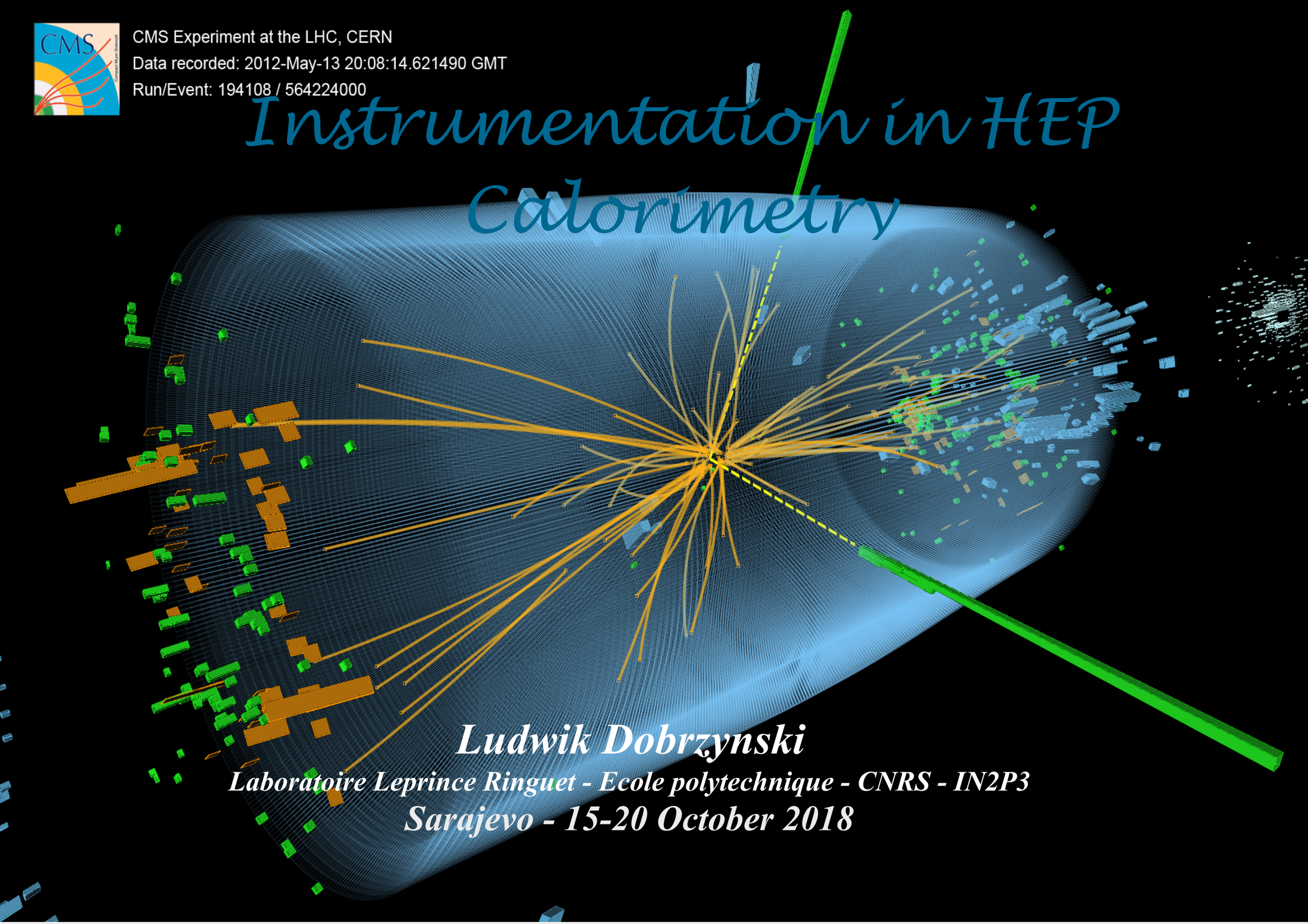


Instrumentation in HEP
Calorimetry

Ludwik Dobrzynski
Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3
Sarajevo - 15-20 October 2018

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

Instrumentation in HEP
Calorimetry

Calorimetry - Basic principles
- *Interaction of charged particles and photons*
- *Electromagnetic cascades*
- *Nuclear interactions*
- *Hadronic cascades*

Homogeneous calorimeters
Sampling calorimeters
Upgrade calorimeters for High Luminosity LHC
Summary

Ludwik Dobrzynski
Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

Sarajevo - 15-20 October 2018

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

Instrumentation in HEP
Calorimetry

Calorimetry - Basic principles
- *Interaction of charged particles and photons*
- *Electromagnetic cascades*
- *Nuclear interactions*
- *Hadronic cascades*

Homogeneous calorimeters
Sampling calorimeters
Upgrade calorimeters for High Luminosity LHC
Summary

Ludwik Dobrzynski
Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3
Sarajevo - 15-20 October 2018

DETECTOR: PRINCIPLE

DETECTOR: PRINCIPLE

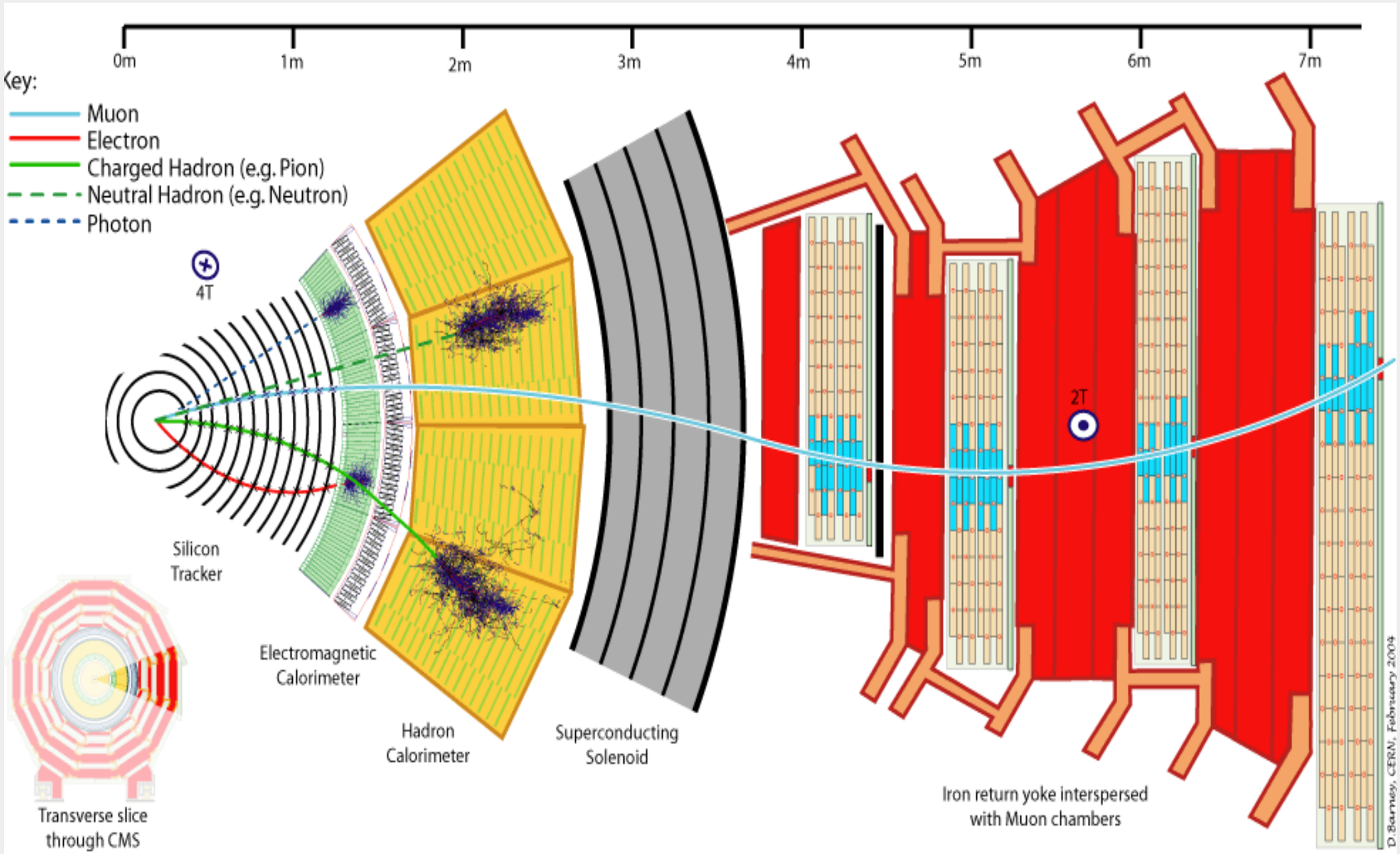
- In order to detect a particle it must
  - interact with the material of the detector
  - transfer its energy in some recognisable way
  - and leave a signal.

Detection of particles happens via their energy loss in the material they traverse.

DETECTOR: PRINCIPLE

- *In order to detect a particle it must*
  - *interact with the material of the detector*
  - *transfer its energy in some recognisable way*
  - *and leave a signal.*

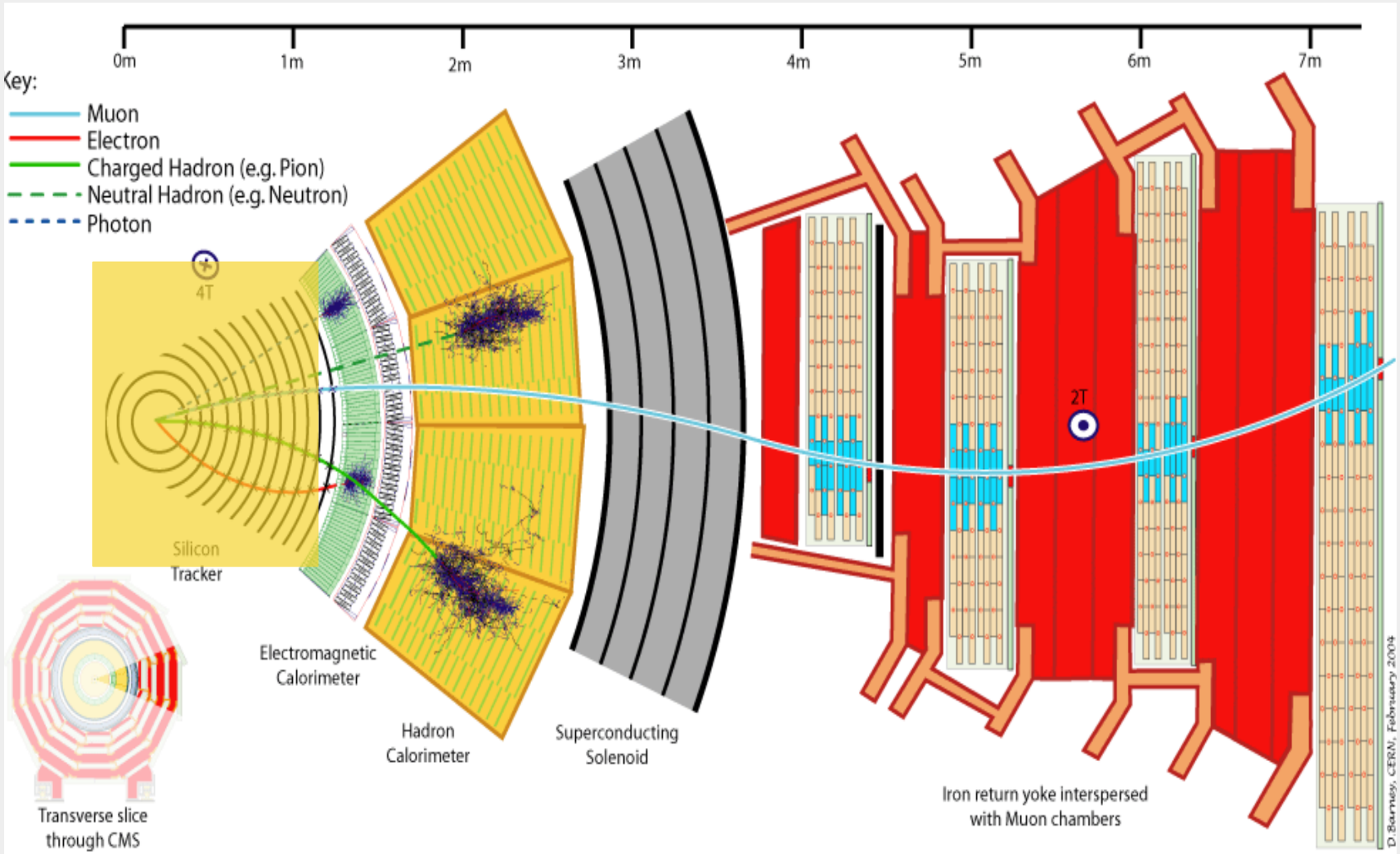
Detection of particles happens via their energy loss in the material they traverse.



DETECTOR: PRINCIPLE

- *In order to detect a particle it must*
  - *interact with the material of the detector*
  - *transfer its energy in some recognisable way*
  - *and leave a signal.*

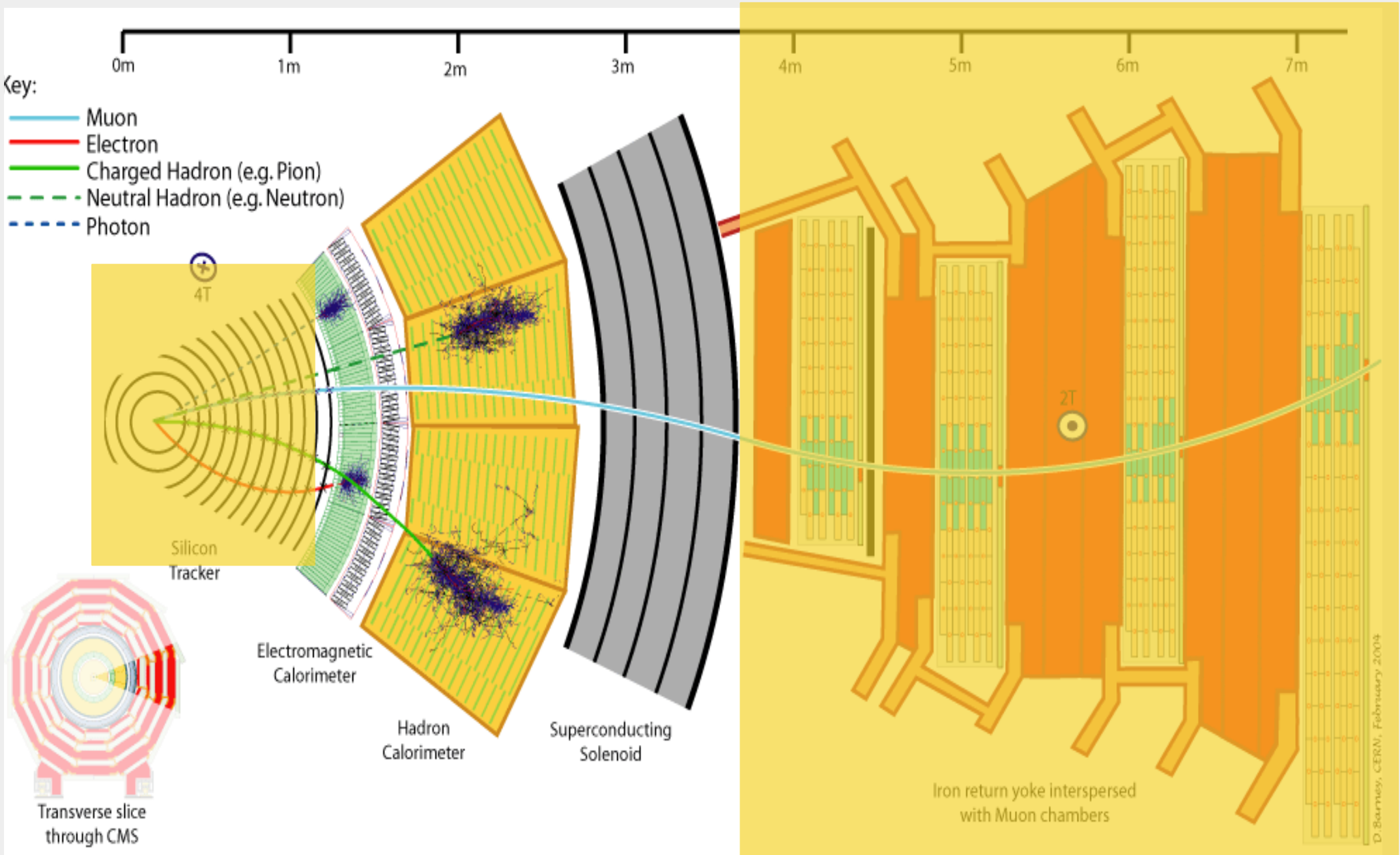
Detection of particles happens via their energy loss in the material they traverse.



DETECTOR: PRINCIPLE

- *In order to detect a particle it must*
  - *interact with the material of the detector*
  - *transfer its energy in some recognisable way*
  - *and leave a signal.*

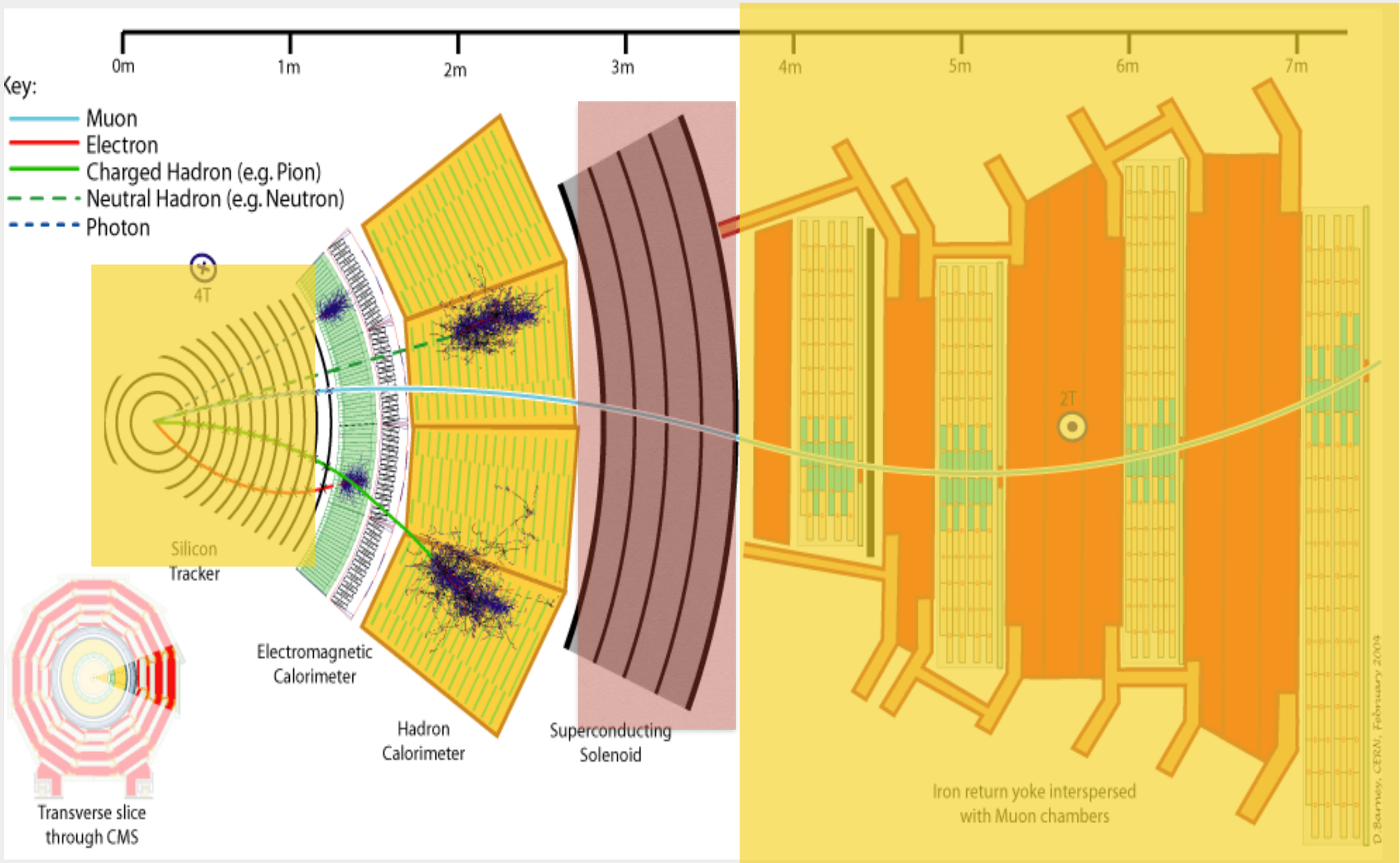
Detection of particles happens via their energy loss in the material they traverse.



DETECTOR: PRINCIPLE

- *In order to detect a particle it must*
  - *interact with the material of the detector*
  - *transfer its energy in some recognisable way*
  - *and leave a signal.*

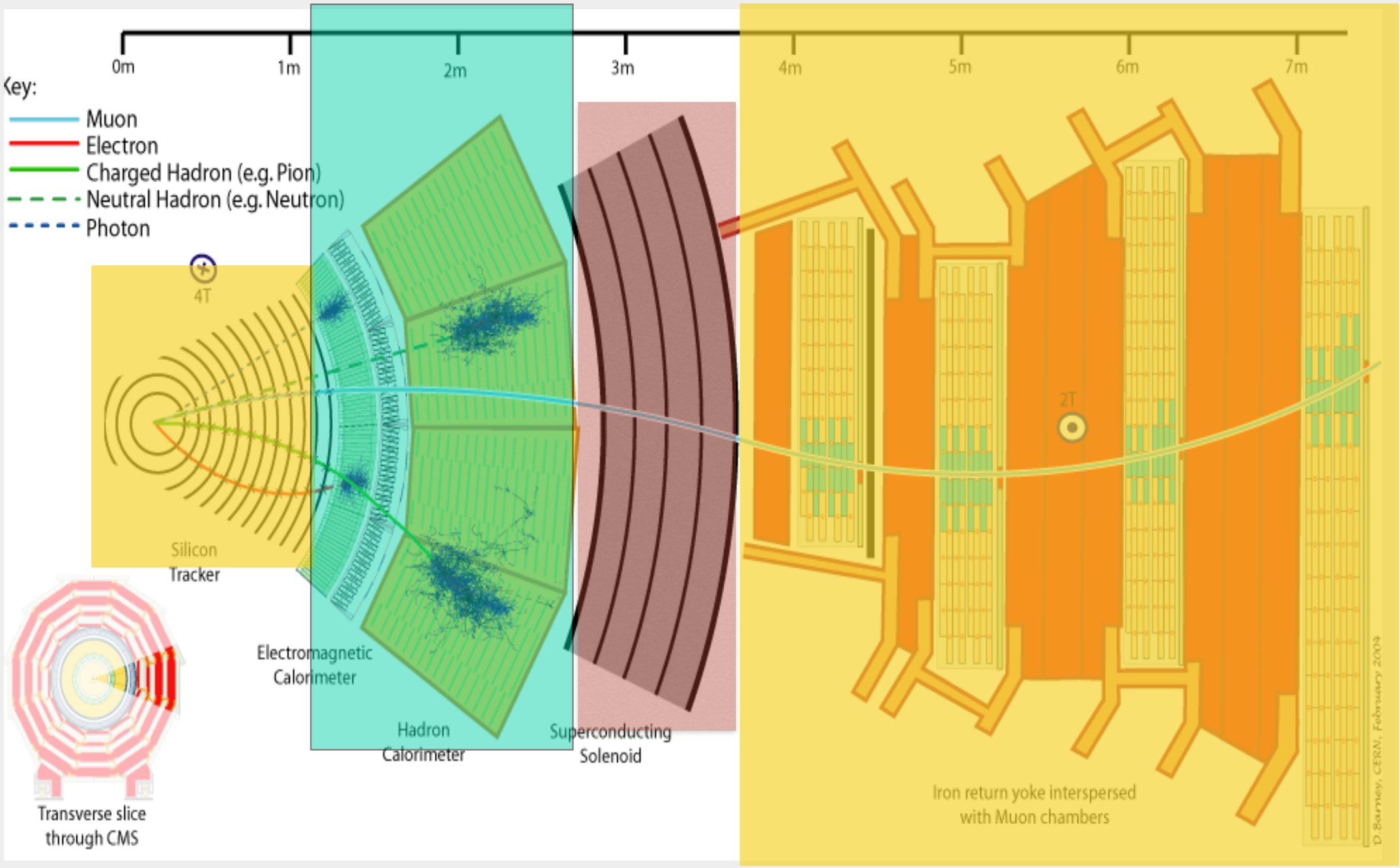
Detection of particles happens via their energy loss in the material they traverse.



DETECTOR: PRINCIPLE

- In order to detect a particle it must
  - interact with the material of the detector
  - transfer its energy in some recognisable way
  - and leave a signal.

Detection of particles happens via their energy loss in the material they traverse.



Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

- Finally, the energy is converted into ionization or excitation of the matter.

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

- Finally, the energy is converted into ionization or excitation of the matter.

Basic mechanism for calorimetry in particle physics is the formation of

⟹ electromagnetic showers

⟹ and/or hadronic showers.

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

- Finally, the energy is converted into ionization or excitation of the matter.

Basic mechanism for calorimetry in particle physics is the formation of

⟹ electromagnetic showers

⟹ and/or hadronic showers.

- Calorimetry works both for:
  - ⟹ charged particles(e± and hadrons) → Complementary information to p (momentum) measurement
  - ⟹ and neutral particles (n,γ) → Only way to get direct kinematical information for neutral particles

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

- Finally, the energy is converted into ionization or excitation of the matter.

Basic mechanism for calorimetry in particle physics is the formation of

⟹ electromagnetic showers

⟹ and/or hadronic showers.

- Calorimetry works both for:
  - ⟹ charged particles(e± and hadrons) → Complementary information to p (momentum) measurement
  - ⟹ and neutral particles (n,γ) → Only way to get direct kinematical information for neutral particles

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

- Finally, the energy is converted into ionization or excitation of the matter.

Basic mechanism for calorimetry in particle physics is the formation of

⟹ electromagnetic showers

⟹ and/or hadronic showers.

- Calorimetry works both for:
  - ⟹ charged particles(e± and hadrons)
  - ⟹ and neutral particles (n,γ)

Complementary information to p (momentum) measurement

Only way to get direct kinematical information for neutral particles

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

- Finally, the energy is converted into ionization or excitation of the matter.

Basic mechanism for calorimetry in particle physics is the formation of

⟹ electromagnetic showers

⟹ and/or hadronic showers.

- Calorimetry works both for:
  - ⟹ charged particles(e± and hadrons)
  - ⟹ and neutral particles (n,γ)

Complementary information to p (momentum) measurement

Only way to get direct kinematical information for neutral particles

Calorimetry: Basic Principle (1)

The calorimeters provide :

- *Energy measurement by total absorption*
- *as well usually some spatial reconstruction.*

- ***Calorimetry is a "destructive" method.*** The energy and the particle get absorbed!

- Detector response ∝ E

- Finally, the energy is converted into ionization or excitation of the matter.

Basic mechanism for calorimetry in particle physics is the formation of

⟹ electromagnetic showers

⟹ and/or hadronic showers.

- Calorimetry works both for:
  - ⟹ charged particles(e± and hadrons)
  - ⟹ and neutral particles (n,γ)

Complementary information to p (momentum) measurement

Only way to get direct kinematical information for neutral particles

INTERACTIONS

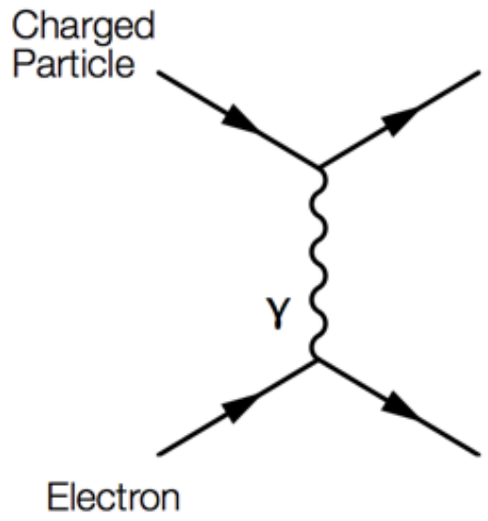
INTERACTIONS

Charged particles	Ionization, Bremsstrahlung, Cherenkov, …	multiple interactions
Photons	Photo/Compton effect, pair production	single interactions…
Hadrons	Nuclear interactions	multiple interactions
Neutrinos	Weak interactions	

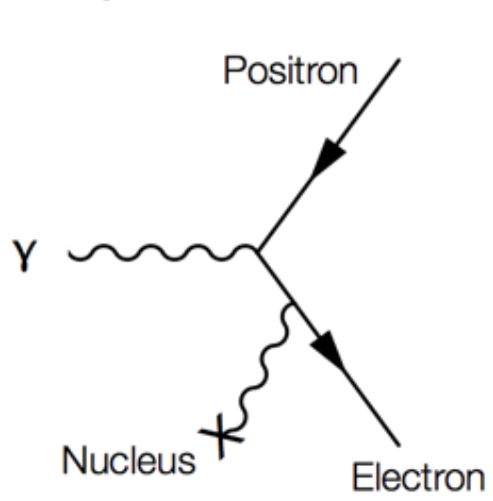
INTERACTIONS

Charged particles	Ionization, Bremsstrahlung, Cherenkov, …	multiple interactions
Photons	Photo/Compton effect, pair production	single interactions…
Hadrons	Nuclear interactions	multiple interactions
Neutrinos	Weak interactions	

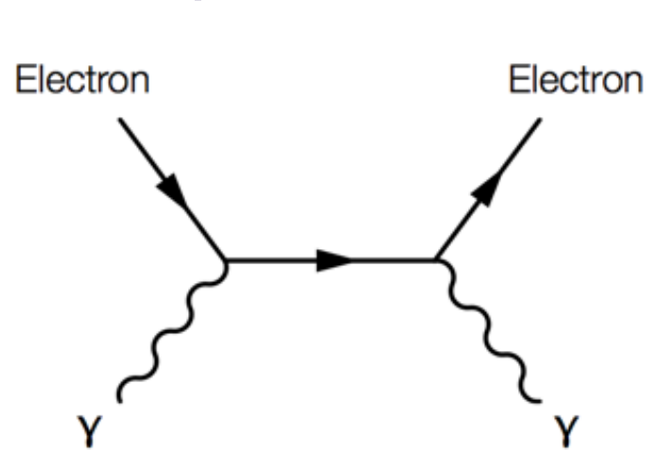
Ionisation

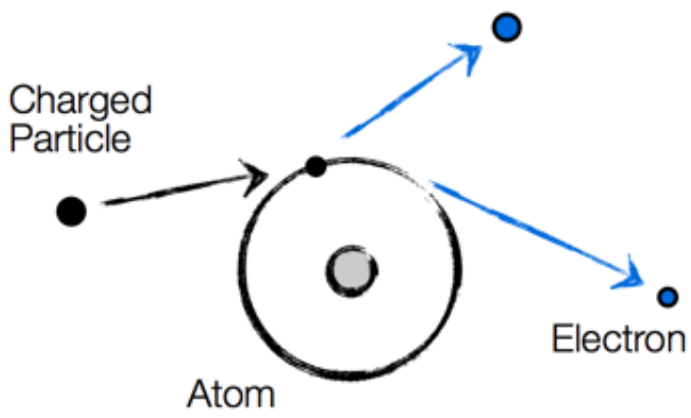


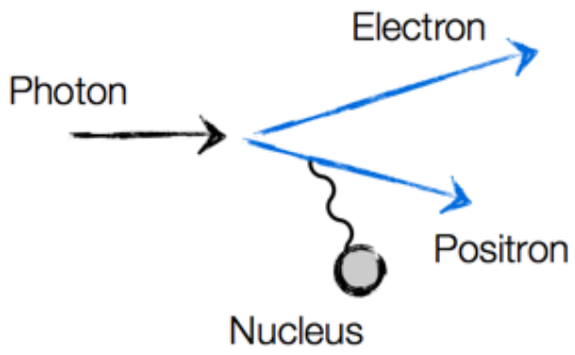
Production de paires e^+e^-

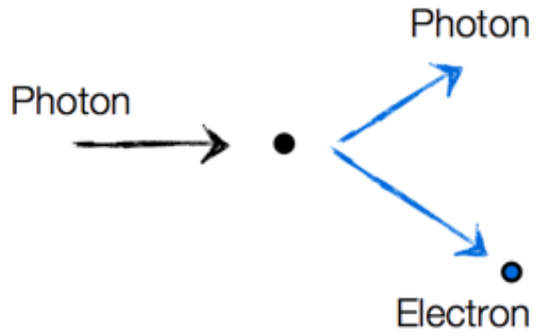


Diffusion Compton

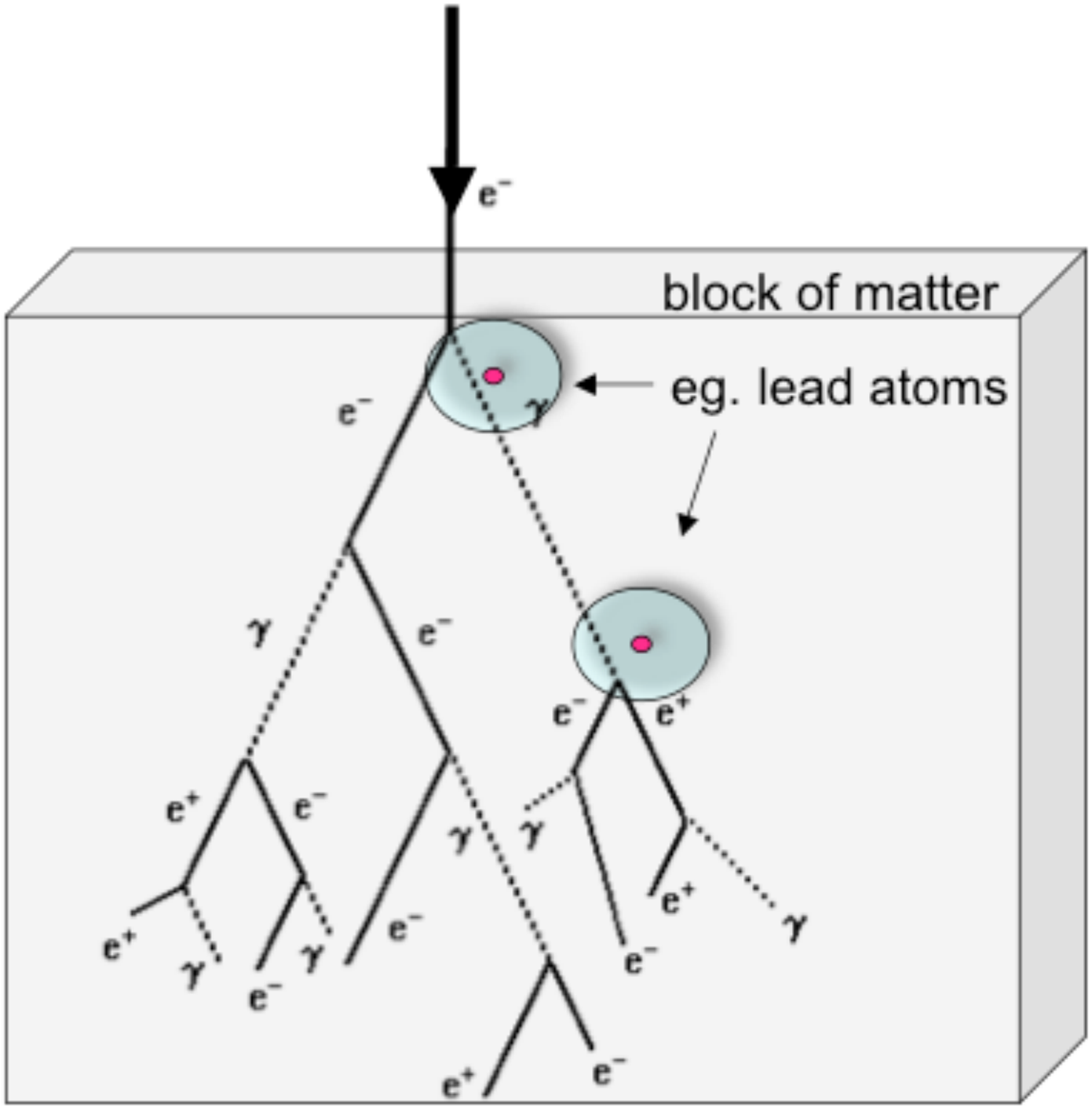








Calorimetry: Basic Principles (2)



Ionization, scintillation, Cherenkov light

- Relevant quantities:

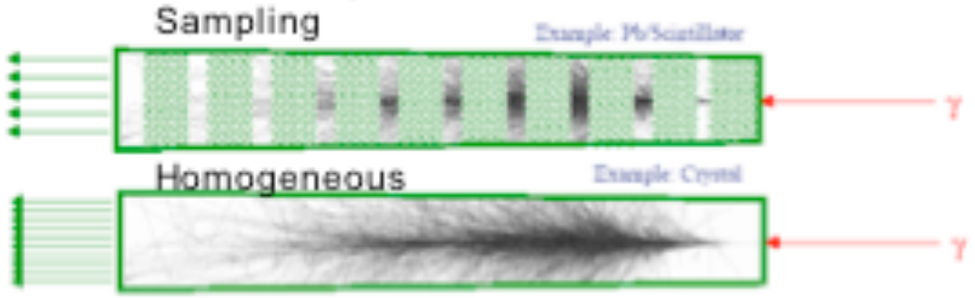
Radiation length X_0 :

- e^- loses 63.2% of its energy via bremsstrahlung over distance X_0
- Mean free path of high-energetic photons = 9/7 X_0

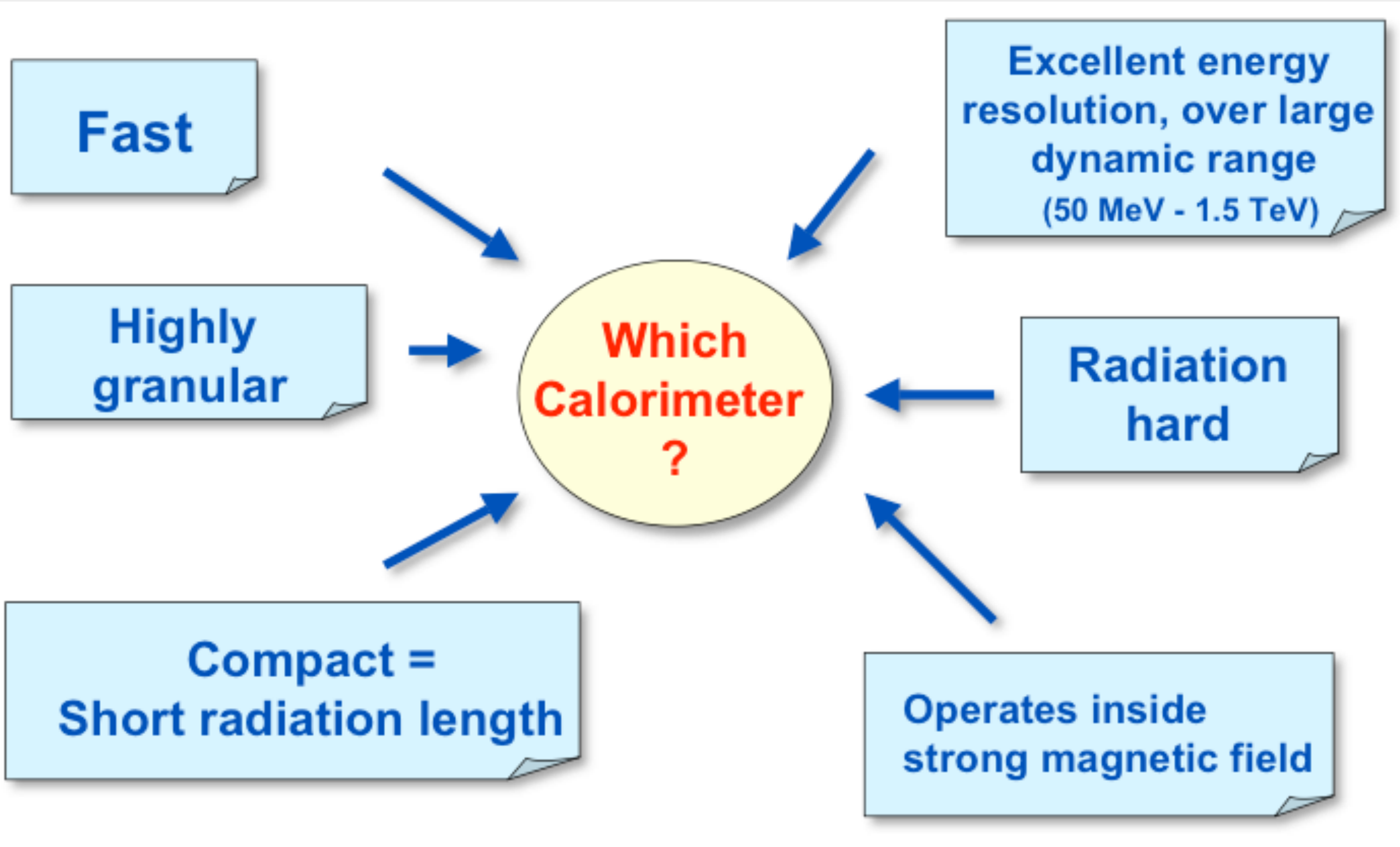
Moliere radius ρ_M :

- Measure for the lateral shower size
- On average, 90% of shower is contained within cylinder of radius ρ_M around the shower axis.

