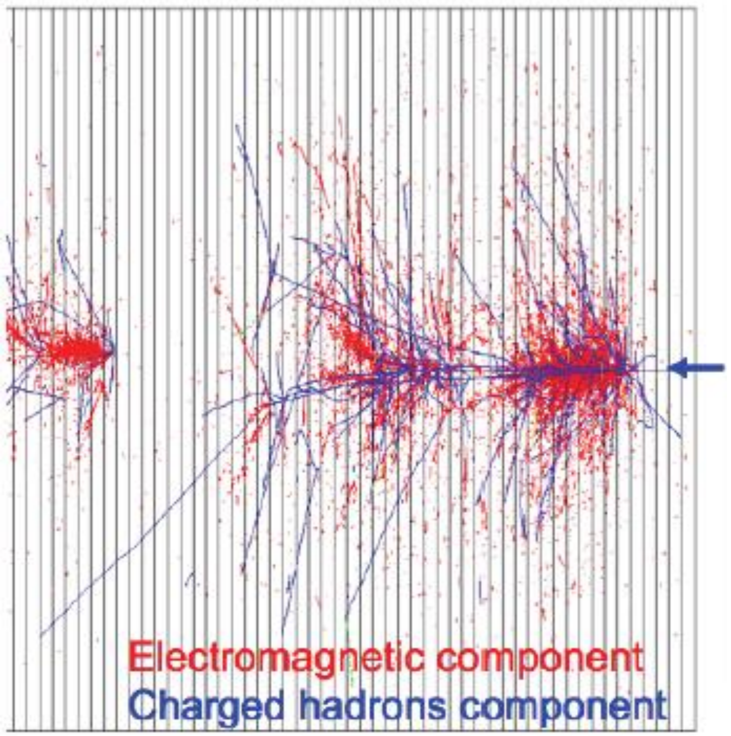
Hadronic showers

More complications: Energy deposit has a EM component

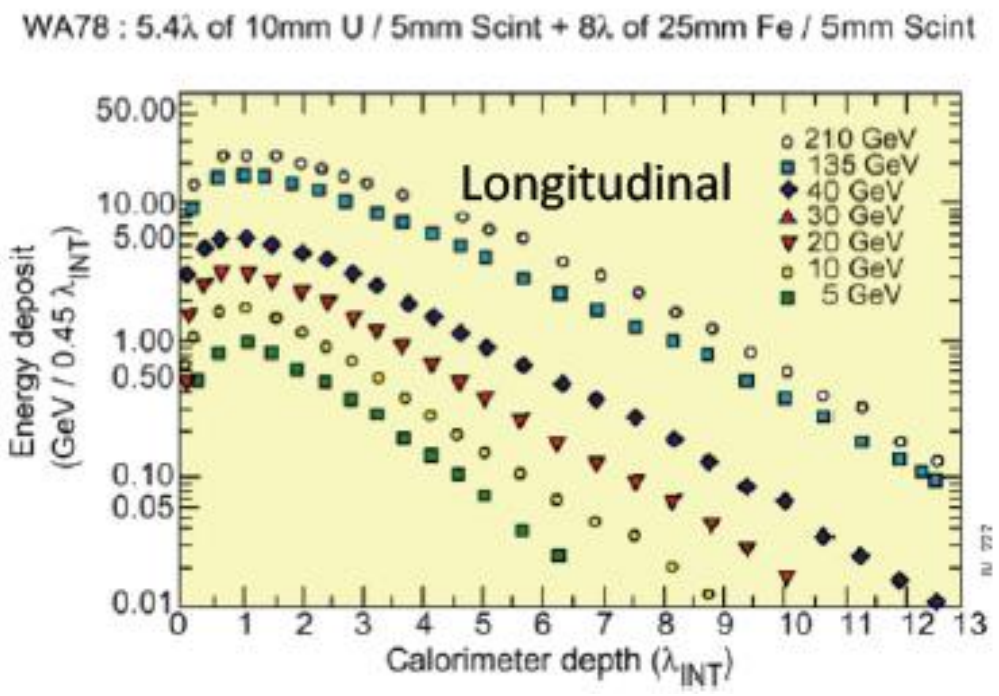
Electromagnetic:
- ionization, excitation ($e^{\pm}$)
- photo effect, scattering (γ)

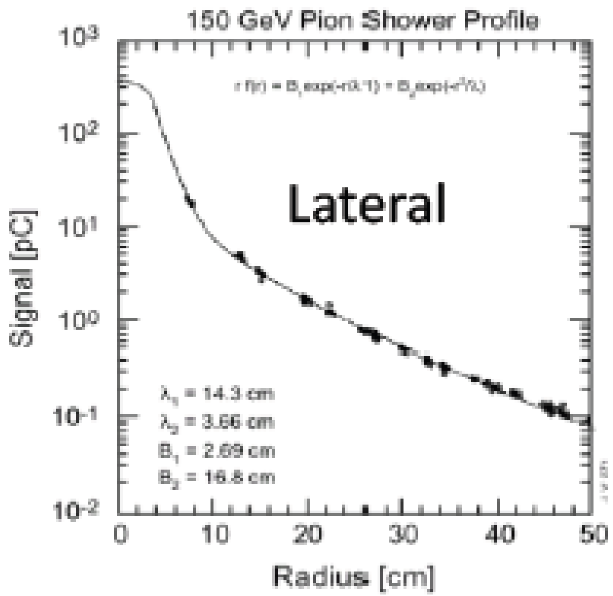


Once a π^0 is produced that energy is deposited as EM energy



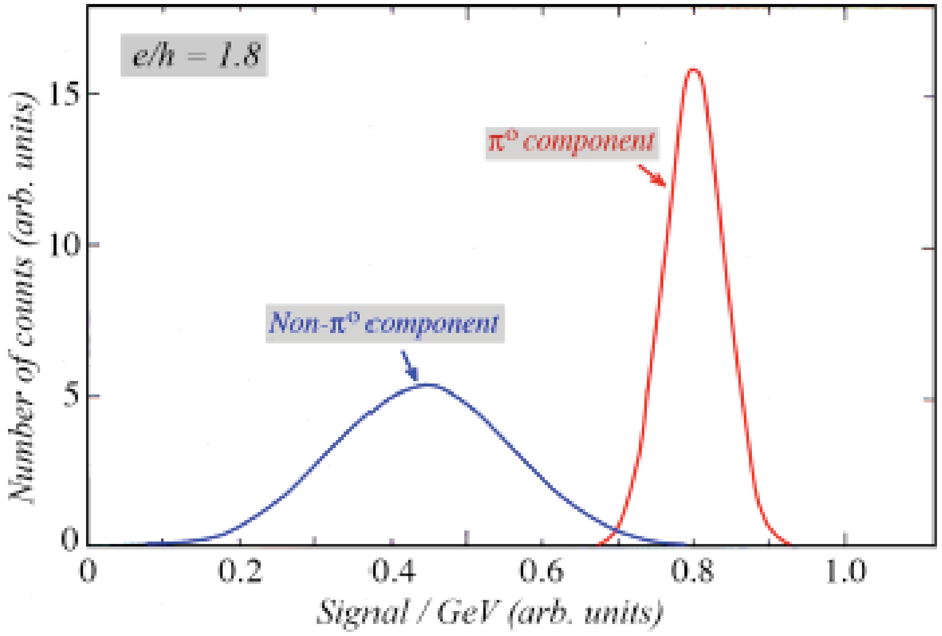
Hadronic showers





- Hadron shower development is parametrized with λ_{int}
- ~10 λ_{int} required to contain a ~300 GeV shower (1-2 m absorber)
- $\rightarrow$ HCAL is always sampling

