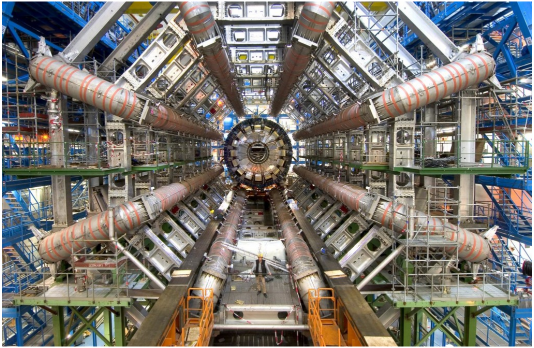
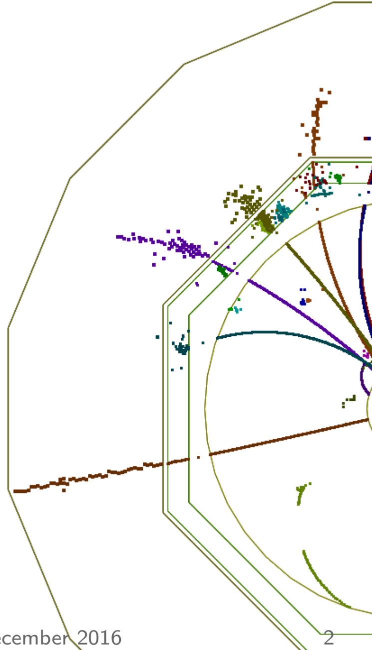
Basic Concepts of Calorimetry



Yasmine Israeli

Outline

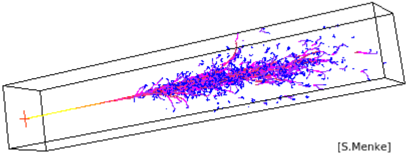
- What is a calorimeter
- Different particle showers
- Calorimeter types
- Problem in detecting an hadron
- Why hadronic **and** EM calorimeters
- Energy reconstruction
- Energy resolution
- Detection in the calorimetry system



What is a Calorimeter?

Calorimeter measures the energy of an incoming particle.

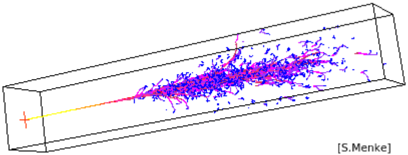
- Stops (absorbs) the particle by generating **showers**.
- Converts particle's (shower's) energy into something **detectable** (like photons, charge).



What is a Calorimeter?

Calorimeter measures the energy of an incoming particle.

- Stops (absorbs) the particle by generating **showers**.
- Converts particle's (shower's) energy into something **detectable** (like photons, charge).

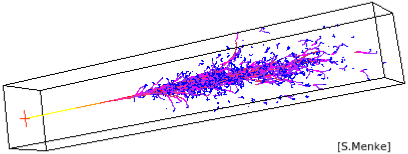


- Detects more stable particles $e^{\pm}, \gamma, \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}, p^{\pm}, n$ ($\mu^{\pm}$ don't induce showers)

What is a Calorimeter?

Calorimeter measures the energy of an incoming particle.

- Stops (absorbs) the particle by generating **showers**.
- Converts particle's (shower's) energy into something **detectable** (like photons, charge).

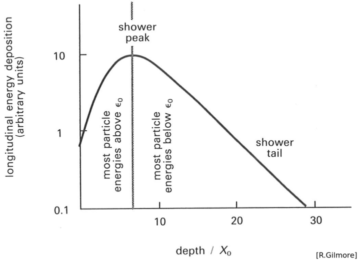


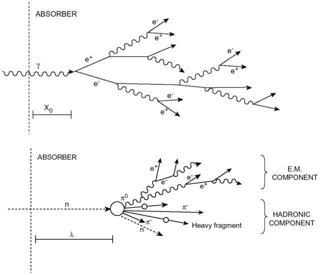
- Detects more stable particles $e^{\pm}, \gamma, \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}, p^{\pm}, n$ ($\mu^{\pm}$ don't induce showers)