- Detector layout



Calorimeter merit's requirements



Calorimeter merit : Energy resolution

- *Ideally, if all shower particles are counted:*

$$E \propto N \qquad \sigma_E \approx \sqrt{N} \approx \sqrt{E}$$

- *In practice*

$$\sigma_E = a\sqrt{E} \oplus bE \oplus c \qquad \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

More

Calorimeter merit : Energy resolution

- *Ideally, if all shower particles are counted:*

$$E \propto N \qquad \sigma_E \approx \sqrt{N} \approx \sqrt{E}$$

- *In practice*

$$\sigma_E = a\sqrt{E} \oplus bE \oplus c \qquad \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- *a: stochastic term*
  - *intrinsic statistical shower fluctuations*
  - *sampling fluctuations*
  - *signal quantum fluctuations (e.g. photo-electron statistics)*

More

Calorimeter merit : Energy resolution

- *Ideally, if all shower particles are counted:*

$$E \propto N \qquad \sigma_E \approx \sqrt{N} \approx \sqrt{E}$$

- *In practice*

$$\sigma_E = a\sqrt{E} \oplus bE \oplus c \qquad \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- *a: stochastic term*
  - *intrinsic statistical shower fluctuations*
  - *sampling fluctuations*
  - *signal quantum fluctuations (e.g. photo-electron statistics)*

- *c: noise term*
  - *readout electronic noise*
  - *Radio-activity, pile-up fluctuations*

More

Calorimeter merit : Energy resolution

- *Ideally, if all shower particles are counted:*

$$E \propto N \qquad \sigma_E \approx \sqrt{N} \approx \sqrt{E}$$

- *In practice*

$$\sigma_E = a\sqrt{E} \oplus bE \oplus c \qquad \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- *a: stochastic term*
  - *intrinsic statistical shower fluctuations*
  - *sampling fluctuations*
  - *signal quantum fluctuations (e.g. photo-electron statistics)*
- *b: constant term*
  - *inhomogeneities (hardware or calibration)*
  - *imperfections in calorimeter construction (dimensional variations, etc.)*
  - *non-linearity of readout electronics*
  - *fluctuations in longitudinal energy containment (leakage)*
  - *fluctuations in energy lost in dead material before or within the calorimeter*
- *c: noise term*
  - *readout electronic noise*
  - *Radio-activity, pile-up fluctuations*

More

Schematic Of a HEP Calorimeter

Typical Calorimeter: two components …

Electromagnetic (EM) + Hadronic section (Had) …

Different setups chosen for optimal energy resolution …

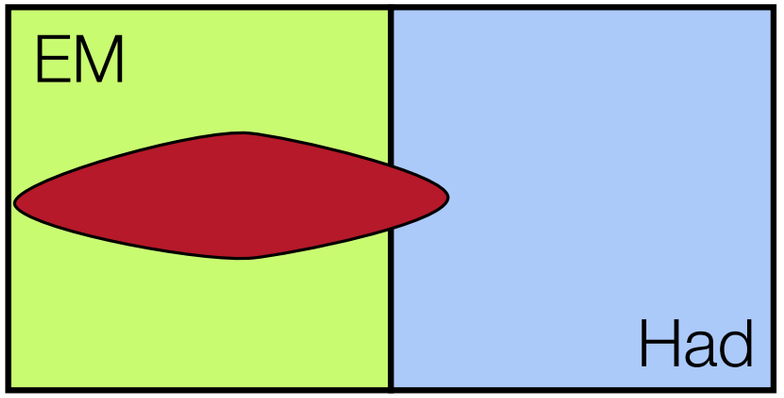
But:

Hadronic energy measured in both parts of calorimeter …

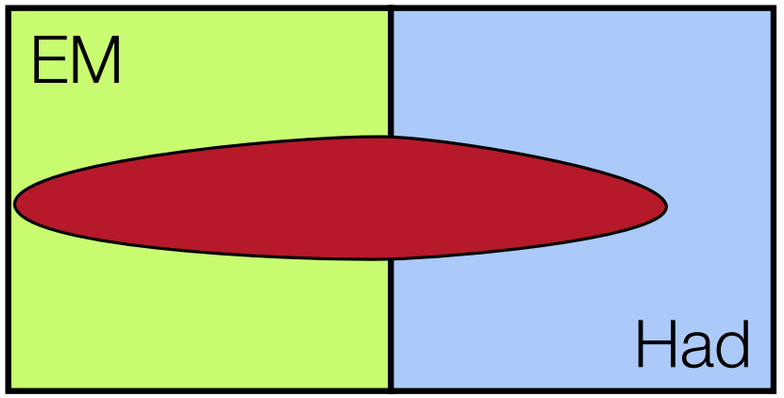
Needs careful consideration of different response …

Schematic of a typical HEP calorimeter

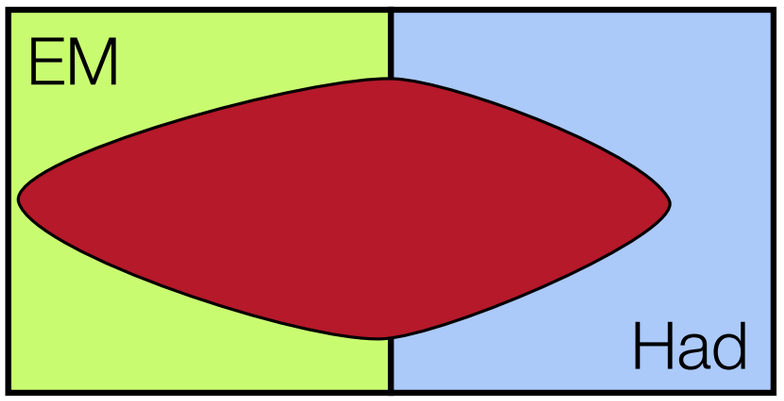
Electrons
Photons



Taus
Hadrons

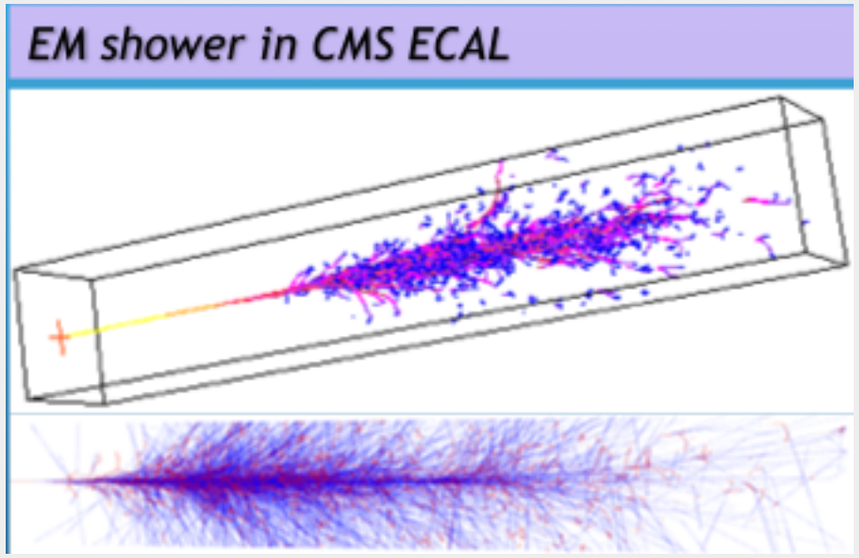


Jets



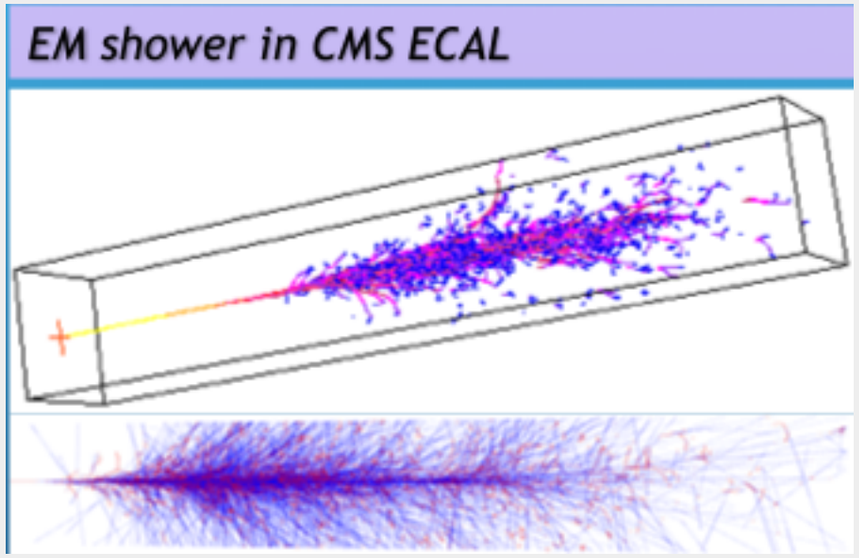
Calorimeter Types

- Homogeneous



Calorimeter Types

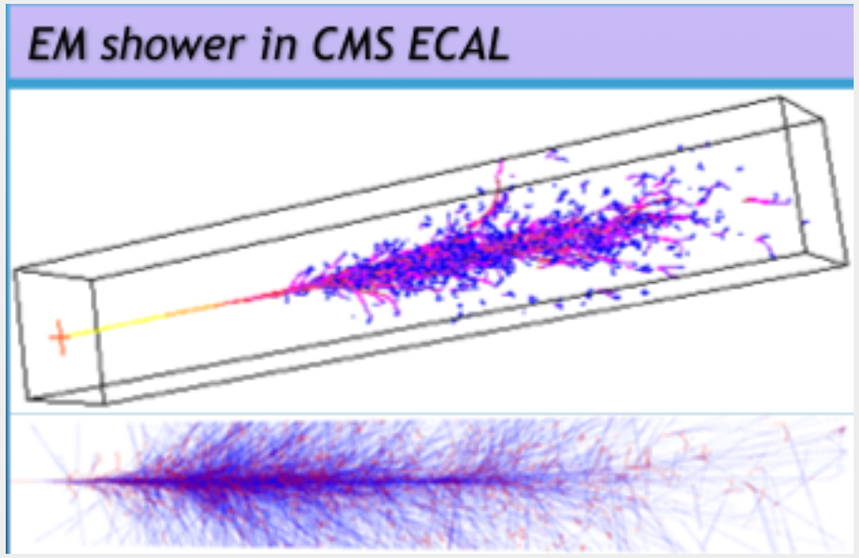
- *Homogeneous*



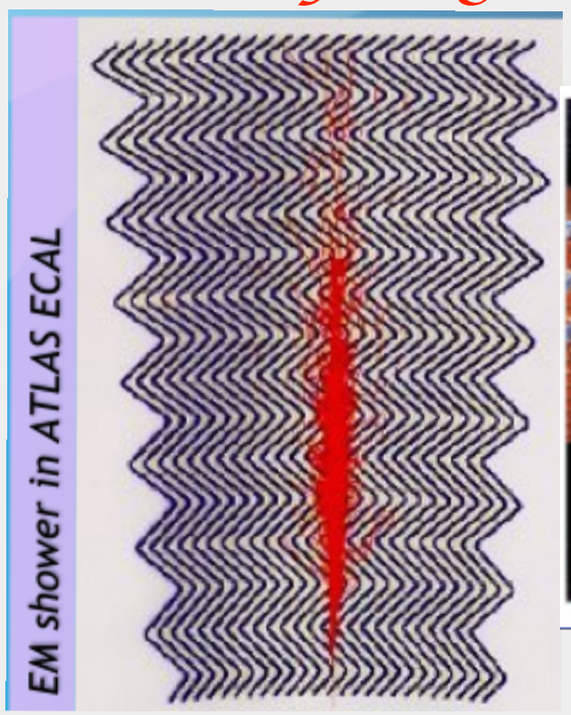
- *Sampling*

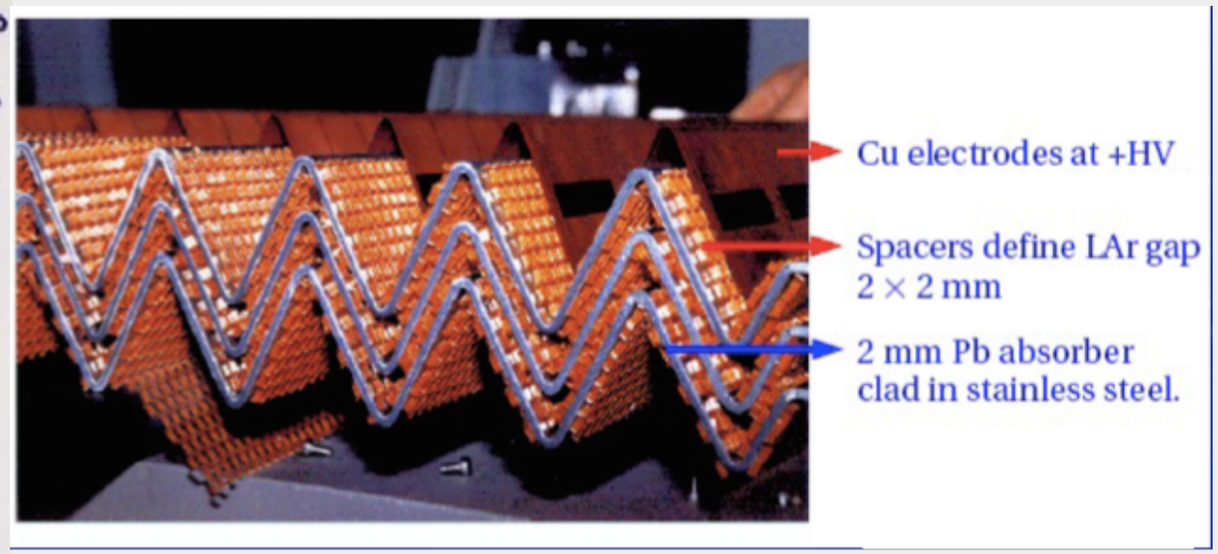
Calorimeter Types

- *Homogeneous*



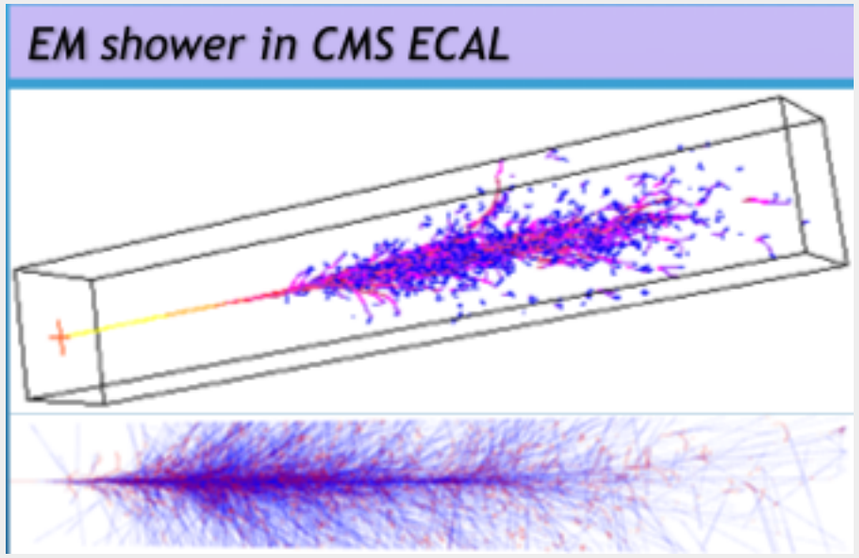
- *Sampling*



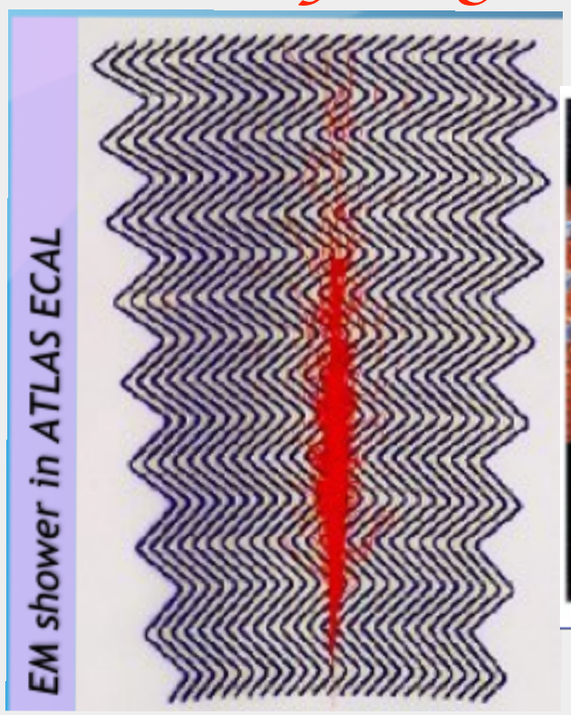


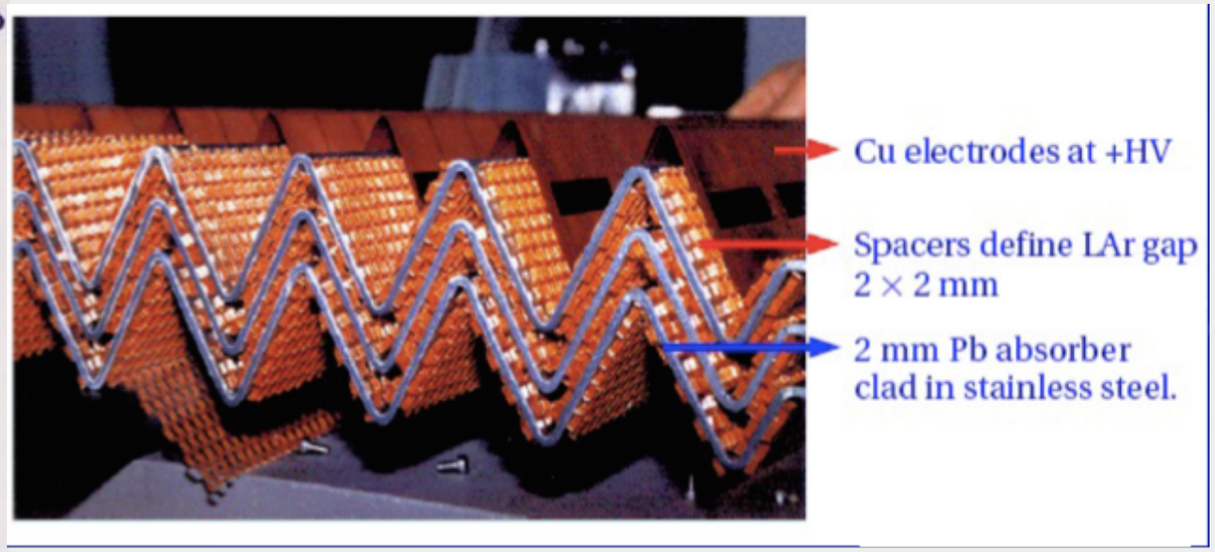
Calorimeter Types

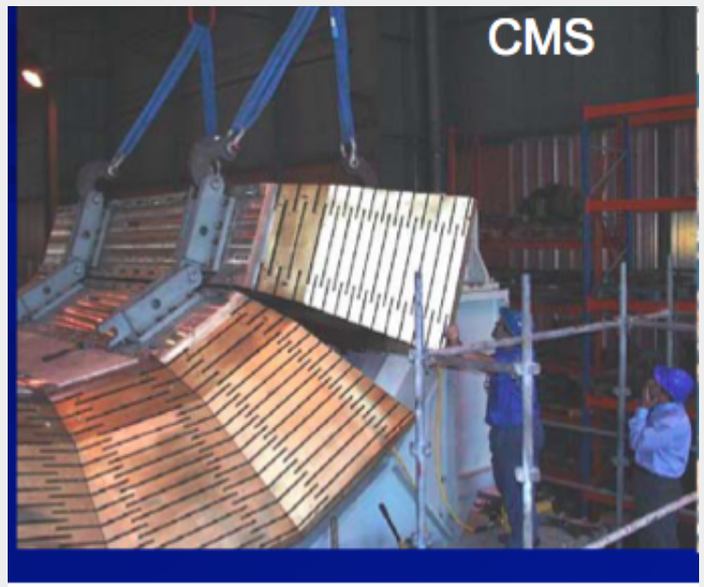
- *Homogeneous*



- *Sampling*







5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

An Homogeneous Calorimeters

CMS Crystal calorimeter

An Homogeneous Calorimeters

CMS Crystal calorimeter

Scintillator : $PBW0_4$ [Lead Tungsten]

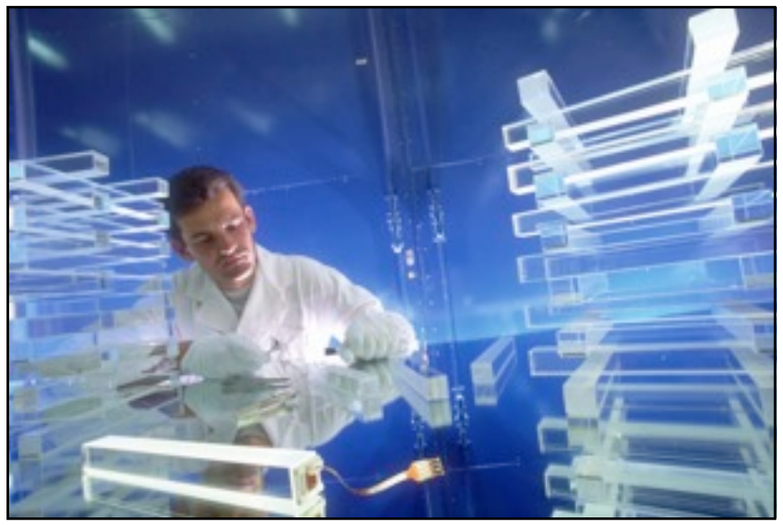
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000

Light output: 4.5 photons/MeV

An Homogeneous Calorimeters

CMS Crystal calorimeter

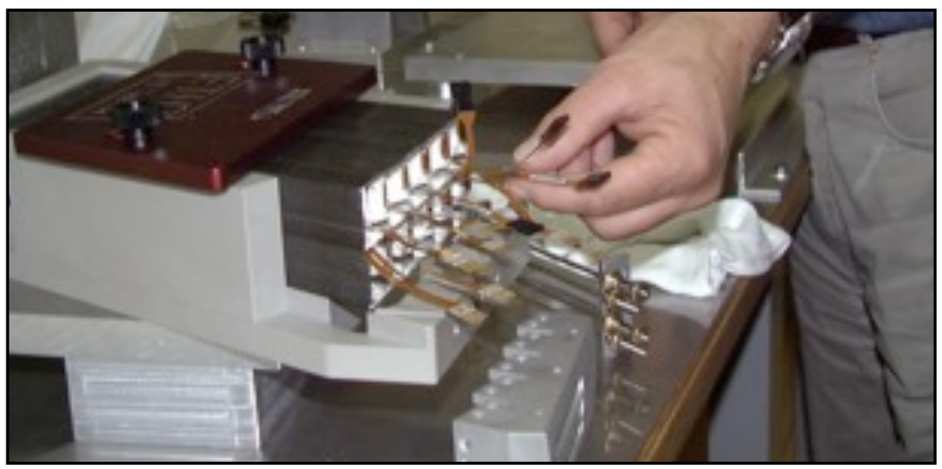


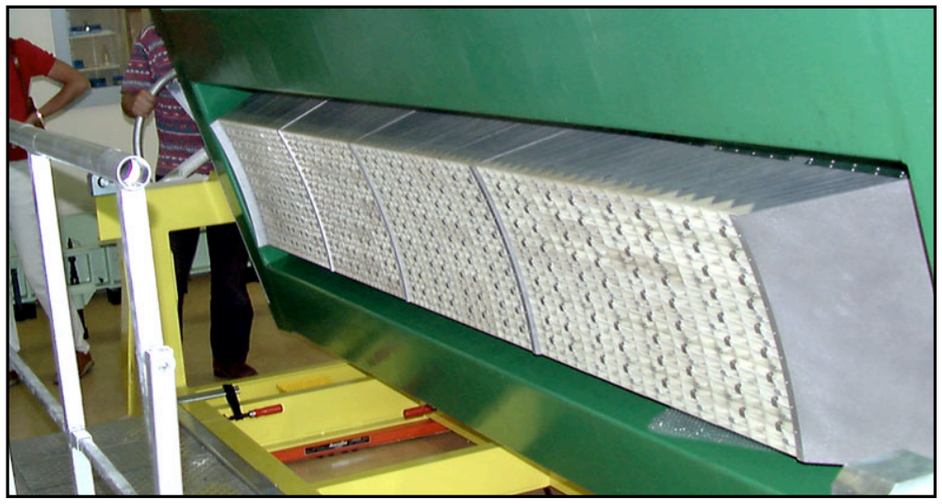
Scintillator : $PBW0_4$ [Lead Tungsten]

Photosensor : APDs [Avalanche Photodiodes]

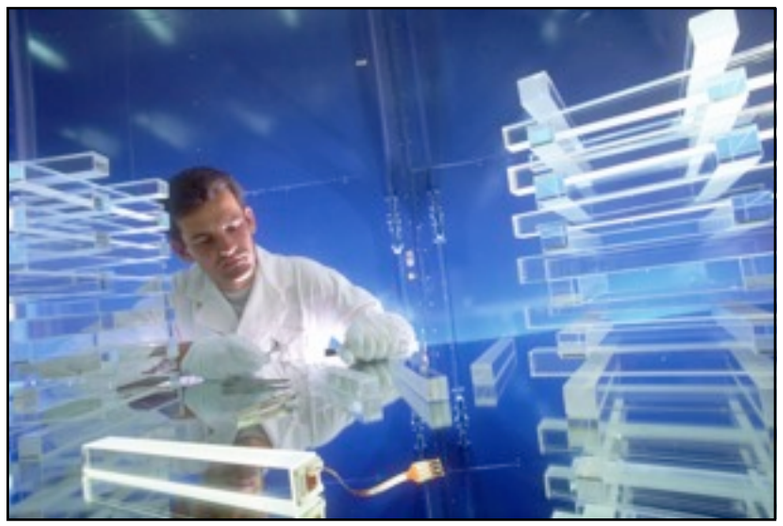
Number of crystals: ~ 70000

Light output: 4.5 photons/MeV



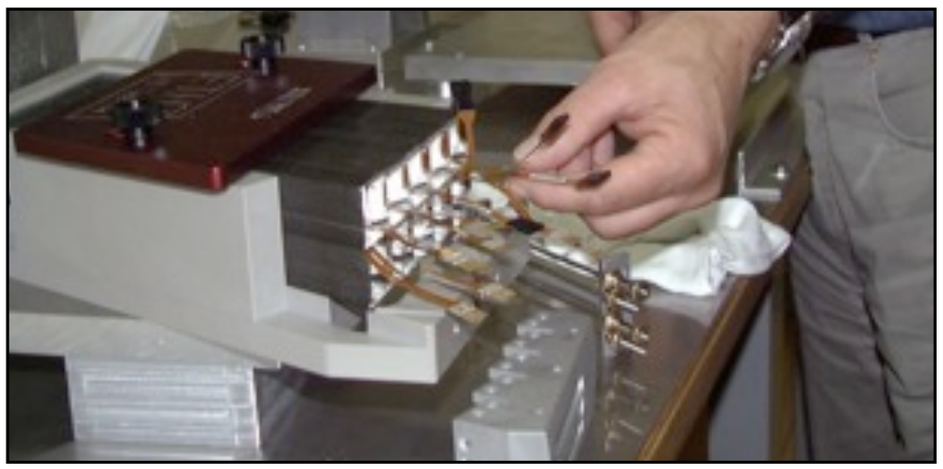


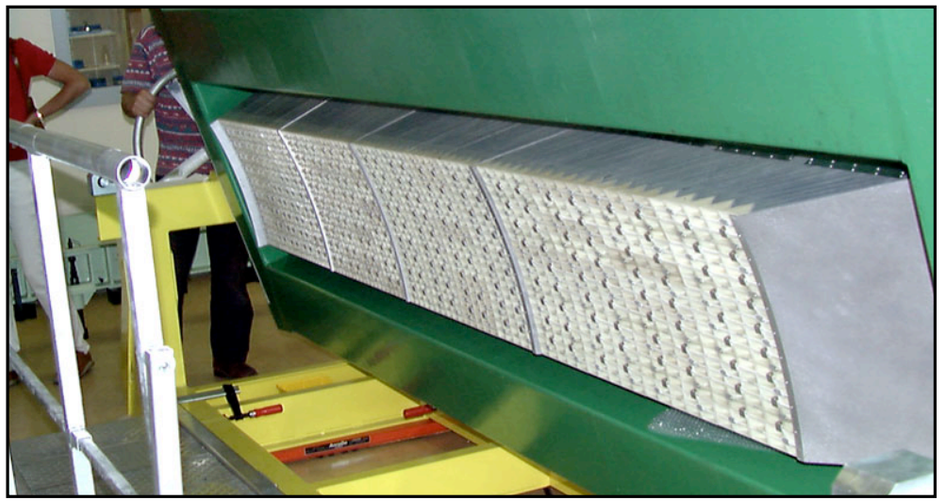
An Homogeneous Calorimeters
CMS Crystal calorimeter

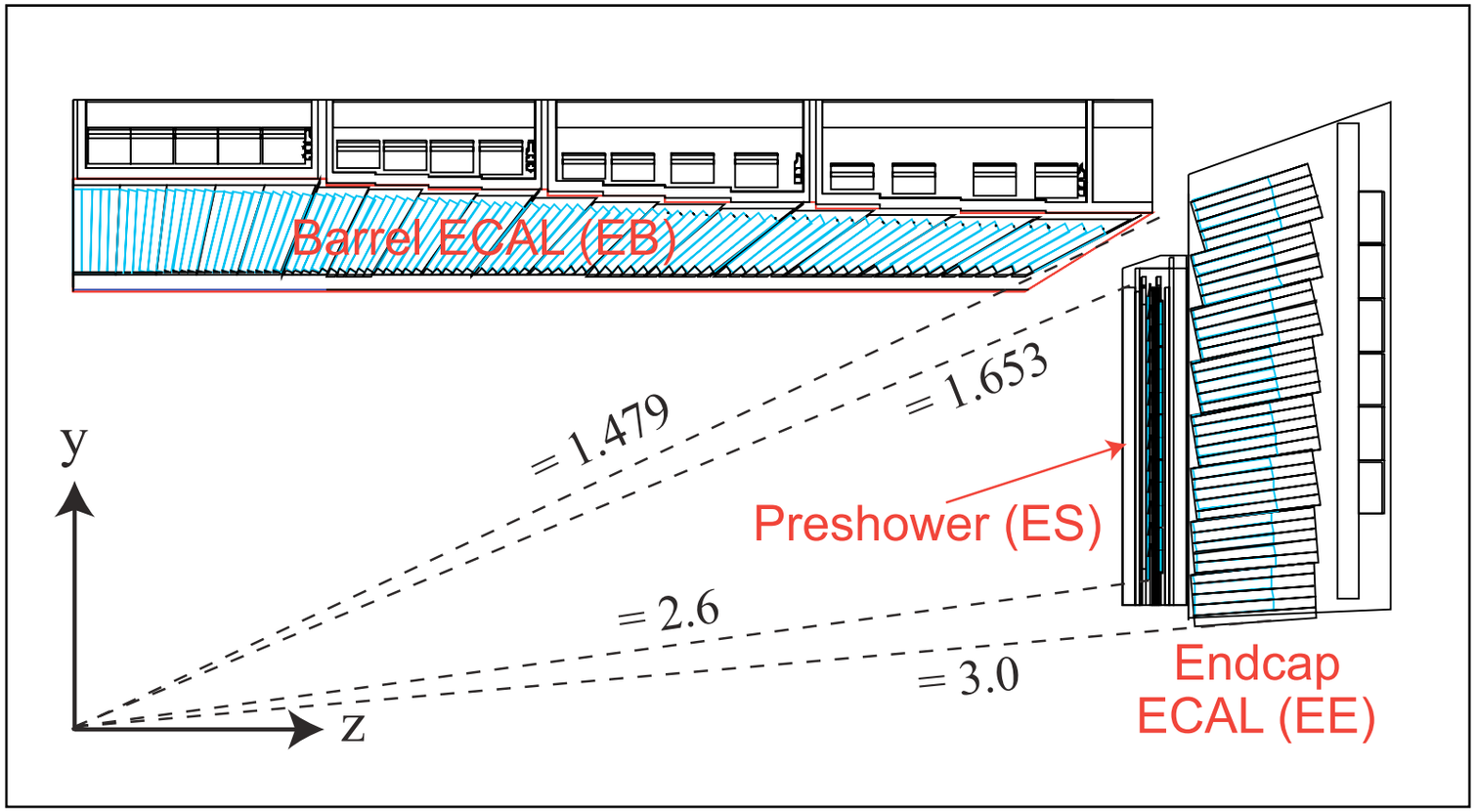


Scintillator : $PBW0_4$ [Lead Tungsten]
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000
Light output: 4.5 photons/MeV







Sampling Calorimeter

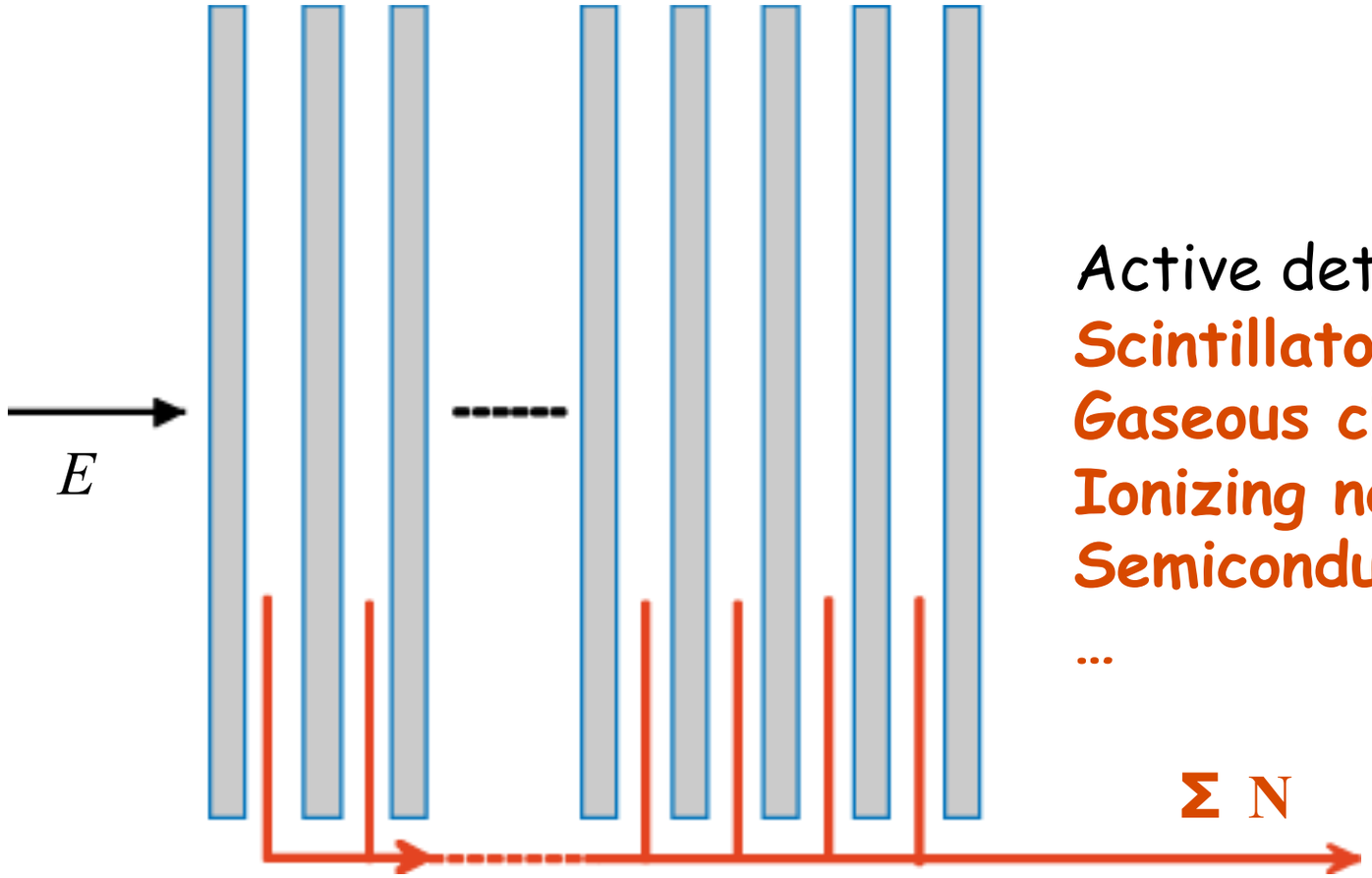
Sampling Calorimeter

Use a different medium to generate the shower and to detect signal : only a fraction of signal (fs) is sampled in the active detector → larger stochastic term

Sampling Calorimeter

Use a different medium to generate the shower and to detect signal : only a fraction of signal (fs) is sampled in the active detector → larger stochastic term

Particle absorption and Shower sampling are separated.

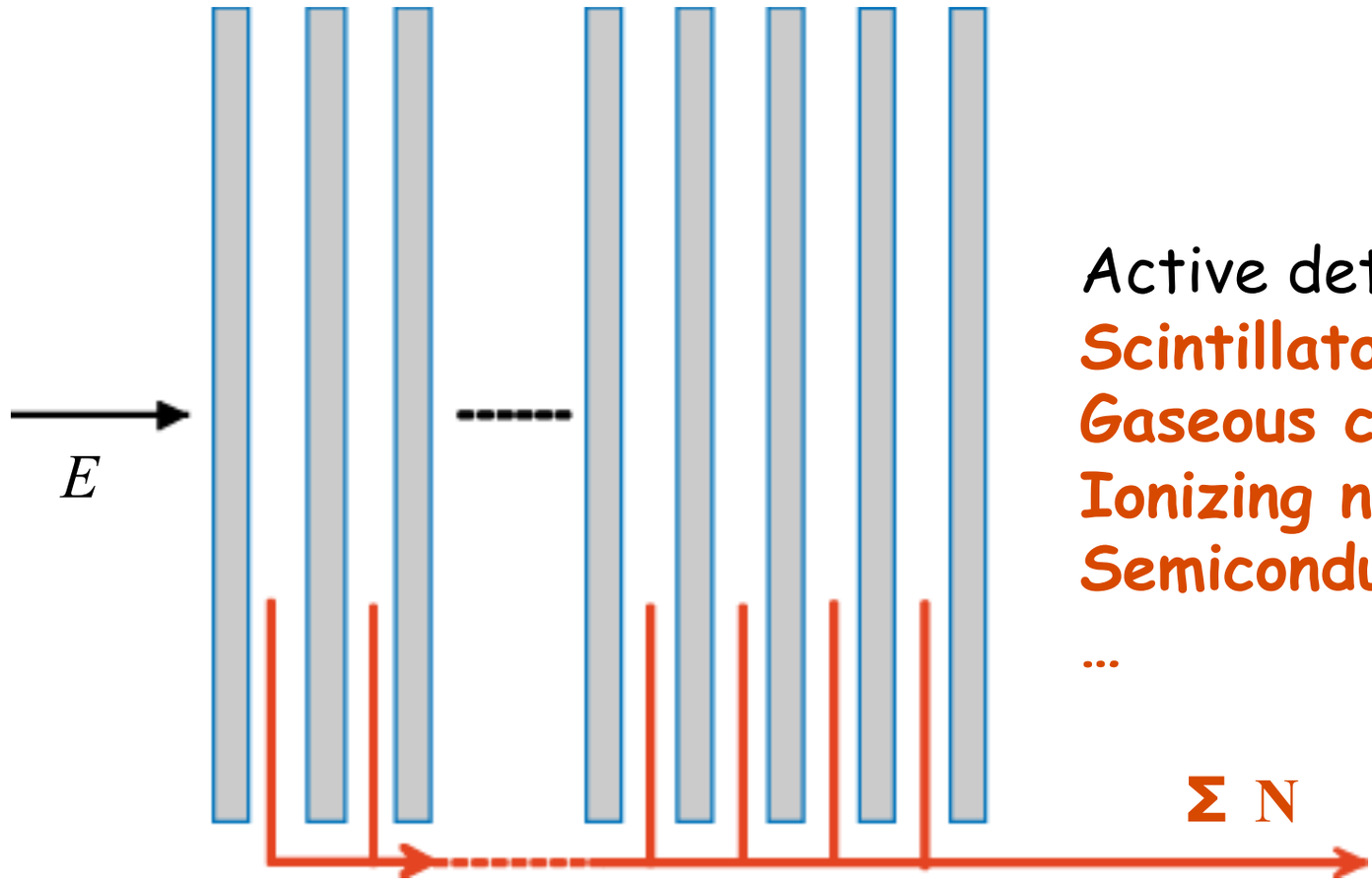


Active detector:
Scintillators
Gaseous chambers
Ionizing noble liquid
Semiconductors
…

Sampling Calorimeter

Use a different medium to generate the shower and to detect signal : only a fraction of signal (fs) is sampled in the active detector → larger stochastic term

Particle absorption and Shower sampling are separated.



Active detector:
Scintillators
Gaseous chambers
Ionizing noble liquid
Semiconductors
…

Intrinsic resolution goes from 1-3 % for crystal or homogeneous noble liquids to 8-12% for sampling calorimeters.