EM Fraction in Hadronic Showers



e = response to the EM component

h = response to the non-EM component

f_{EM} = fraction of hadronic energy deposited via EM processes

$f_{EM} \rightarrow$ **1** in the high energy limit

Response to a pion initiated shower

$$\pi = f_{em} e + (1 - f_{em}) h$$

Comparing pion and electron showers

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

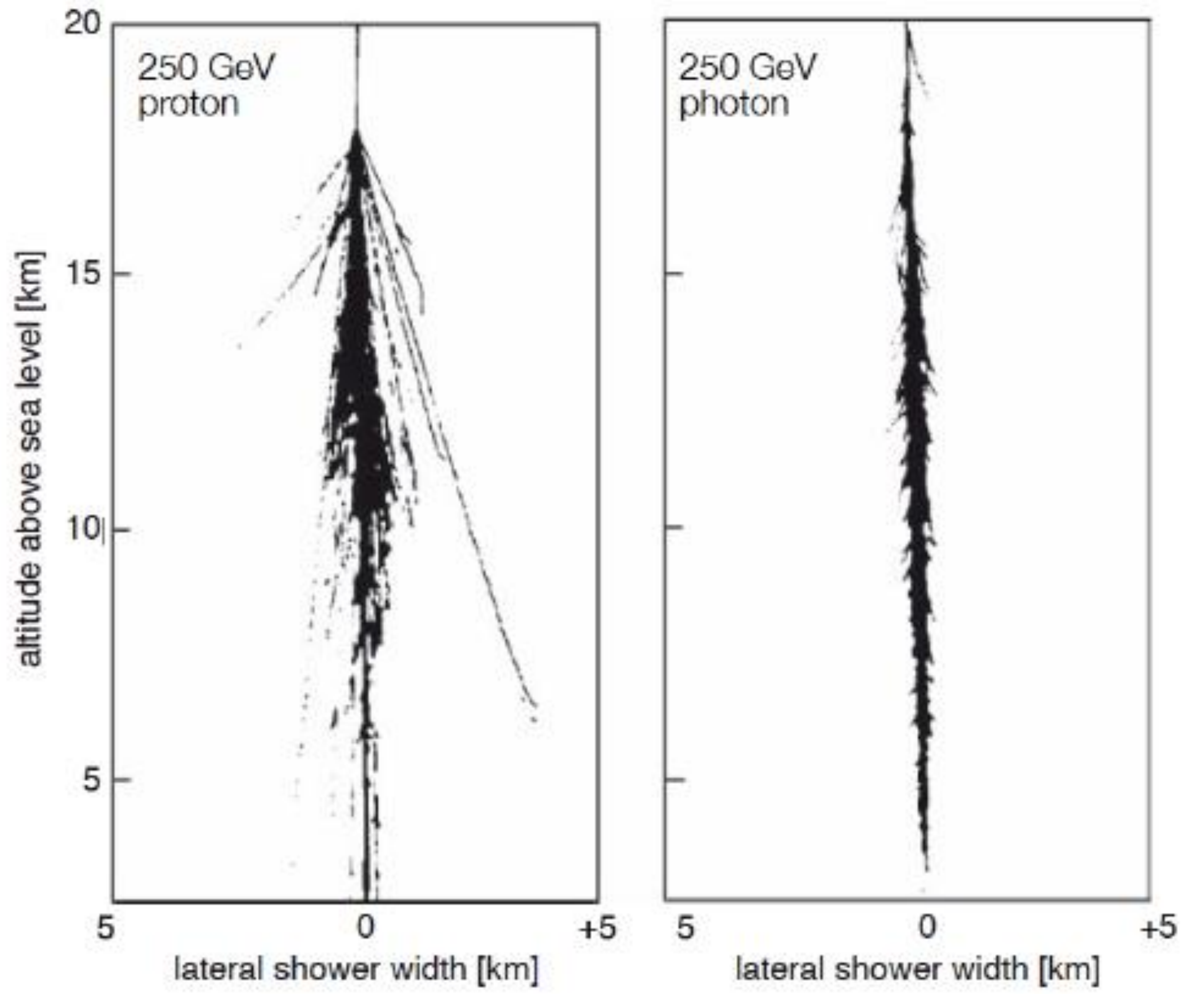
Calorimeters can be:

- Overcompensating e/h < 1
- Undercompensating e/h > 1
- Compensating e/h = 1

e/h (degree of non-compensation) is not directly measurable

e/π, ratio of response between electron-induced and pion-induced shower is measured

Hadronic Showers vs EM Showers



Simulated air showers

Measurement of energy

Required quantities

1. Relationship between measured signal and deposited energy

Calibration:

- Calibrate η-ϕ cells to make all cells the same (use ~200 GeV muons (mip))
- Calibrate the total energy (3x3 or 5x5 or 9x9 towers) with e or π beams of known energy (50 or 100 GeV)

Check how good the calibration is – response vs beam energy

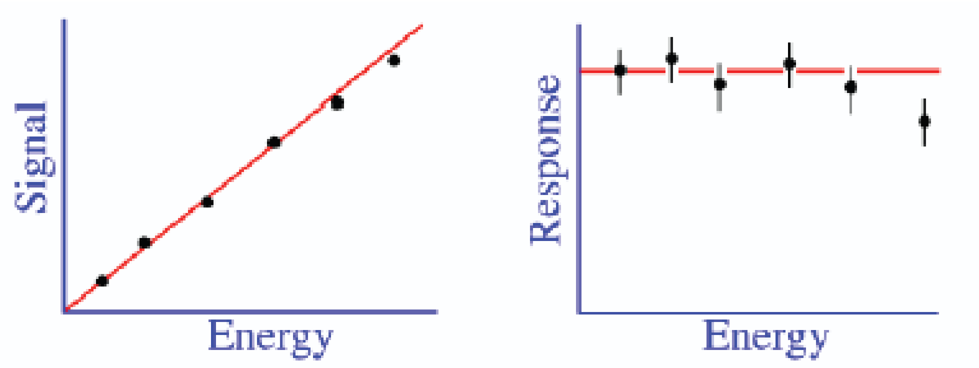
2. Precision with which the unknown energy can be measured

Check how the precision changes with energy -
Resolution vs beam energy

Response and Linearity

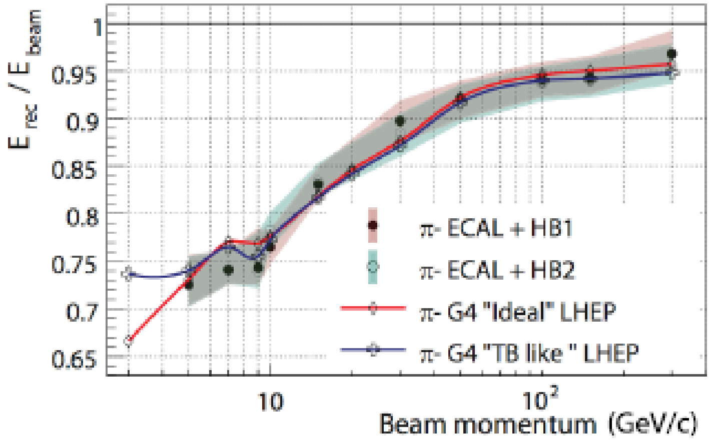
Response = average energy per unit deposited energy
e.g., # photoelectrons/GeV, picocoulombs/MeV

A linear calorimeter ha
constant response



HCAL Test Beam

Pions



In general, EM calorimeters are linear, Hadronic calorimeters are not

Sources of non - linearity

Instrumental effects – Saturation of gas detectors, scintillators, photo-detectors, electronics (signal readout)
Response varies with something that varies with energy – Deposited energy counts differently, depending on depth and depth increases with incident energy
Energy leakage – increases with incident energy

Energy Resolution

Measured energy in calorimeters is the energy of electrons and positrons interacting with the active detector material

$$E_0 \propto N_{tot}$$

Multiplication process is stochastic and therefore guided by Poisson statistics

$$\sigma(E_0) \propto \sigma(N_{tot}) \propto \sqrt{N_{tot}}$$

$$\frac{\sigma(E_0)}{E_0} \propto \frac{\sigma(N_{tot})}{N_{tot}} \propto \frac{\sqrt{N_{tot}}}{N_{tot}} \propto \frac{1}{\sqrt{E_0}}$$

Intrinsic energy resolution improves with E

Energy Resolution

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Resolution improves with increasing energy of the incident particle

- Stochastic term, fluctuations in shower development
- Sampling fluctuations with sampling calorimeters
- Photo-electron statistics

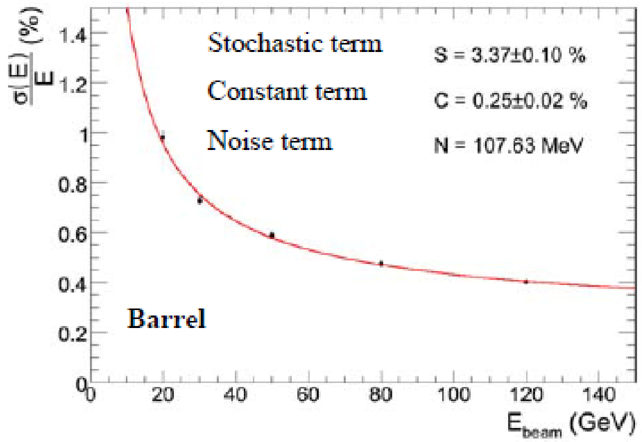
- inhomogeneities
- Non-linearities
- Inter-calibration between calorimeter cells
- Energy variation of beam particles