"Ideal" calorimeter:
Calorimeter signal $\propto$ deposited energy $\propto$ energy of primary particle

Particle Showers

- a high-energy particle interacting with **dense matter**.
- secondary particles are produced



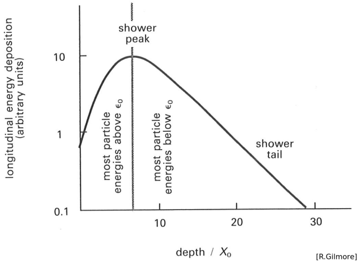


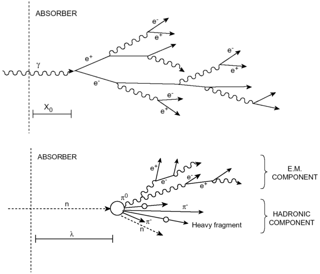
- each secondary particle interacts with the same dense matter and produces more particles
- This process continues → the particle number is growing as long as the energy of the "secondaries" is sufficient to create new particles

Particle Showers

Shower length scales:

- EM Shower: Radiation length X_0
- Had. Shower: Interaction length λ_{Int}





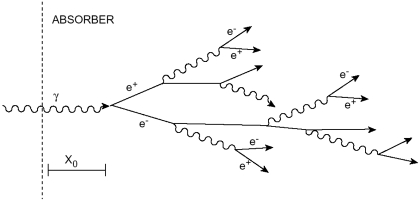
Simplified Model:

- 1 Step = X_0 $\Rightarrow$ 2 new particles
- t Steps = $t \cdot X_0$ $\Rightarrow$ 2^t particles,with $E = E_0 2^{-t}$ (E_0 energy of initial particle)
- t_{max} steps = shower maximum, $E = \epsilon_c$

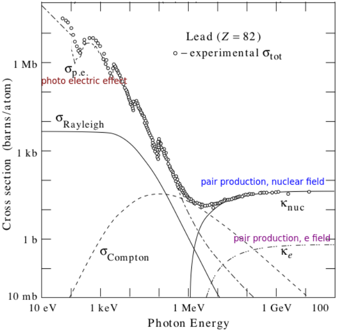
$$t_{max} = \log_2\left(\frac{E_0}{\epsilon_c}\right)$$ $\Rightarrow$ logarithmic increase of shower depth with E_0

EM Showers

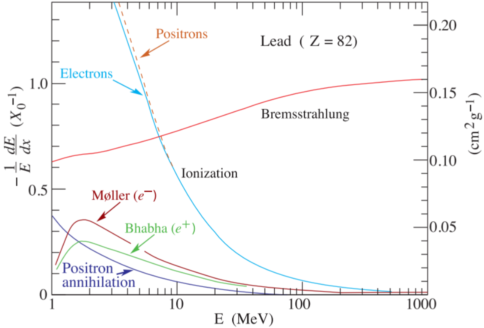
Origin: **energtic e^-,e^+ or γ interacts with dense matter** $\rightarrow e^-, e^+, \gamma$



- electron-positron pairs
- photo-electric effect
- Bremsstrahlung
- ionization

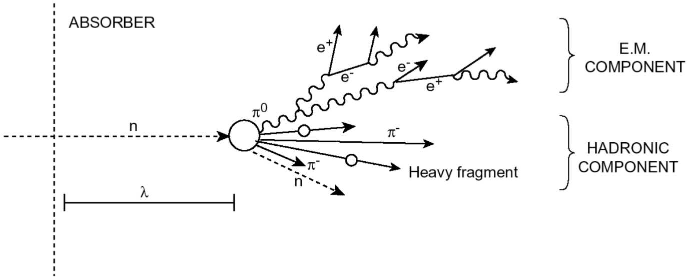


[Hubbell, Gimm, and Øverbø]