Sampling calorimeters

Sampling calorimeters

Advantages:

By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements …

By freely choosing high-density material for the absorbers one can built very compact calorimeters …

Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters …

Sampling calorimeters

Advantages:

By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements …

By freely choosing high-density material for the absorbers one can built very compact calorimeters …

Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters …

Disadvantages:

Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only ~10^{-5}] …

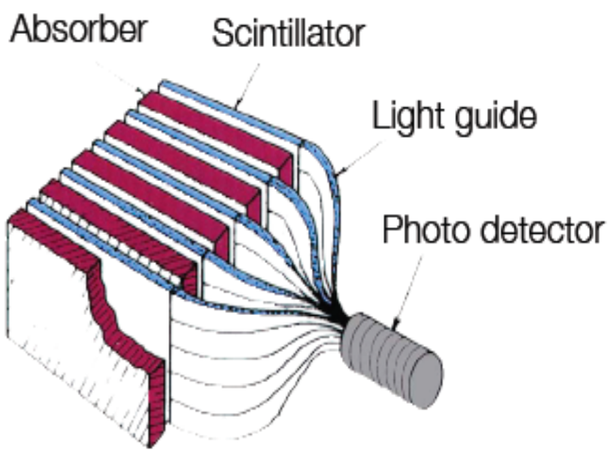
Due to this sampling-fluctuations it result a reduced energy resolution for sampling calorimeters …

Sampling calorimeters : READOUT

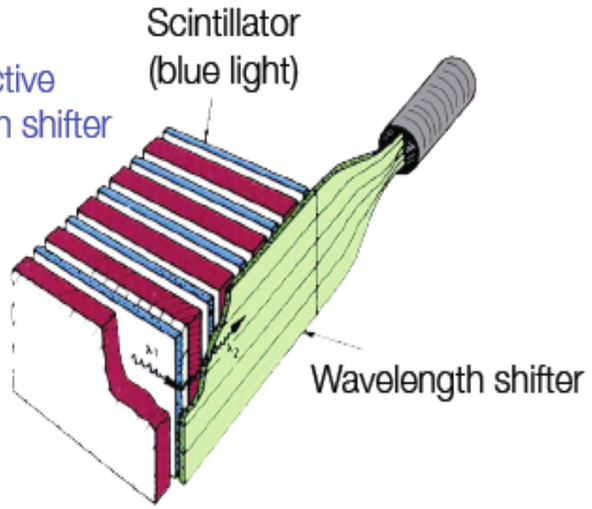
Sampling calorimeters = Absorber + detector (gaseous, liquid, solid)

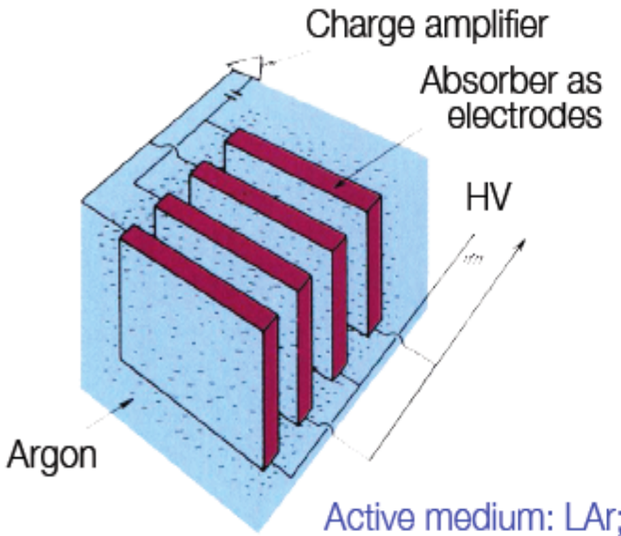
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



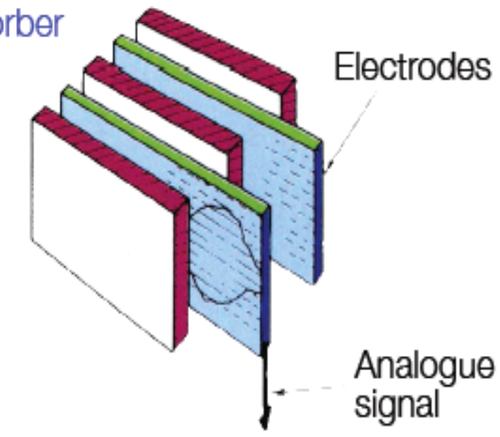
Scintillators as active layer; wave length shifter to convert light

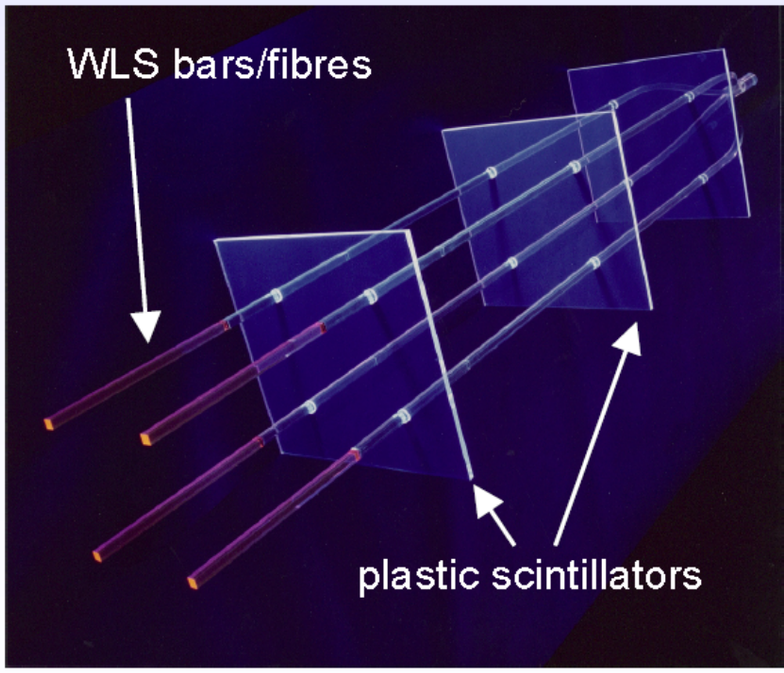




Active medium: LAr; absorber embedded in liquid serve as electrods

Ionization chambers between absorber plates





'Shashlik' readout

- MWPC, streamer tubes
- warm liquids (TMP = tetramethylpentane, TMS = tetramethylsilane)
- cryogenic noble gases: mainly LAr (LXe, LKr)
- scintillators, scintillation fibres, silicon detectors

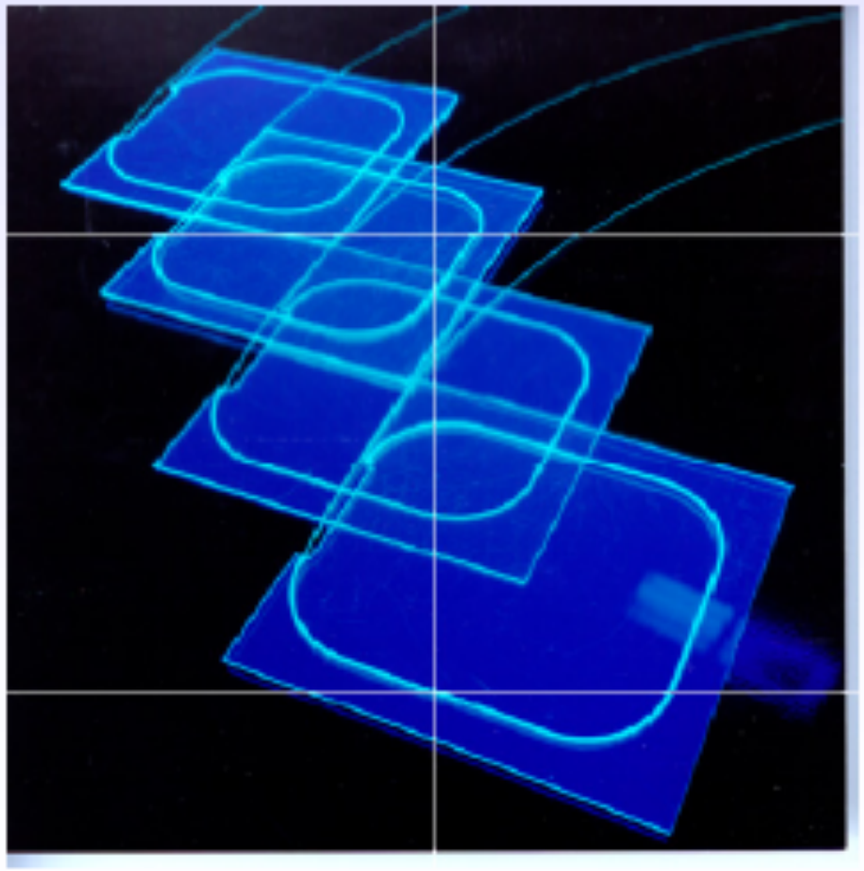
Sampling calorimeters: CMS HCAL

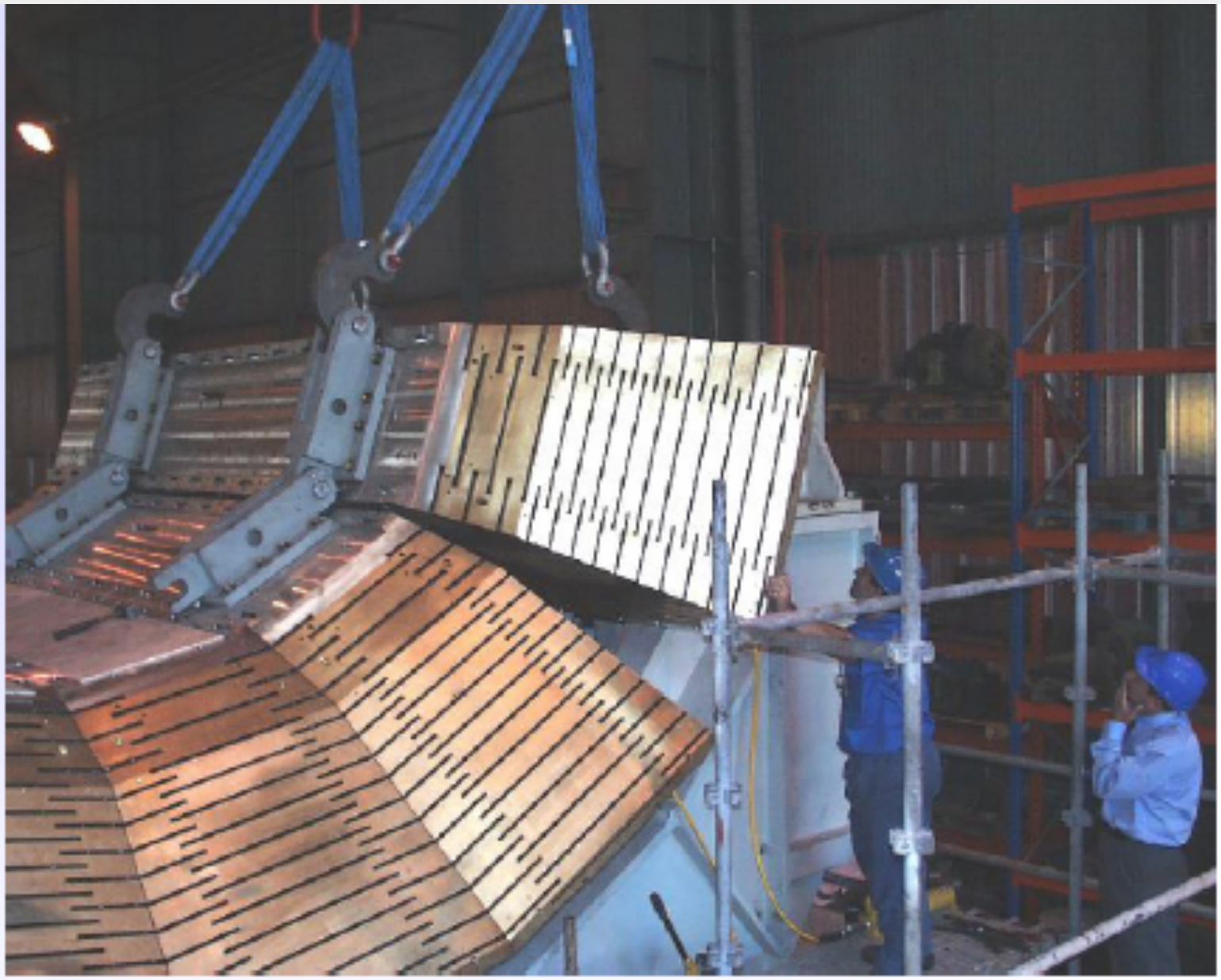
CMS Hadron calorimeter

Brass absorber + plastic scintillators

2 x 18 wedges (barrel)
+ 2 x 18 wedges (endcap)
~ 1500 T absorber
5.8 λ_i *at* $\eta = 0$.

Scintillators fill slots and are read out via WLS fibres by HPDs (B = 4T!)





Test beam resolution for single hadrons

$$\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\%$$

ELECTROMAGNETIC SHOWER DEVELOPMENT

ELECTROMAGNETIC SHOWER DEVELOPMENT

- The shower develops as a cascade by energy transfer from the incident particle to a multitude of particles ($e^{\pm}$ and γ).

- The number of cascade particles is proportional to the energy deposited by the incident particle

- The role of the calorimeter is to count these cascade particles
  The relative occurrence of the various processes briefly described is a function of the material (Z)

- The radiation length (X_0) allows to universally describe the shower development

Electromagnetic showers

Electromagnetic showers

- *Above 1 GeV the dominant processes become energy <u>independent</u>:*
  - *bremsstrahlung for e+ and e-*
  - *and pair production for photons*

Electromagnetic showers

- Above 1 GeV the dominant processes become energy independent:
  - bremsstrahlung for e+ and e-
  - and pair production for photons
- Through a succession of these energy losses an e.m cascades is propagated until the energy of the charged secondaries has been degraded to the regime dominated by ionization loss (below Ec)

Electromagnetic showers

- Above 1 GeV the dominant processes become energy independent:
  - bremsstrahlung for e+ and e-
  - and pair production for photons
- Through a succession of these energy losses an e.m cascades is propagated until the energy of the charged secondaries has been degraded to the regime dominated by ionization loss (below Ec)
- Below Ec a slow decrease in number of particles occurs as electrons are stopped and photons absorbed

Electromagnetic showers

- Above 1 GeV the dominant processes become energy independent:
  - bremsstrahlung for e+ and e-
  - and pair production for photons
- Through a succession of these energy losses an e.m cascades is propagated until the energy of the charged secondaries has been degraded to the regime dominated by ionization loss (below Ec)
- Below Ec a slow decrease in number of particles occurs as electrons are stopped and photons absorbed

Interaction with matter :

- More of EM shower development : (for details clic

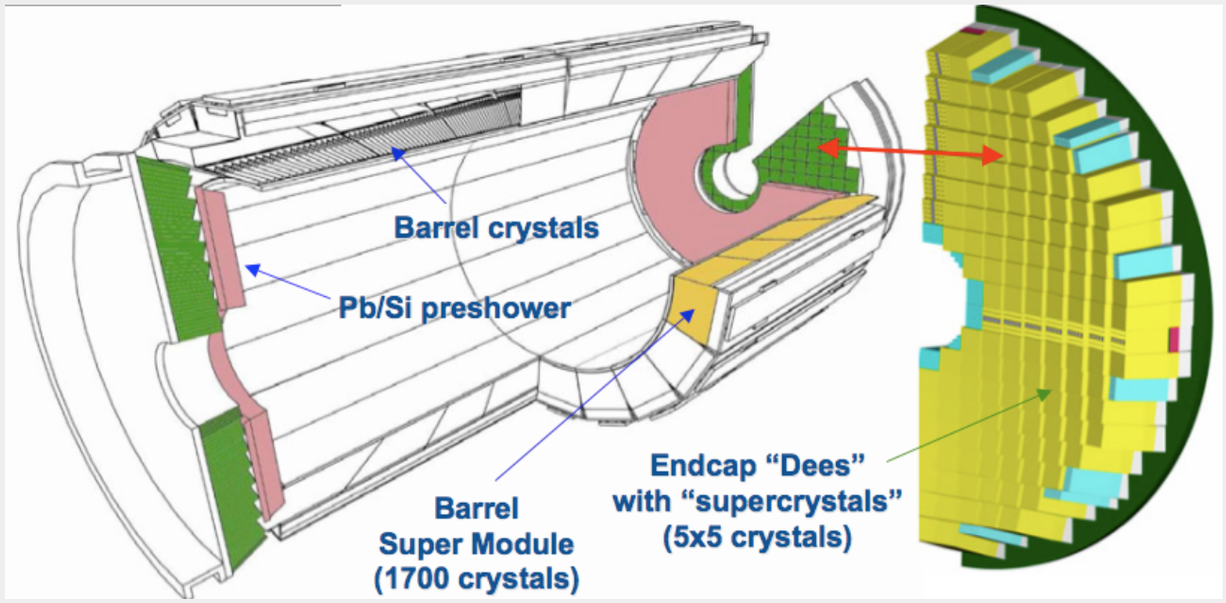
Electromagnetic showers

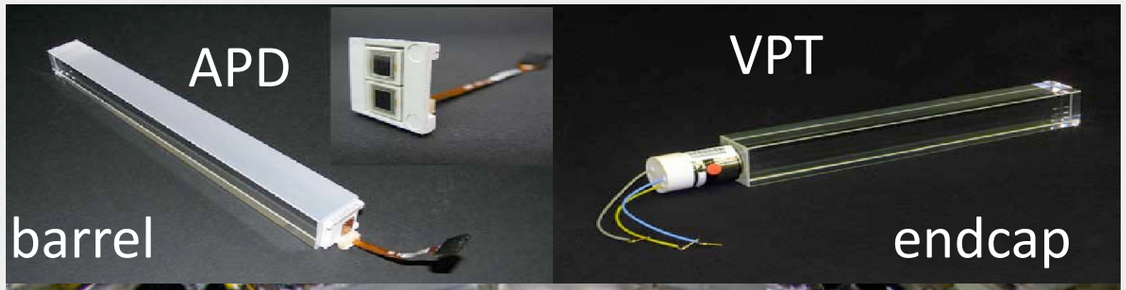
- *Above 1 GeV the dominant processes become energy <u>independent</u>:*
  - *bremsstrahlung for e+ and e-*
  - *and pair production for photons*
- *Through a succession of these energy losses an e.m cascades is propagated until the energy of the charged secondaries has been degraded to the regime dominated by ionization loss (below Ec)*
- *Below Ec a slow decrease in number of particles occurs as electrons are stopped and photons absorbed*

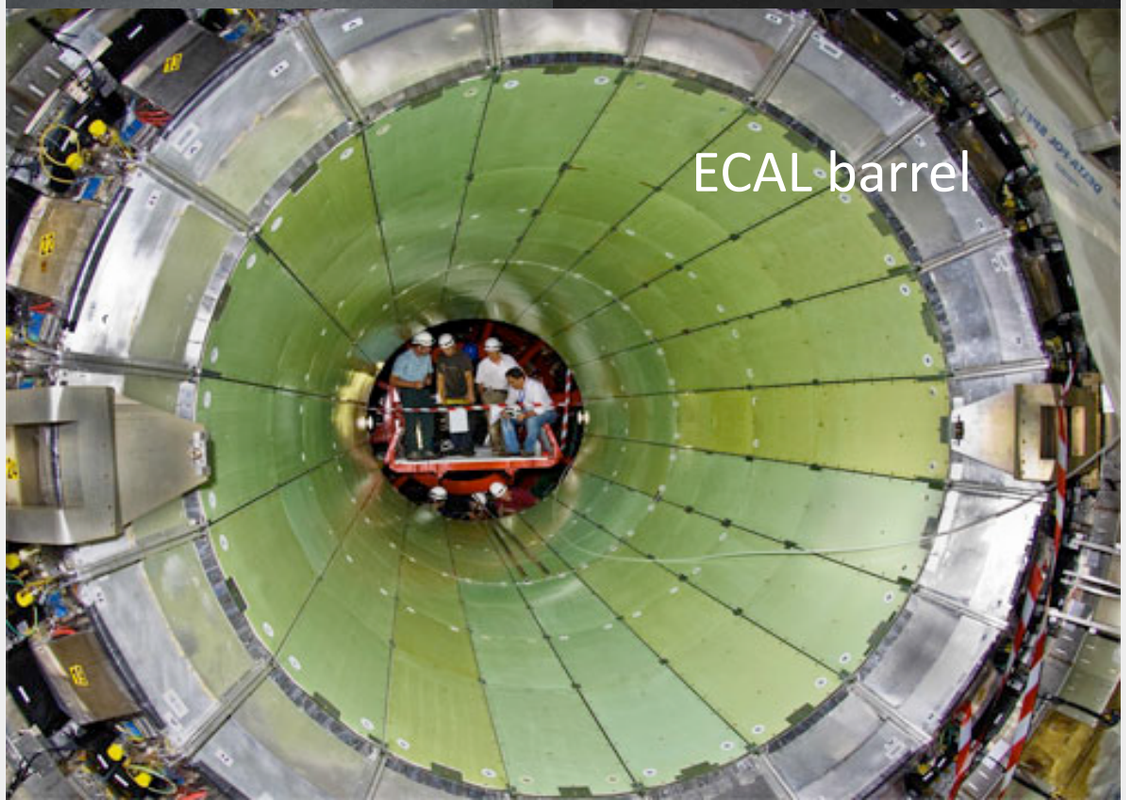
Interaction with matter :

- More of EM shower development : (for details clic

Electromagnetic calorimeter







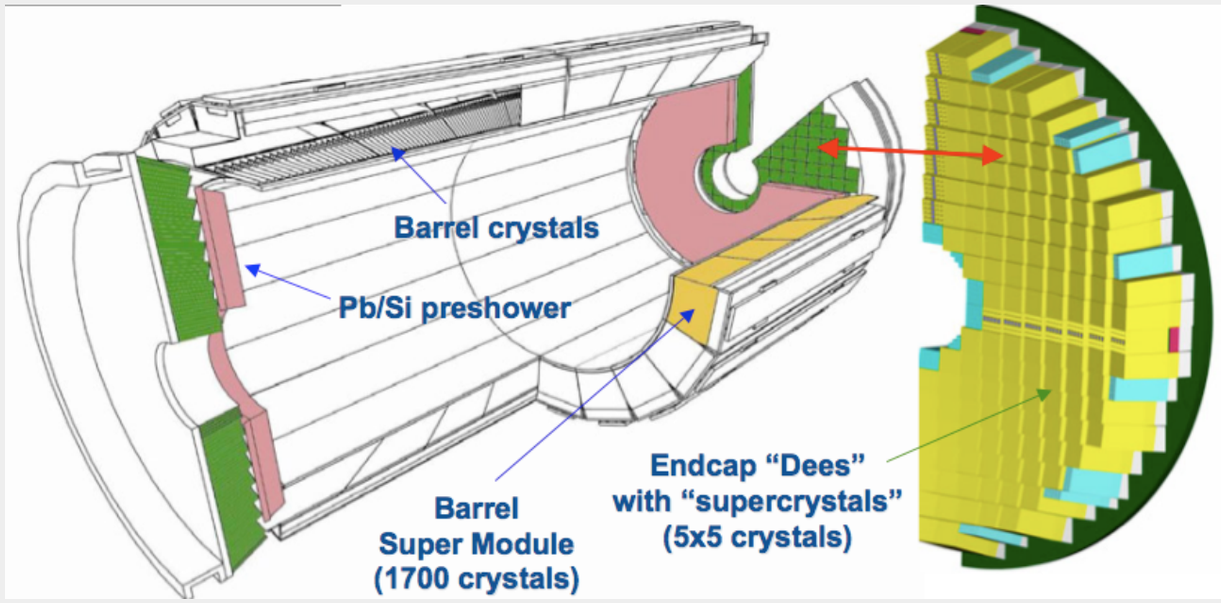
Electromagnetic calorimeter

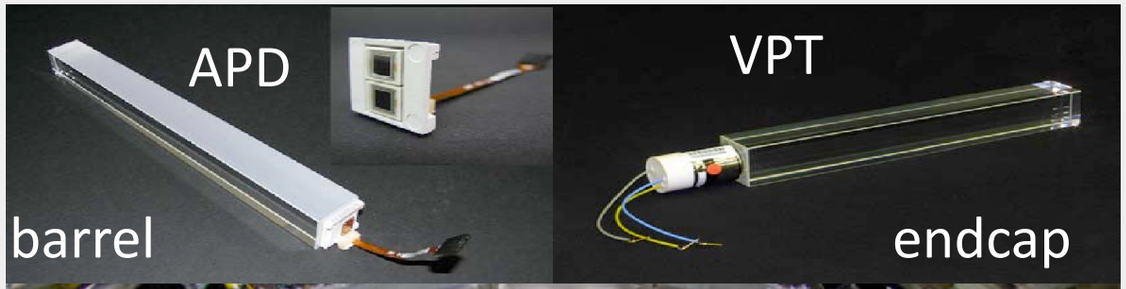
- Homogeneous Lead tungstate $PbWO_4$ crystals
- Fast scintillation response, excellent time resolution
  - about 80% of the light emitted in 25 ns
- Compact & high granularity
  - Molière radius 2.2 cm
  - Radiation length X_0 0.89 cm

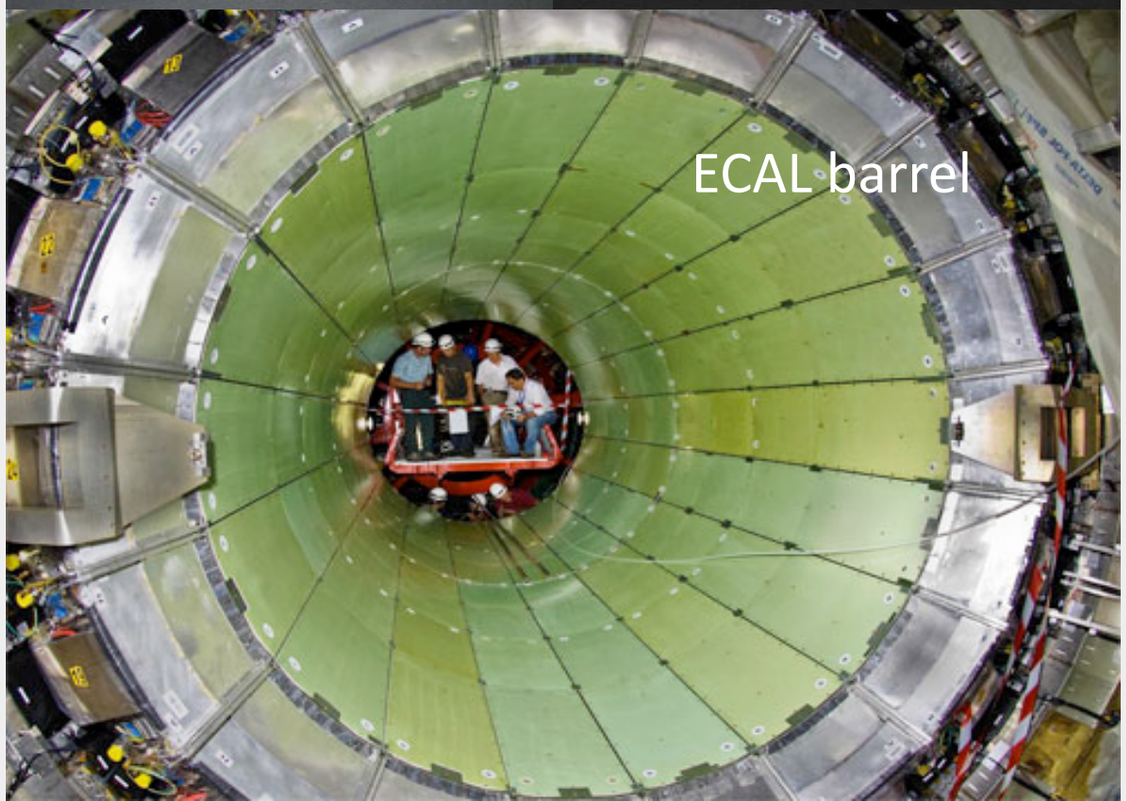
- Barrel $|\eta|<1.48$:
  - ~61K crystals in 36 SuperModules (SM)
  - 2x2x23 cm^3 covering 26 X_0
  - Photodetector: Avalanche Photo Diodes (APD)
- Endcap $1.48<|\eta|<3.0$
  - ~15k crystals in 4 Dees
  - 3x3x22 cm^3 covering 24 X_0
  - Photodetector: Vacuum Photo Triodes (VPT)
- Preshower $1.65<|\eta|<2.6$
  - ~137k silicon strips in 2 planes per endcap
  - $3X_0$ of lead radiator

- No longitudinal segmentation

- Energy resolution for electrons impinging on the center of a 3x3 barrel crystal matrix from Test Beam (no upstream material, no magnetic field, etc…)







Electromagnetic calorimeter

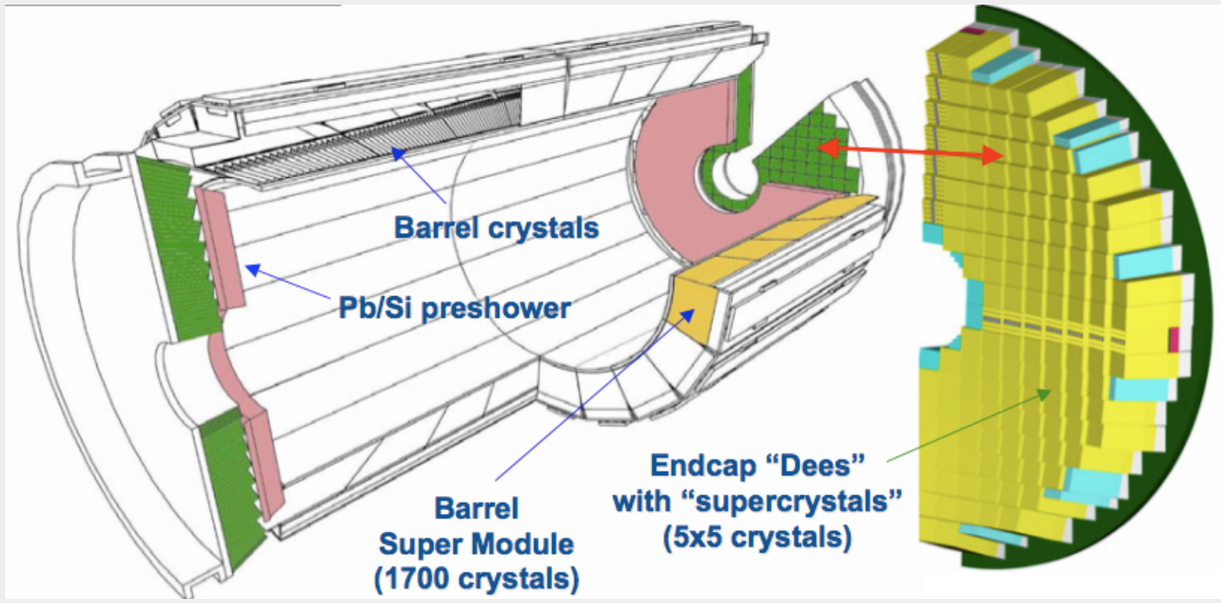
- Homogeneous Lead tungstate $PbWO_4$ crystals
- Fast scintillation response, excellent time resolution
  - about 80% of the light emitted in 25 ns
- Compact & high granularity
  - Molière radius 2.2 cm
  - Radiation length X_0 0.89 cm

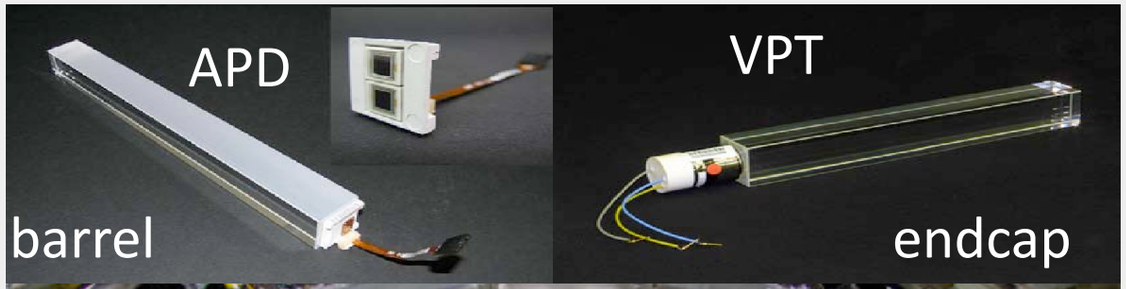
- Barrel $|\eta|<1.48$:
  - ~61K crystals in 36 SuperModules (SM)
  - 2x2x23 cm^3 covering 26 X_0
  - Photodetector: Avalanche Photo Diodes (APD)
- Endcap $1.48<|\eta|<3.0$
  - ~15k crystals in 4 Dees
  - 3x3x22 cm^3 covering 24 X_0
  - Photodetector: Vacuum Photo Triodes (VPT)
- Preshower $1.65<|\eta|<2.6$
  - ~137k silicon strips in 2 planes per endcap
  - 3X_0 of lead radiator

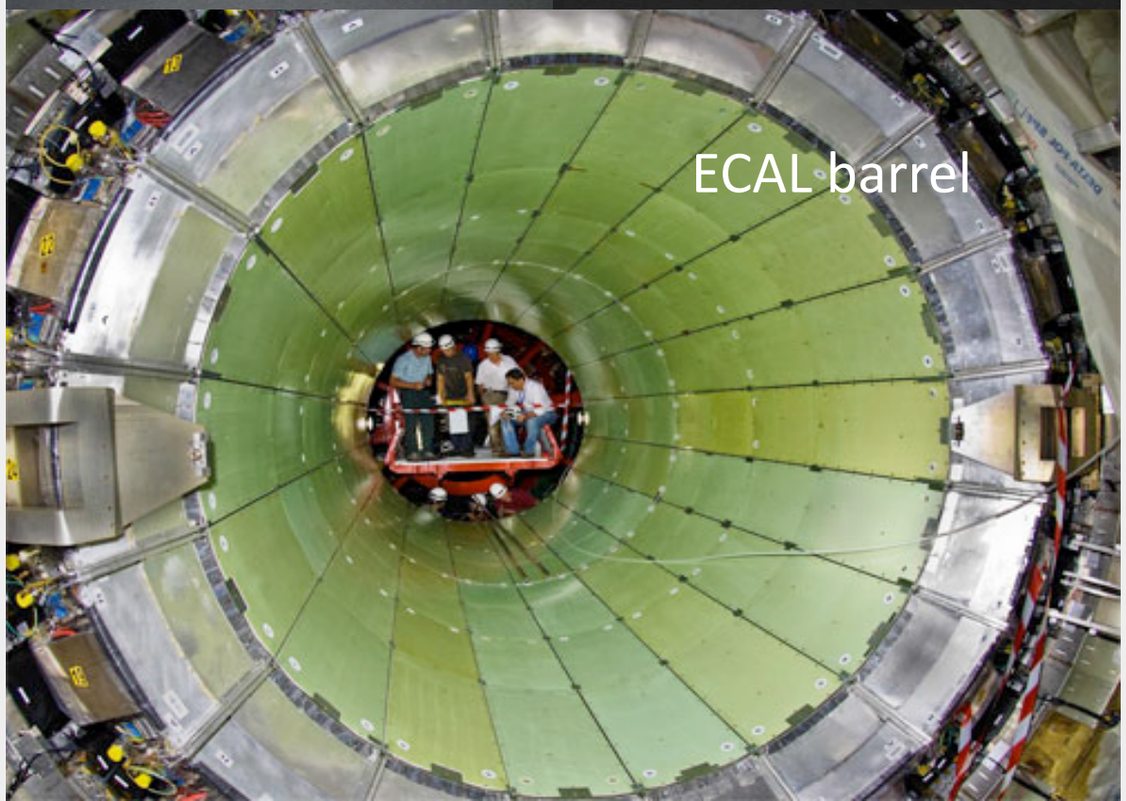
- No longitudinal segmentation

- Energy resolution for electrons impinging on the center of a 3x3 barrel crystal matrix from Test Beam (no upstream material, no magnetic field, etc…)

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\,(GeV)}} \oplus \frac{0.128}{E\,(GeV)} \oplus 0.3\%$$





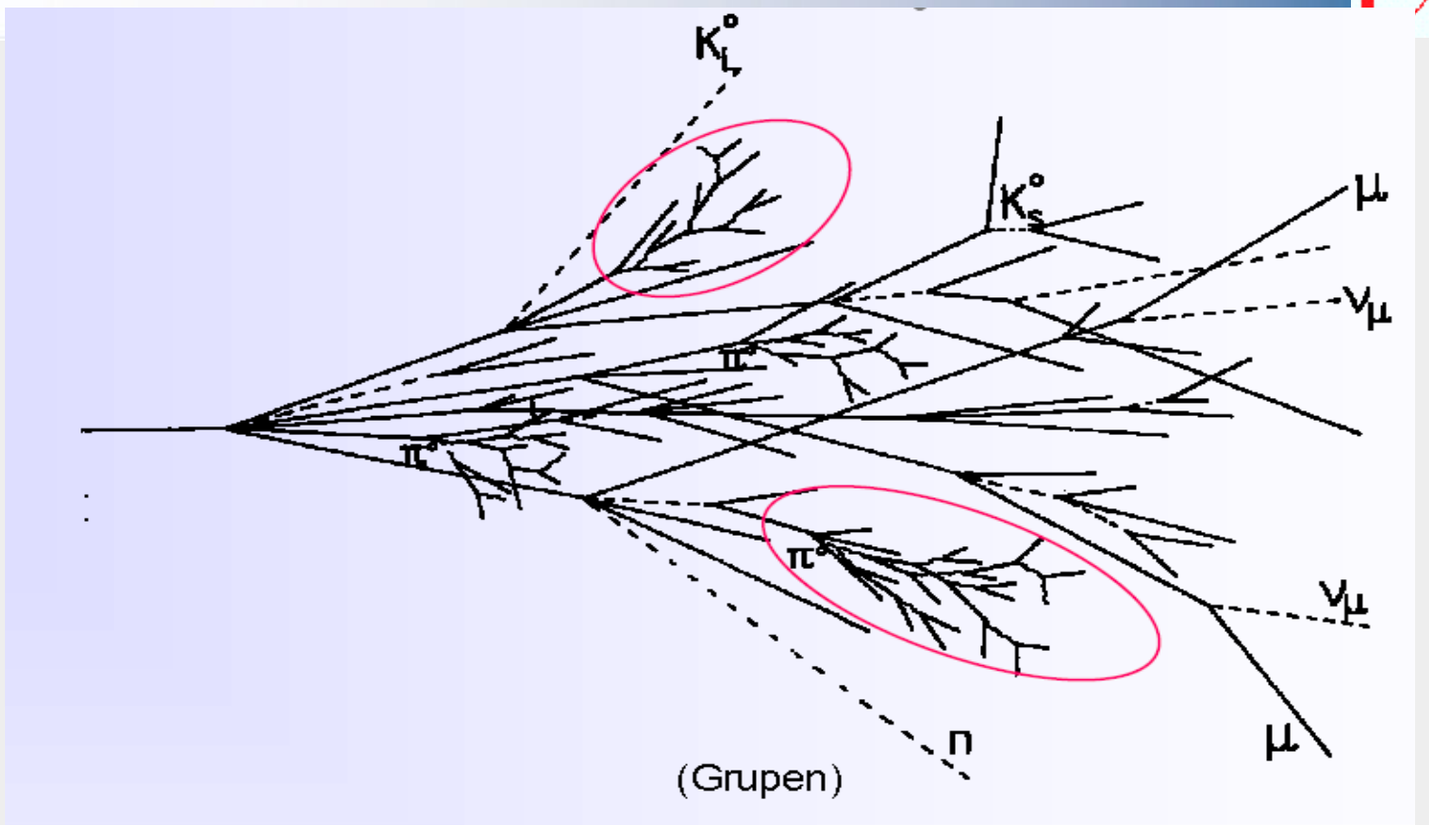


HADRONIC SHOWERS

HADRONIC SHOWERS

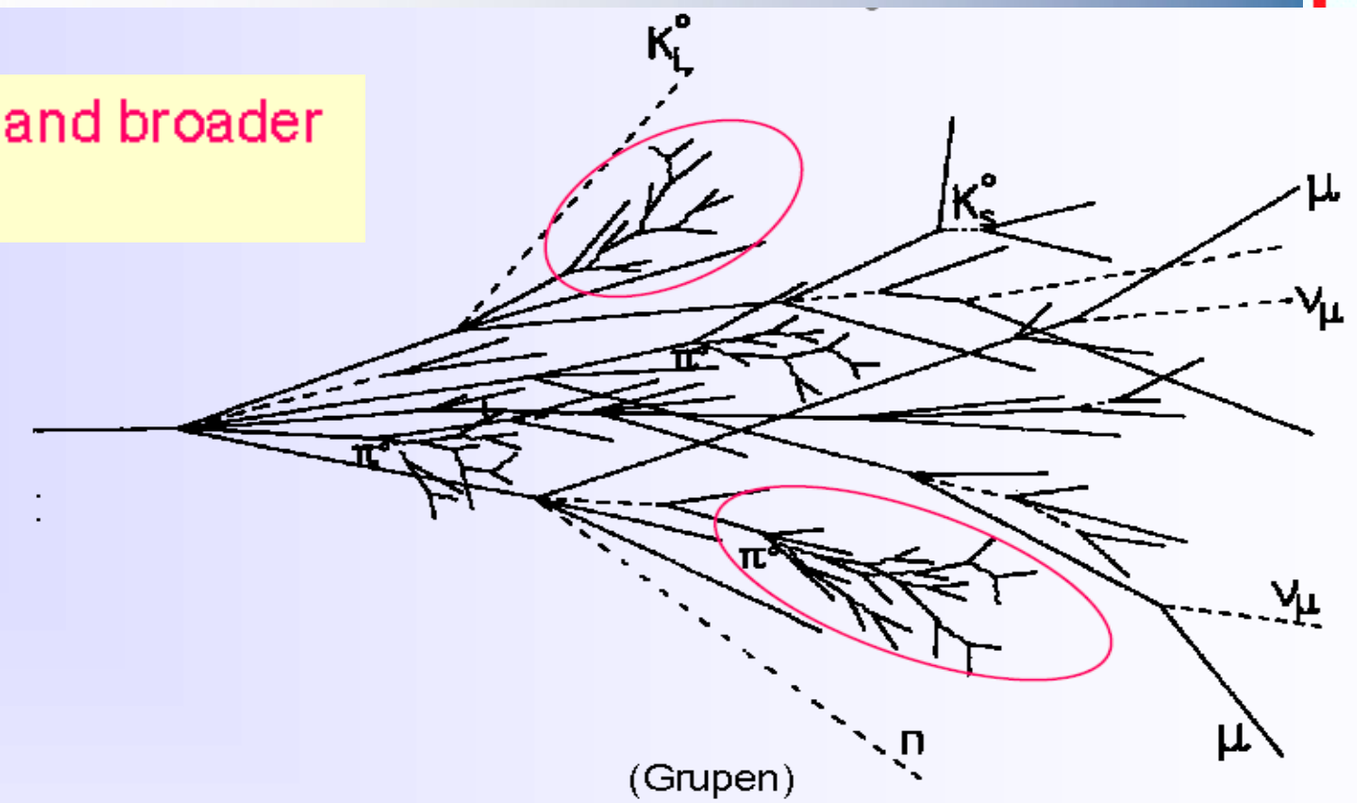
- Hadronic cascades develop in an analogous way to e.m. showers
  - Strong interaction controls overall development
  - High energy hadron interacts with material, leading to multi-particle production of more hadrons
  - They interact with further nuclei
  - Nuclear breakup and spallation neutrons
  - Multiplication continues down to the pion production threshold ($E \sim 2m_{\pi} = 0.28\ GeV/c^2$)
  - Neutral pions result in an electromagnetic component to the total énergy (immediate decay: $\pi^0 \rightarrow \gamma\gamma$) and (also: $\eta \rightarrow \gamma\gamma$)

Hadronic cascades



Hadronic cascades

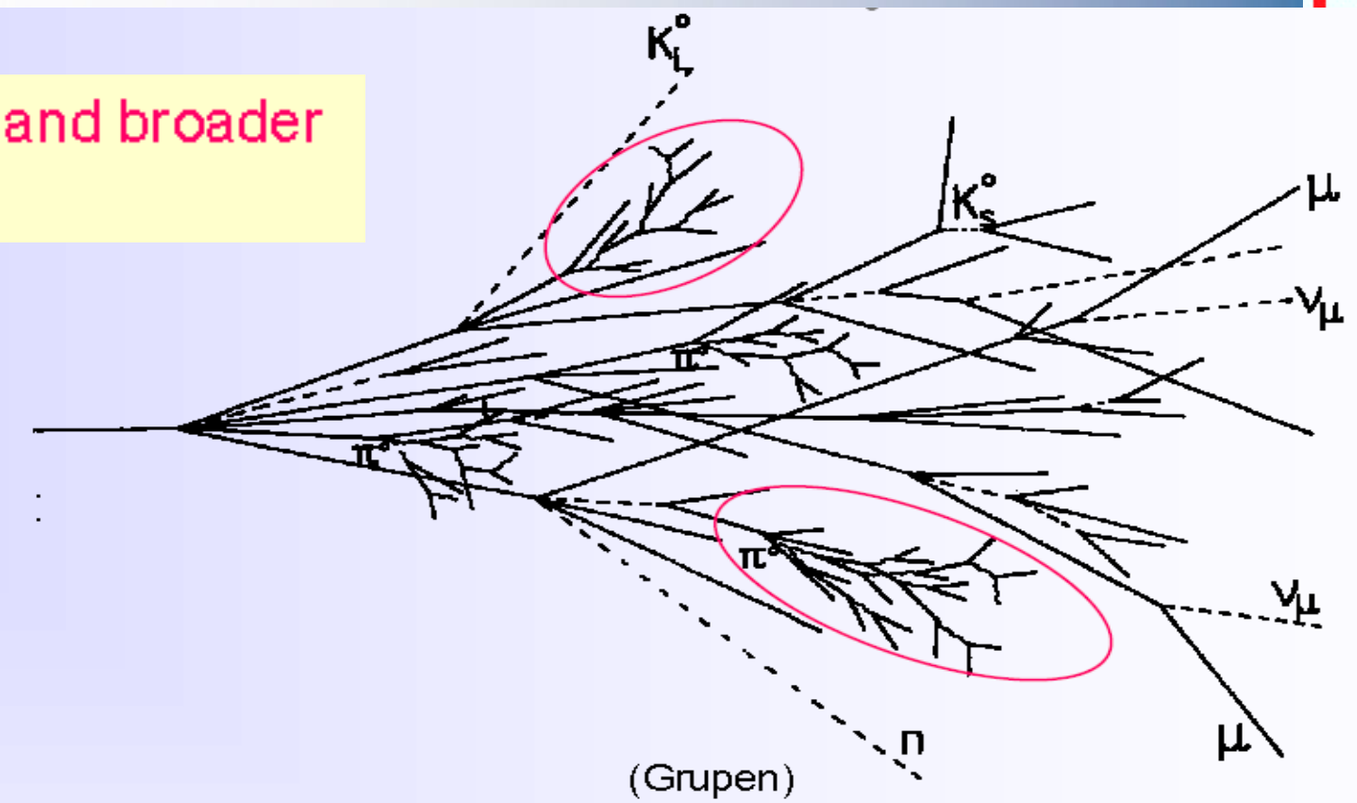
Hadronic showers are much longer and broader than electromagnetic ones !



(Grupen)

Hadronic cascades

Hadronic showers are much longer and broader than electromagnetic ones !



(Grupen)

A hadronic shower contains two components:

hadronic + **electromagnetic**

- charged hadrons p,$\pi^{\pm}$,$K^{\pm}$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ's, muons

neutral pions $\rightarrow 2\gamma$

$\rightarrow$ electromagnetic cascades

$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example $E = 100$ GeV: $n(\pi^0) \approx 18$

invisible energy $\rightarrow$ large energy fluctuations $\rightarrow$ limited energy resolution

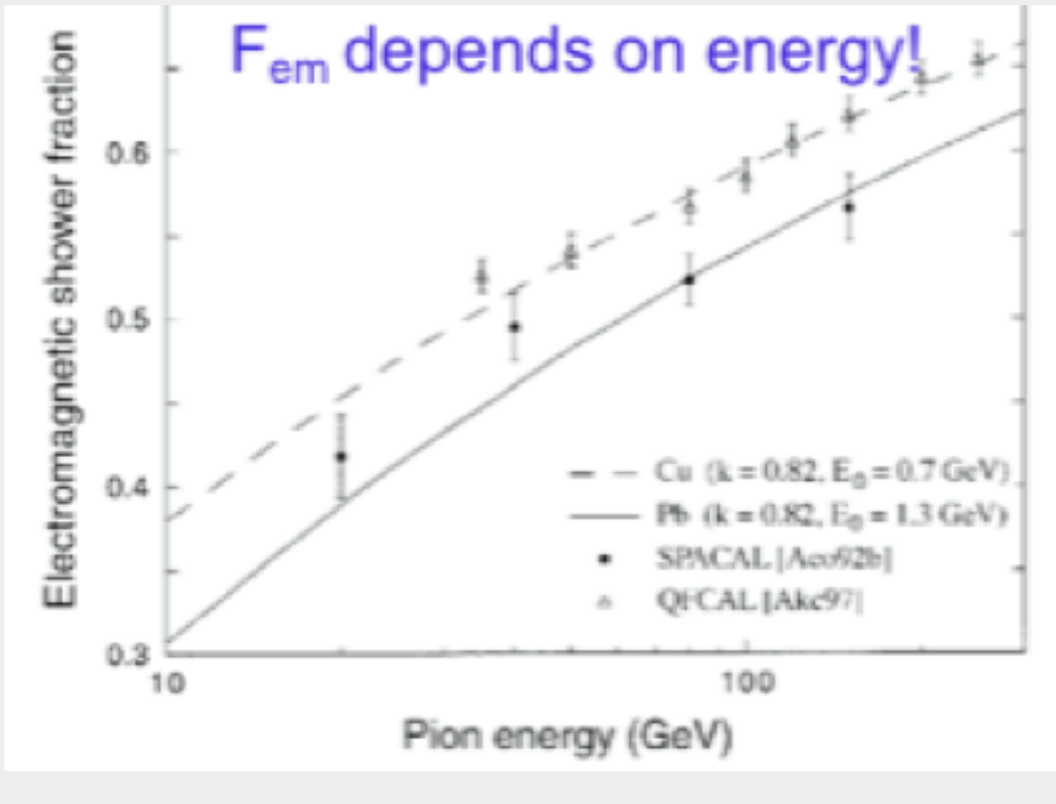
Hadron showers

Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.