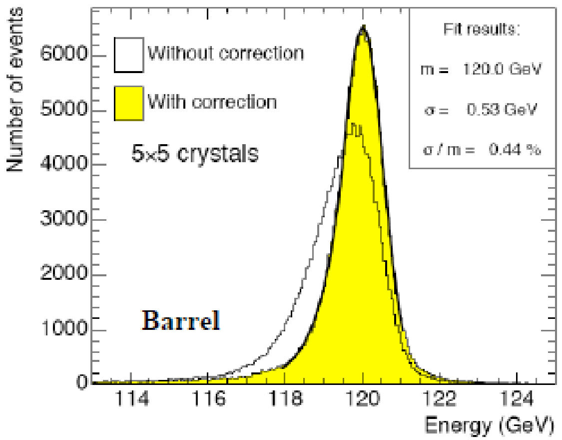
- Electronic noise
- Radioactivity
- Overlapping /pileup of events

Additional contributions to the energy resolution

- Longitudinal shower leakage
- Transverse shower leakage
- Dead material effect

CMS ECAL (Lead-tungstate crystals)





150 GeV electron beam

CMS experiment

EM: $\sigma/E = 2.83\%/\sqrt{E} + 0.26\%$

HAD: $\sigma/E = 100\%/\sqrt{E} + 5\%$

EM + HAD: $\sigma/E = 127\%/\sqrt{E} + 6.5\%$

Types of Calorimeter

Particle type

Electromagnetic calorimeters :

$E^{+/-}$, γ, π^0

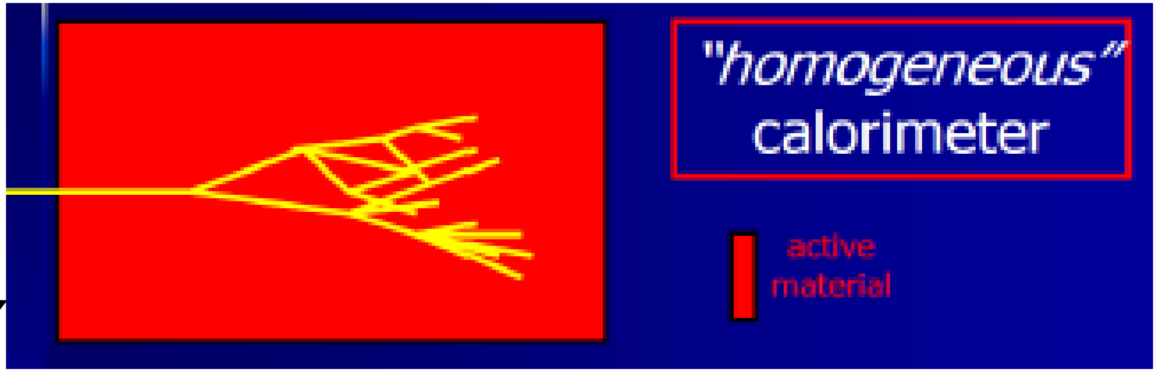
Signal detection:
- scintillator/crystal
- Semiconductor
- Cherenkov
- Ionization (Noble Liquids - Ar)

Hadron calorimeters :
charged and neutral hadrons, particle jets

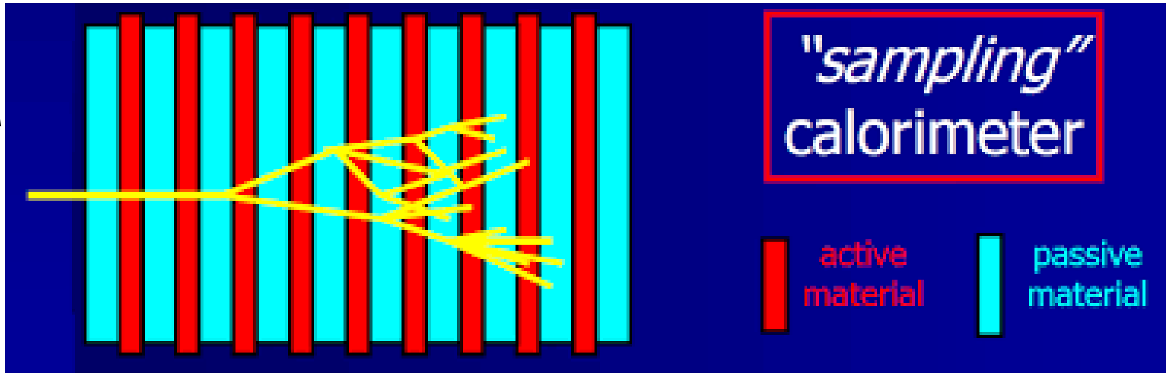
Signal detection:
- scintillator
- Semiconductor
- gas

Common absorbers : Pb, Fe, Cu, U, W

Construction technique



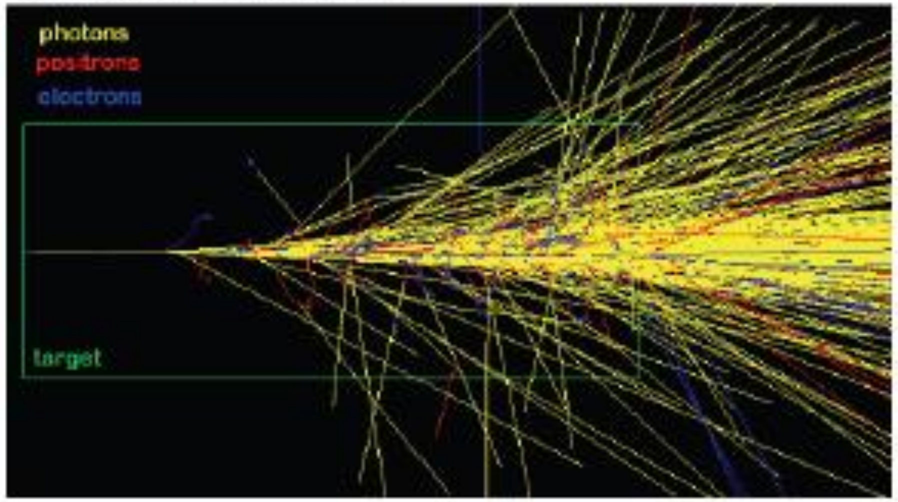
Full absorption detector, active medium for energy degradation and signal generation



Alternate layers of absorbers to degrade particle energy and active medium to provide detectable signal.

Homogeneous vs Sampling

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

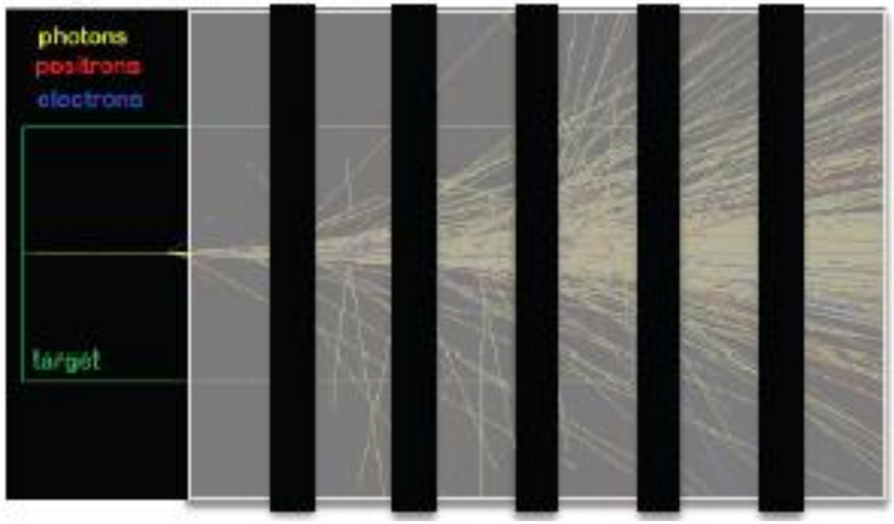


Active medium (with high X0) coincides with the absorber

- Very good energy resolution (small “a”)
- No information on longitudinal development of the shower
- Cost effective
- Easy to calibrate

a ~ 1-10 %

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.