Hadronic Showers

Origin: $\pi^{\pm}, K^{\pm}, K^{0}, p^{\pm}$ **or** n **entering dense matter → strong interaction!**



- spallation
- excitation of nuclei
- production of hadrons and mesons
- nuclear fission
- EM sub-shower: natural measons (π^0, η) →photons

  ⋆pair production ⋆photo-electric effect ⋆Bremsstrahlung ⋆ionization

Calorimeter Types:

$$Calorimeter \begin{cases} \textbf{Absorbs}\ the\ particle\ by\ generating\ shower \leftrightarrow\ \text{Absorber} \\ Converts\ particle's\ energy\ into\ something\ \textbf{detectable} \leftrightarrow\ \text{Detector} \end{cases}$$

Calorimeter Types:

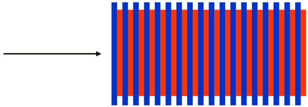
$$\textit{Calorimeter}\begin{cases}\textbf{Absorbs}\ \textit{the particle by generating shower} \leftrightarrow \ \text{Absorber} \\ \textit{Converts particle's energy into something}\ \textbf{detectable} \leftrightarrow \ \text{Detector}\end{cases}$$

Homogenous Calorimeter

- Absorber+detector in **one medium**
- Measures the **complete** energy deposit

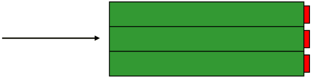
Sampling Calorimeter

- Absorber and detector are separated
- Showers develop in **passive layers**
- Particles are detected in **active layers**

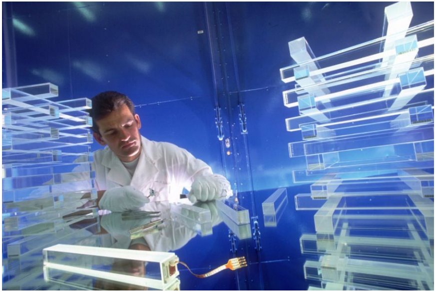


Homogeneous Calorimeter

Absorber+detector in one medium



- Dense scintillating crystals
- lead loaded glass (Cerenkov light)
- Noble gas liquids



Read-out

⋆Mostly based on light detection:

- Photomultiplier
- Avalanche Photo-Diodes
- Silicon-Photo-multipliers
- Cherenkov detectors

⋆Always at the end

Calorimeter Types: Sampling Calorimeter

Absorber and detector are separated
⇒flexible and compact design

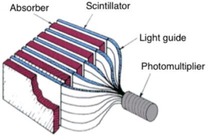
Passive Layers:

- Generate the shower
- High density, high atomic number
    - iron, lead, uranium

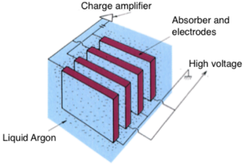
Active layers:

- Record the particle within the shower
- Different technologies can be applied
    - Plastic scintillators+ photo-detectors
    - Silicon detectors
    - Noble liquid ionization chambers
    - Gas detectors

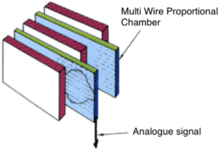
Scintillator plates



Liquid noble gas



Proportional chambers



W. Lucha, M. Regler, *Elementarteilchenphysik*

Homogenous vs Sampling

Homogenous Calorimeters:

- Good energy resolution for EM showers
- Very non-linear for hadrons
- Limited granularity
- Crystals are expensive
- no direct information on shower development

Sampling Calorimeters:

- Compact
- Flexible design
- Can be cheap
- Energy resolution is limited by **sampling fluctuations**
  ↪ The fractions of how much is energy is deposited in the absorber and in the detector varies from event to event

Problem: Detecting an Hadron

Calorimeter:

- Stops (absorbs) the particle by generating **showers**.
- Converts particle's shower's energy into something **detectable**
- Our detectors detect: **Charge or Photons**