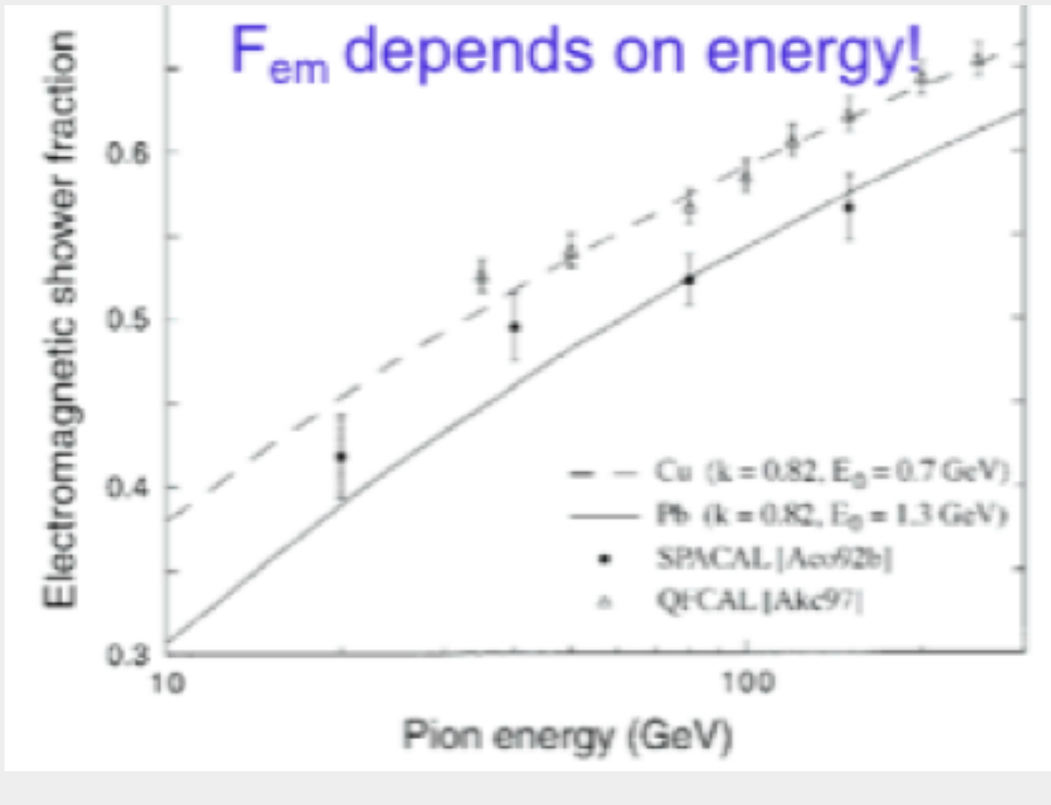
Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.



Hadron showers

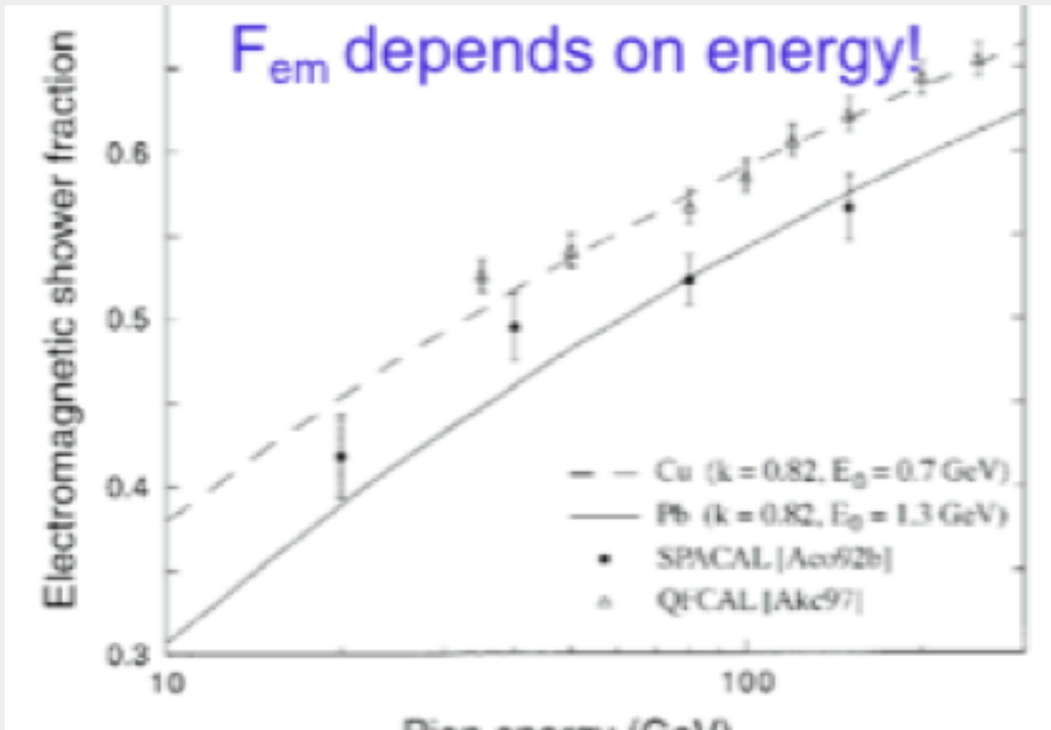
- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.



- How to obtain e/h=1 (compensation)
  - Suppress/reduce em component (use high Z absorber
  - enhance n production through fission
  - enhance response to n using active materials hydrogen rich

Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.

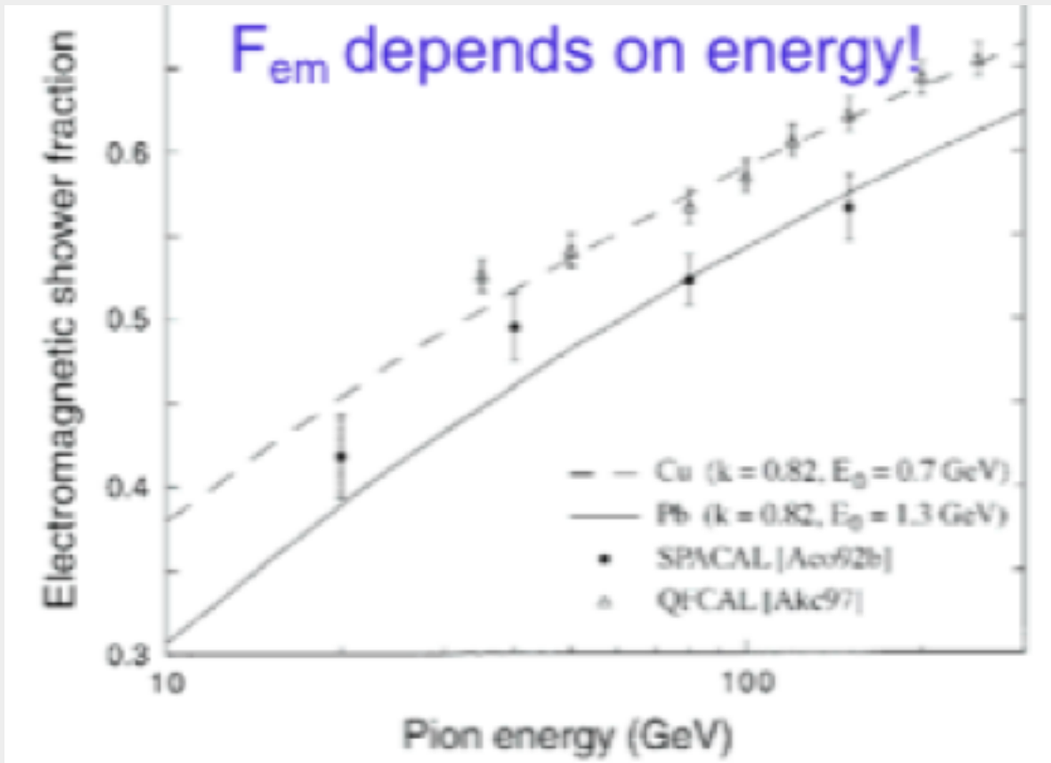


- How to obtain e/h=1 (compensation)
  - Suppress/reduce em component (use high Z absorber
  - enhance n production through fission
  - enhance response to n using active materials hydrogen rich

More about compensation : for details clic

Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.

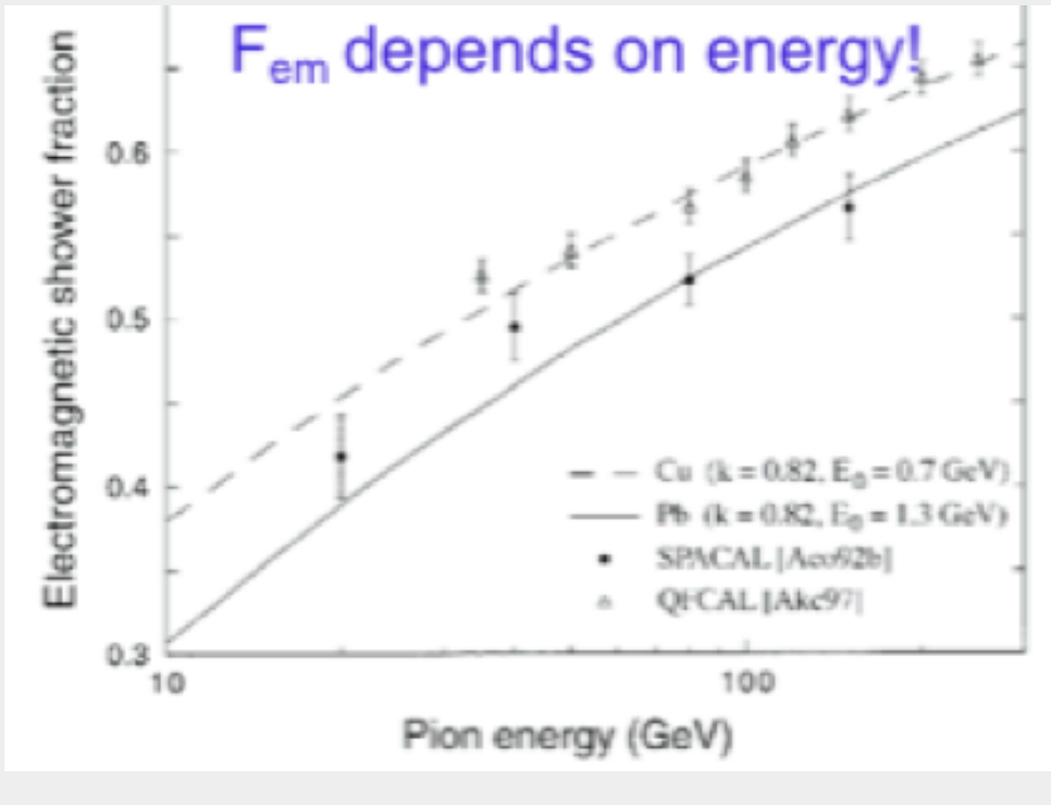


- How to obtain e/h=1 (compensation)
  - Suppress/reduce em component (use high Z absorber
  - enhance n production through fission
  - enhance response to n using active materials hydrogen rich

More about compensation : for details clic

Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.



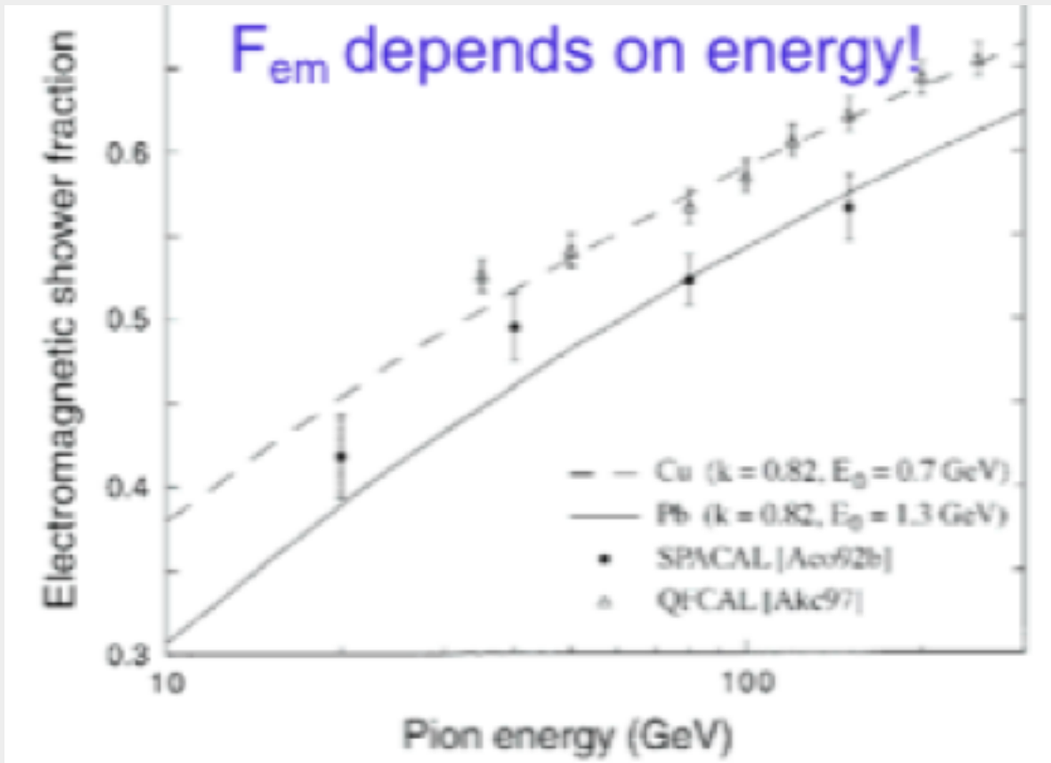
- How to obtain e/h=1 (compensation)
  - Suppress/reduce em component (use high Z absorber
  - enhance n production through fission
  - enhance response to n using active materials hydrogen rich

More about compensation : for details clic

Intrinsic hadronic resolution

Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.



- How to obtain e/h=1 (compensation)
  - Suppress/reduce em component (use high Z absorber
  - enhance n production through fission
  - enhance response to n using active materials hydrogen rich

More about compensation : for details clic

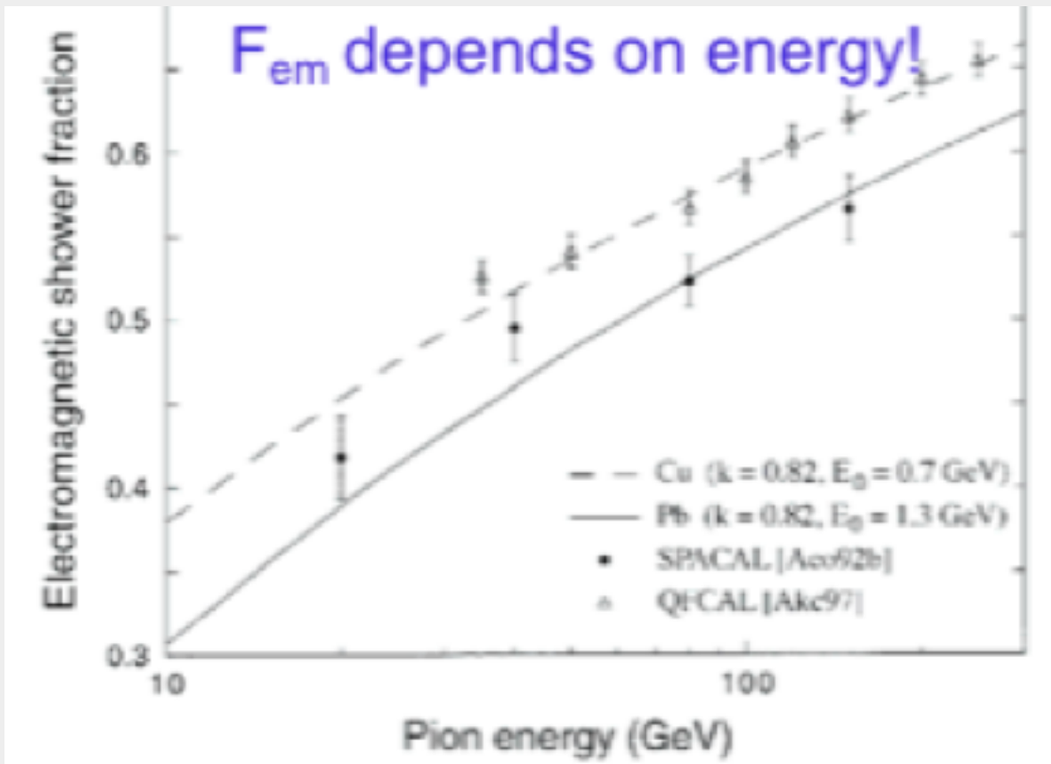
Intrinsic hadronic resolution

$$\sigma / E \sim (20 \div 40)\% / \sqrt{E(GeV)}$$

+ sampling…+…

Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.



- How to obtain e/h=1 (compensation)
  - Suppress/reduce em component (use high Z absorber
  - enhance n production through fission
  - enhance response to n using active materials hydrogen rich

More about compensation : for details clic

Intrinsic hadronic resolution

$$\sigma / E \sim (20 \div 40)\% / \sqrt{E(GeV)}$$

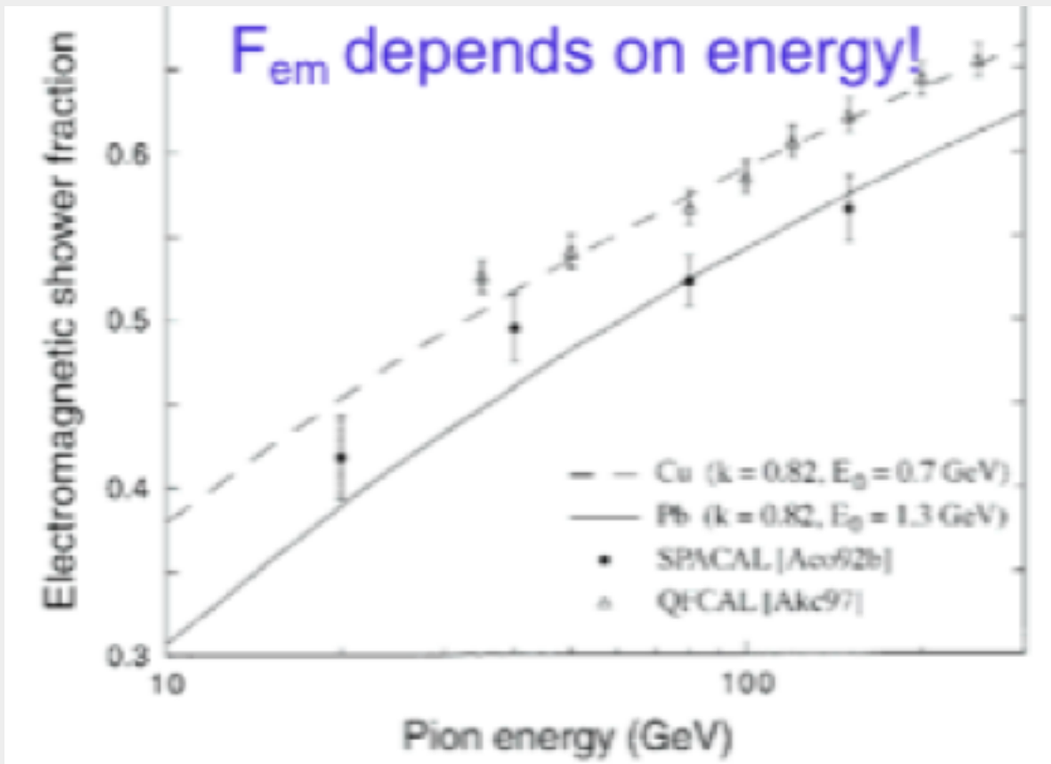
+ sampling…+…

Hadrons interaction with matter :

More of Hadron shower development : (for details clic

Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation of the fraction of energy deposited by e and h limit the measured energy resolution.
- Moreover in average this fraction (e/h) is energy dependent inducing non linearity in detector response.



- How to obtain e/h=1 (compensation)
  - Suppress/reduce em component (use high Z absorber
  - enhance n production through fission
  - enhance response to n using active materials hydrogen rich

More about compensation : for details clic

Intrinsic hadronic resolution

$$\sigma / E \sim (20 \div 40)\% / \sqrt{E(GeV)}$$

+ sampling…+…

Hadrons interaction with matter :

More of Hadron shower development : (for details clic

Clusters of energy

Clusters of energy

- Calorimeters are segmented in cells

Clusters of energy

- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the "center-of-gravity" of the deposits in the various cells

Clusters of energy

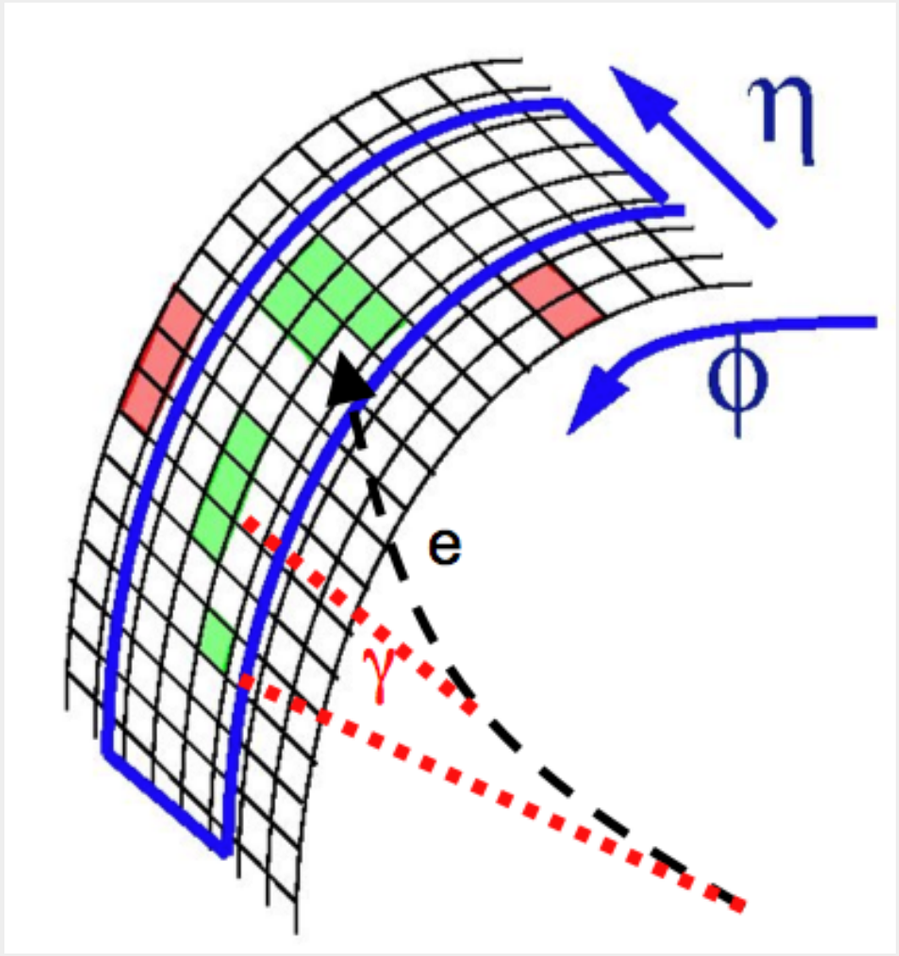
- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the "center-of-gravity" of the deposits in the various cells
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %

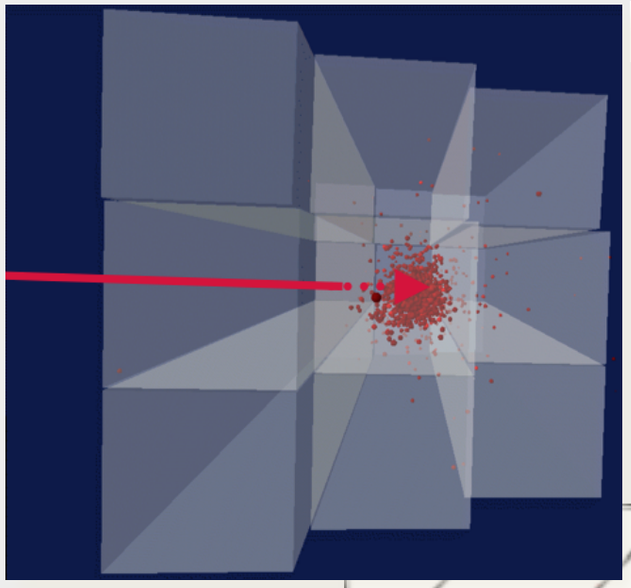
Clusters of energy

- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the "center-of-gravity" of the deposits in the various cells
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %
- So the task is :
  - identify these constituents of the clusters and reconstruct the energy they contain

Clusters of energy

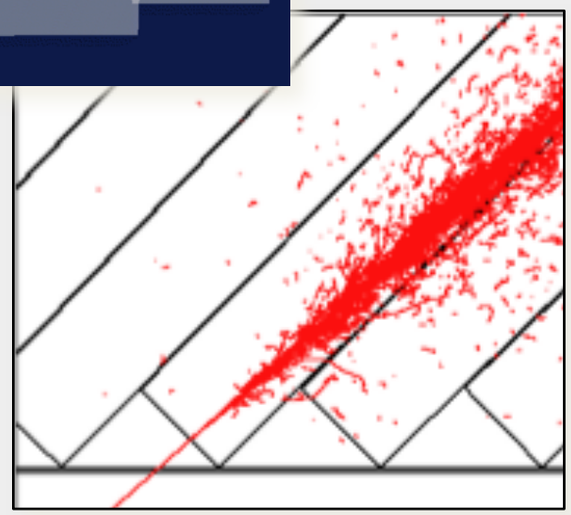
- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the "center-of-gravity" of the deposits in the various cells
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %
- So the task is :
  - identify these constituents of the clusters and reconstruct the energy they contain

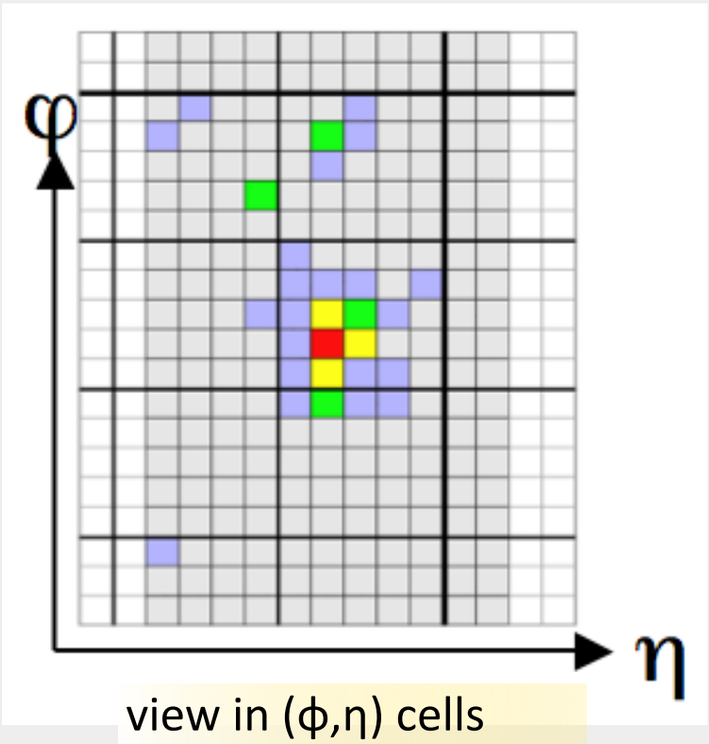




front view

side view





view in (ϕ,η) cells

Cluster Finding

- Clusters of energy in a calorimeter are due to the particles issued from the collisio
  - Clustering algorithm groups individual channel energies
  - Don't want to miss any; don't want to pick up fakes

Cluster Finding

- Clusters of energy in a calorimeter are due to the particles issued from the collisio
  - Clustering algorithm groups individual channel energies
  - Don't want to miss any; don't want to pick up fakes

Simple algorithm example

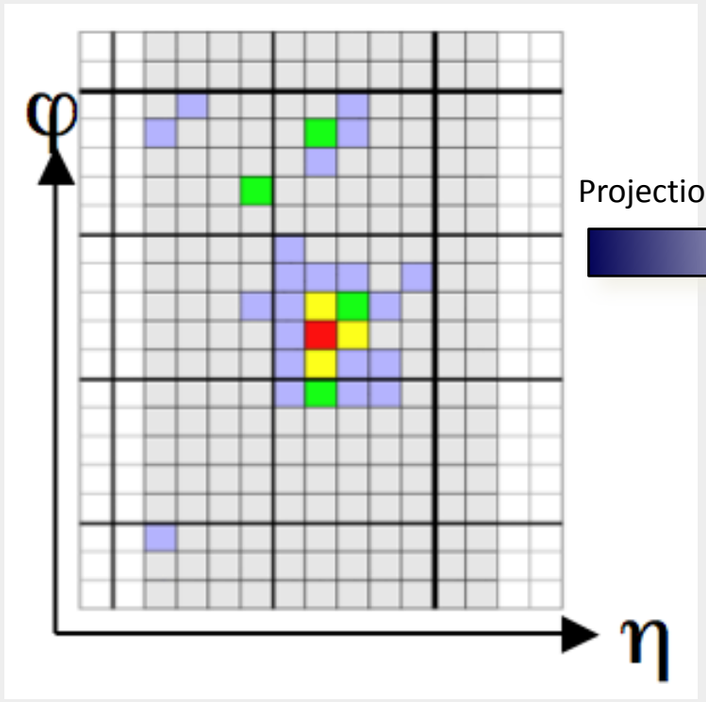
- Scan for seed crystals = local energy maximum above a defined seed threshold
- Starting from the seed position, adjacent crystals are examined, scanning first in φ and then in η
- Along each scan line, crystals are added to the cluster if
  - The crystal's energy is above the noise level (lower threshold)
  - The crystal has not been assigned to another cluster already

Cluster Finding

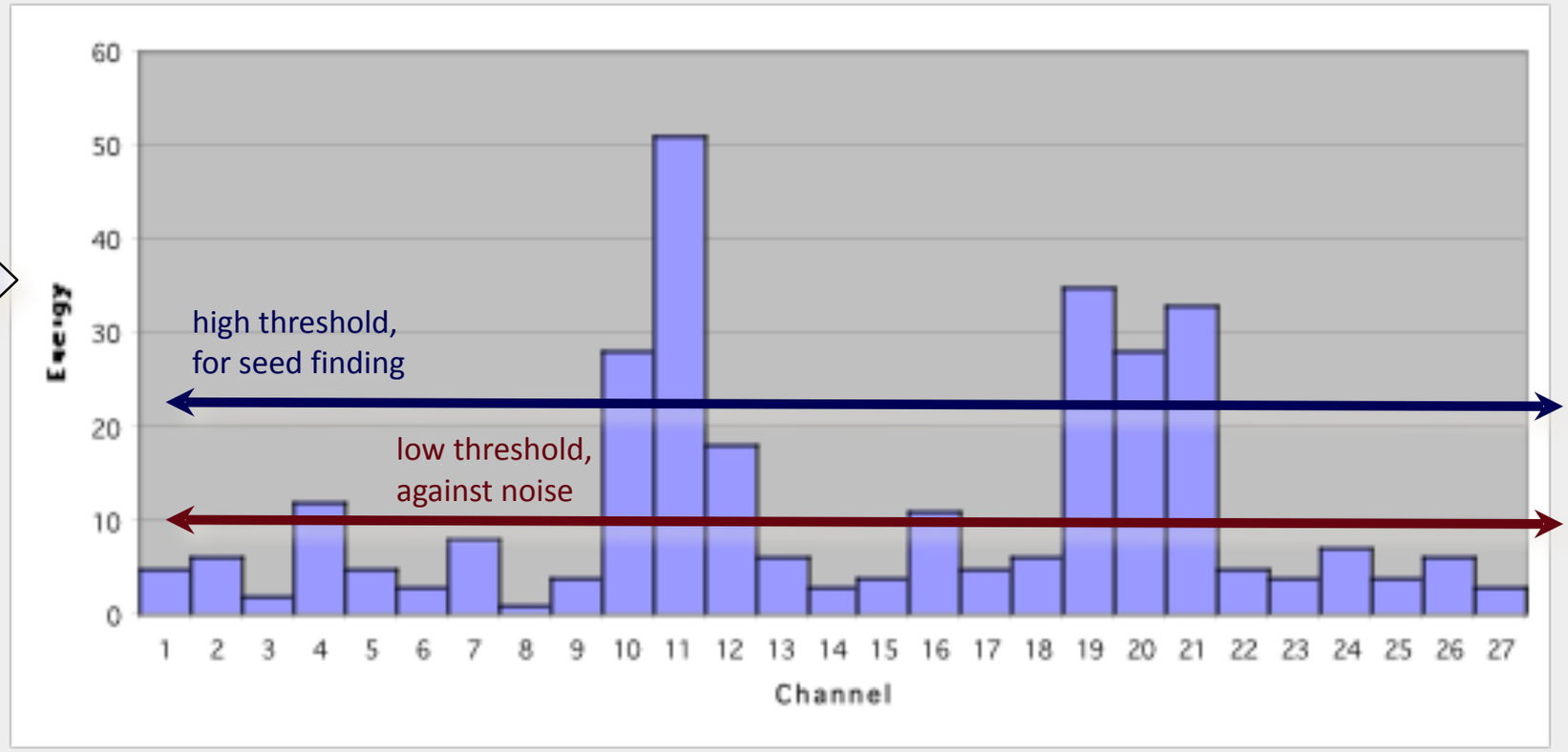
- Clusters of energy in a calorimeter are due to the particles issued from the collisio
  - Clustering algorithm groups individual channel energies
  - Don't want to miss any; don't want to pick up fakes

Simple algorithm example

- Scan for seed crystals = local energy maximum above a defined seed threshold
- Starting from the seed position, adjacent crystals are examined, scanning first in φ and then in η
- Along each scan line, crystals are added to the cluster if
  - The crystal's energy is above the noise level (lower threshold)
  - The crystal has not been assigned to another cluster already



Projection



Energy reconstruction

Energy reconstruction

Obtain energy cluster and the best possible resolution

Energy Flow technique

Energy reconstruction

Obtain energy cluster and the best possible resolution

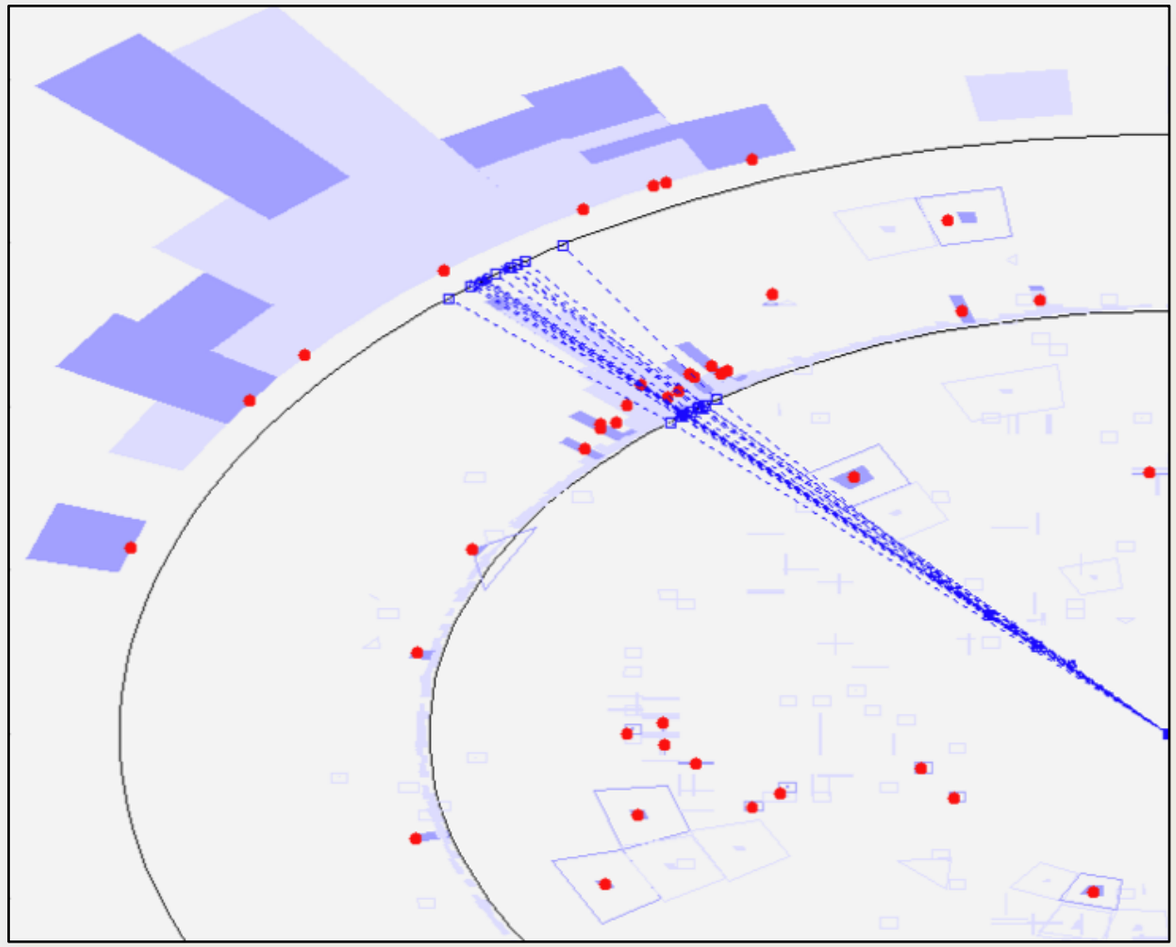
Energy Flow technique

- *Reconstruct energy deposited by charged and neutral particles in tracker and colorimeters*
- *Determine position of deposit, from direction of incident particles*
- *Be insensitive to noise and "un-wanted" (un-correlated) energy (pileup)*

Energy reconstruction

Obtain energy cluster and the best possible resolution
Energy Flow technique

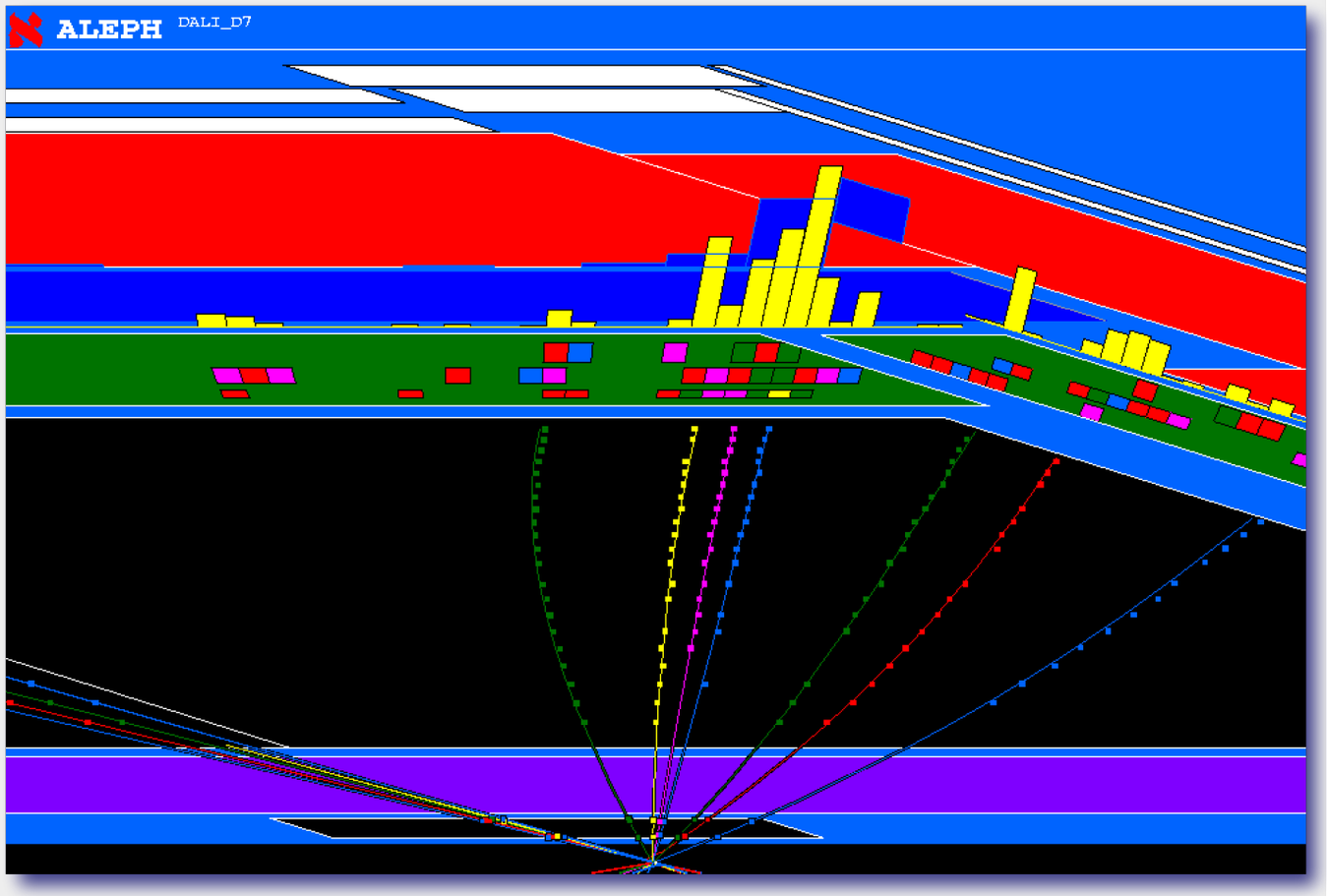
- *Reconstruct energy deposited by charged and neutral particles in tracker and colorimeters*
- *Determine position of deposit, from direction of incident particles*
- *Be insensitive to noise and "un-wanted" (un-correlated) energy (pileup)*