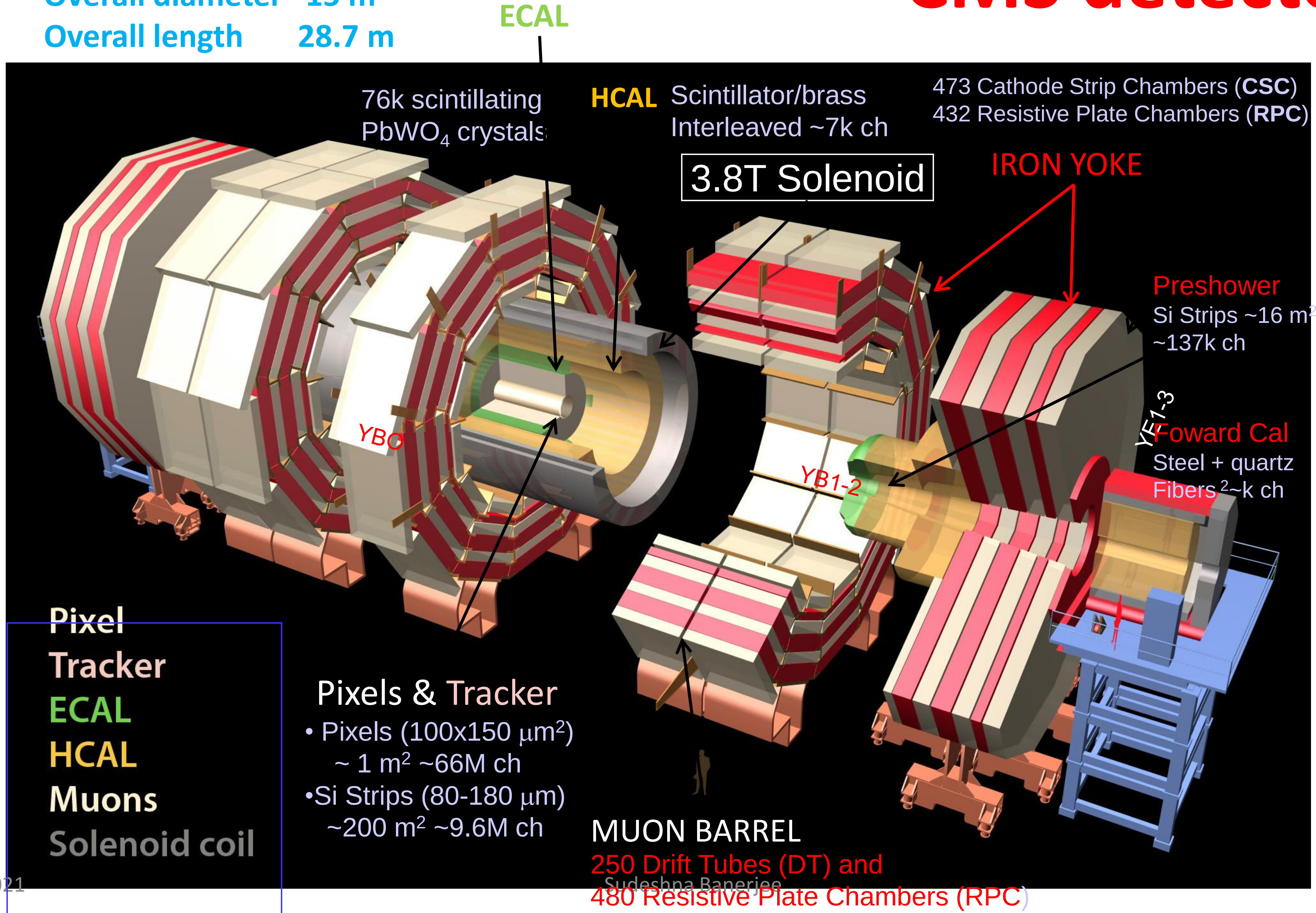
Alternating layers of active medium (smaller X_0, λ_{int}) and absorber (larger X_0, λ_{int}: Pb, Cu, Fe)

- Energy is sampled: sampling fraction introduces and additional contribution to the stochastic term
- Shower shape information
- Normally cheaper than homogeneous
- Calibration is complicated

a ~ 10-20 %

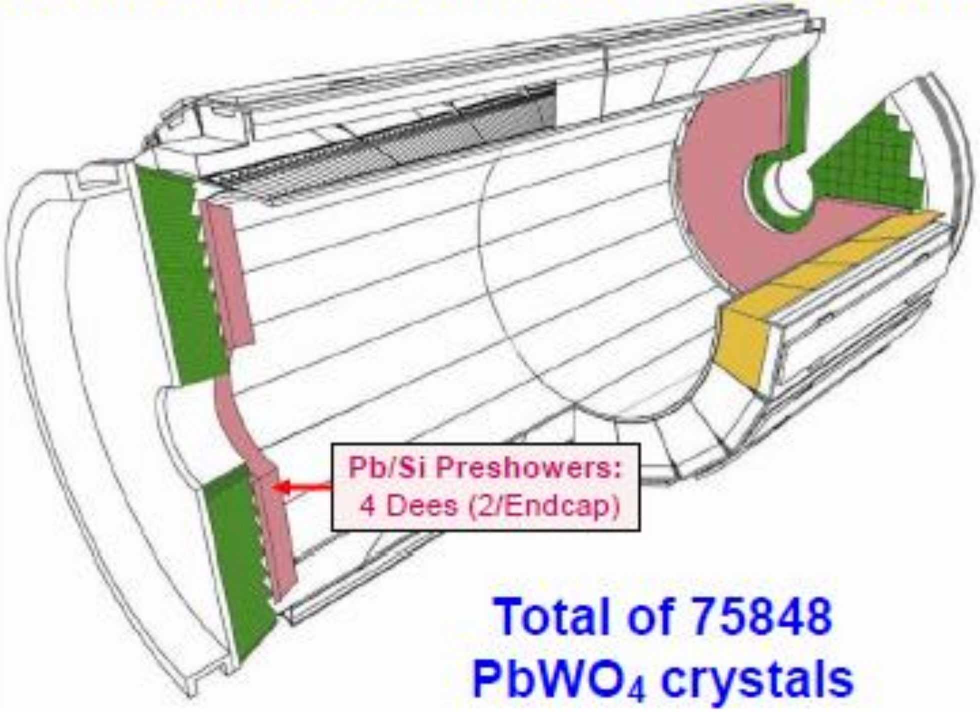
CMS detector

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

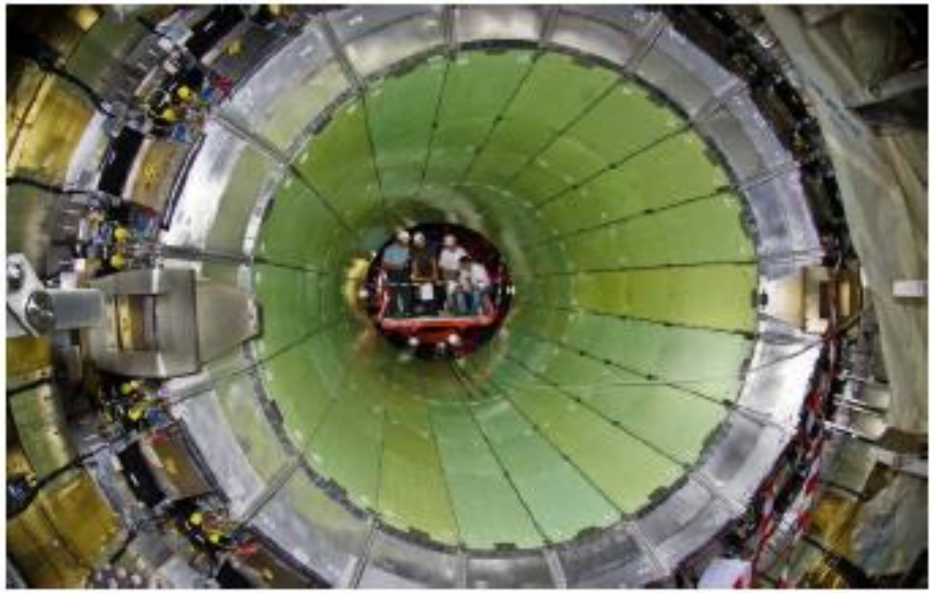


EM Calorimeter – CMS experiment

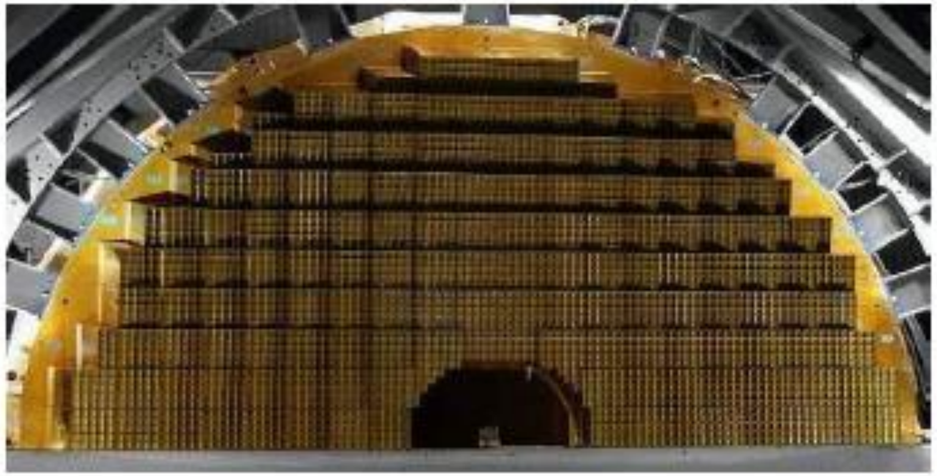
CMS at the LHC – scintillating $PbWO_4$ crystals



Total of 75848 $PbWO_4$ crystals



CMS Barrel



Barrel: 36 Supermodules (18 per half-barrel)
61200 Crystals (34 types) – total mass 67.4 t