Problem: Detecting an Hadron

Calorimeter:

- Stops (absorbs) the particle by generating **showers**.
- Converts particle's shower's energy into something **detectable**
- Our detectors detect: **Charge or Photons**

In EM shower: e^-, e^+ *or* γ produces more e^-, e^+, γ ☺☺☺

Problem: Detecting an Hadron

Calorimeter:

- Stops (absorbs) the particle by generating **showers**.
- Converts particle's shower's energy into something **detectable**
- Our detectors detect: **Charge or Photons**

In EM shower: e^{-}, e^{+} *or* γ produces more e^{-}, e^{+}, γ ☺☺☺

In hadronic shower: **invisible energy!!**

- nuclear binding energy
- slow neutrons
- neutrinos

☹

- The fraction of invisible energy varies
- The fraction of the electromagnetic sub-shower varies

Problem: Detecting an Hadron

Calorimeter:

- Stops (absorbs) the particle by generating **showers**.
- Converts particle's shower's energy into something **detectable**
- Our detectors detect: **Charge or Photons**

In EM shower: e^{-}, e^{+} *or* γ produces more e^{-}, e^{+}, γ ☺☺☺

In hadronic shower: **invisible energy!!**

- nuclear binding energy
- slow neutrons
- neutrinos

☹

- The fraction of invisible energy varies
- The fraction of the electromagnetic sub-shower varies

$$\frac{e \text{ detection}}{\pi \text{ detection}} > 1$$

Had. and EM Calorimeters?!

EM Showers:

-$e^{\pm}, \gamma$ production

-EM shower size $\propto$ to radiation length X_0

Hadronic Showers:

-Hadrons, mesons, baryons production.

-EM sub-shower:$e^{\pm}, \gamma$ production

-Had. shower size $\propto$interaction length λ_{Int}

Had. and EM Calorimeters?!

EM Showers:
-$e^{\pm}, \gamma$ production
-EM shower size $\propto$ to radiation length X_0

Hadronic Showers:
-Hadrons, mesons, baryons production.
-EM sub-shower:$e^{\pm}, \gamma$ production
-Had. shower size $\propto$interaction length λ_{Int}

$$X_0 < \lambda_{Int}$$

$\Rightarrow$ EM showers are more compact!

Had. and EM Calorimeters?!

EM Showers:

-$e^{\pm}, \gamma$ production

-EM shower size $\propto$ to radiation length X_0

Hadronic Showers:

-Hadrons, mesons, baryons production.

-EM sub-shower:$e^{\pm}, \gamma$ production

-Had. shower size $\propto$interaction length λ_{Int}

$$X_0 < \lambda_{Int}$$

$\Rightarrow$ EM showers are more compact!

EM shower* usually:

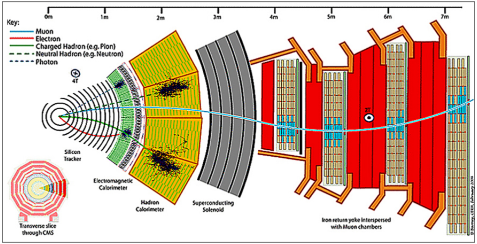
- Starts before Had. shower.
- Every "generation" in the shower happens in a smaller scale.
- The shower ends before the Had. shower

* also the EM sub-shower in the Had. shower

Had. and EM Calorimeters?!

A small EM calorimeter before Had. calorimeter

- Using two different technologies
  ↪can use homogeneous calorimeter for Ecal (EM calorimeter).
- Optimizing Ecal for EM showers (including the EM sub-shower)
- Optimizing Hcal (hadronic calorimeter) for Had. showers
- Different granularity (cell size in the detector) is needed
- Cheaper
- Improving the energy resolution



Standard Energy Reconstruction:

For each event:

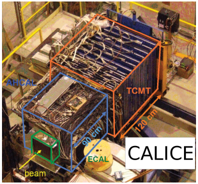
- Collect all the signal's energy from Ecal : $E_{total}^{Ecal} = \sum_{All\ \ signals}^{ECal} E_{signal}$
- Collect all the signal's energy from Hcal : $E_{total}^{Hcal} = \sum_{All\ \ signals}^{HCal} E_{signal}$
- Add together, including calibration factors for each detector:

  $E_{reco}^{event} = E_{total}^{Ecal} \cdot \omega_E + E_{total}^{Hcal} \cdot \omega_H$

All events:

- Fill a histogram with "enough" events
- Determine what is E_{reco} and $\Delta E_{reco}/E_{reco}$

Energy Reconstruction in CALICE:



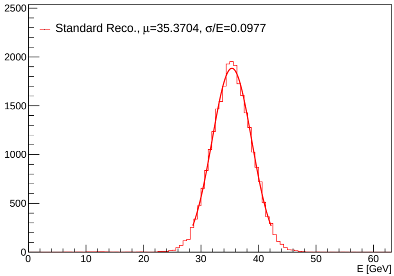
SiW ECAL

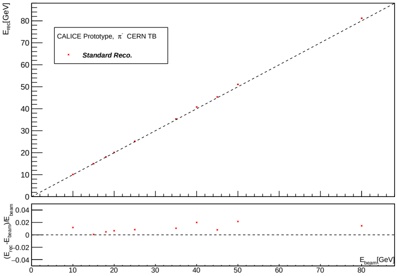
- Silicon sensors
- Absorber : tungsten

AHCAL+TCMT

- SiPM
- Absorber : steel

- Gaussian fit $\Longrightarrow \mu, \sigma$
- Energy resolution: $\frac{\sigma_{reco}}{E_{reco}}$





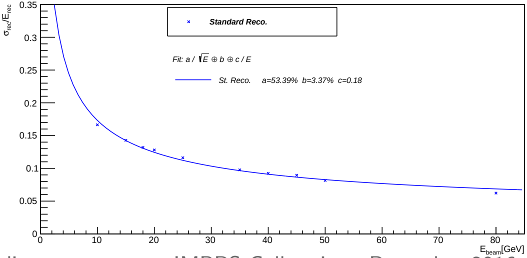
Energy Resolution

$$\frac{\Delta E_0}{E_0} = \frac{\sigma(E_0)}{E_0} = \frac{a}{\sqrt{E_0}} \oplus \frac{b}{E_0} \oplus c$$

Stochastic term:
Fluctuation in the number of measured particles (a simple statistical error)

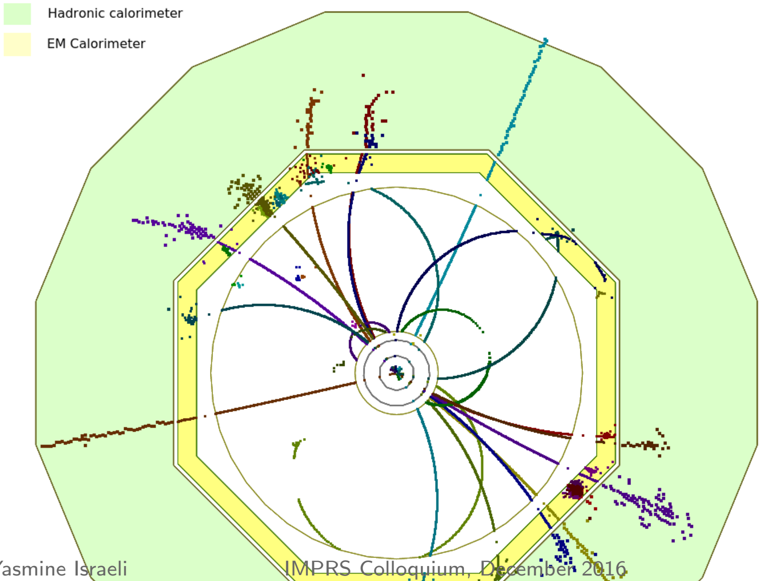
Noise term:
Readout electronic noise, pile-up fluctuations