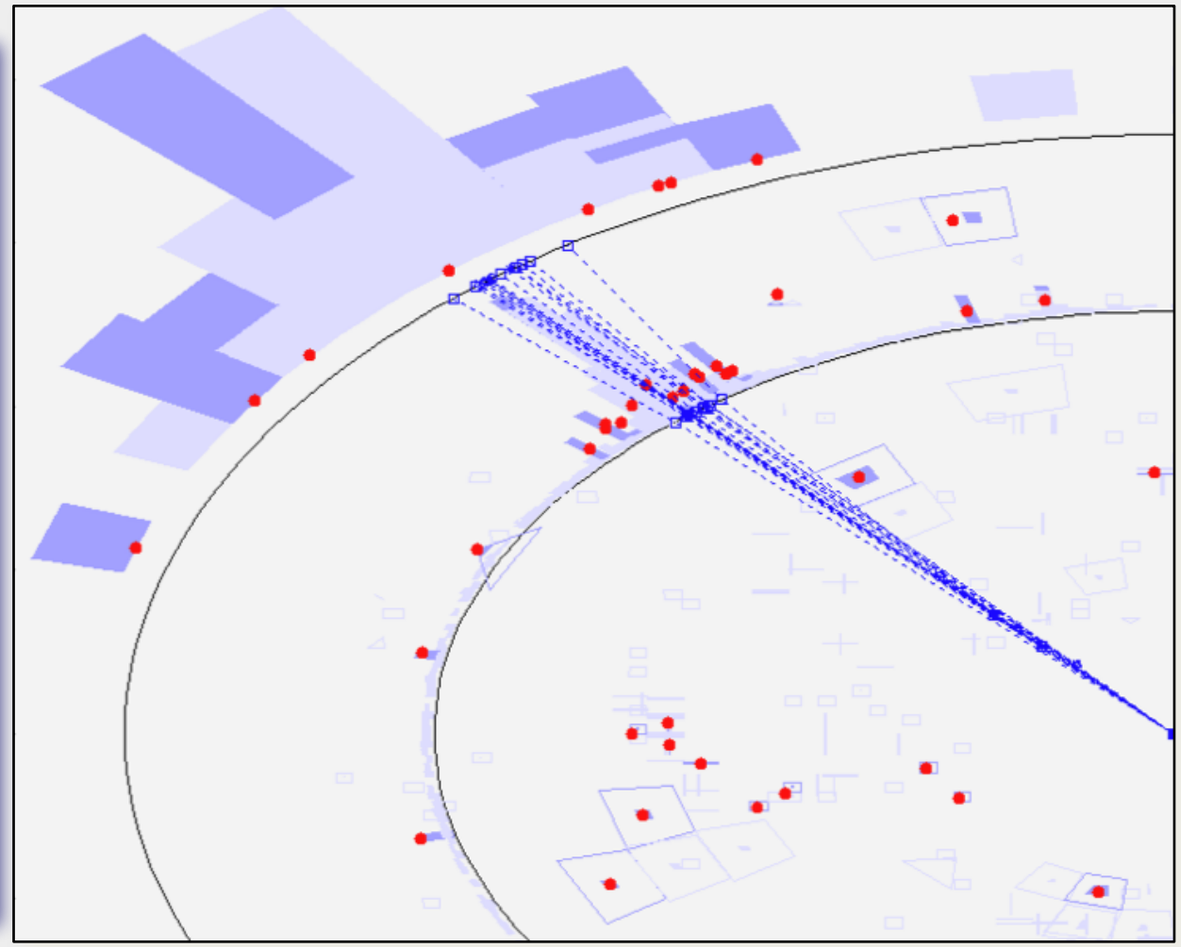


Energy reconstruction

Obtain energy cluster and the best possible resolution
Energy Flow technique

- *Reconstruct energy deposited by charged and neutral particles in tracker and colorimeters*
- *Determine position of deposit, from direction of incident particles*
- *Be insensitive to noise and "un-wanted" (un-correlated) energy (pileup)*

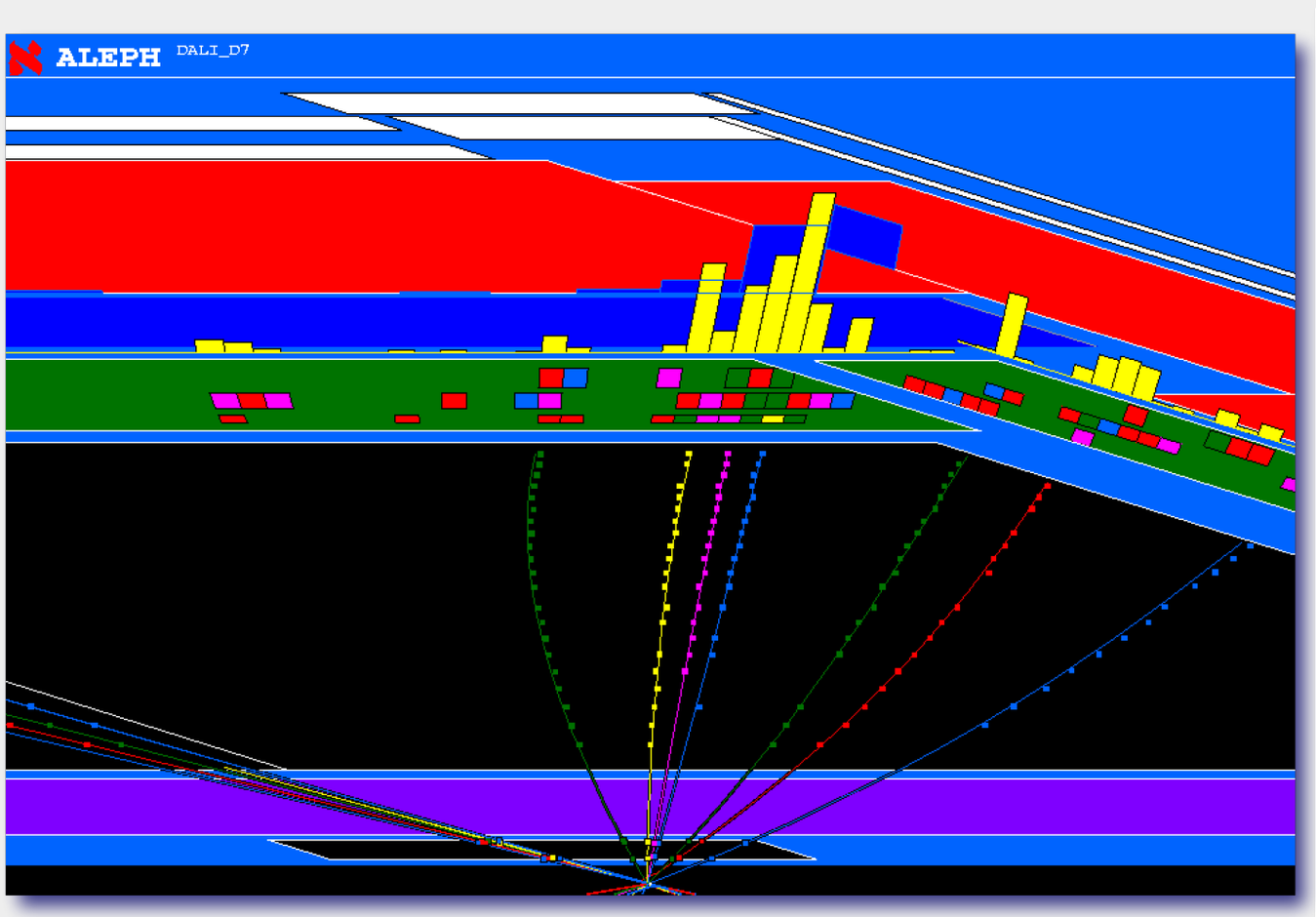


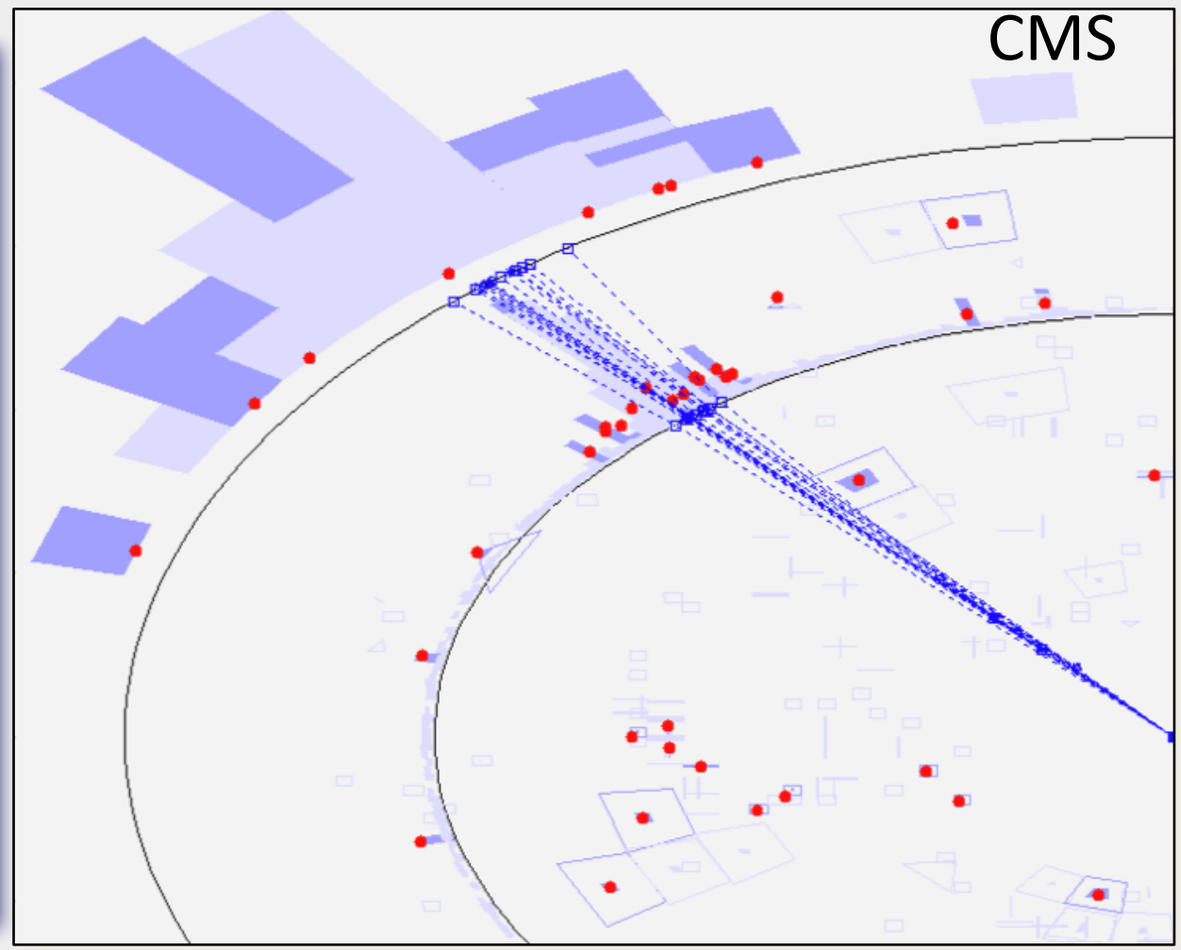


Energy reconstruction

Obtain energy cluster and the best possible resolution
Energy Flow technique

- *Reconstruct energy deposited by charged and neutral particles in tracker and colorimeters*
- *Determine position of deposit, from direction of incident particles*
- *Be insensitive to noise and "un-wanted" (un-correlated) energy (pileup)*





Calibration of calorimeter systems

- Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  - Different shower components are sampled differently
  - Shower composition changes as shower develops

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  - Different shower components are sampled differently
  - Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  - Different shower components are sampled differently
  - Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  - Different shower components are sampled differently
  - Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

Calibration of calorimeter systems

- Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)
- *Fundamental problem in sampling calorimeters*:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - *Sampling fraction changes with the shower age* (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons

Calibration of calorimeter systems

- Determine relationship between *signal* (pC, p.e.) and *energy* (GeV)
- *Fundamental problem in sampling calorimeters*:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - *Sampling fraction changes with the shower age* (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources
- Low-level, stable radioactive background

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources
- Low-level, stable radioactive background
- Cell-weighting to optimize resolution, uniformity

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources
- Low-level, stable radioactive background
- Cell-weighting to optimize resolution, uniformity
- In situ physics:

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources
- Low-level, stable radioactive background
- Cell-weighting to optimize resolution, uniformity
- In situ physics:
  - Electromagnetic particles :

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:

  Different shower components are sampled differently

  Shower composition changes as shower develops

  - Sampling fraction changes with the shower age (also E dependent)
  - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources
- Low-level, stable radioactive background
- Cell-weighting to optimize resolution, uniformity
- In situ physics:

  - Electromagnetic particles :
  - Hadronic particles :

Calibration of calorimeter systems

- Determine relationship between signal (pC, p.e.) and energy (GeV)
- Fundamental problem in sampling calorimeters:
  Different shower components are sampled differently
  Shower composition changes as shower develops
    - Sampling fraction changes with the shower age (also E dependent)
    - How to intercalibrate the sections of a longitudinally segmented calorimeter? (quite a challenge...)

Calibration Techniques:

- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided 60 Co sources
- Low-level, stable radioactive background
- Cell-weighting to optimize resolution, uniformity
- In situ physics:
  - Electromagnetic particles : $Z, J/\psi \to e^+e^-;\ \pi^0, \eta \to \gamma\gamma$
  - Hadronic particles : $W, Z \to q\bar{q};\ 'Z, \gamma - jet\ balancing'$

The calibration

From single channel electrical signal to $E_{e,\gamma}$

(The case of CMS)

TBD

E_i

$$E_{e,\gamma} = G \times \mathcal{F} \times \sum_{i}^{\text{Cluster}} c_i \times A_i,$$

absolute energy scale

algorithmic corrections

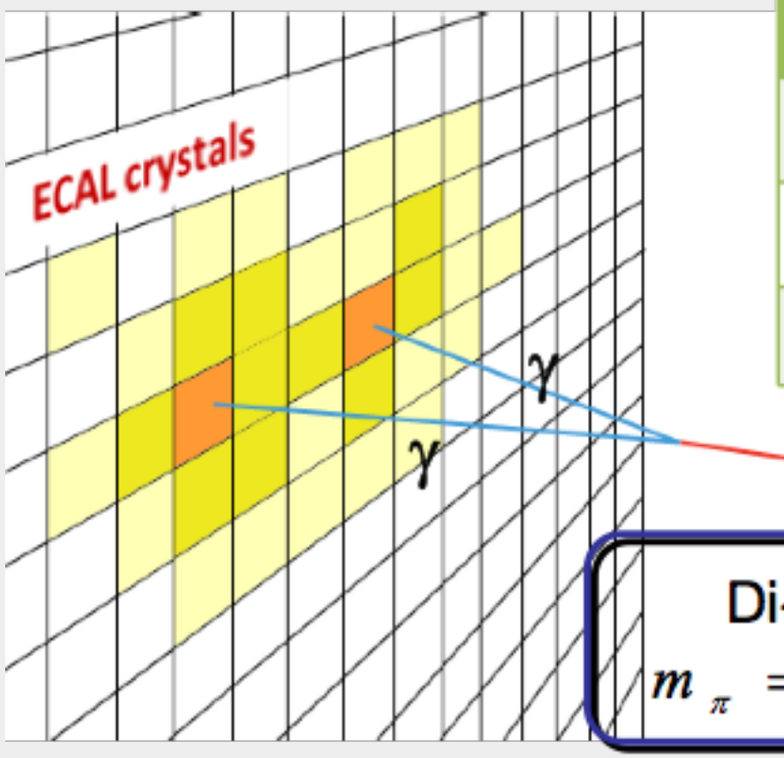
amplitudes

inter-calibration constants

(particle type, momentum, position & clustering algo)

Account for energy losses due to containment variations

π° calibration



Pros
High Statistics
xl by xl inter-calibration
Energy scale calibration

Cons
Reco of low energy γ
High energy γ overlap
Sizeable background

Di-photon invariant mass

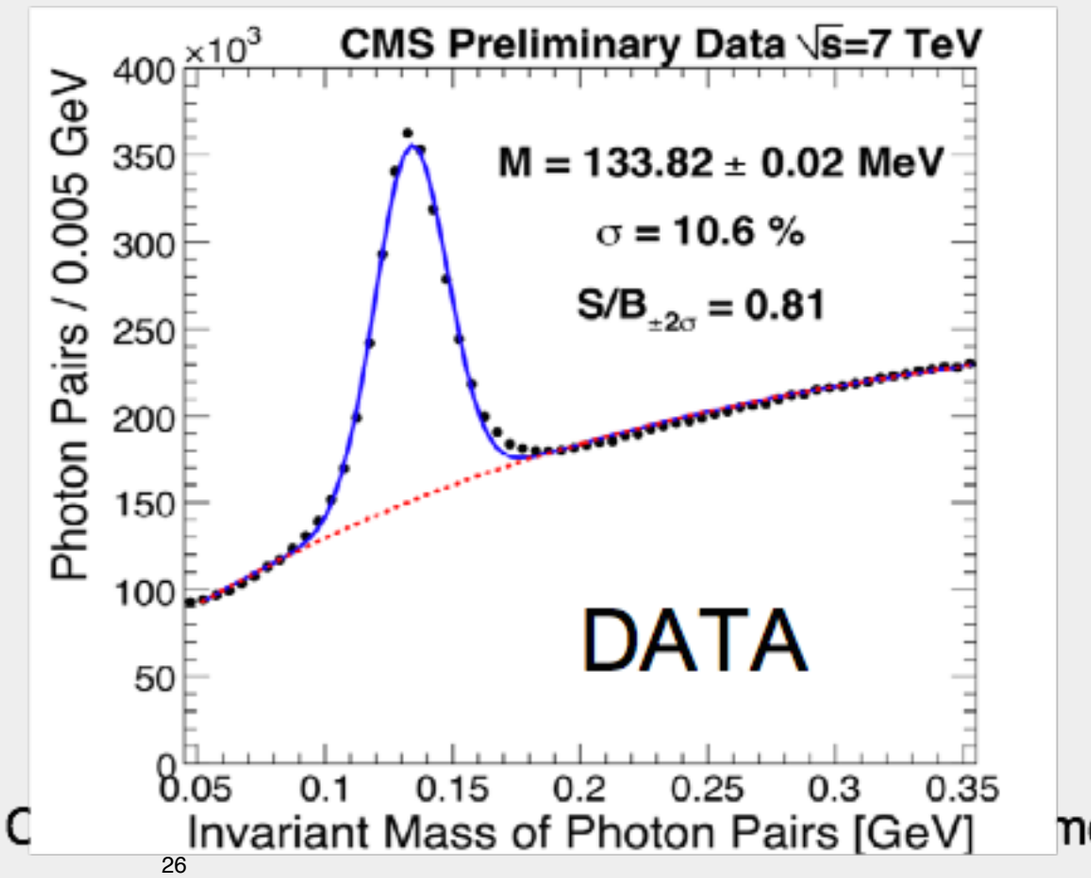
$$m_{\pi} = \sqrt{2 E_1 E_2 (1 - \cos \vartheta)}$$

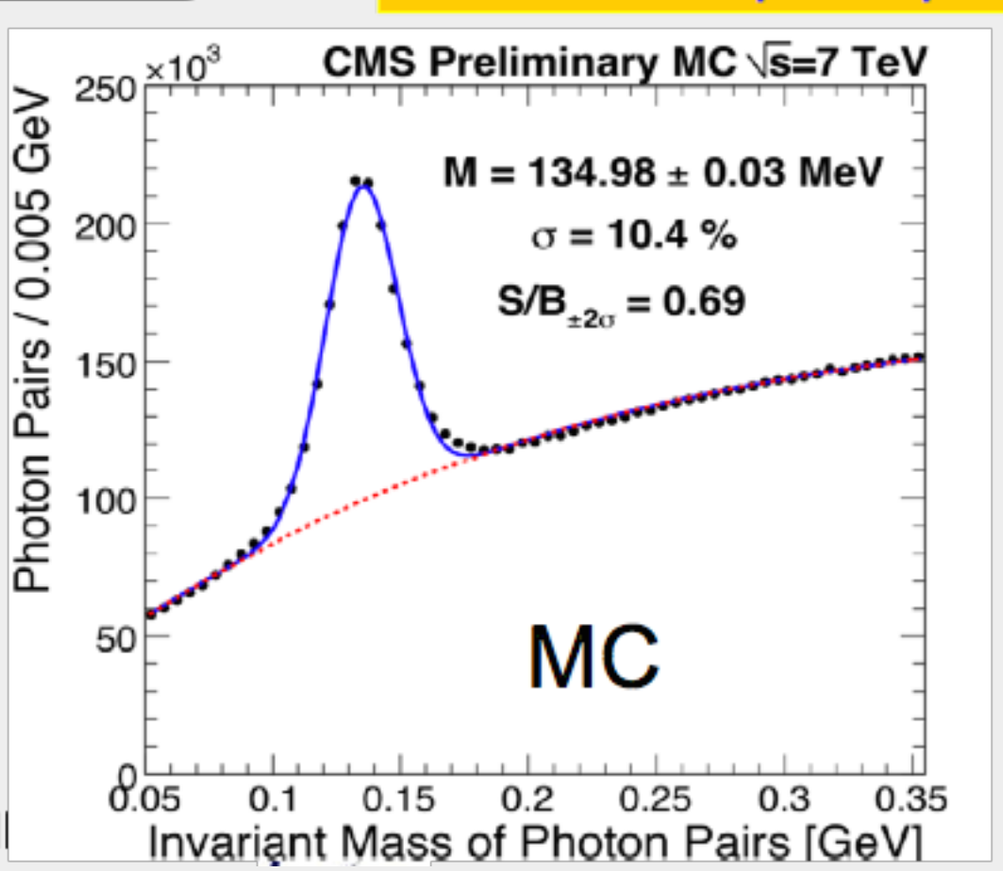
Calibrated photon energy

⇓

π^0 mass peak at right position

Minimum peak spread

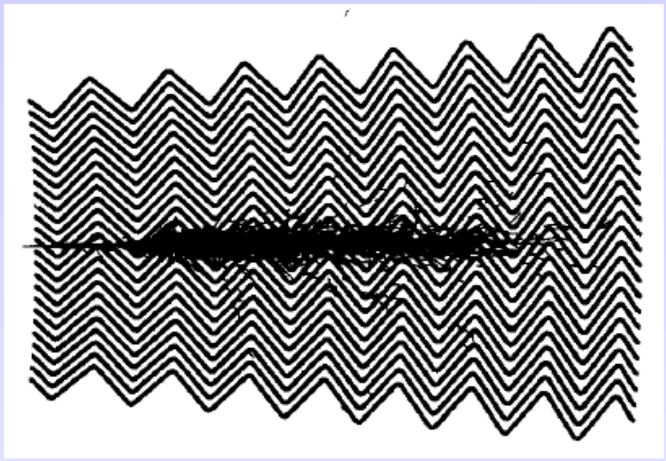




Sampling calorimeters: ATLAS ECAL

ATLAS electromagnetic Calorimeter

Accordion geometry absorbers immersed in Liquid Argon

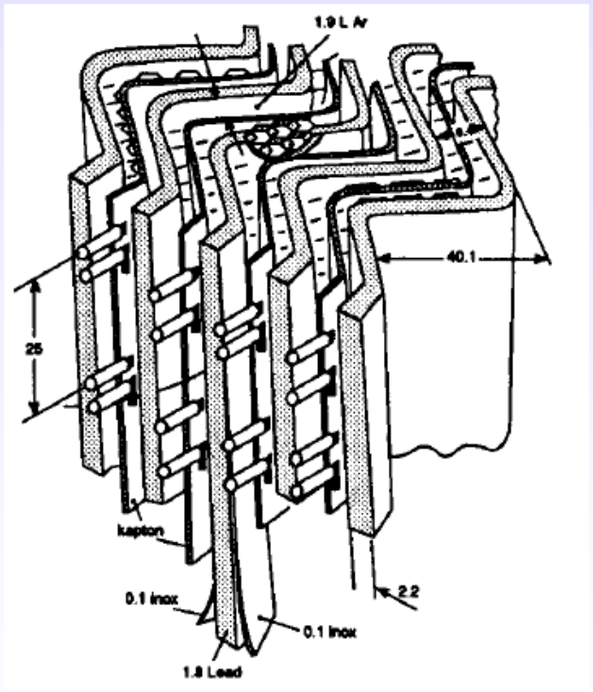


Liquid Argon (90K)

+ lead-steal absorbers (1-2 mm)
+ multilayer copper-polyimide readout boards

→ Ionization chamber.

1 GeV E-deposit → 5 x10^6 e^-



- Accordion geometry minimizes dead zones.
- Liquid Ar is intrinsically radiation hard.
- Readout board allows fine segmentation (azimuth, pseudo-rapidity and longitudinal) acc. to physics needs

Test beam results $\sigma(E)/E = 9.24\%/\sqrt{E} \oplus 0.23\%$

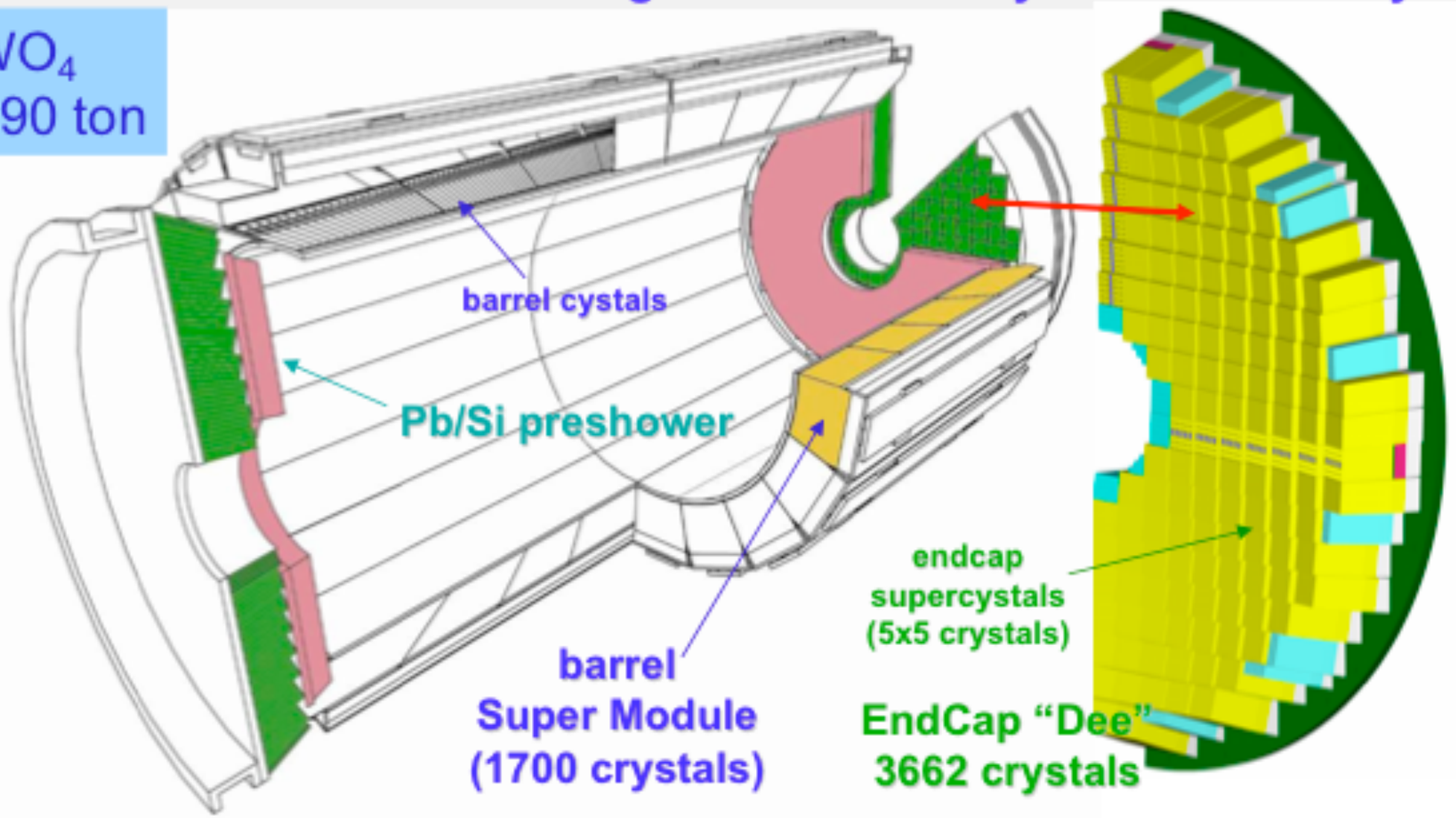
Spatial resolution ≈ 5 mm / √E

CMS ECAL

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m^3, 90 ton

Previous Crystal calorimeters: max $1m^3$



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2x2x23cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3x3x22cm^3$)

More about CMS EM calorimeter : for details clic

Atlas and CMS EM calorimetry

Atlas and CMS EM calorimetry

Atlas and CMS made different choices:

- *sampling calorimeter allow to have redundant measurement of "photon" angle*
- *homogenous calorimeter with very low stochastic term aims to excellent energy resolution, the measure of the "photon" angle relies on vertex reconstruction from tracking.*

Atlas and CMS EM calorimetry

Atlas and CMS made different choices:

- *sampling calorimeter allow to have redundant measurement of "photon" angle*
- *homogenous calorimeter with very low stochastic term aims to excellent energy resolution, the measure of the "photon" angle relies on vertex reconstruction from tracking.*

CMS

- Compact
- Excellent energy resolution
- Fast
- High granularity
- Radiation resistance
- E range MIP → TeV

•Homogeneous calorimeter made of 75000 $PbW0_4$ scintillating crystals + PS FW

Atlas

- Good energy resolution
- Fast
- High granularity
- Longitudinally segmented
- Radiation resistance
- E range MIP → TeV

•Sampling LAr-Pb, 3 Longitudinal layers + PS

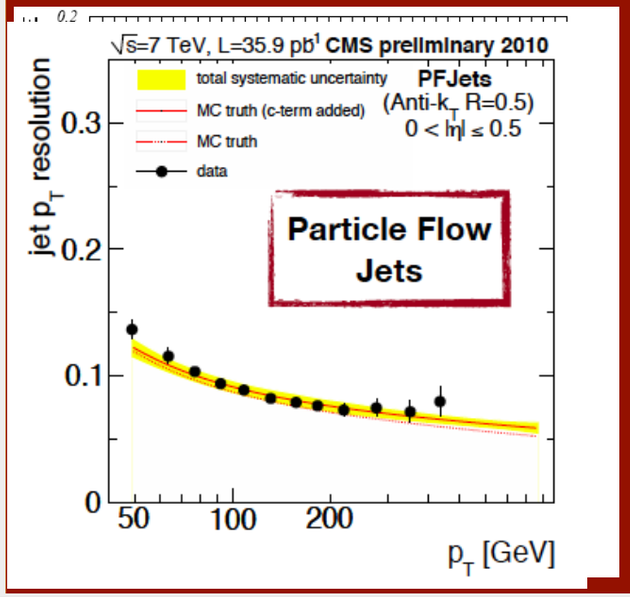
CMS/Atlas Hadron Calorimeters

5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

14 mm iron / 3 mm scint.
sci. fibres, read out by phototubes

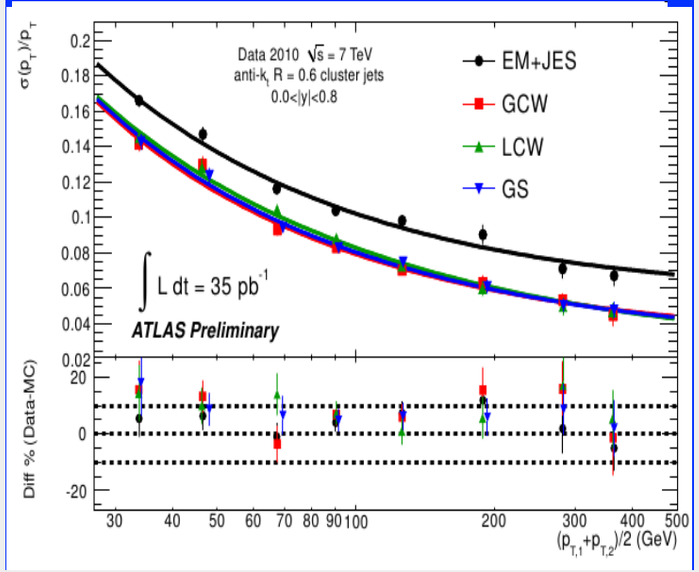
CMS

- HCAL only
  $\sigma/E = (93.8)\%/\sqrt{E} \oplus (7.4)\%$
- ECAL+HCAL
  $\sigma/E = (82.6)\%/\sqrt{E} \oplus (4.5)\%$

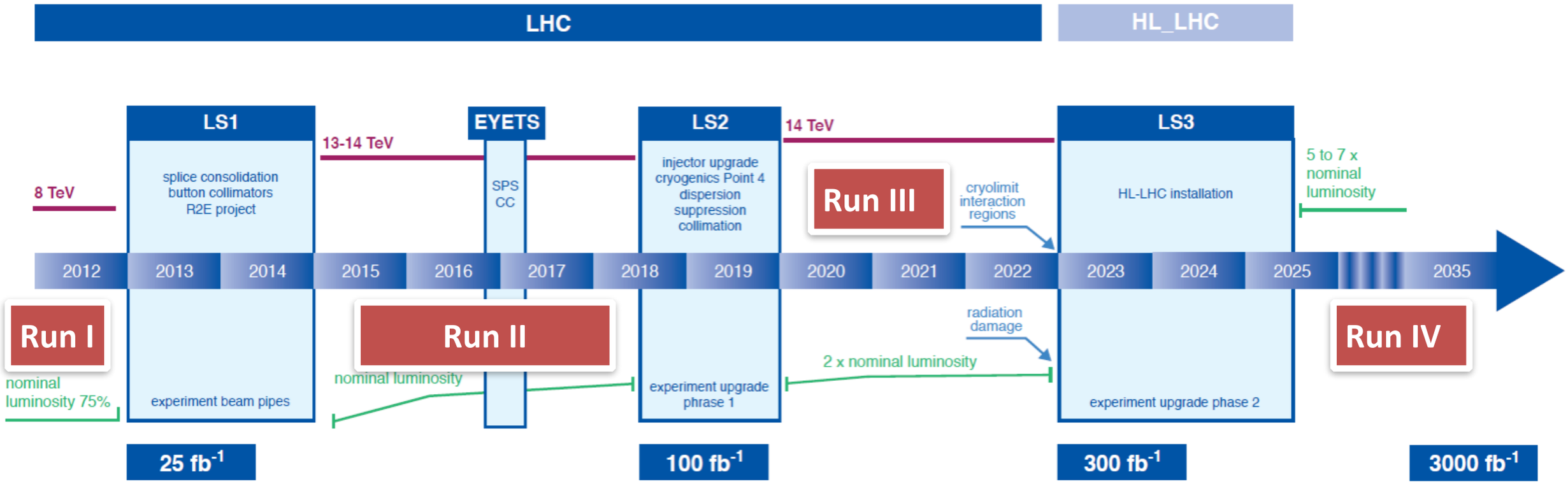


ATLAS

- Standalone tile calorimeter
  $\sigma/E = (52.9)\%/\sqrt{E} \oplus (5.7)\%$
- Improved resolution using full calorimetric system (ECAL+HCAL)
  $\sigma/E = (42)\%/\sqrt{E} \oplus (2)\%$



LHC / HL-LHC Plan



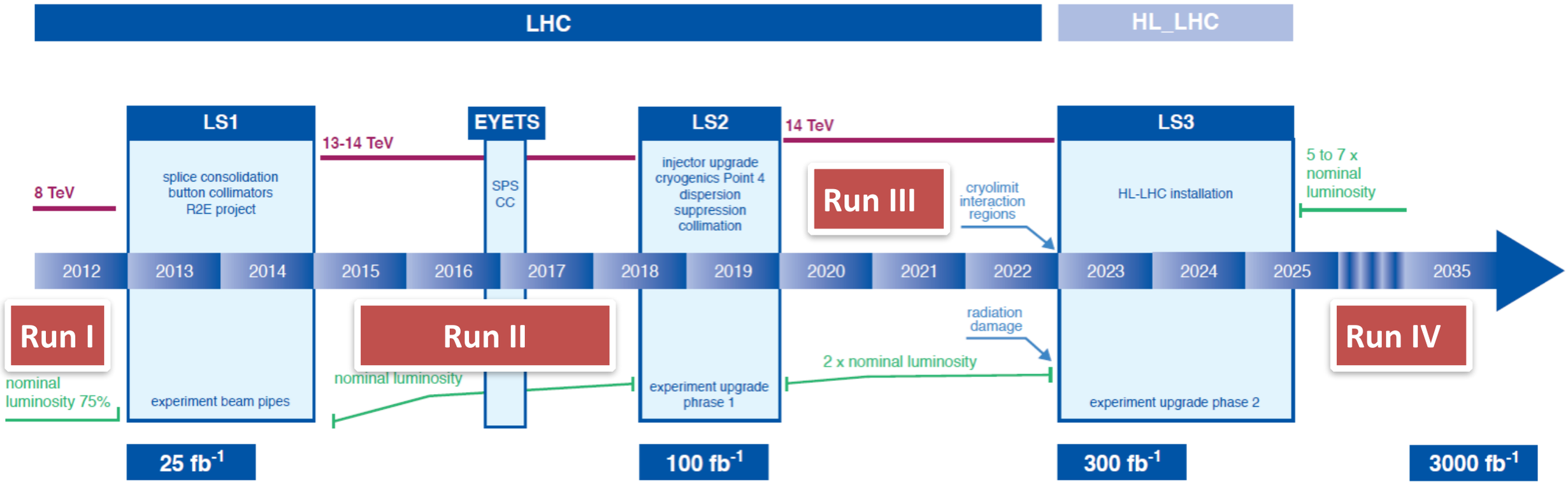
0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

1.7-2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

~5(7.5!) 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~140 - 200

LHC / HL-LHC Plan



0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

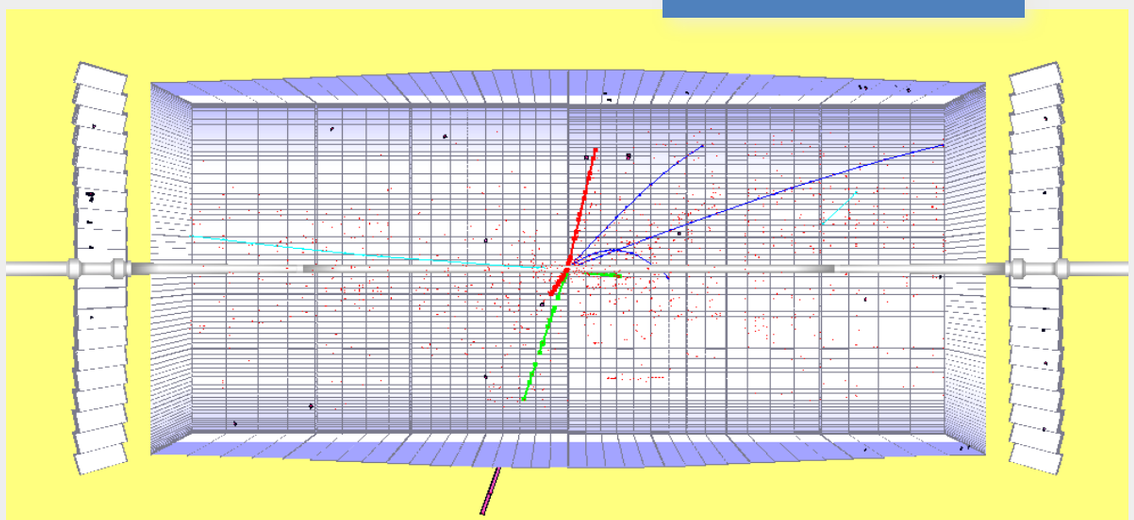
50 ⇒ 25 ns

1.7-2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

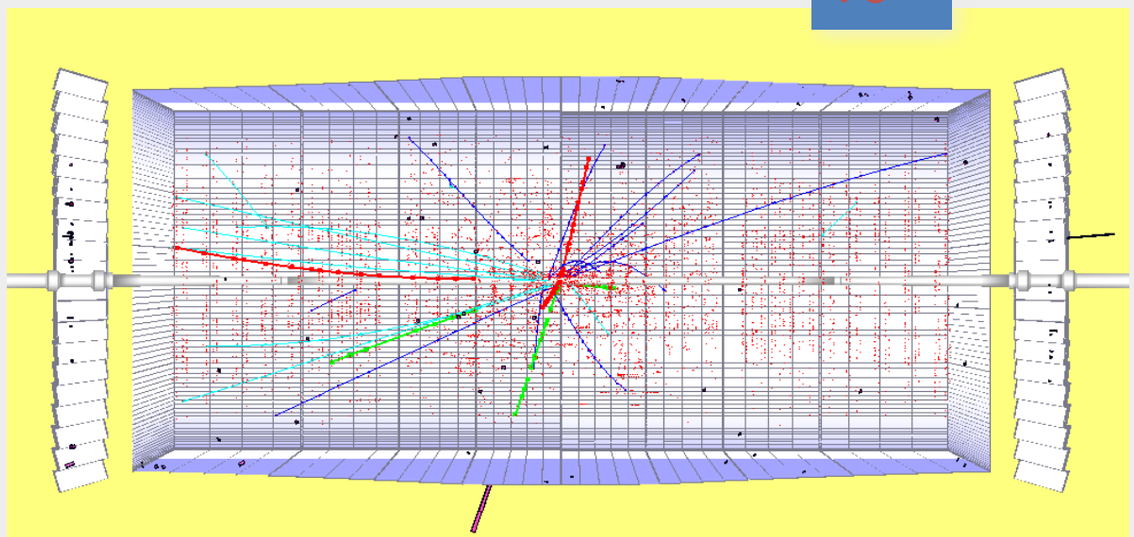
~5(7.5!) 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~140 - 200

Detector occupancy
The challenge from simulation ….