Endcaps: 4 Dees (2 per Endcap)
14648 Crystals (1 type) – total mass 22.9 t

CMS Hadron Sampling Calorimeter

CMS Hadron calorimeter at the LHC

Brass absorber preparation

Workers in Murmansk sitting on brass casings of **decommissioned shells of the Russian Northern Fleet**

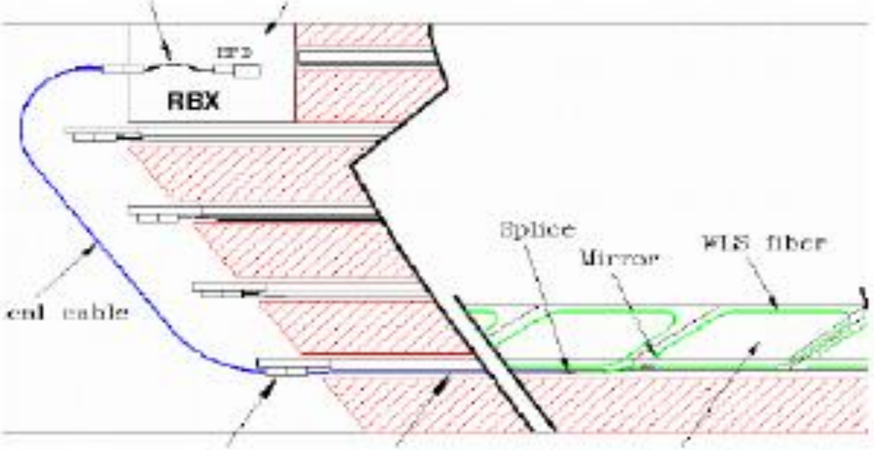
Explosives previously removed!

Casings melted in St Petersburg and turned into raw brass plates

Machined in Minsk and mounted to become absorber plates for the CMS Endcap Hadron Calorimeter

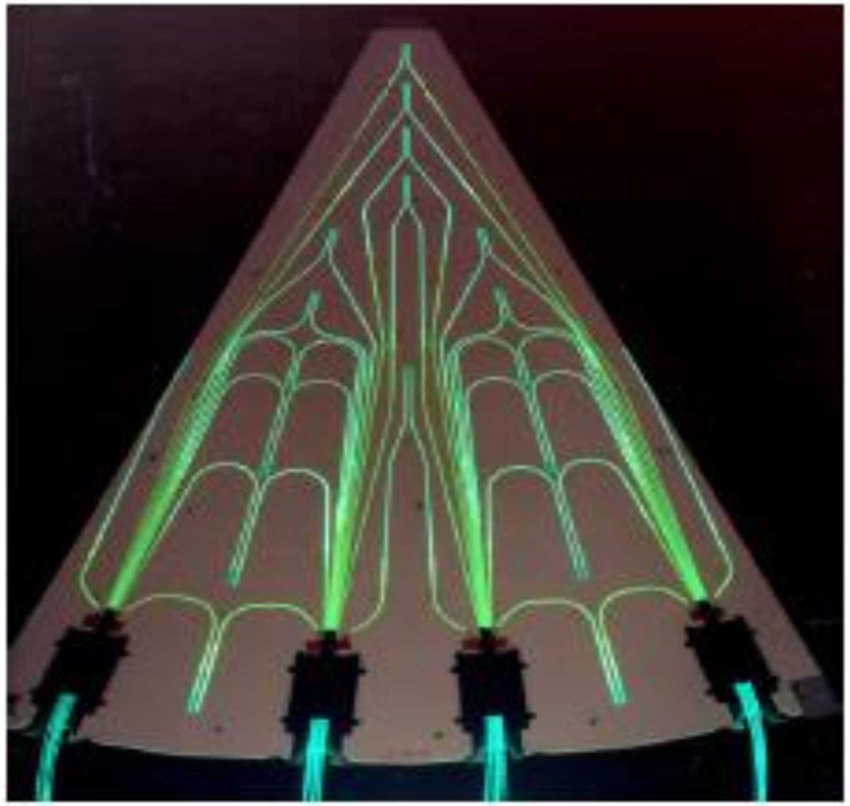
CMS Hadron Sampling Calorimeter

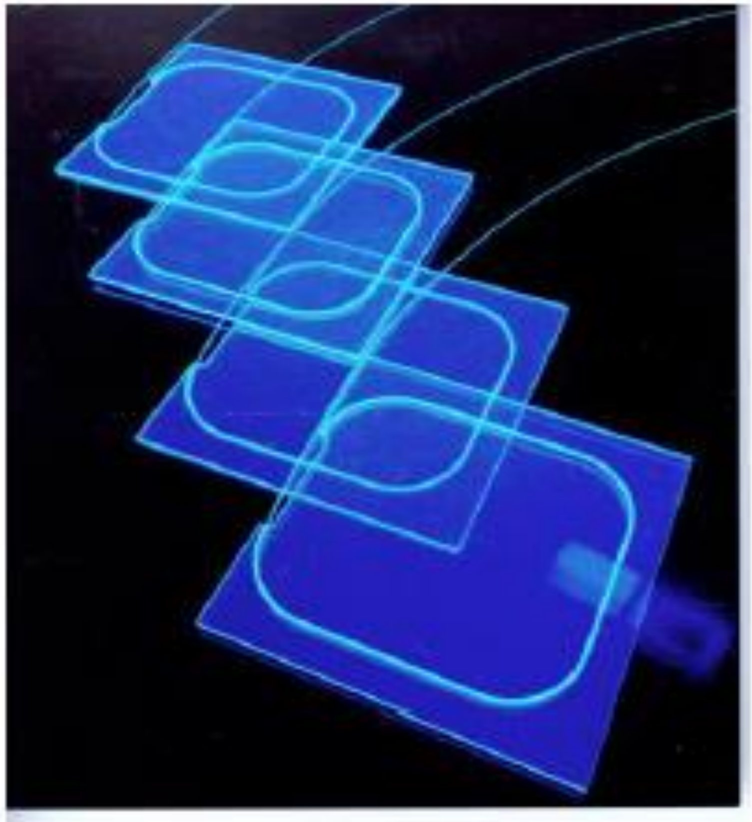
The CMS HCAL being inserted into the solenoid



Light produced in the scintillators is transported through optical fibres to Hybrid Photo Diode (HPD) detectors

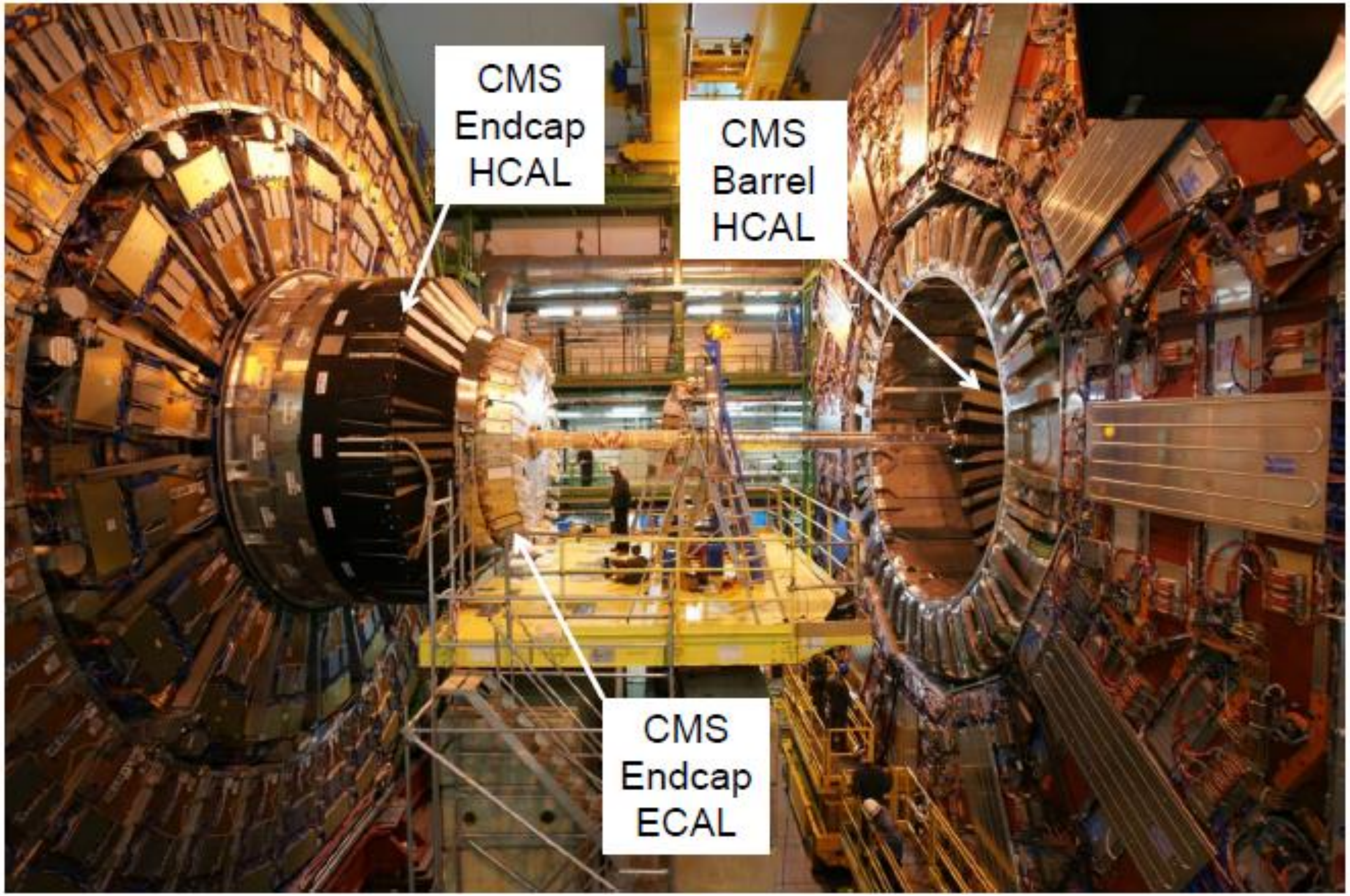
CMS Hadron Sampling Calorimeter - Readout