Constant term:
⋆ Non-uniform detector response ⋆ Channel to channel inter-calibration errors
⋆ Fluctuations in longitudinal energy containment
⋆ Energy lost in dead material, before or in detector



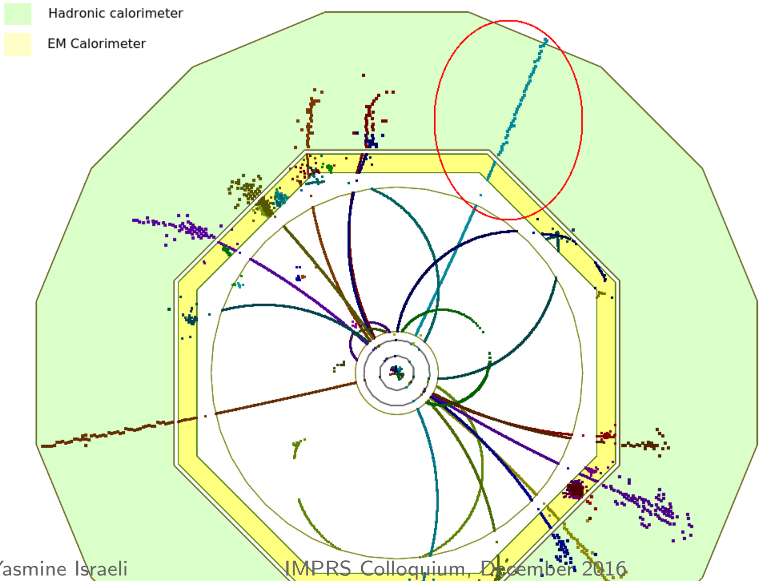
Detection in the Calorimetry System

$e^+e^- \to Zh \to \mu^+\mu^- h$



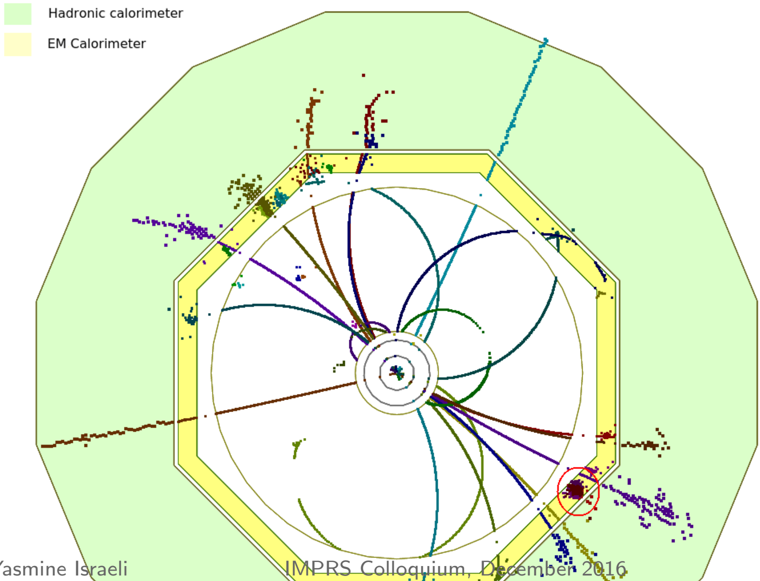
Detection in the Calorimetry System

$e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^- h$



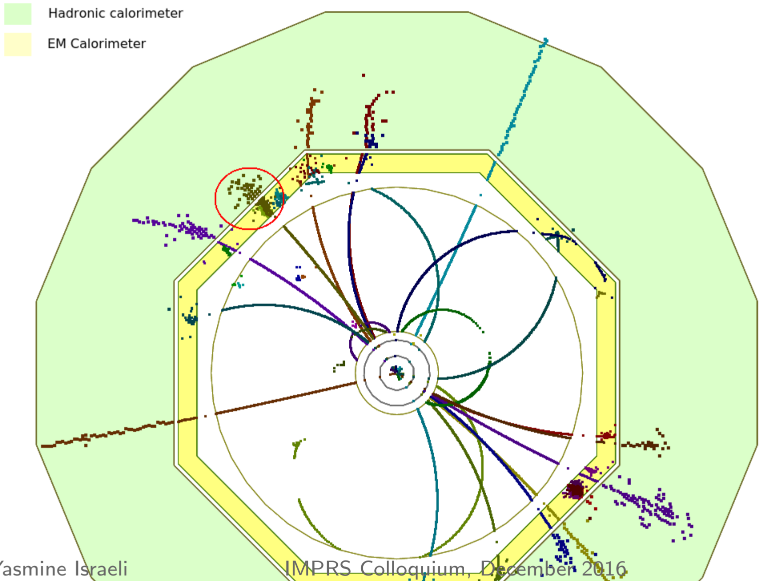
Detection in the Calorimetry System

$e^+e^- \to Zh \to \mu^+\mu^- h$



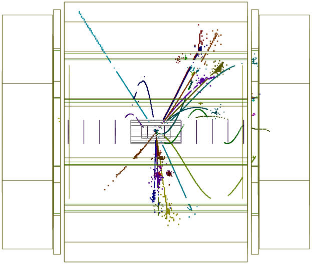
Detection in the Calorimetry System

$e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^- h$