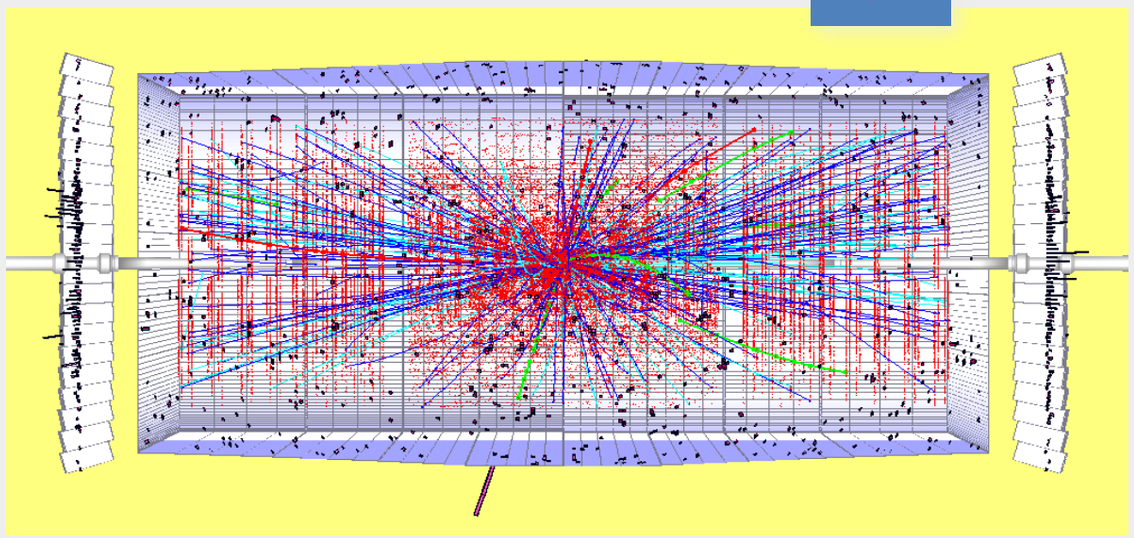
10^{32} cm^{-2} s^{-1}



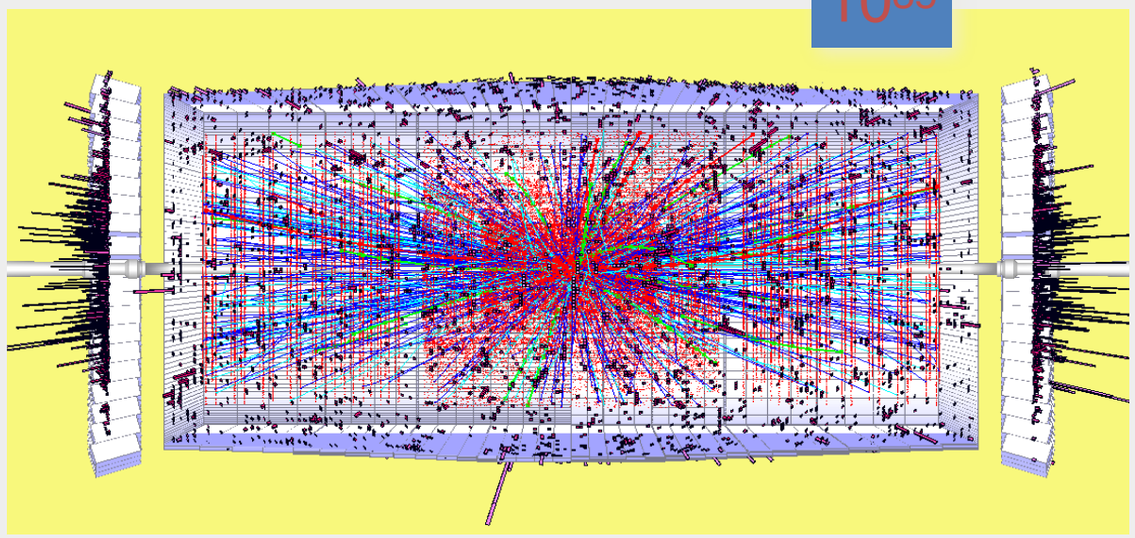
10^{33}



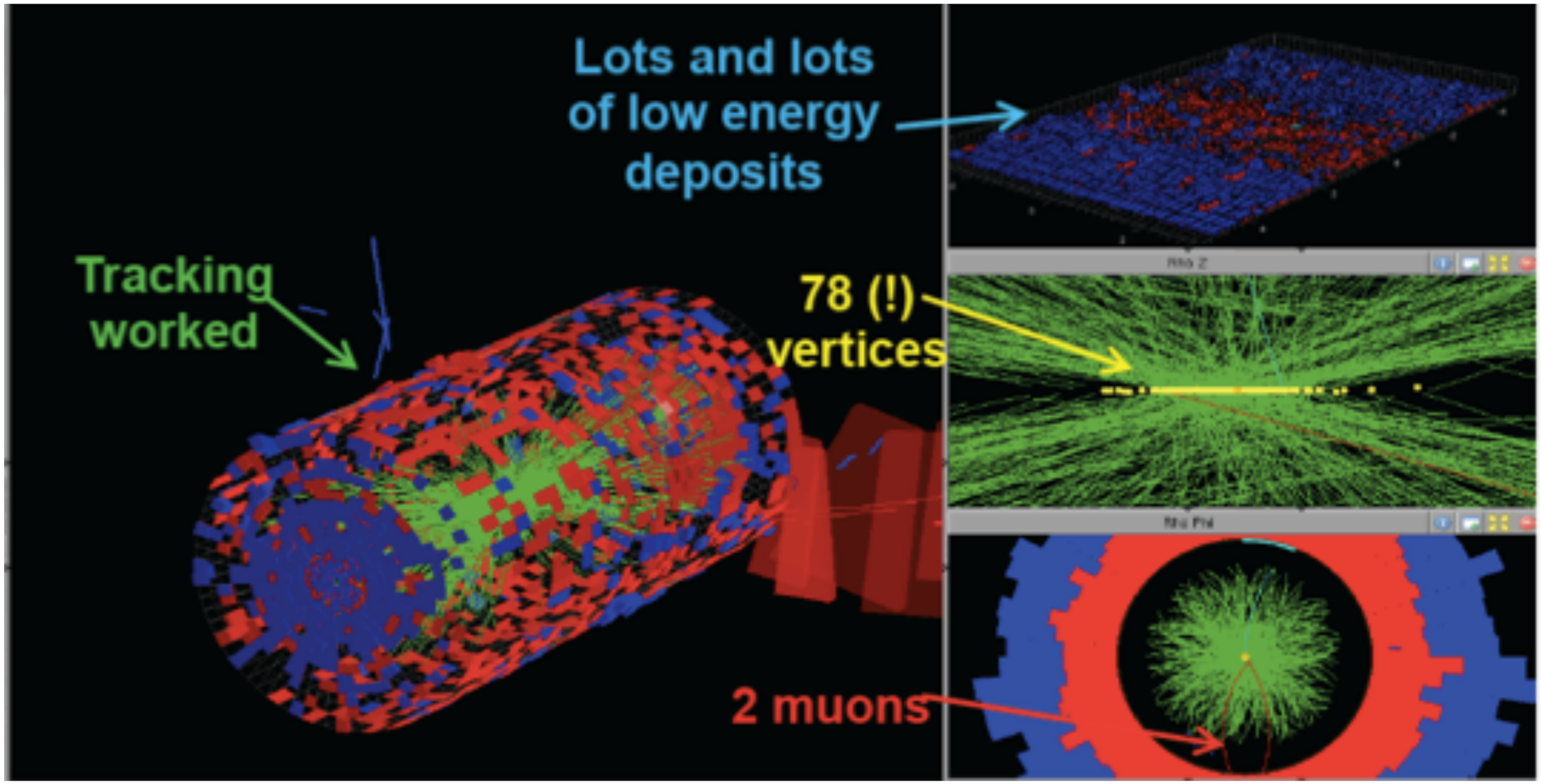
10^{34}



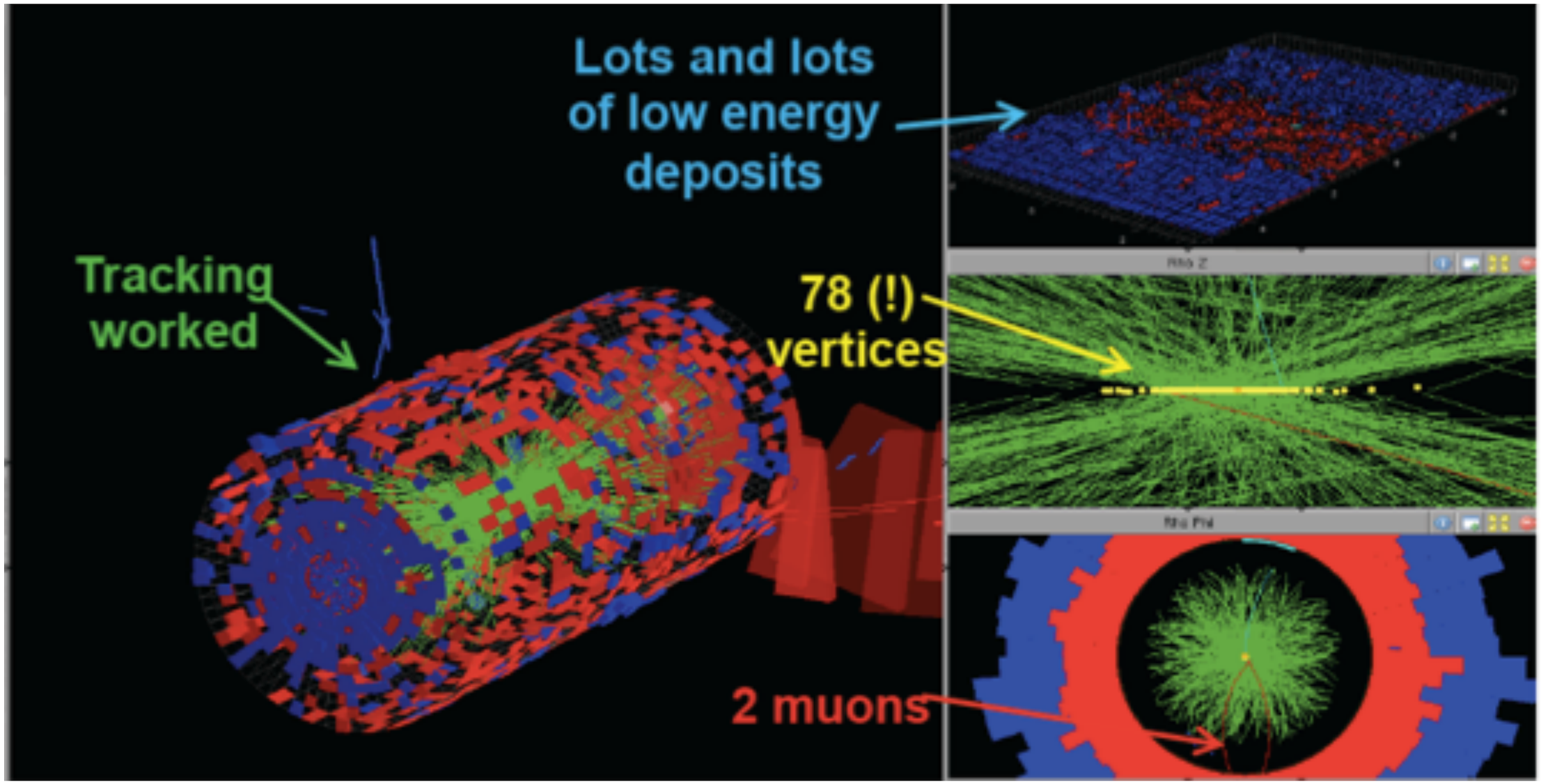
10^{35}



… and reality


Lots and lots
of low energy
deposits
Tracking
worked
78 (!)
vertices
2 muons

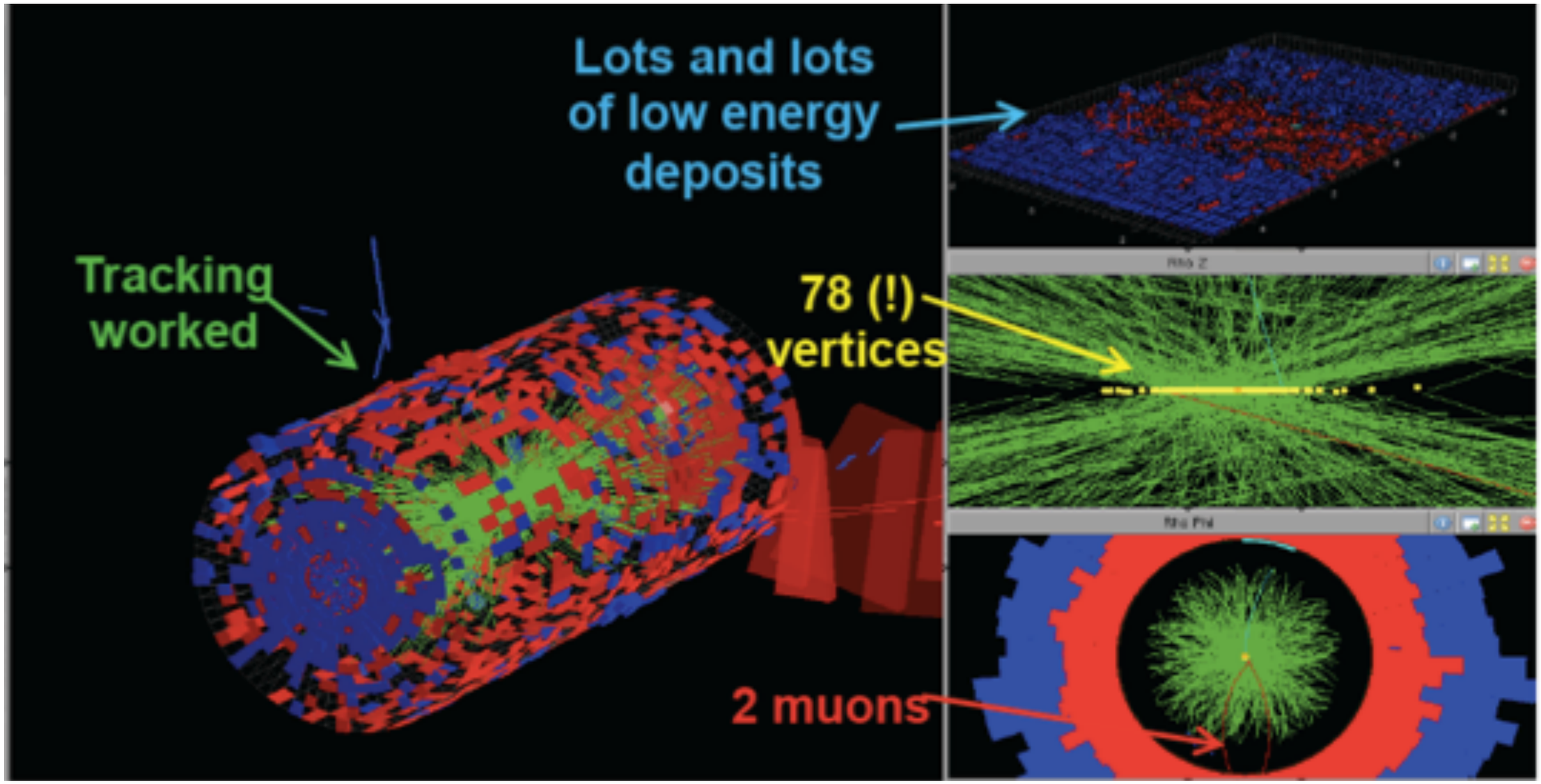
… and reality



Extreme conditions for:

- *radiation*
- *pileup*
- *Trigger / DAQ*
- *Data handling*

… and reality



Extreme conditions for:

- *radiation*
- *pileup*
- *Trigger / DAQ*
- *Data handling*

Take advantage of all LHC downtimes to improve, upgrade and repair detector!

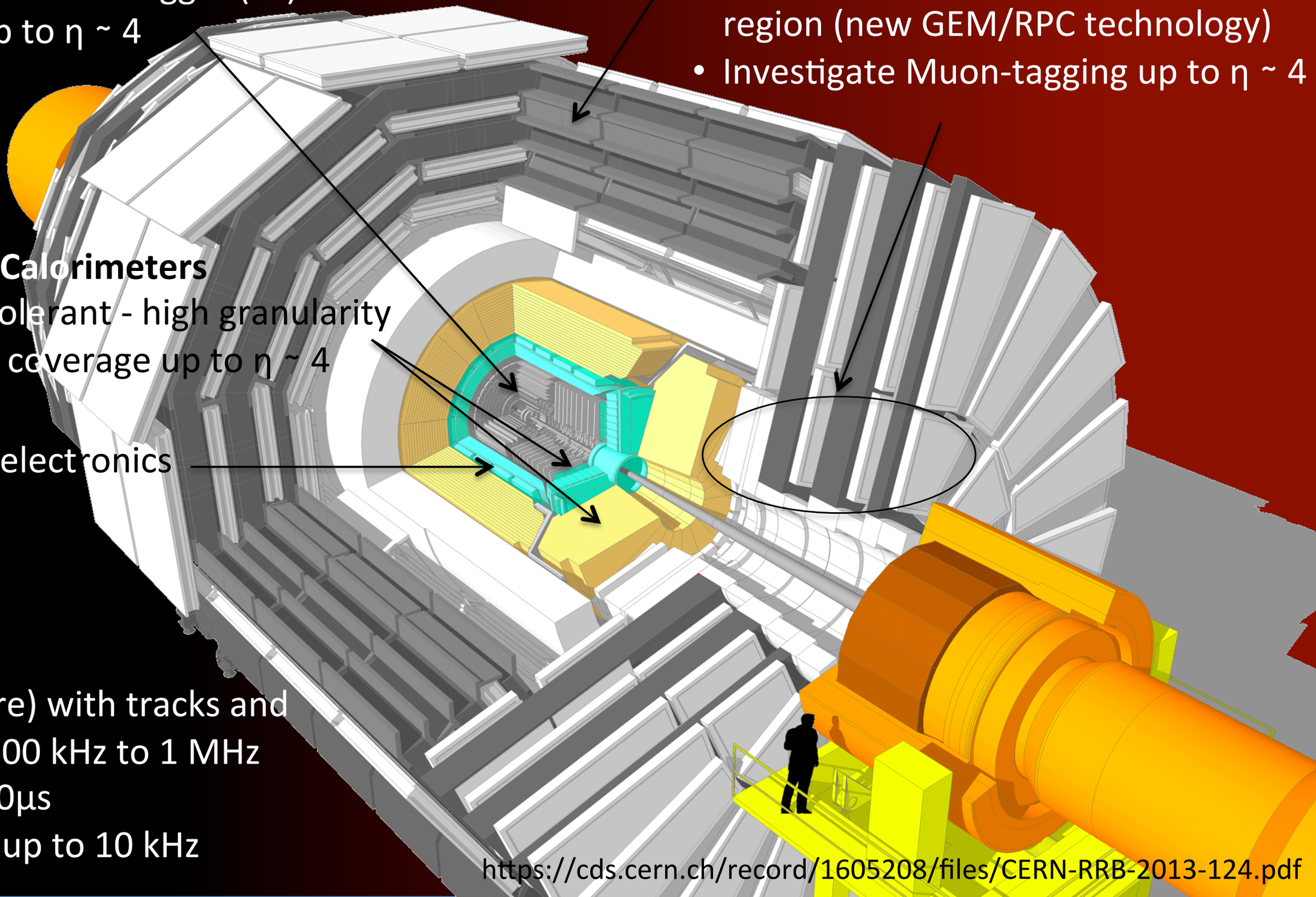
CMS Upgrades for HL-LHC

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 4

New Endcap Calorimeters
- Radiation tolerant - high granularity
- Investigate coverage up to η ~ 4

Barrel ECAL
- Replace FE electronics



Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
- Latency ≥ 10μs
- HLT output up to 10 kHz

https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

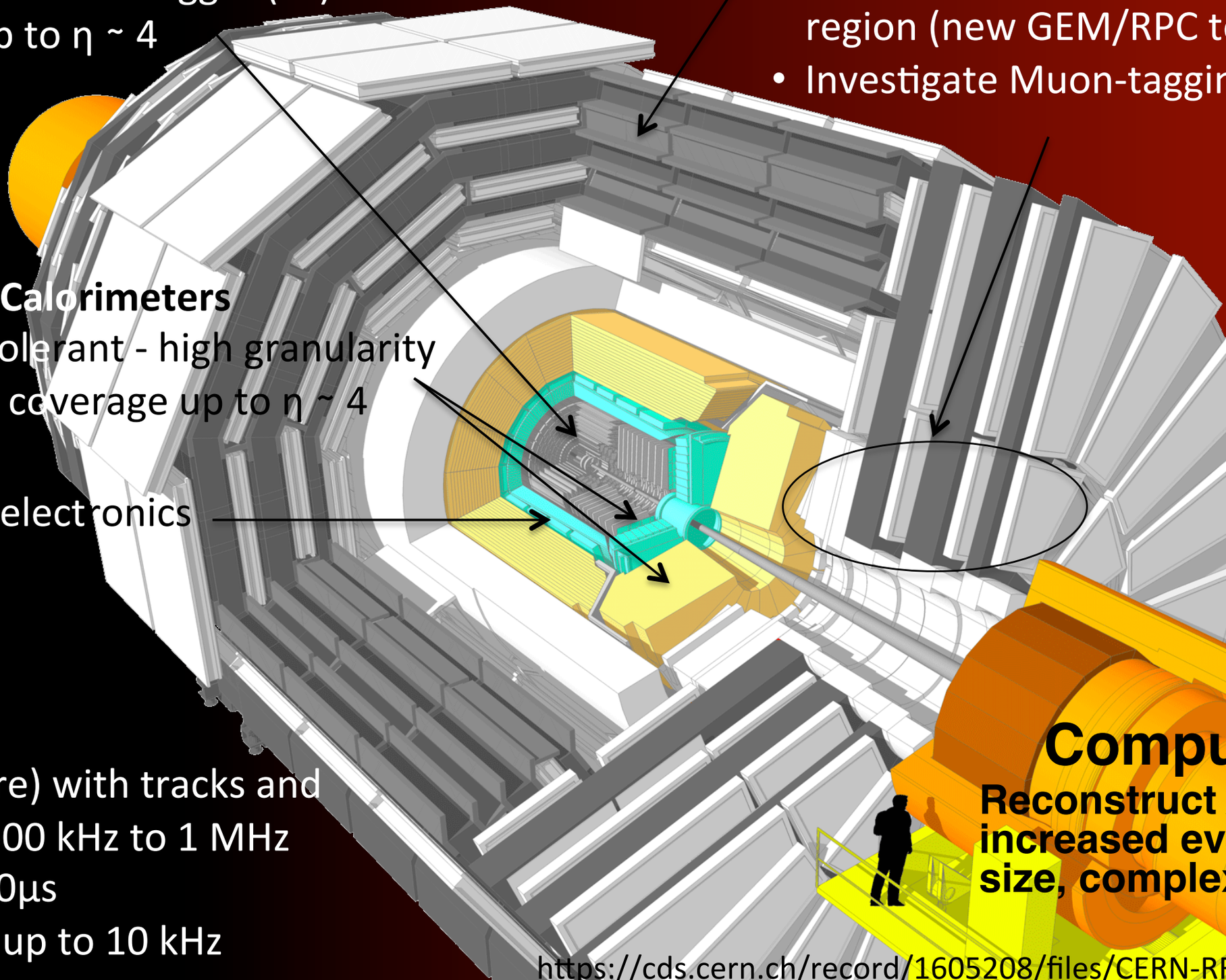
CMS Upgrades for HL-LHC

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 4

New Endcap Calorimeters
- Radiation tolerant - high granularity
- Investigate coverage up to η ~ 4

Barrel ECAL
- Replace FE electronics



Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
- Latency ≥ 10μs
- HLT output up to 10 kHz

Computing
Reconstruct / analyze increased event rate, size, complexity

https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

- Also looking for more radiation hard crystals

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

- Also looking for more radiation hard crystals

New developments:

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

- Also looking for more radiation hard crystals

New developments:

- ***Shashlik***
- ***Crystals : LSO/LYSO***
- ***HGCAL***

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

- Also looking for more radiation hard crystals

New developments:
- ***Shashlik***
- ***Crystals : LSO/LYSO***
- ***HGCAL***

CMS Generic:

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

- Also looking for more radiation hard crystals

New developments:
- ***Shashlik***
- ***Crystals : LSO/LYSO***
- ***HGCAL***

CMS Generic:

- Replace the forward calorimeter by a radiation hard detector capable of withstanding the very high luminosities expected at HL-LHC

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

- Also looking for more radiation hard crystals

New developments:
- ***Shashlik***
- ***Crystals : LSO/LYSO***
- ***HGCAL***

CMS Generic:

- Replace the forward calorimeter by a radiation hard detector capable of withstanding the very high luminosities expected at HL-LHC

HGCAL Specific:

Future calorimeters

- Concentrate on improvement of jet energy resolution to match the requirement of the new physics expected in the next 10-30 years
- Two approaches:
  - minimize the influence of the calorimeter and measure jets using the combination of all detectors! ==>Particle Flow technique.
  - measure the hadronic shower components in each event & weight directly access to the source of fluctuations ! ==> Dual (Triple) Readout

- Also looking for more radiation hard crystals

New developments:
- ***Shashlik***
- ***Crystals : LSO/LYSO***
- ***HGCAL***

CMS Generic:

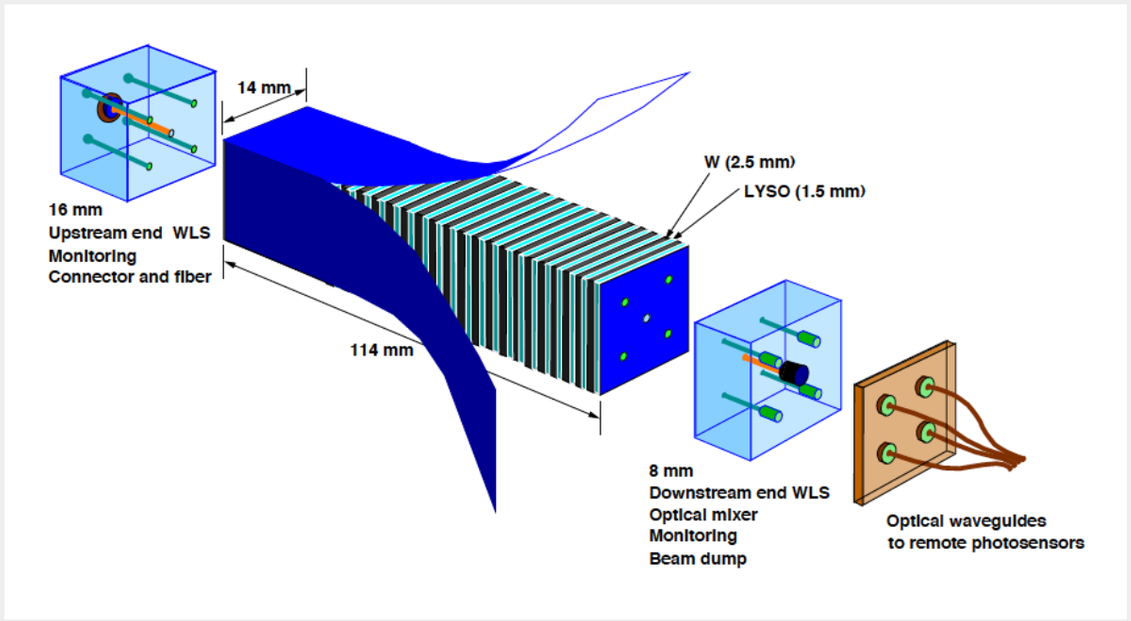
- Replace the forward calorimeter by a radiation hard detector capable of withstanding the very high luminosities expected at HL-LHC

HGCAL Specific:

- Aim for a dense and highly granular 3D sampling calorimeter inspired by CALICE (ILC), adapted to HL-LHC very high event rates
- Exploit topology of deposits and shower tracking capabilities in a particle flow reconstruction both for trigger and offline analysis

Shashlik Module

(Super modules are 5x5 Arrays of these Individual tiny modules)



Shashlik module cross section is very small, ~ Moliere radius, to minimize pileup.

Materials:

Absorber: W

Active Material: LYSO(Ce) (primary)

Active material: CeF_3 also under study

Structure:

2.5 mm W plates (28 per module)

1.5 mm LYSO(Ce) plates (29 per module)

Module Dimensions:

Transverse Size: Front Face 14 x 14 mm^2

Length 114 mm

Readout:

WLS Capillaries (4 per module)

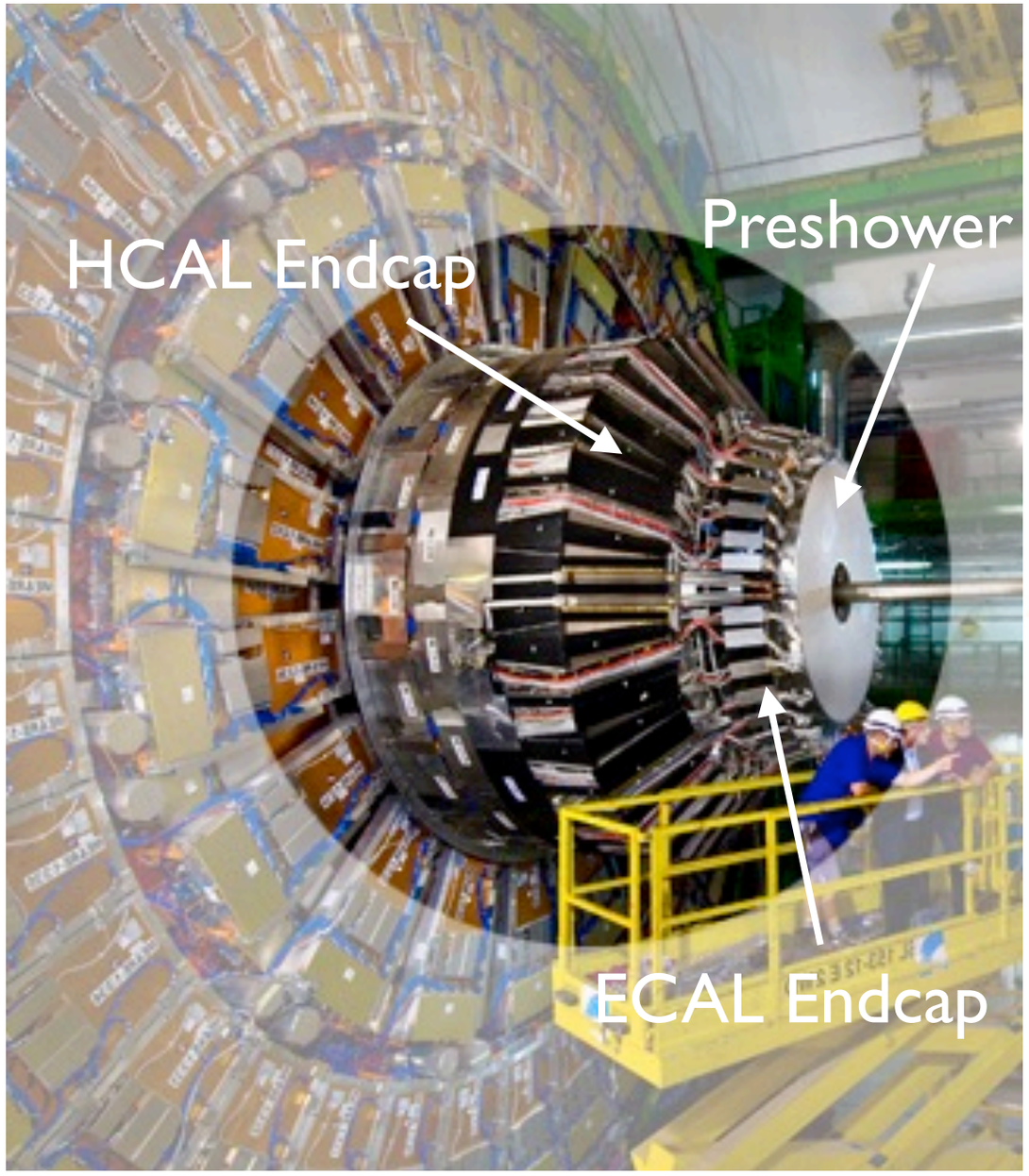
GaInP/SiPM Photosensors (4 per module)

One QIE13 channel per module

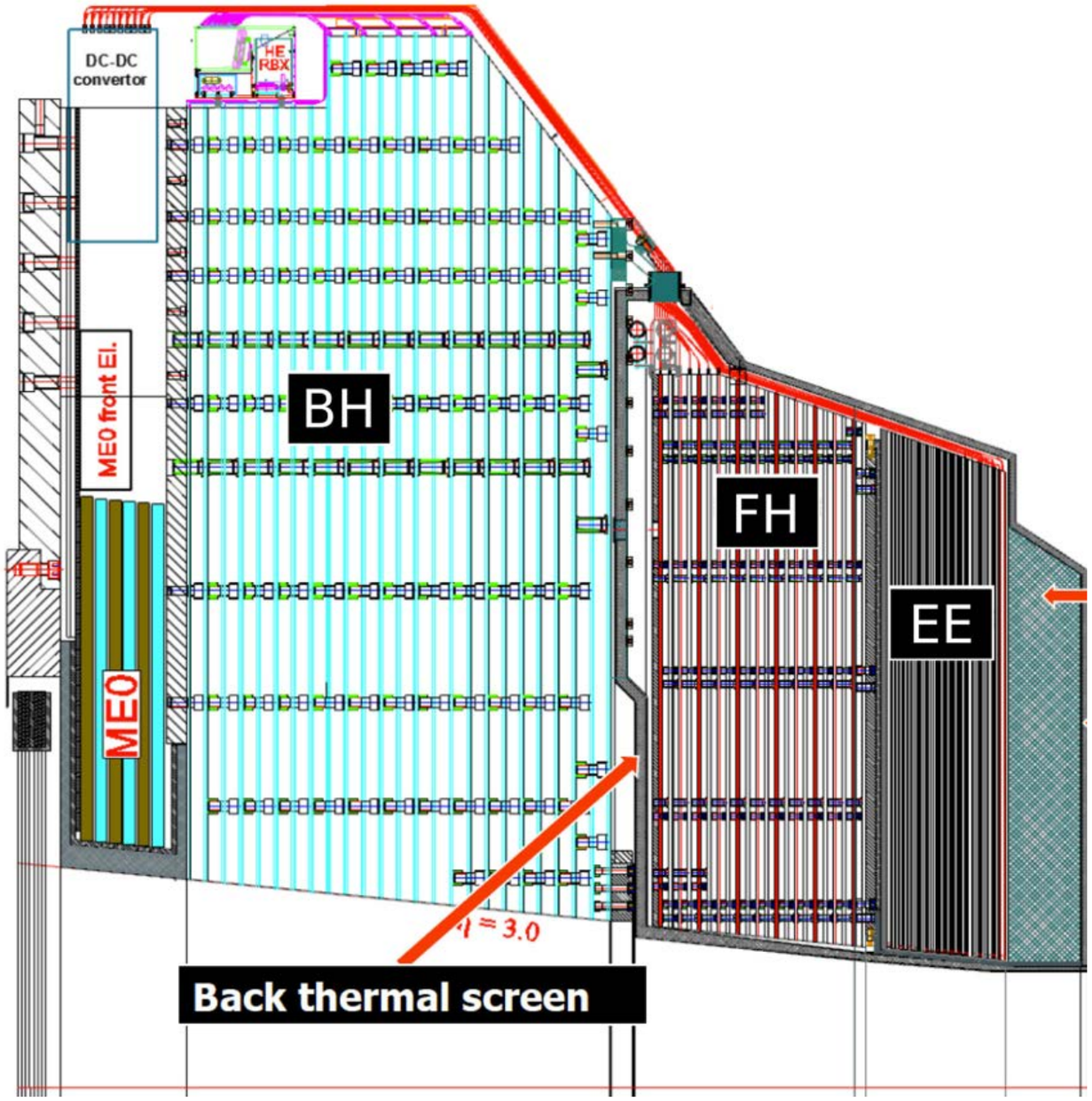
Segmentation in depth: Unsegmented except for the possible extraction of a signal near shower max

HL-LHC Endcap Calorimeter Upgrade

Current Endcap Calorimeter



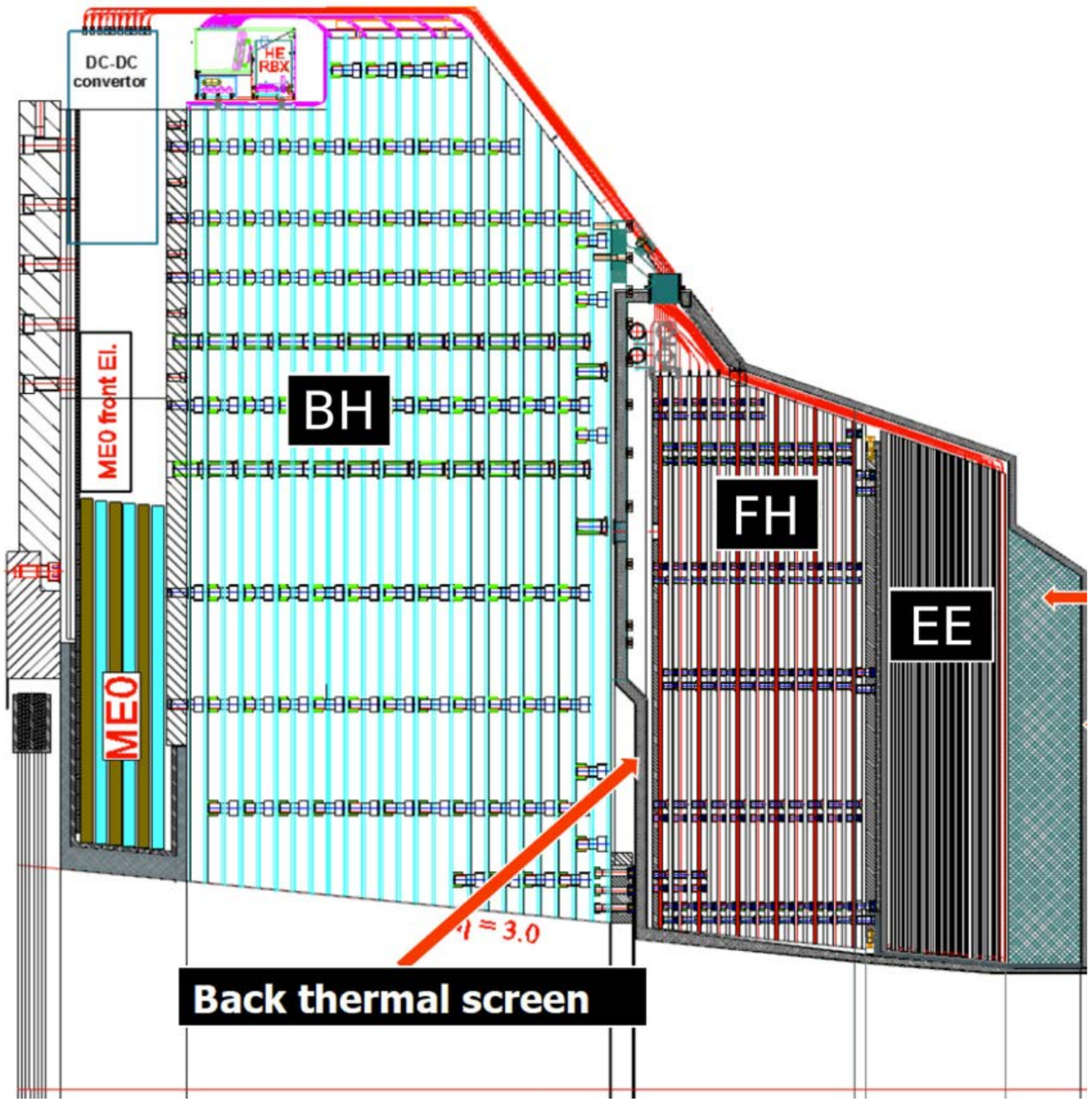
High Granularity Endcap Calorimeter



HL-LHC Endcap Calorimeter Upgrade

- *Challenging conditions push toward new paradigm*
  - ✦*EE : High-granularity silicon-readout, based on ILC/ CALICE detector*
  - ✦*FH : Si/W EE, 26X_0, 1.5l; Si/ brass FH, 3.5l*
  - ✦*BH : Plastic scintillator/brass BH, 5l*
- *high R&D activity*
  - ✦*Radiation-tolerant on-detector electronics*
  - ✦*Cold plastic scintillator*

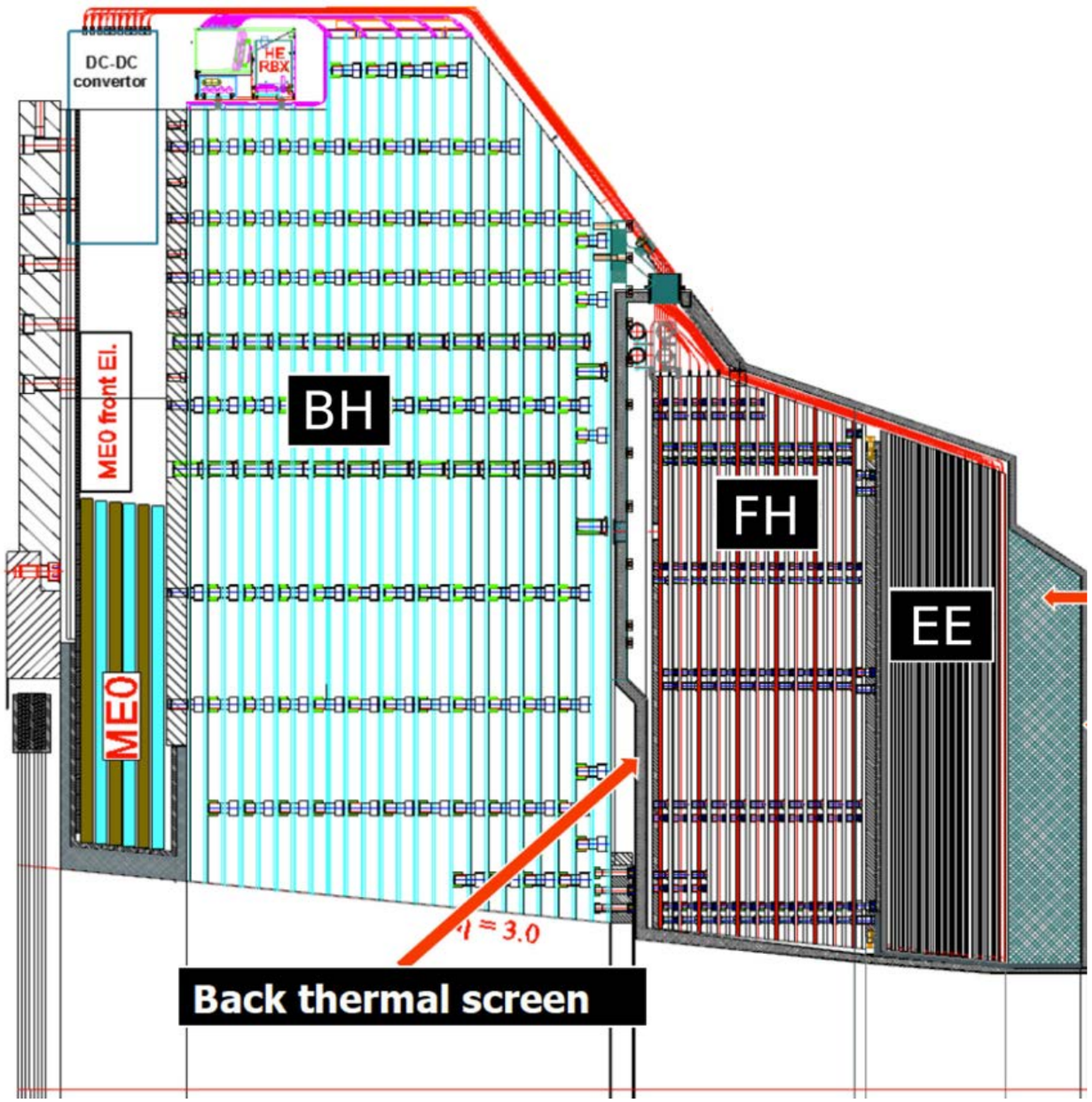
High Granularity Endcap Calorimeter



HL-LHC Endcap Calorimeter Upgrade

- *Challenging conditions push toward new paradigm*
  - ✦ *EE : High-granularity silicon-readout, based on ILC/ CALICE detector*
  - ✦ *FH : Si/W EE, 26X_0, 1.5l; Si/ brass FH, 3.5l*
  - ✦ *BH : Plastic scintillator/brass BH, 5l*
- *high R&D activity*
  - ✦ *Radiation-tolerant on-detector electronics*
  - ✦ *Cold plastic scintillator*

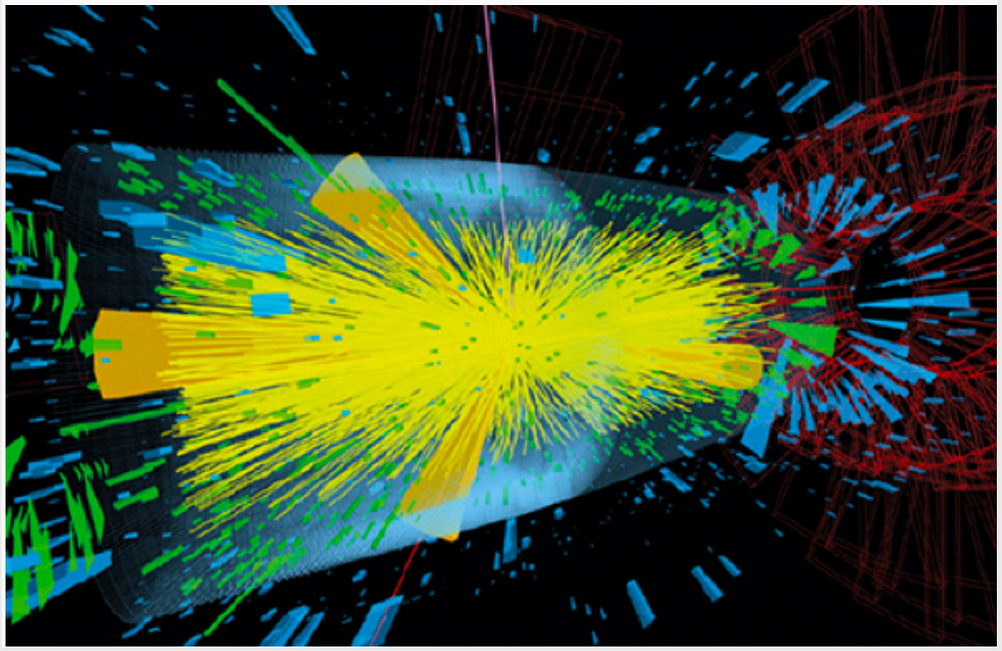
High Granularity Endcap Calorimeter

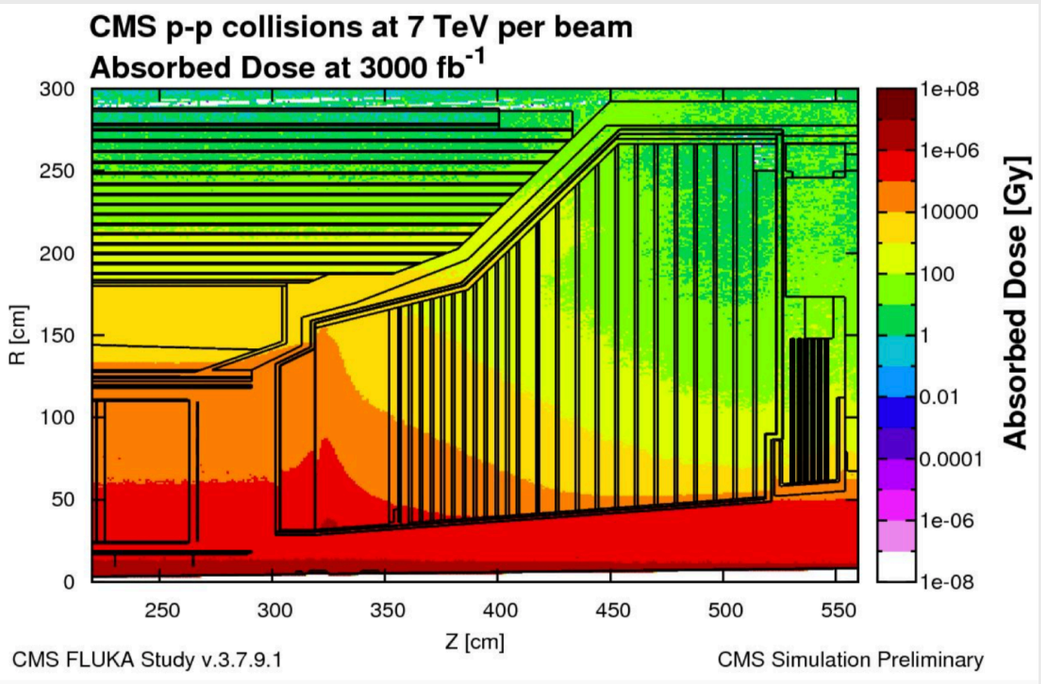


Fine granularity calorimetry (~26X_0 in 28 layers W/Cu ECAL, 10.5 λ_0 over 52 layers) enables precise particle flow techniques and ideas applied to calorimetry