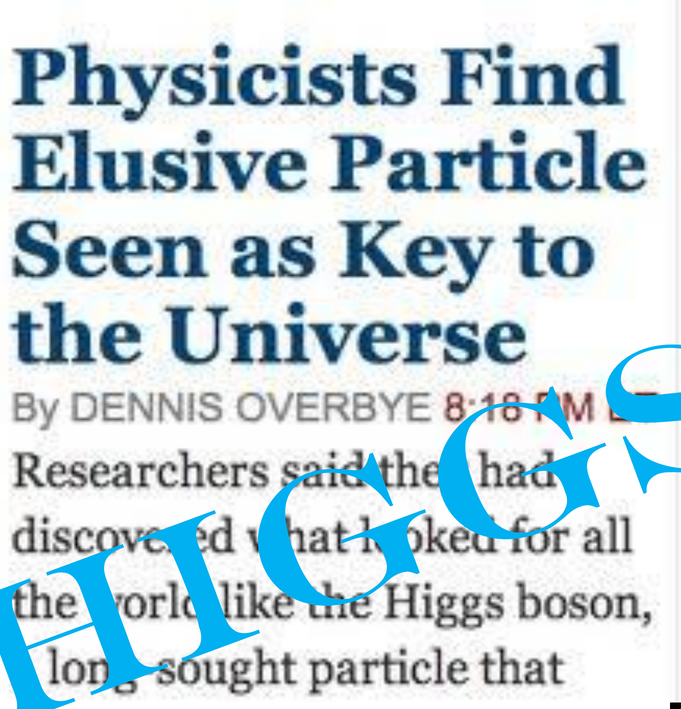




- Light emission from the scintillaror tiles blue – violet, λ = 410 – 425 nm
- This light is absorbed by wavelength shifting fibres which fluoresce in the green, λ = 490 nm
- The green light is conveyed via clear fiber waveguide to connectors at the ends of the scintillator megatiles

CMS Hadron Sampling Calorimeter





Physicists Find Elusive Particle Seen as Key to the Universe

By DENNIS OVERBYE 8:18 PM ET

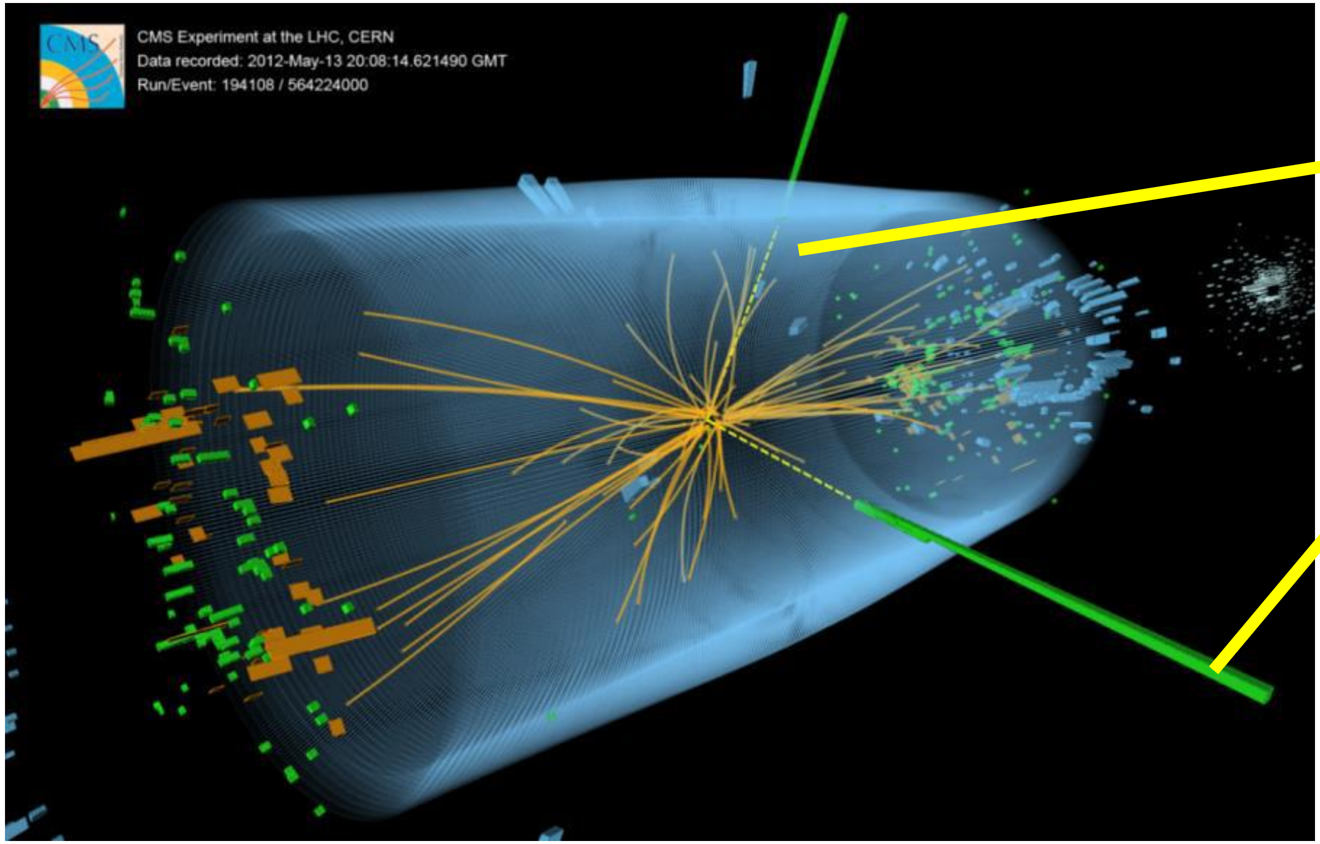
Researchers said they had discovered what looked for all the world like the Higgs boson, a long-sought particle that

HIGGS EXISTS

'Typical! I've found the Higgs boson, but I've lost my glasses again'