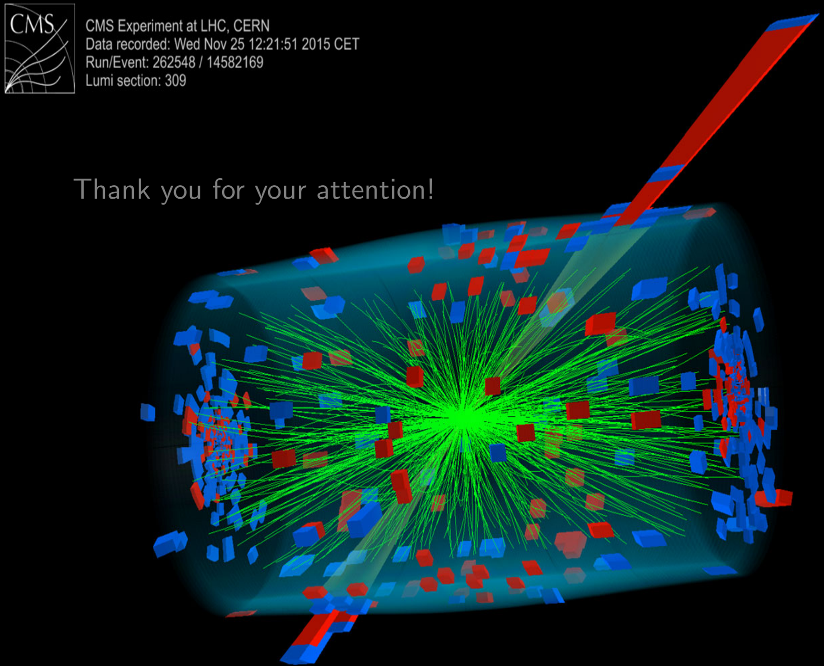


Summary

- We can measure particle's energy with calorimeters.
- There are many different technologies in use.
- The main challenge is detecting hadrons.
- Good energy resolution is essential for valid reconstruction.
- Calorimeter R&D is an active field.



Thank you for your attention!



BACKUP

Local Software Compensation:

Problem in detection: $\frac{e}{\pi} > 1 \Rightarrow$ Lost energy in the hadron decay.

- EM showers are denser than hadronic showers.
  → Classification of hits based on the energy density
- χ^2 minimization:

$$\chi^2 = \sum_{events} \left(\sum_{hits} E_{hit}\omega_j - E_{beam} \right)^2$$

j=Energy density index