- ✦ *Now must follow particles through the calorimeter layers*
- ✦ *Fine sampling brings robustness against pileup*

CMS CALORIMETER ENDCAP FOR THE HL-LHC

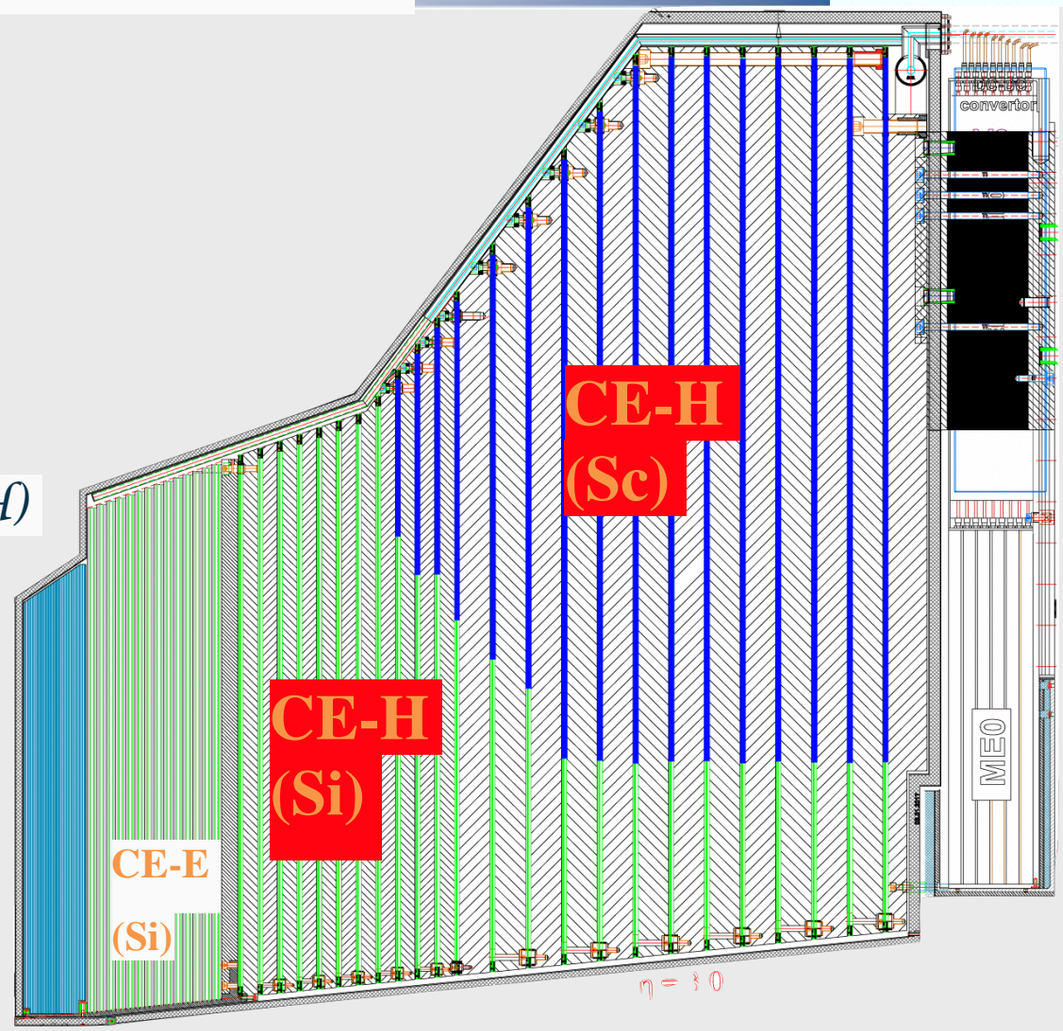




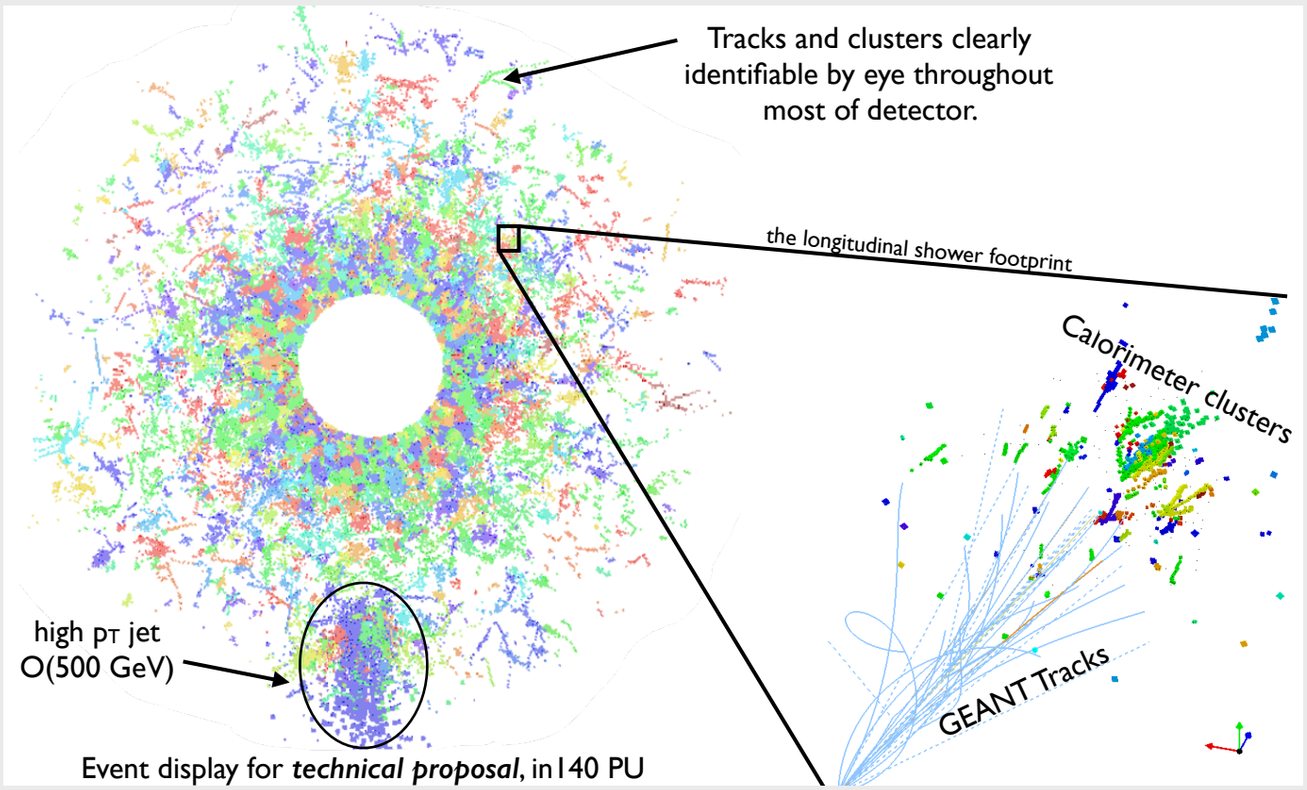
- CMS Phase-2 Upgrades are required to cope with the HL-LHC demanding environment of high radiation levels and large pileup <200> PU
- Current endcap calorimeters will need to be replaced
  - Preserve or even improve sensitivity in the interesting and busy forward region for VBS/VBF
- The High Granularity Calorimeter (HGCAL) will become the new Calorimeter Endcap (CE):
  - Radiation hard technology based on a mix of silicon and scintillator detectors
  - High transverse and longitudinal granularity + timing (5D!) for enhanced particle flow reconstruction and ID/pileup mitigation

ENDCAP FOR THE HL-LHC

- The high luminosity and high granularity are a big challenge for the detector design:
  - Silicon/scintillator detectors in the high/low radiation regions
  - Triggering and reading data of >6M channels at 40 MHz
  - 28 layers in the ECAL (CE-E) + 24 layers in the HCAL (CE-H) compartments



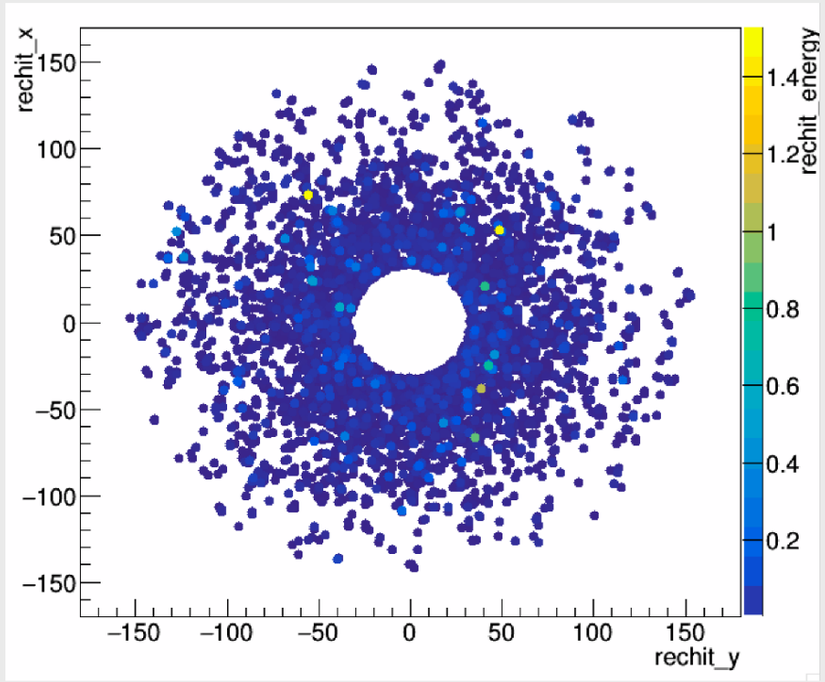
Imaging Showers with the HGCal



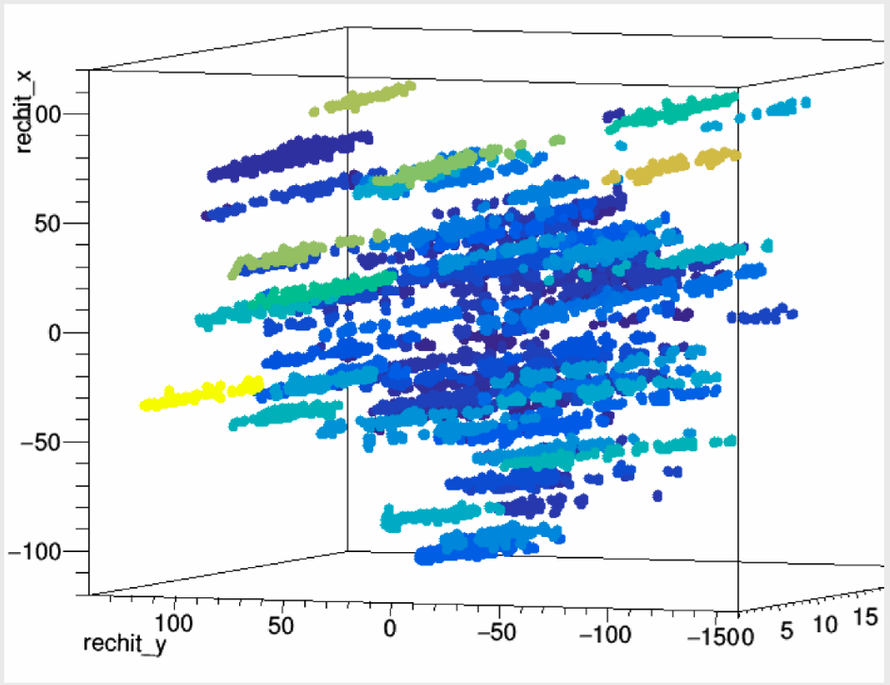
Endcap coverage: $1.5 < \lvert\eta\rvert < 3.0$		
Total	**Silicon sensors**	**Scintillator**
Area	600 m²	500 m²
Number of modules	27 000	4 000
Cell size	0.5 — 1 cm²	4 — 30 cm²
N of channels	6 000 000	400 000
Power	Total at end of HL-LHC: ~180 kW @ -30°C	

PHYSICS PERFORMANCE

- The high occupancy and pileup are both big challenges for the particle reconstruction
  - But HGCAL is an 5D imaging calorimeter: 3D position, energy and time
  - Ultimate detector to perform Particle Flow
- The very first step is the clustering of the hits. Currently, the clustering is done in two steps:
  - 2D clustering in every layer using an energy density-based imaging algorithm
  - 3D clustering in an IP-pointing cylinder
- Great opportunity for novel tracking, clustering and imaging techniques as DBSCAN and CNNs!



All hits in layer 1 for a 200 PU event



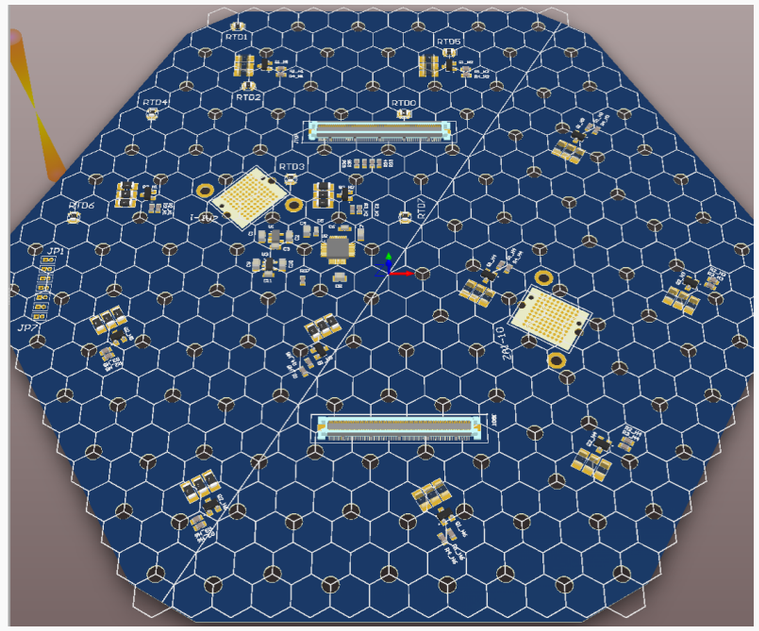
Clustered hits for clusters with pt > 1 GeV

From (CHEP2018 : Artur Lobanov LLR — École polytechnique)

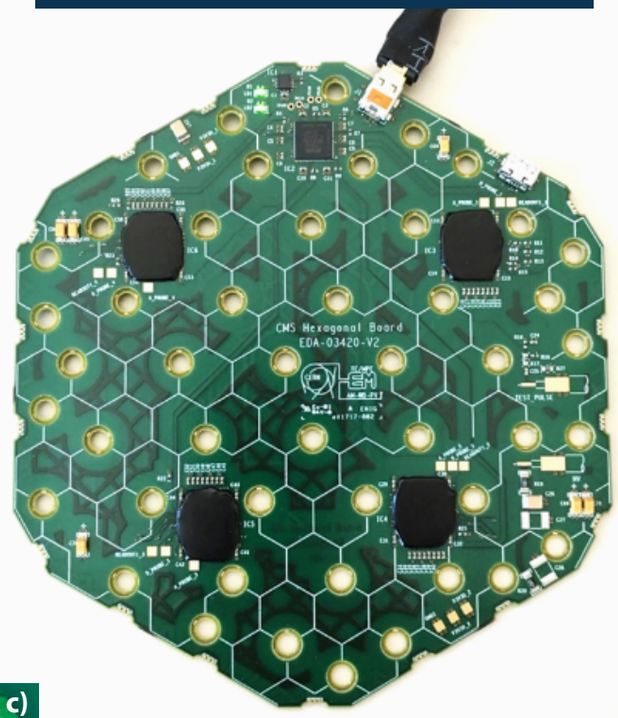
FRONT-END ELECTRONICS

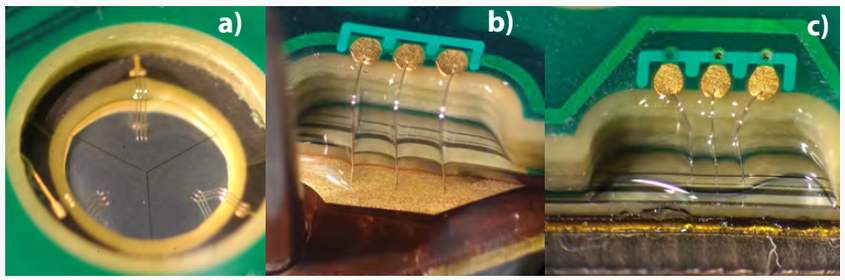
- *Detector modules with 2 PCBs < 6mm thick:*
  1. *PCB: "hexaboard" Wire-bonds to Si-sensor and very-FE ASICs*
  2. *PCB: Motherboard for powering, data concentration, trigger generation and bi-directional communication*
- *Trigger/data transfer: low-power GBT links (lpGBT)*

Hexaboard design for HGCROC



Hexaboard PCB for Test Beam



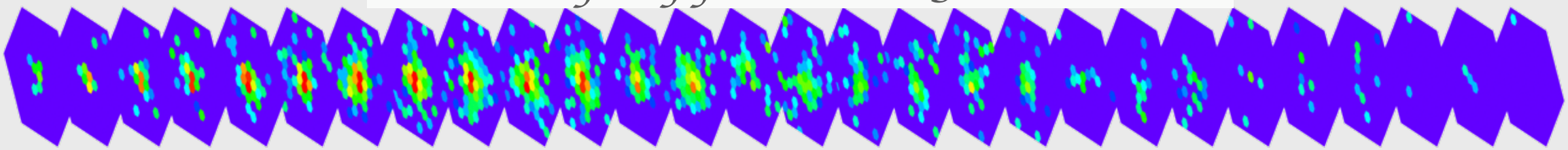


Wire-bonds from Silicon to 1. PCB

From (CHEP2018 : Artur Lobanov LLR — École polytechnique)

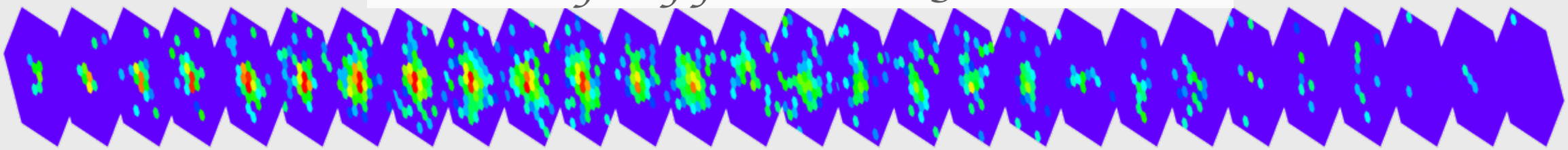
Beam test results (June 2018)

Event display for an 80 GeV electron



Beam test results (June 2018)

Event display for an 80 GeV electron

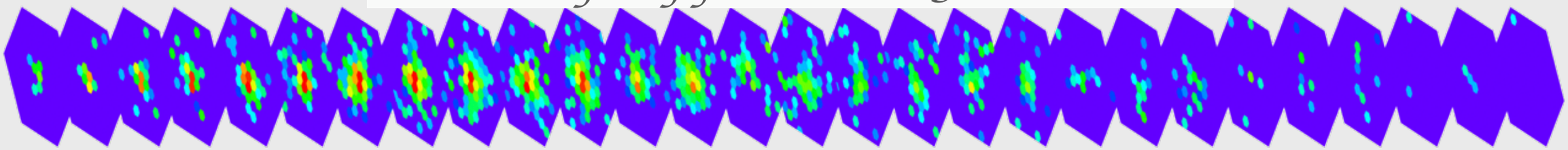


Preliminary results:

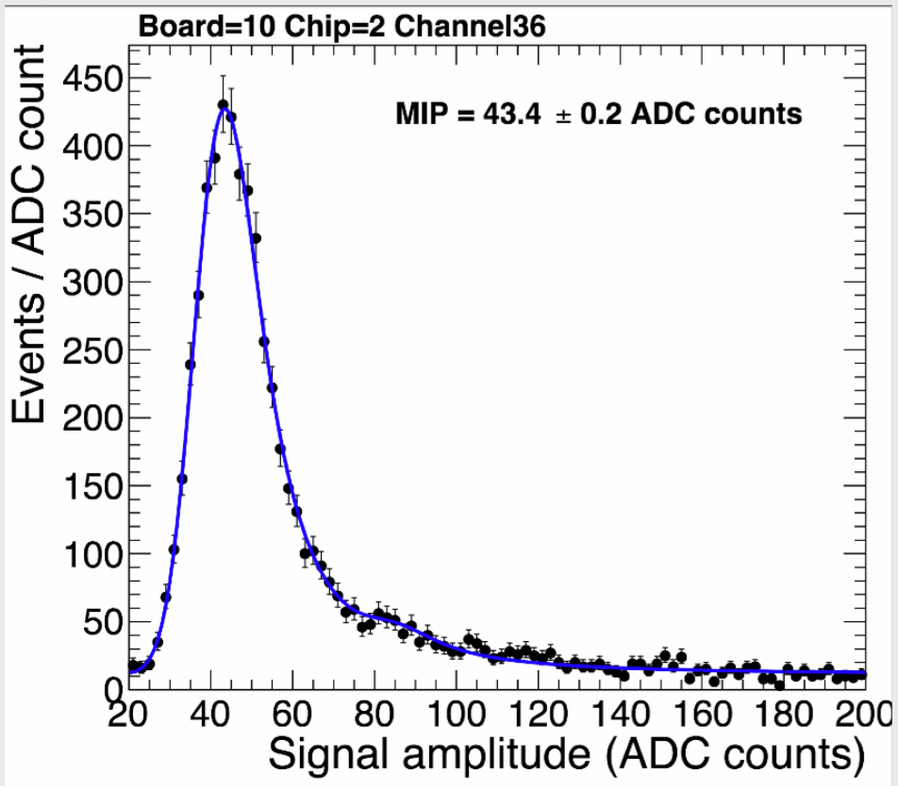
- Clean MIP spectra for calibration
- Longitudinal shower shapes distinguishable for electrons/pions
- Energy reconstruction works well
- Basic agreement with Geant4 simulation for energy and multiplicity

Beam test results (June 2018)

Event display for an 80 GeV electron



Muon MIP spectrum for a single channel

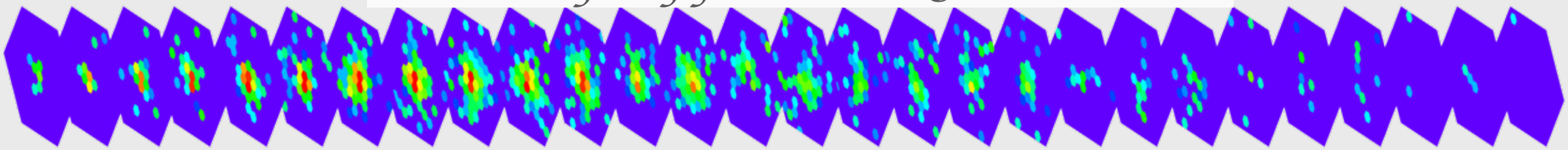


Preliminary results:

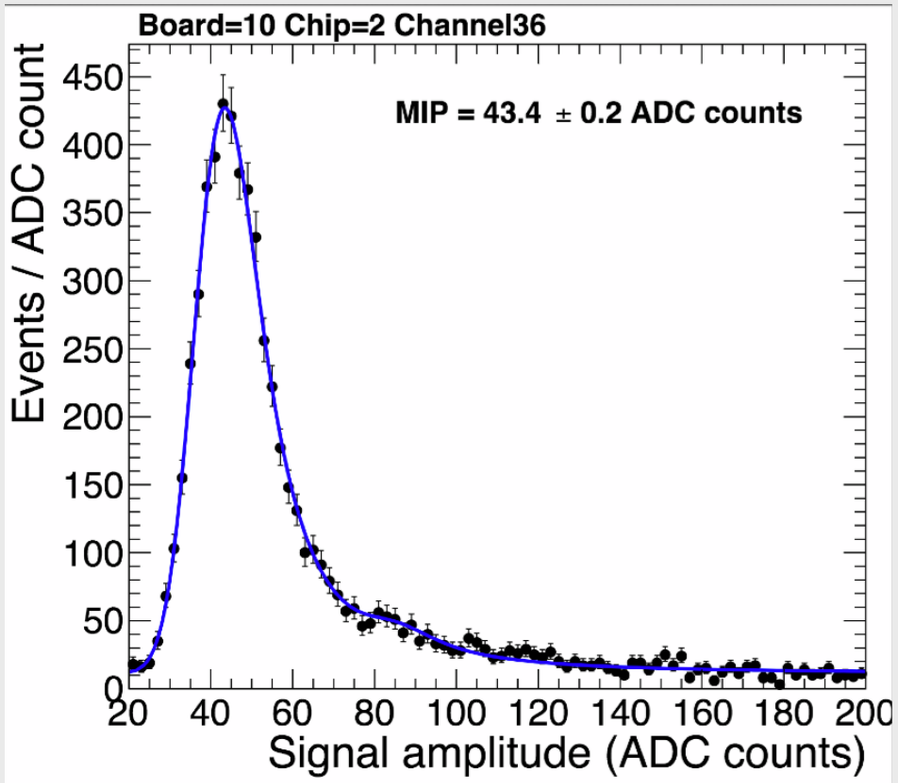
- *Clean MIP spectra for calibration*
- *Longitudinal shower shapes distinguishable for electrons/pions*
- *Energy reconstruction works well*
- *Basic agreement with Geant4 simulation for energy and multiplicity*

Beam test results (June 2018)

Event display for an 80 GeV electron



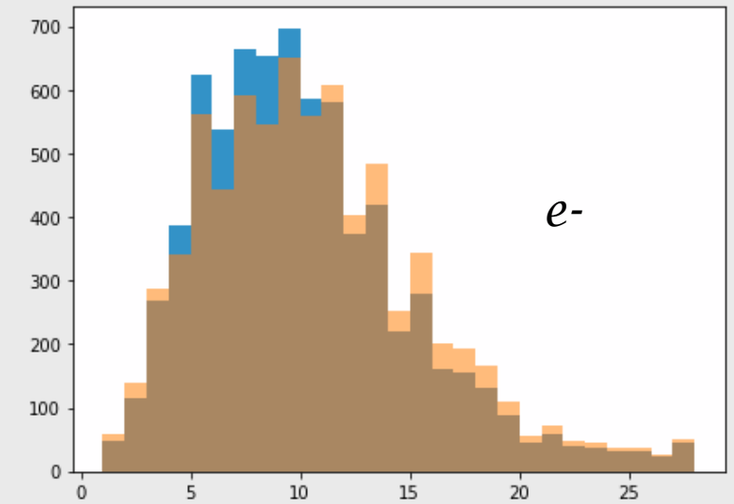
Muon MIP spectrum for a single channel

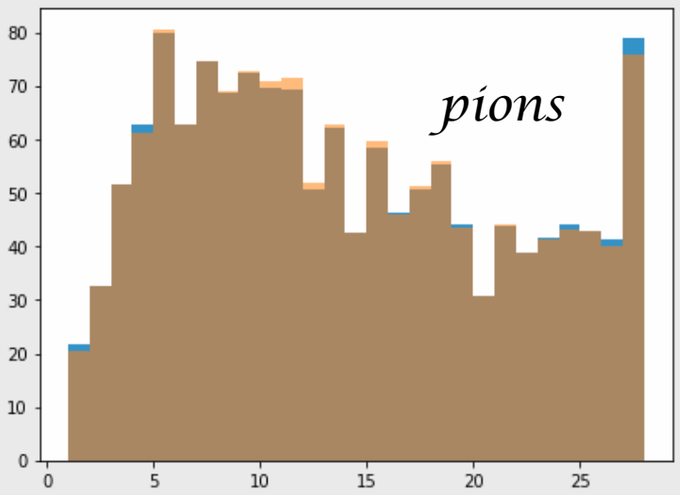


Preliminary results:

- Clean MIP spectra for calibration
- Longitudinal shower shapes distinguishable for electrons/pions
- Energy reconstruction works well
- Basic agreement with Geant4 simulation for energy and multiplicity

Longitudinal energy profiles





Conclusion

- *Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.*

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.
  - This can take quite some time : ATLAS/CMS :

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.
  - This can take quite some time : ATLAS/CMS :
    - R&D started in 1990,

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.
  - This can take quite some time : ATLAS/CMS :
    - R&D started in 1990,
    - experiment general concept and approval (1994),

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.
  - This can take quite some time : ATLAS/CMS :
    - R&D started in 1990,
    - experiment general concept and approval (1994),
    - start of construction ~1998,

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.
  - This can take quite some time : ATLAS/CMS :
    - R&D started in 1990,
    - experiment general concept and approval (1994),
    - start of construction ~1998,
    - integration in pit from 2004, commissioned in 2008 and now operational.....

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.
  - This can take quite some time : ATLAS/CMS :
    - R&D started in 1990,
    - experiment general concept and approval (1994),
    - start of construction ~1998,
    - integration in pit from 2004, commissioned in 2008 and now operational.....
- Understanding the detector response correctly is an absolutely needed step before claiming any physics results !!!

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

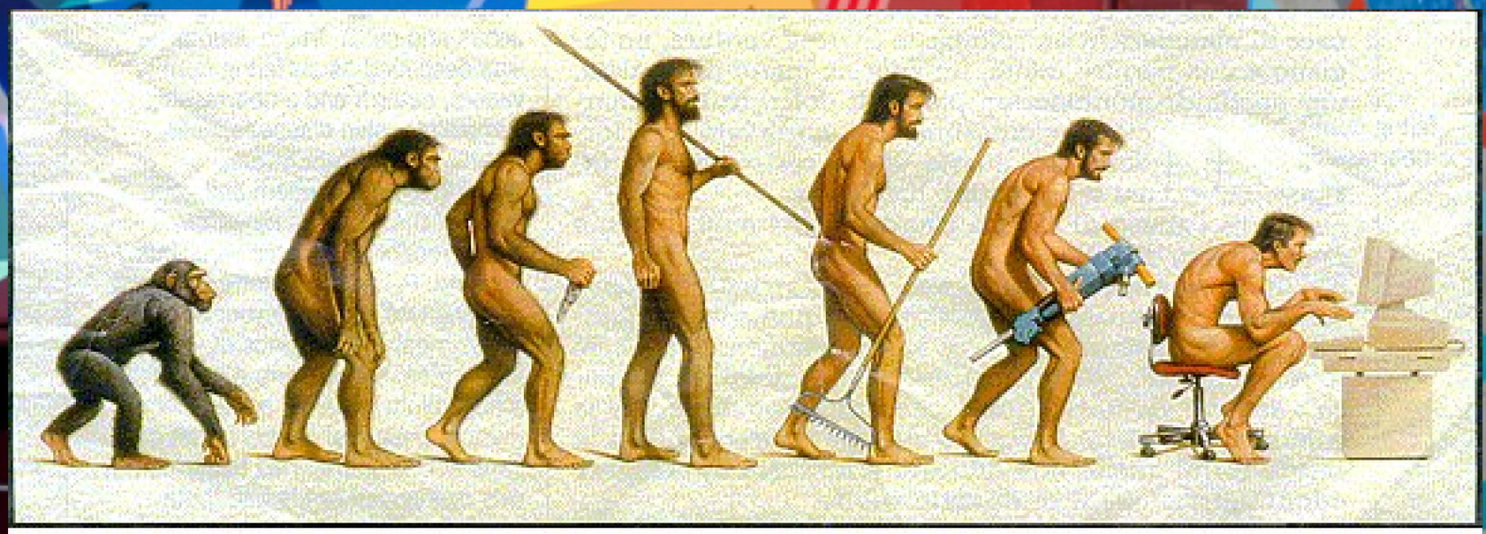
Conclusion

- Detection of particle is based on quite simple mechanisms, most of them are very well known and simulated.
- Detectors R&D is a very rich domain in continuous evolution.
- Conception of an experiment is always a difficult enterprise : the best technology can be spoiled by the environment where it is used.
  One should define it with respect to the physics goals.
  - This can take quite some time : ATLAS/CMS :
    - R&D started in 1990,
    - experiment general concept and approval (1994),
    - start of construction ~1998,
    - integration in pit from 2004, commissioned in 2008 and now operational.....
- Understanding the detector response correctly is an absolutely needed step before claiming any physics results !!!
- Missing in my lecture : Photon detectors, scintillators, Cherenkov light detector (see in my Backup slides)

Credit to :
Christian Joram / CERN, R. Forty/CERN, C. Joram/CERN, F. Sauli/CERN, T. Rodrigo/Santander, O. Villalobos Baillie/Univ. of Birmingham, D. Fournier/LAL Orsay, L. Serin/LaL Orsay, S. Barsuk/ LAL Orsay, M. Titov/IRFU Saclay, M. Krammer / DESY Hambourg, M. Diemoz Rome, D. Lelas University of SPLIT FESB, D. Dissertory ETHZ Zurich and many other.

Computing behind this all…

Computing behind this all…



Somewhere, something went terribly wrong

Materials based upon:

This presentation is widely based on:

C. Joram, **Particle detectors : principles and techniques, Part 4, Calorimetry,**
CERN Academic training lectures 2005,
http://indico.cern.ch/conferenceDisplay.py?confId=a042932

J. Crittenden, Calorimetry in High-Energy Elementary-Particle Physics,
Joint Dutch Belgian German Graduate School, Bad Honnef, 8-9 September 2006,

R. Wigmans, **LHC luminosity upgrade: detector challenges (3/5),**
CERN Academic training programme 2006,
http://indico.cern.ch/conferenceDisplay.py?confId=a056410

Bibliography

R. Wigmans, ***Energy Measurement in Particle Physics (2000)***

P.B. Cushman, ***Electromagnetic and Hadronic Calorimeters,***
in Instrumentation in High Energy Physics, ed. F.Sauli (1992)

C. Fabjan, ***Calorimetry in High-Energy Physics,***
in Experimental Techniques in High-Energy Physics, ed. T.Ferbel (1987)

U. Amaldi, ***Calorimetry in High-Energy Physics,***
in Experimental Techniques in High-Energy Physics, ed. T.Ferbel (1987)

R. Fernow, ***Introduction to Experimental Particle Physics (1986)***

C. Grupen, ***Particle Detectors (1996)***

Questions

- Q1

Silicon detectors ➔ Position resolution: ~ 5 μm

Gaseous detectors ➔ Position resolution: ~ 50 μm

Calorimeters ➔ Position resolution: few mm

Why (and whether) moderate position resolution of calorimeter can be used ?

Q2

What can be the problems for a) very low, b) very high shower energy measurement ?

Q3

Which background can you imagine to fake a muon reconstructed in a muon detector ?

Questions

Q1

Which part of the ECAL will degrade more from the irradiation in the experiment ?

Q2

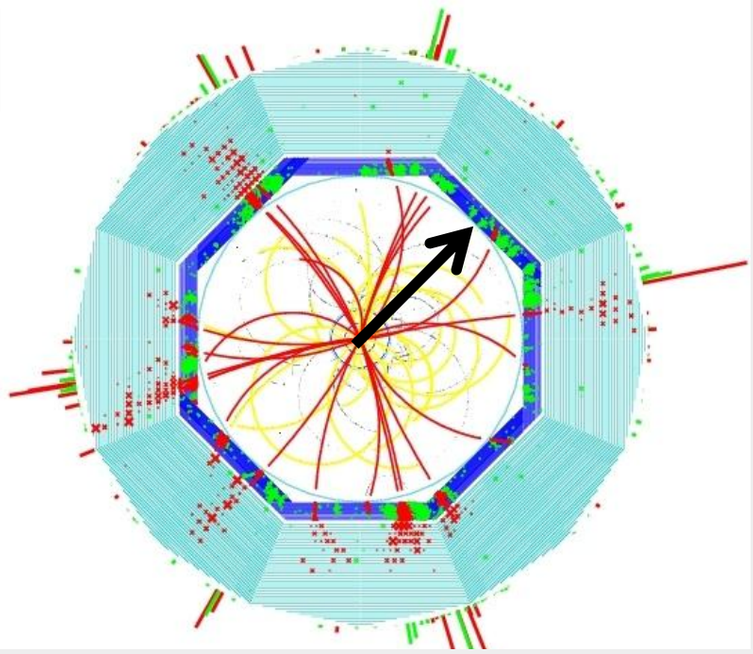
Reminder : EM Calorimeters: MANY (15-30) Xo deep

H Calorimeters: many (5-8) λ_I deep

Why full shower containment is not always required ?

Q3

In order for the Particle Flow Analysis to perform better, would you position your calorimeter at
a) 3m or b) 10m from the interaction point ?
Resolution/granularity stays the same.



Backup

- Photon Detection — MORE
- Scintillators - General Characteristics — MORE
- Energy loss by electron and photons — MORE
- Interaction of charged particles: — MORE
  Multiple Scattering — MORE
- Position resolution of EM shower — MORE
- Nuclear Interactions — MORE
- Hadronic Showers — MORE
- Energy resolution — MORE
- Particle Flow Calorimeter — MORE
- CMS ECAL — MORE
- Why HGCAL? — MORE
- HGCAL Mechanical Design — MORE

Photon Detection

Purpose : Convert light into a detectable electronic signal

Principle : Use photo-electric effect to convert photons to photo-electrons (p.e.)

Requirement :

High Photon Detection Efficiency (PDE) or Quantum Efficiency; Q.E. = $N_{p.e.}/N_{photons}$

TO BACKUP

Available devices [Examples]:

- Photomultipliers [PMT]
- Micro Channel Plates [MCP]
- Photo Diodes [PD]
- HybridPhoto Diodes [HPD]
- Visible Light Photon Counters [VLPC]
- Silicon Photomultipliers [SiPM]

Photomultipliers

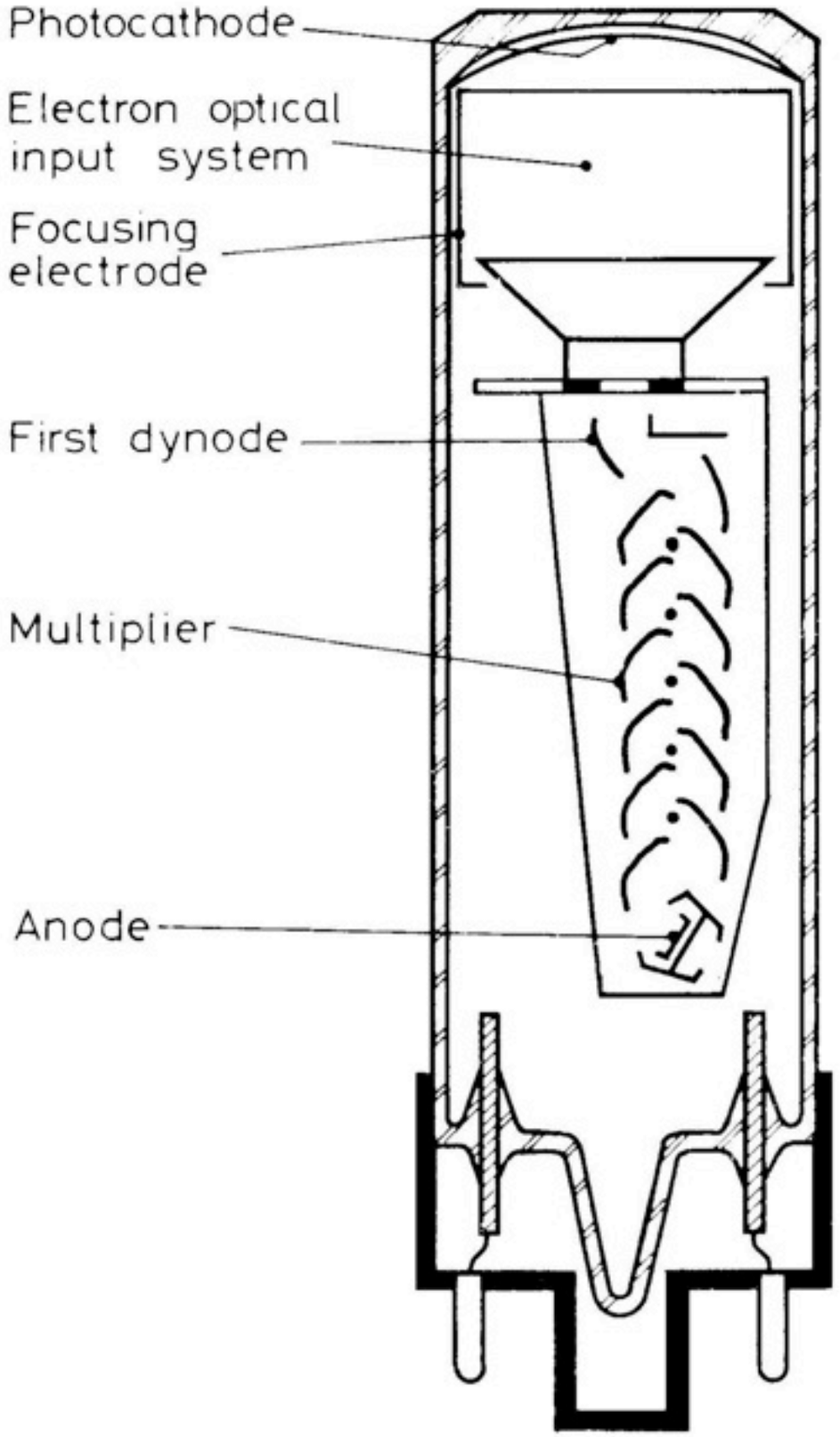
Principle:

Electron emission
from photo cathode

Secondary emission
from dynodes; dynode gain: 3-50 [f(E)]

Typical PMT Gain: > 10^6
[PMT can see single photons ...]