Calorimeters in the Discovery of the Higgs Boson

Event recorded with the CMS detector in 2012
Higgs boson decay to 2 photons



No charged tracks, Must be photons

EM calorimeter

EM energy proportional to green tower heights

Hadron calorimeter

Hadron energy proportional to orange tower heights

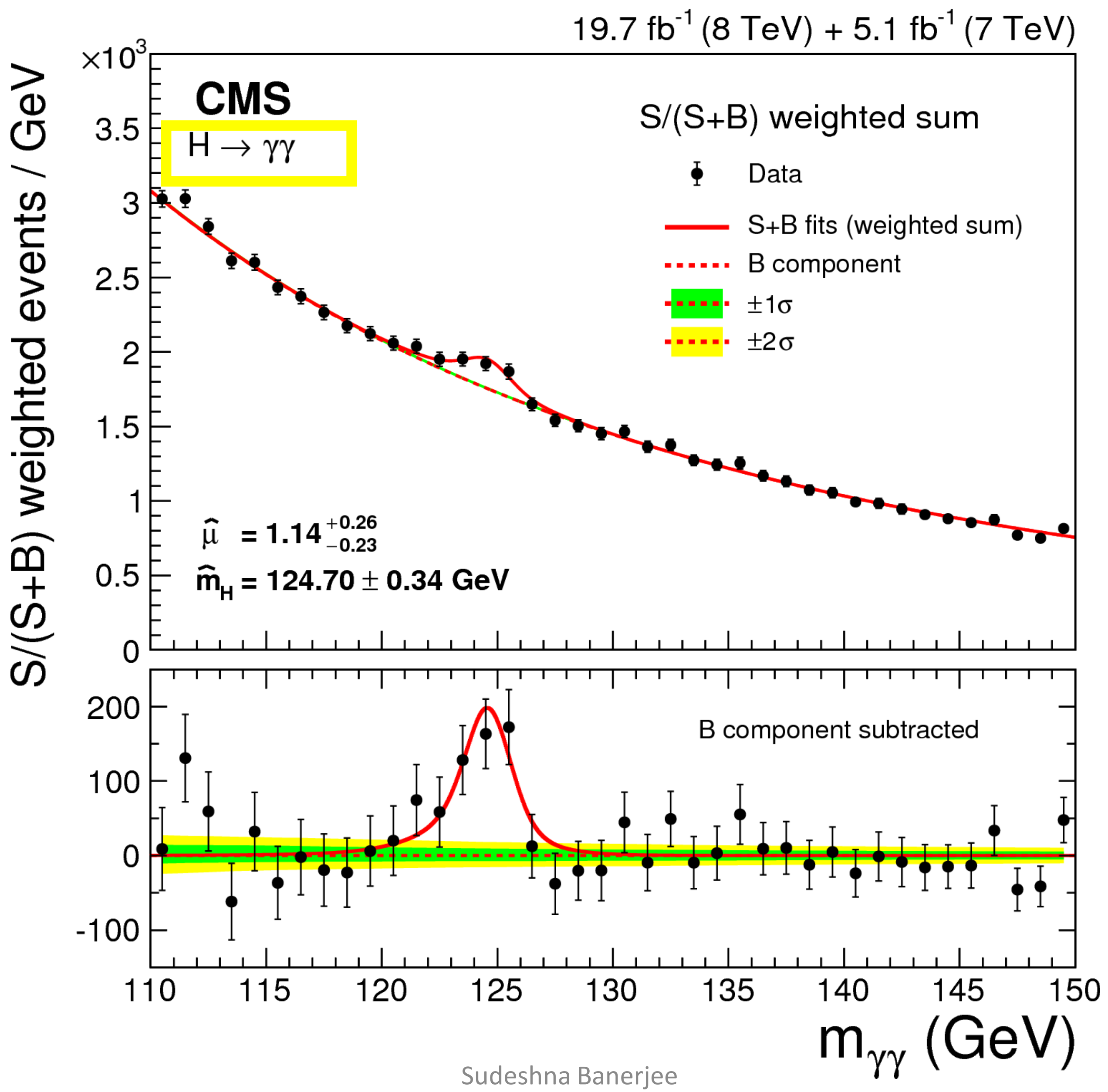
Tracker

Charged tracks Orange curves

Muon detector

Blue towers

Calorimeters in the Discovery of the Higgs Boson



References

- R. Wigmans,Calorimetry – Energy Measurement in Particle Physics (2nd edition), International Seriesof Monographs on Physics, Vol. 168, Oxford University Press (2017)
- Introduction to Experimental Particle Physics by Richard C. Fernow

BACKUP

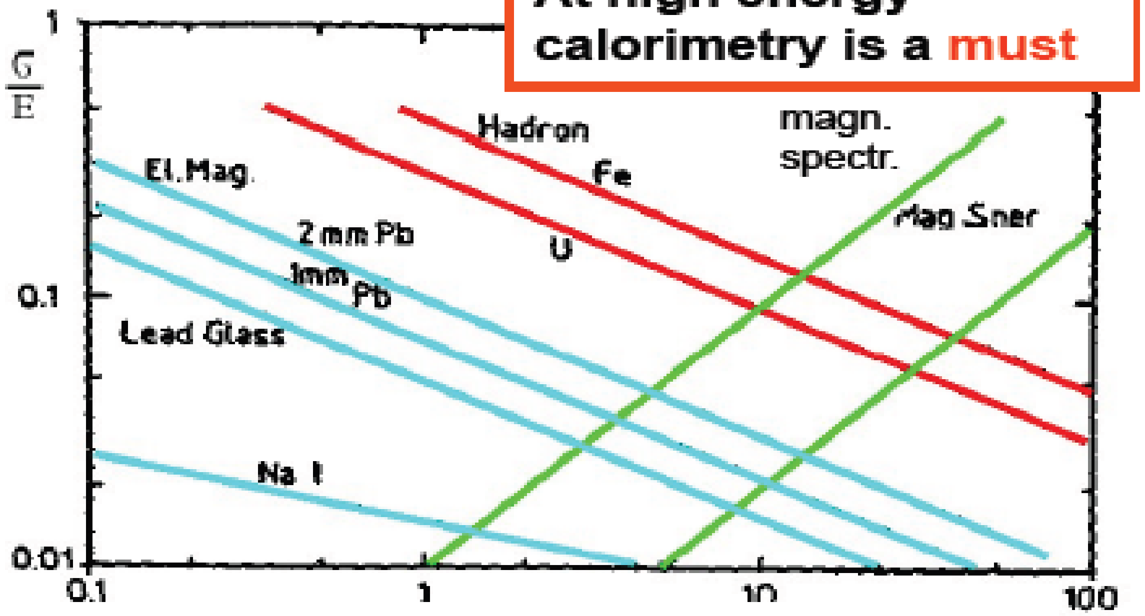
Why Calorimetry?

At high energy calorimetry is a must

Measure *charged + neutral* particles

- Performance of calorimeters *improves with energy* and is ~constant over 4π

(Magn. Spectr. anisotropy due to B field)



Calorimeter: [see below] $$\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$$

Gas detector: [see above] $$\frac{\sigma_p}{p} \sim p$$

e.g. ATLAS:

$$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$$

i.e. $\sigma_E/E = 1\%$ @ 100 GeV

$$\frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t$$

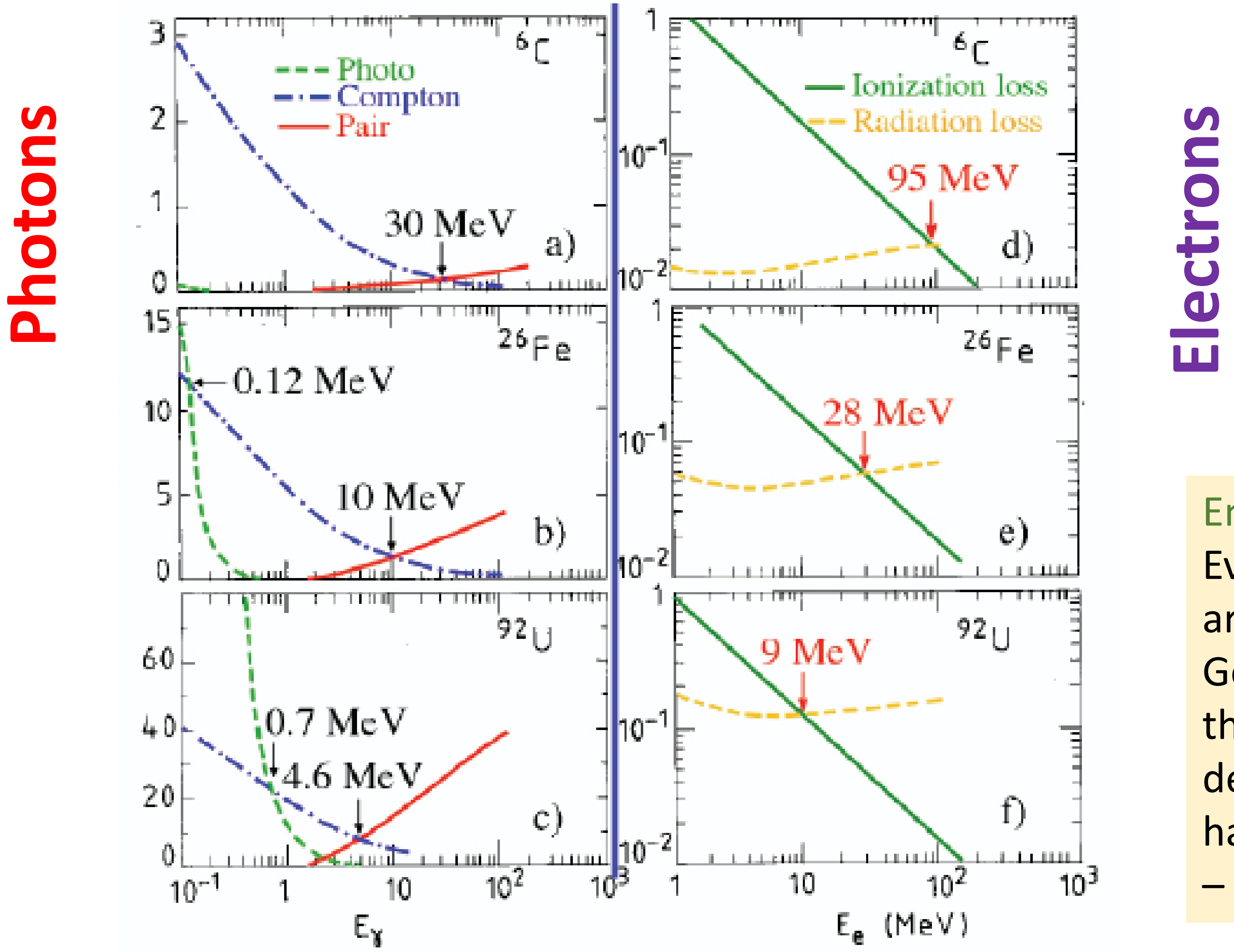
i.e. $\sigma_p/p = 5\%$ @ 100 GeV

Obtain information *fast* (<100ns feasible)

→→ recognize and select interesting events in real time (*trigger*)

Material Dependence

Increasing Z



Energy Scale:
Even though calorimeters are intended to measure GeV, TeV energy deposits, their performance is determined by what happens at the MeV – KeV – eV level

HCAL Test Beam (H2 area)

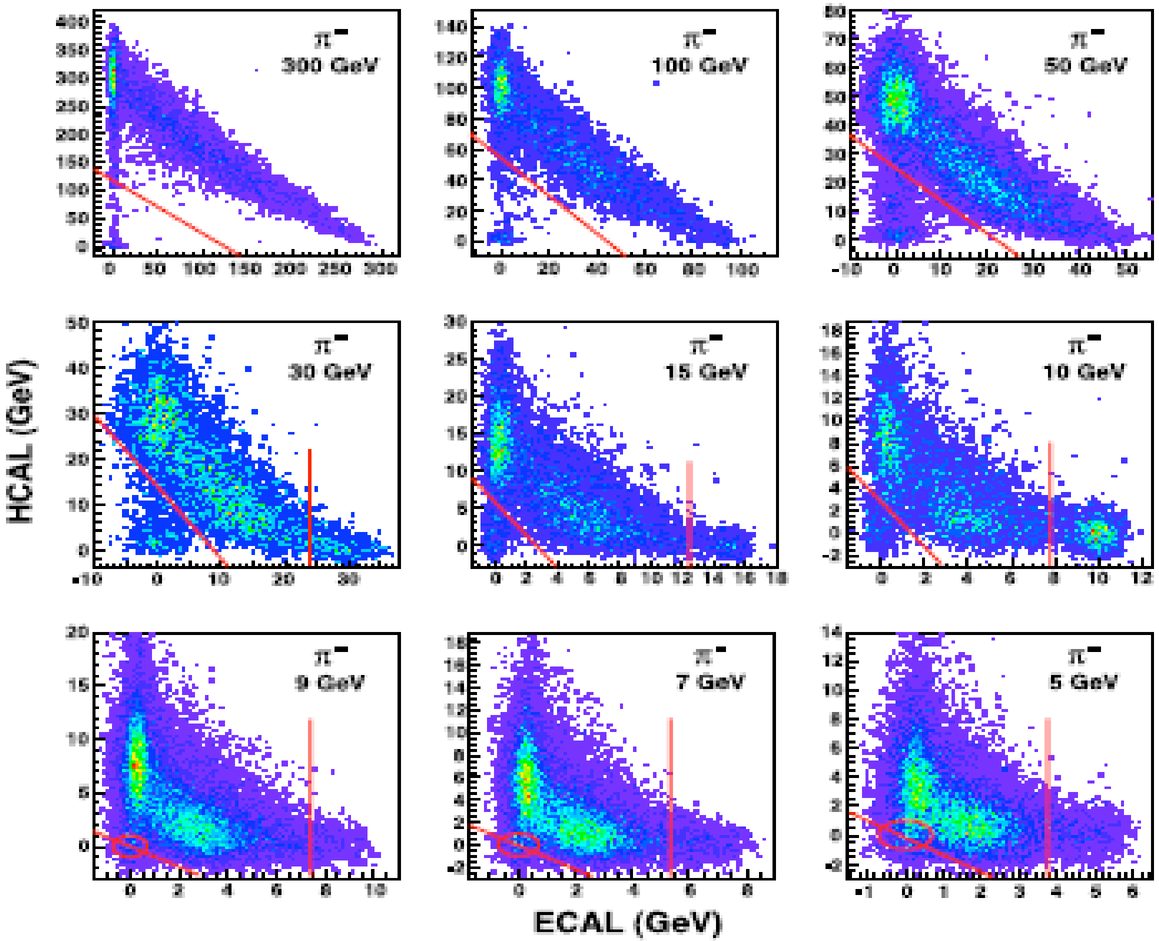


Figure 3: Energy observed in HCAL vs. energy observed in EBP for beams of 300, 100, 50, 30, 15, 10, 9, 7, and 5 GeV/c pions. Cuts used to reject electrons (vertical lines) and muons (diagonal lines and ellipses) are indicated. A long "tail" with little EBP energy and reduced HCAL energy due to upstream interactions is also evident.

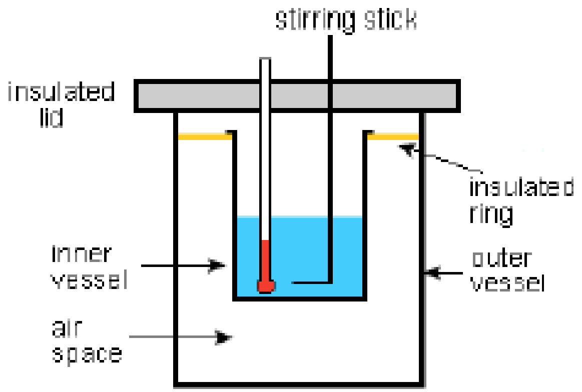
Calorimeter History (1)

Calorimetry (calor = heat in latin) is originally a concept used in thermodynamics/chemistry :

- Isolated box with a substance to study
- Exchange of heat measured by temperature variation
- 1 calorie = 4.185 Joule = 2.6 10^7 TeV

→increases by 1 °c in normal condition 1g of water

1 GeV induces a $\Delta T \sim 4.10^{-14}$ K in 1 liter of water



First use in 1878 (Langley) to measure electromagnetic radiation from sun :

- 2 platinum strips, one isolated from radiation, and the second receiving the radiation connected to a Wheaston bridge
- measure Energy/Temperature through resistance change

→30 % accuracy measurement :1.77 kW/m^2 instead of 1.38kW/m^2

Orthmann & Meitner (1930) : differential calorimeter used to measure mean energy of electrons in ^{210}B beta decay : E=0.33 MeV @ 6 %

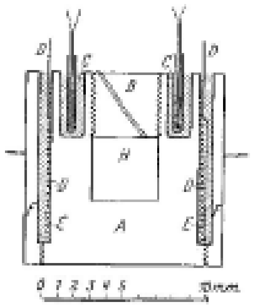


Fig. 1.

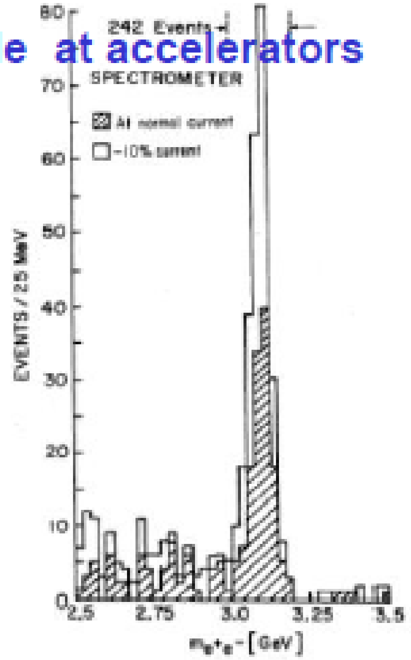
→ Such calorimeters still used in the field, named " Bolometers", used in dark matter experiments (Edelweiss, CDMS….) or Cosmic Microwave Background (Planck) (see M. Charles' lesson)

Calorimeter History (2)

First HEP sampling calorimeter in 1953
for High Energy cosmic ray particle $E > 10^{14}$ eV

Sandwich of ionization chambers and scintillation counters interleaved with iron :
-visible energy extracted from numbers of secondary particle (n(x)) and energy loss ionisation and scintillation Counters ($E_{visible} = dE/dx \int n(x).dx$)
- Fraction of the visible energy lost in absorbers plate

→ **Need to be calibrated with particle of known energy, not yet available at accelerators**



- 60-70' accelerators became main facilities for particle physics :
  - Need to measure also neutral particles (π^0, γ, neutrons…)
  - Charged particle accurately measured with large spectrometers detectors : 10m arms for electrons from J/Ψ

→ Plenty of calorimeters development/technologies