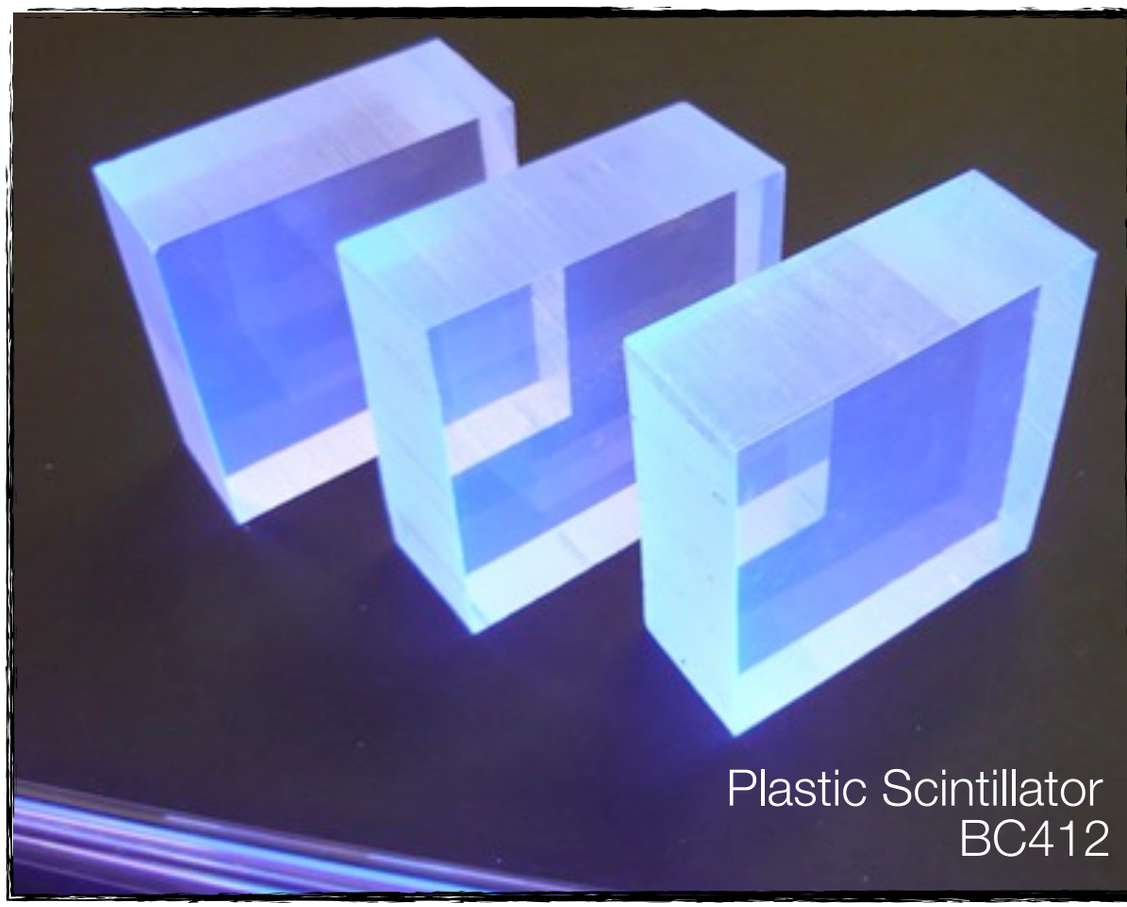
PMT Collection



Scintillators - General Characteristics

Principle:

dE/dx converted into visible light
Detection via photosensor
[e.g. photomultiplier, human eye ...]



Main Features:

Sensitivity to energy
Fast time response
Pulse shape discrimination

Requirements

High efficiency for conversion of excitation energy to fluorescent radiation
Transparency to its fluorescent radiation to allow transmission of light
Emission of light in a spectral range detectable for photosensors
Short decay time to allow fast response

TO BACKUP

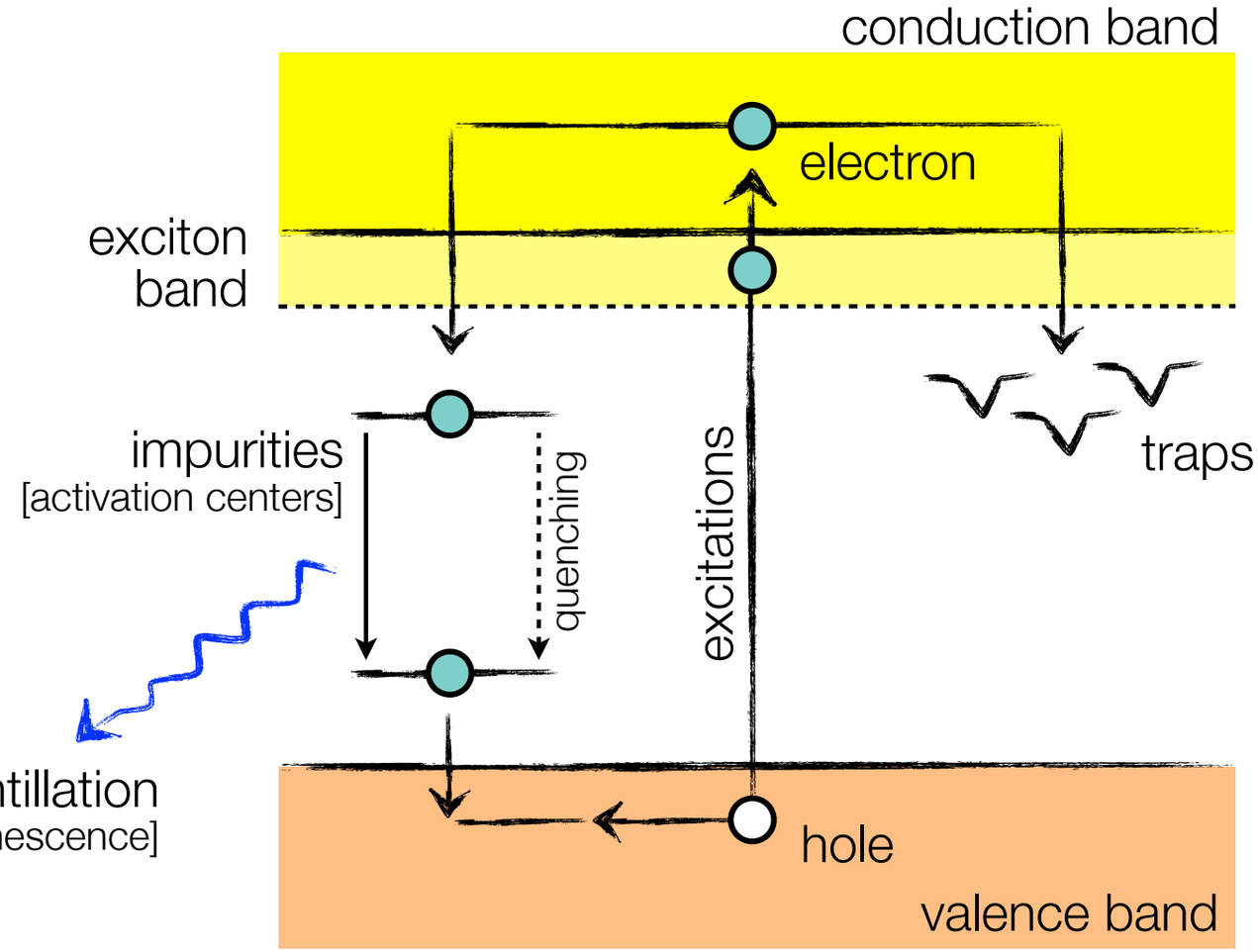
Inorganic Crystals

Materials:

Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)
...

Mechanism:

Energy deposition by ionization
Energy transfer to impurities
Radiation of scintillation photons



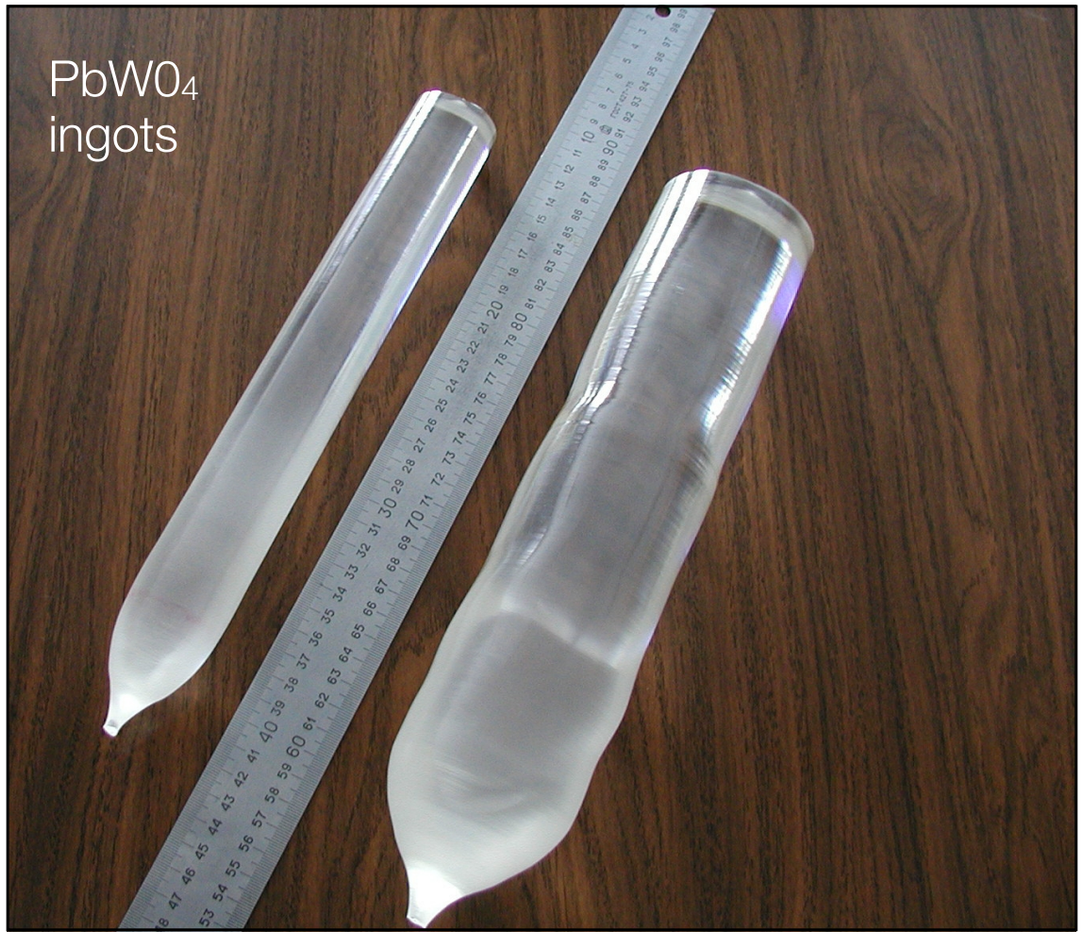
Energy bands in impurity activated crystal showing excitation, luminescence, quenching and trapping

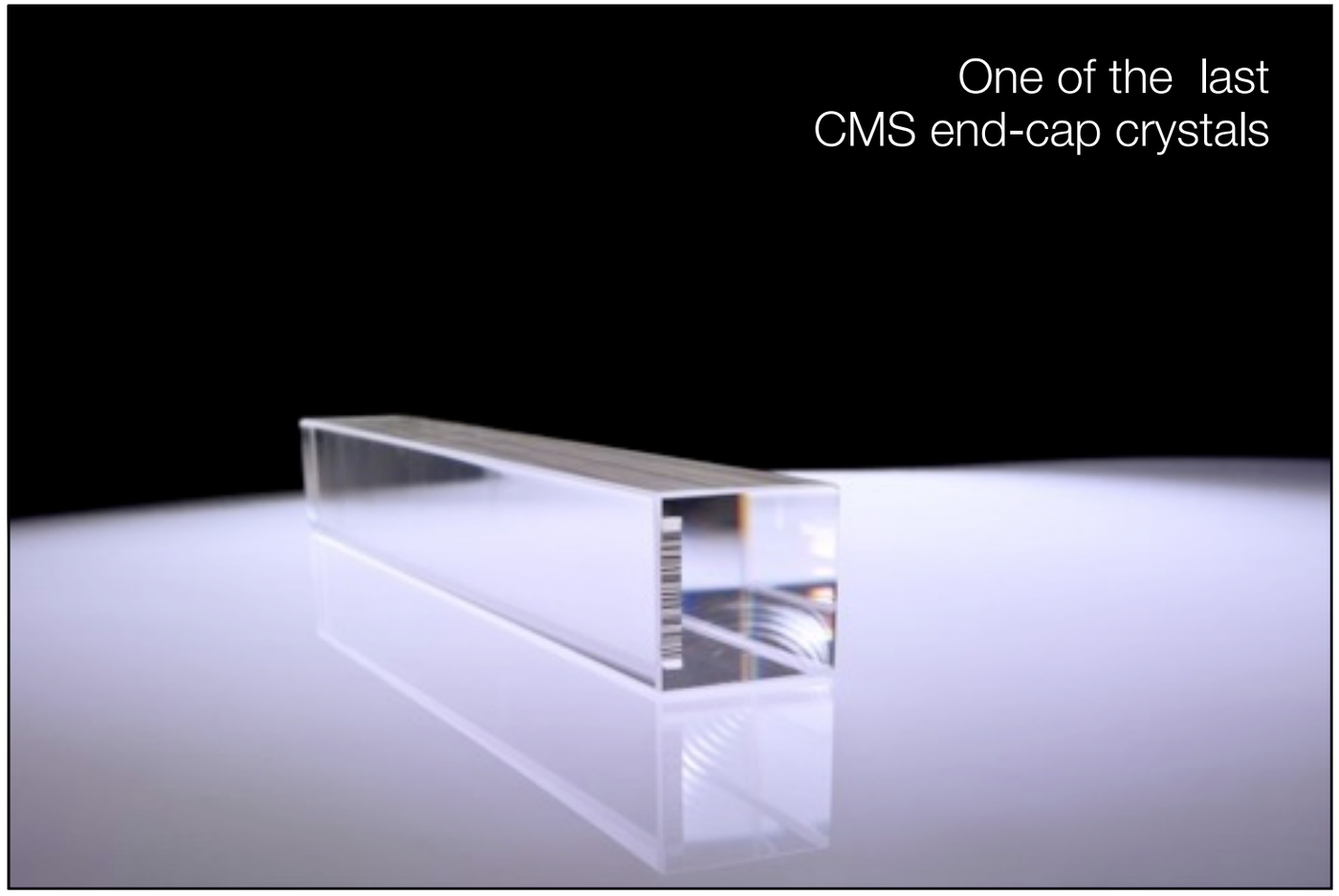
Time constants:

Fast: recombination from activation centers [ns ... µs]
Slow: recombination due to trapping [ms ... s]

Inorganic Crystals

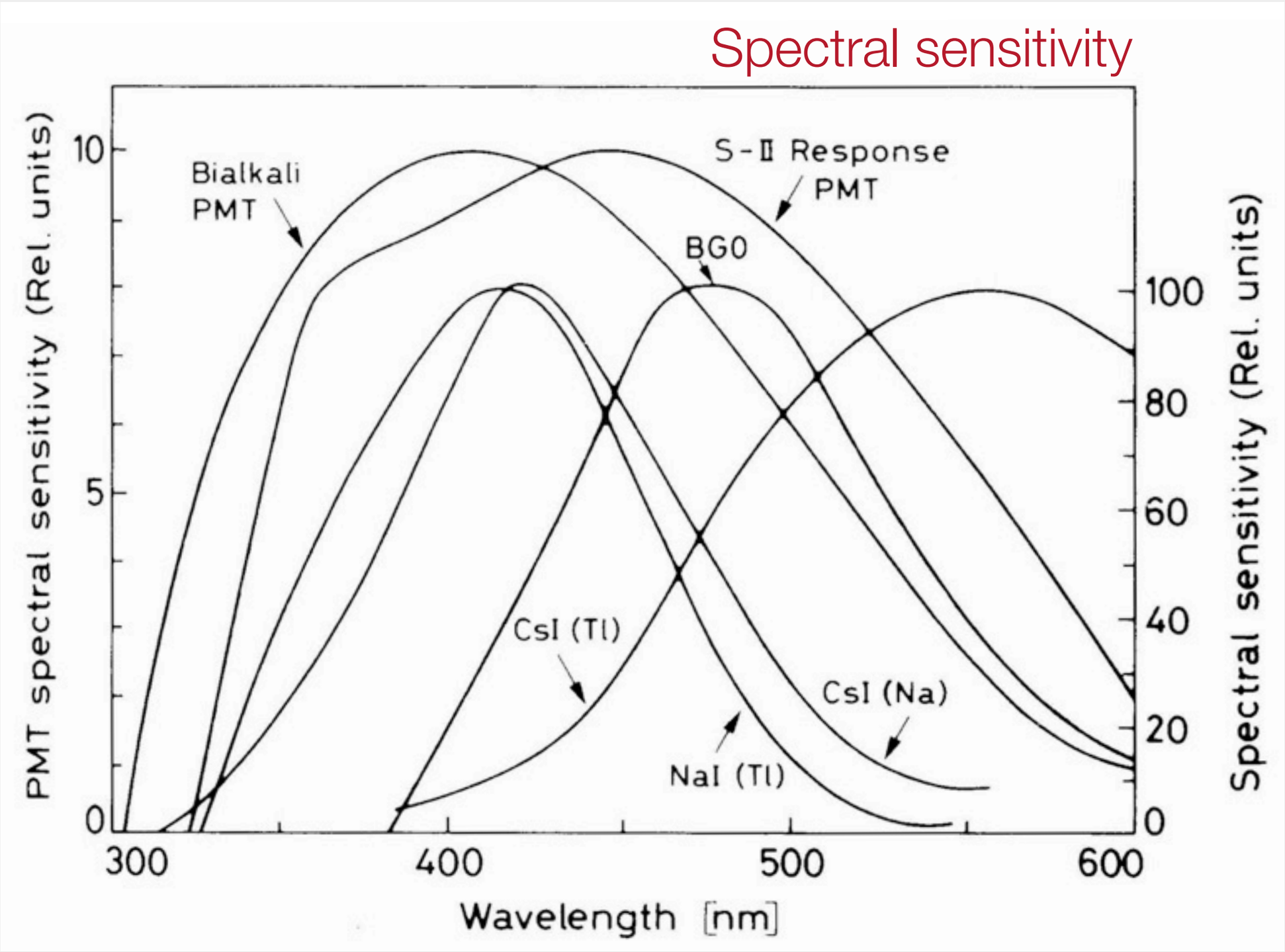
Example CMS
Electromagnetic Calorimeter





Inorganic Crystals

Light Output and PMT Sensitivity



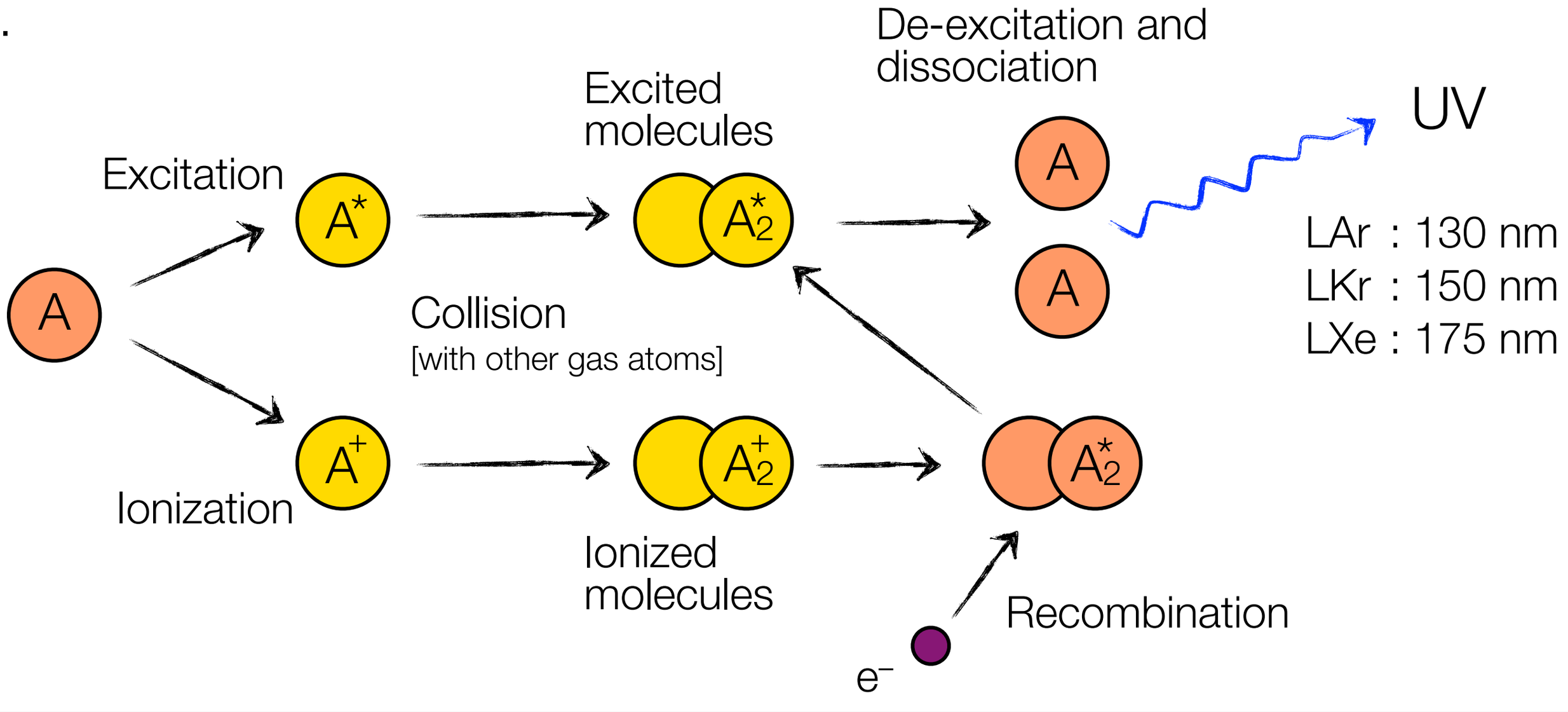
Sintillation in Liquid Nobel Gases

Materials:

Helium (He)
Liquid Argon (LAr)
Liquid Xenon (LXe)
...

Decay time constants:

Helium : $\tau_1 = .02\ \mu s$, $\tau_2 = 3\ \mu s$
Argon : $\tau_1 \leq .02\ \mu s$

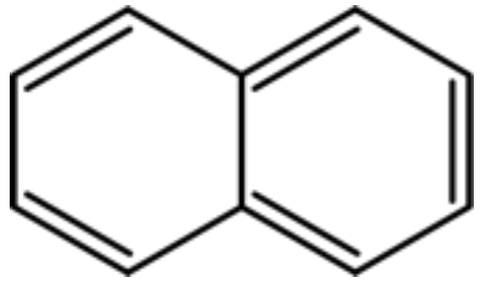


Organic Scintillators

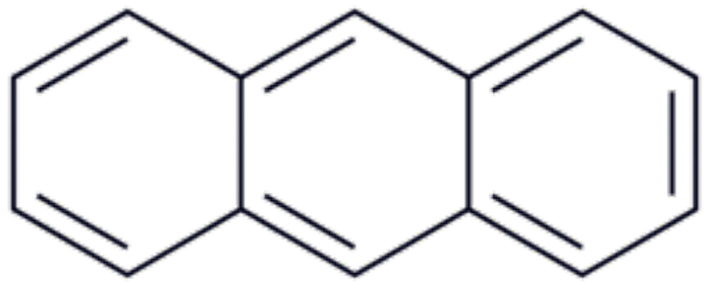
Aromatic hydrocarbon compounds:

e.g. Naphtalene [$C_{10}H_8$]
Antracene [$C_{14}H_{10}$]
Stilbene [$C_{14}H_{12}$]
...

Naphtalene



Antracene



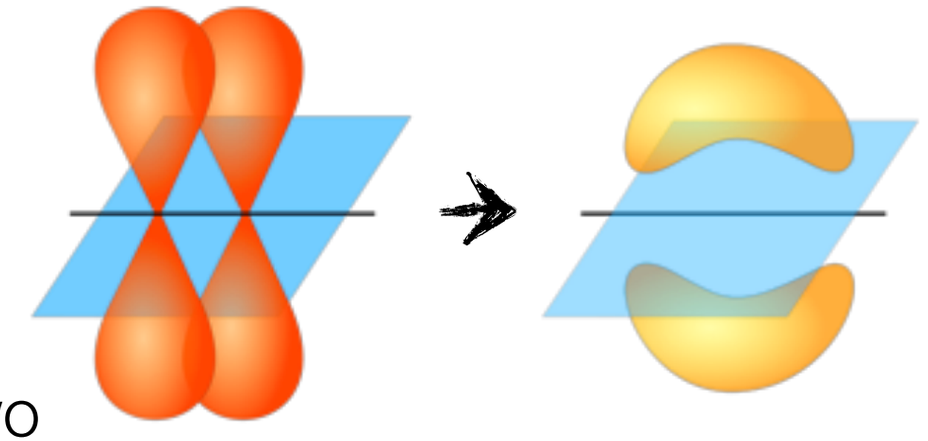
Very fast!
[Decay times of O(ns)]

Scintillation light arises from
delocalized electrons in π-orbitals ...

Transitions of 'free' electrons ...

Scintillation is based on electrons of the C = C bond ...

π bond



Two
p_z orbitals

Inorganic Scintillators

Advantages	high light yield [typical; $\varepsilon_{SC} \approx 0.13$]
	high density [e.g. $PBWO_4$: 8.3 g/cm^3]
	good energy resolution
Disadvantages	complicated crystal growth
	large temperature dependence

Expensive

Organic Scintillators

Advantages	very fast
	easily shaped
	small temperature dependence
	pulse shape discrimination possible
Disadvantages	lower light yield [typical; $\varepsilon_{SC} \approx 0.03$]
	radiation damage

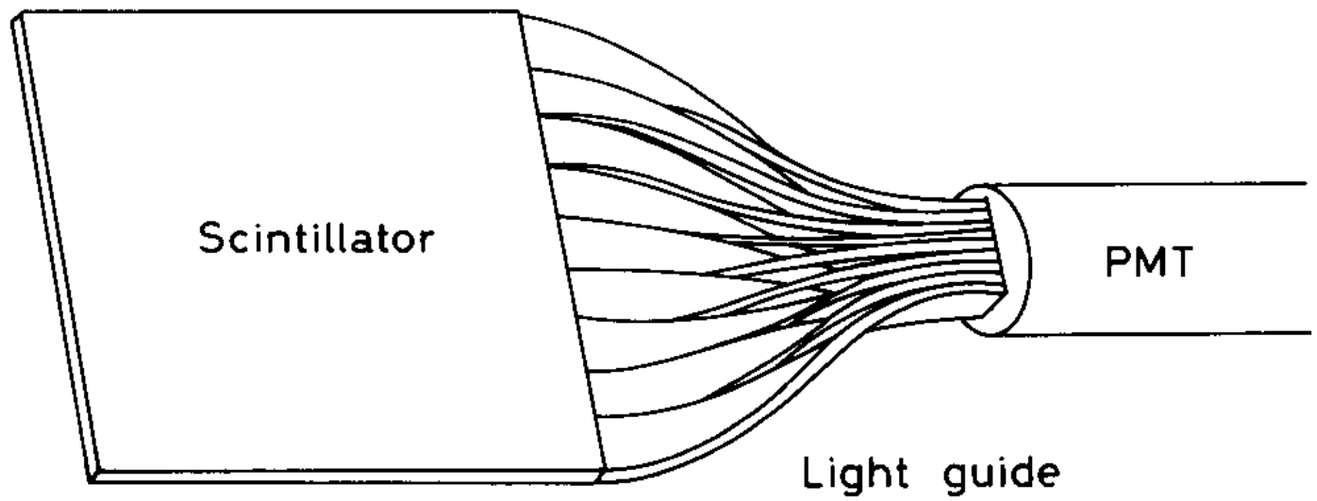
Cheap

Scintillation Counters - Setup

Scintillator light to be guided to photosensor

➔ Light guide
[Plexiglas; optical fibers]

Light transfer by
total internal reflection
[maybe combined with wavelength shifting]

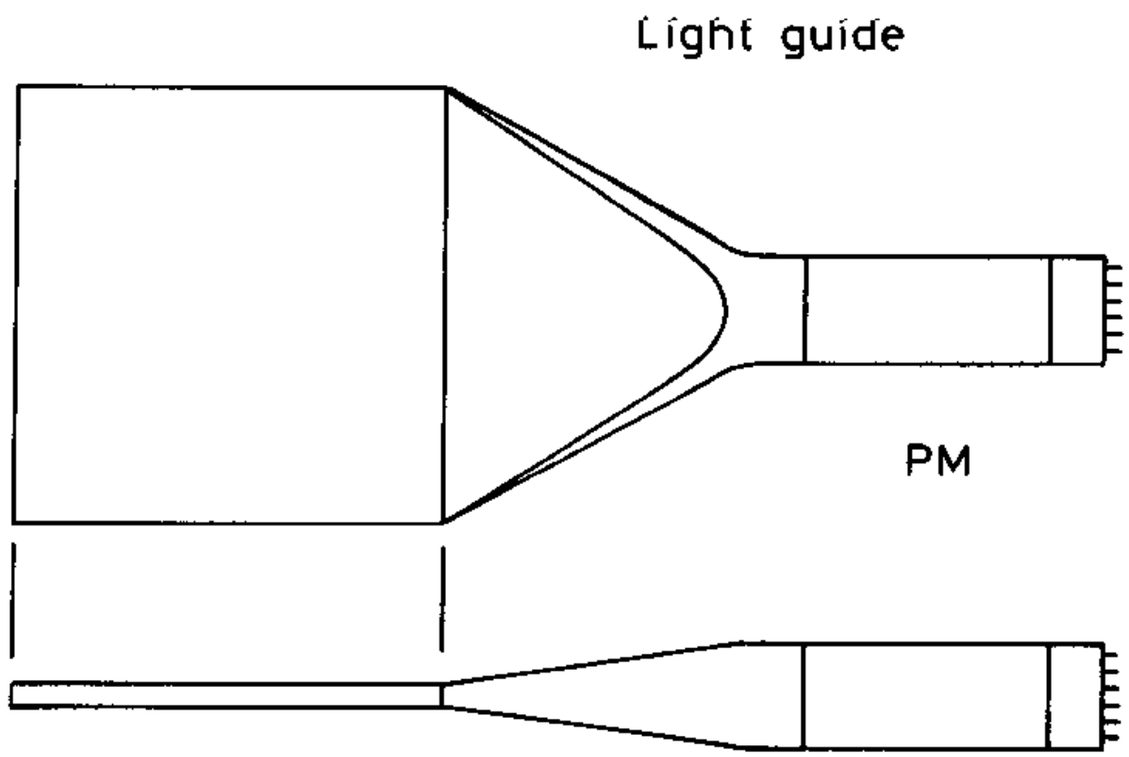


Liouville's Theorem:

Complete light transfer
impossible as $\Delta x \, \Delta\theta = \text{const.}$
[limits acceptance angle]

Use adiabatic light guide
like 'fish tail';

➔ appreciable energy loss



'fish tail'

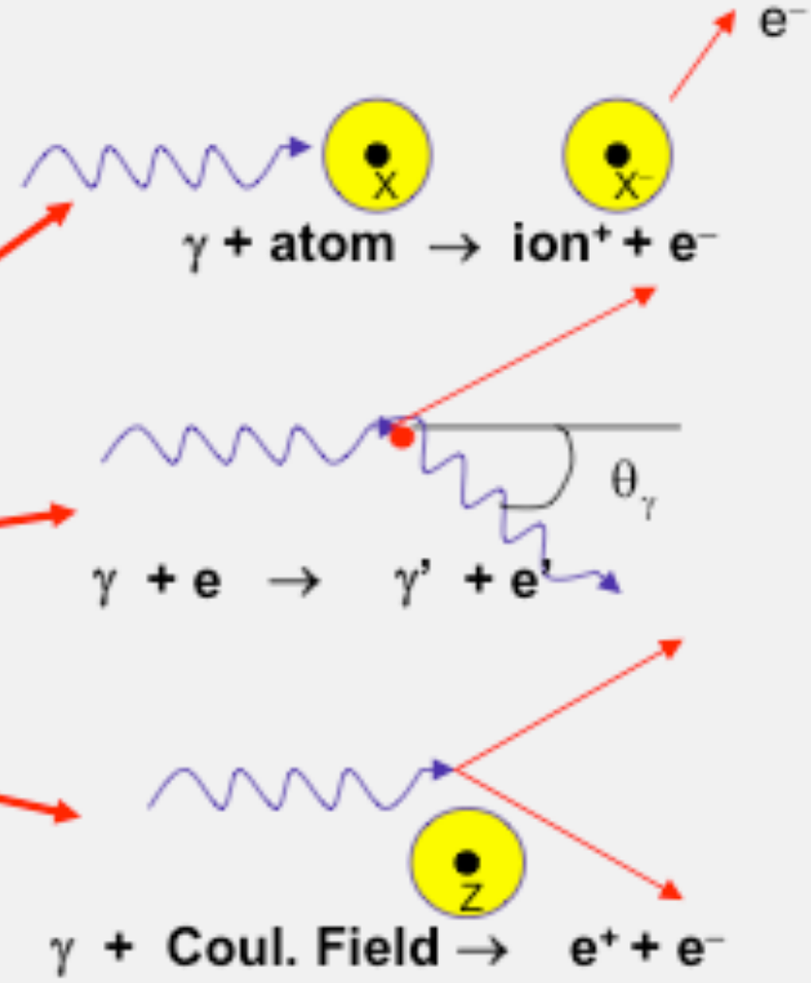
Energy losses by e & γ

BACK

In matter electrons and photons loose energy interacting with nuclei and atomic electrons

Electrons
- ionization (atomic electrons)
- bremsstrahlung (nuclear)

Photons
- photoelectric effect (atomic electrons)
- Compton scattering (atomic electrons)
- pair production (nuclear)



Above 1 GeV radiative processes dominate energy loss by e/γ

TO BACKUP

Reminder: basic electromagnetic interactions

e^+ / e^-

- Ionisation

- Bremsstrahlung

γ

- Photoelectric effect

- Compton effect

- Pair production

Electrons

- Ionization

$$-\frac{dE}{dx}\Big|_{ion} = N_A \frac{Z}{A} \frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2} \frac{Z_i^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

  - $\sigma \propto Z$; $\sigma \propto \ln E/m_e$

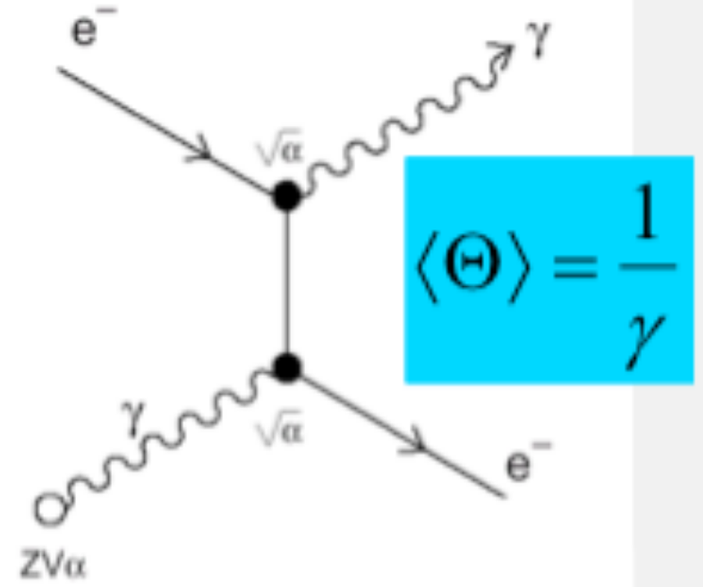
- Bremsstrahlung

$$-\frac{dE}{dx}\Big|_{rad} = \left[4n \frac{Z^2\alpha^3(\hbar c)^2}{m_e^2 c^4} \ln\frac{183}{Z^{1/3}}\right] E$$

$$-\frac{dE}{dx} \propto \frac{Z^2 E}{m^2}$$

$$X_0 = \left[4n \frac{Z^2\alpha^3(\hbar c)^2}{m_e^2 c^4} \ln\frac{183}{Z^{1/3}}\right]^{-1}$$

$$\frac{dE}{dx} = -\frac{E}{X_0} \qquad X_0 \approx \frac{180A}{Z^2}\ g.cm^{-2}$$



$$\langle\Theta\rangle = \frac{1}{\gamma}$$

  - $\sigma \propto Z(Z+1)$; $\sigma \propto A/X_0$ E>1 GeV, $\sigma \propto \ln E/m_e$ E<1 GeV

Radiation length: thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e. For dense materials Xo ~ 1 cm.

Interaction of photons: Summary

In summary: $I_\gamma = I_0 e^{-\mu x}$

μ: mass attenuation coefficient $\mu_i = \frac{N_A}{A}\sigma_i \quad \left[cm^2/g\right]$ $\mu = \mu_{photo} + \mu_{Compton} + \mu_{pair} + \ldots$

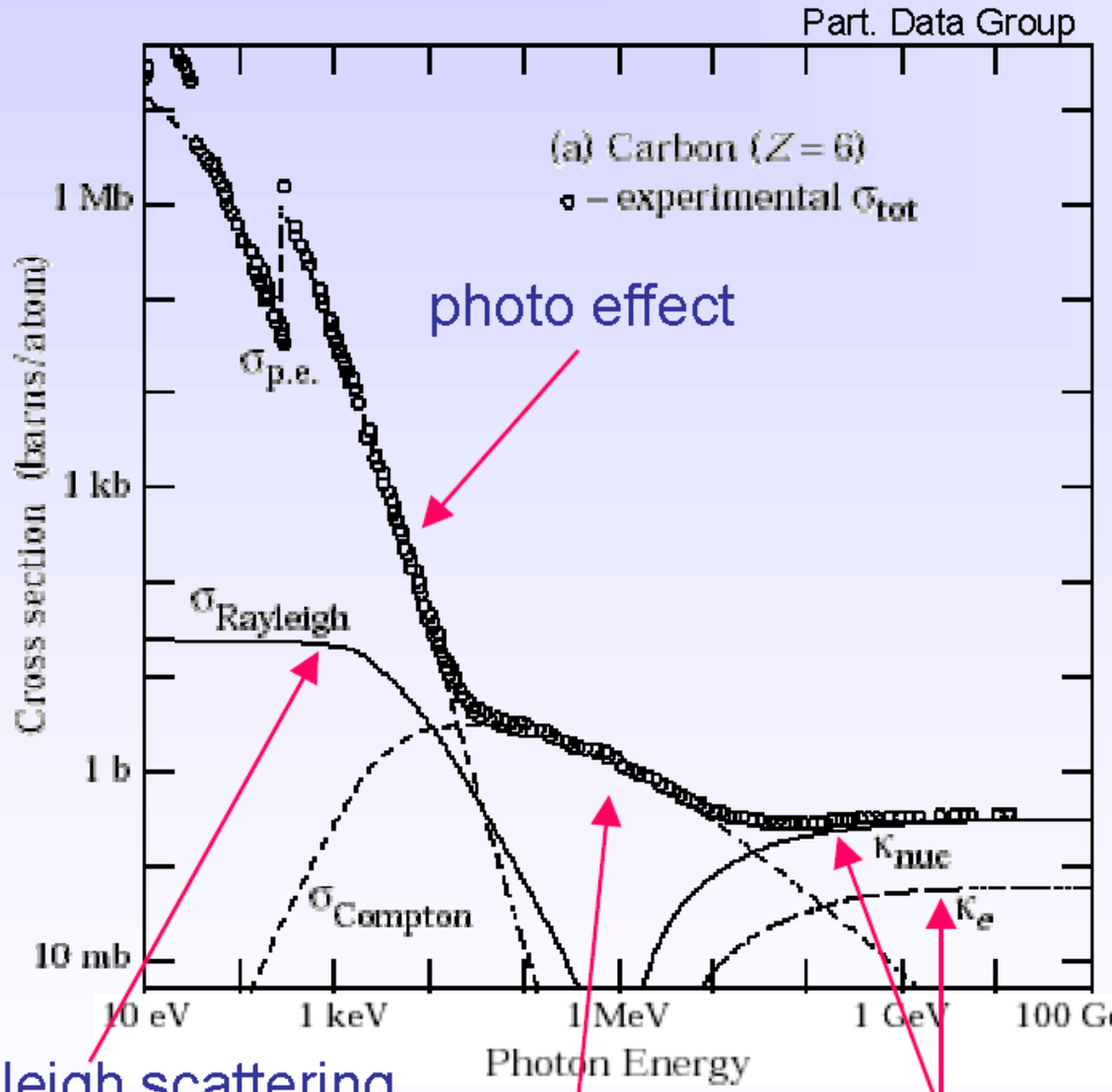
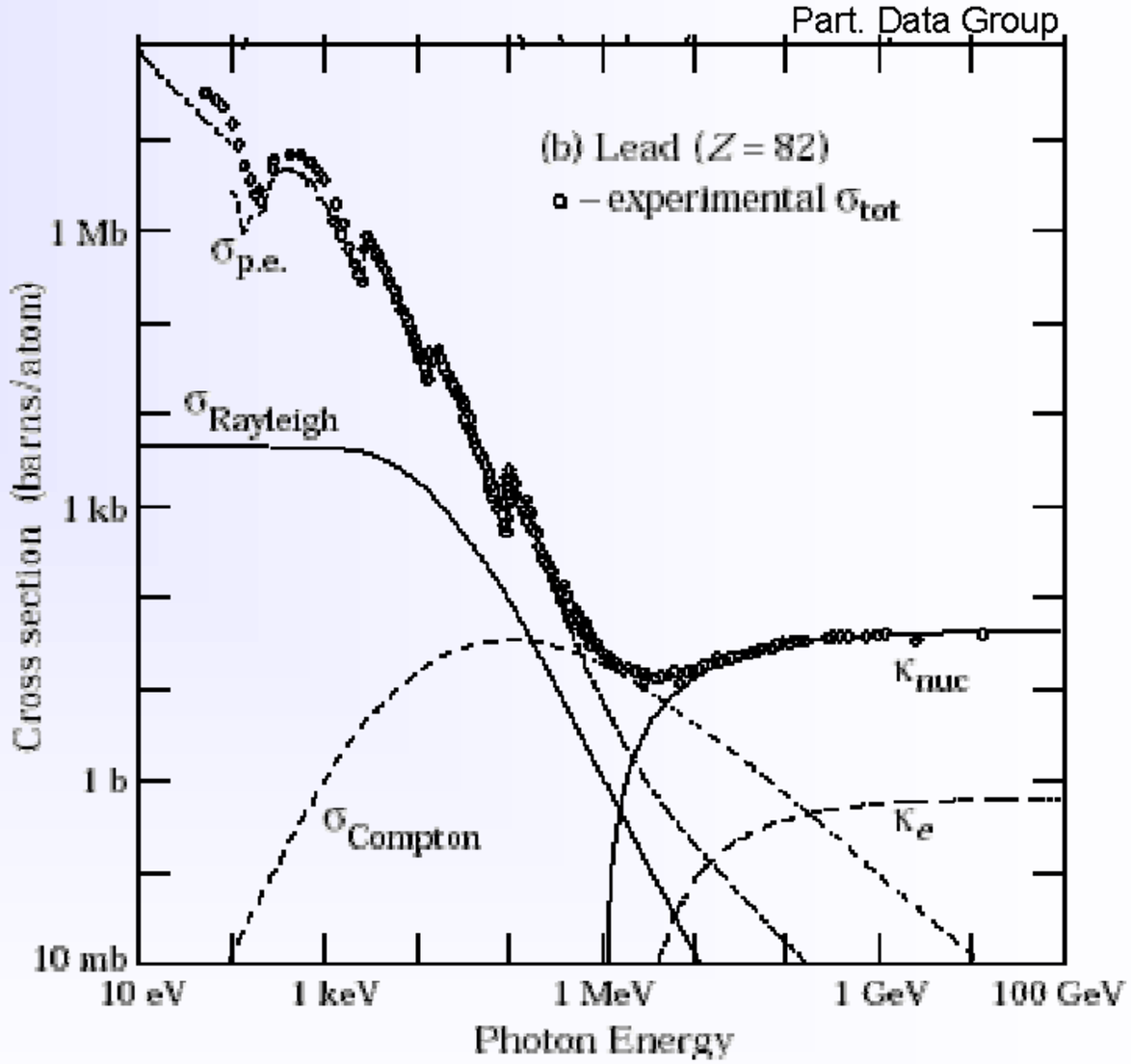


photo effect

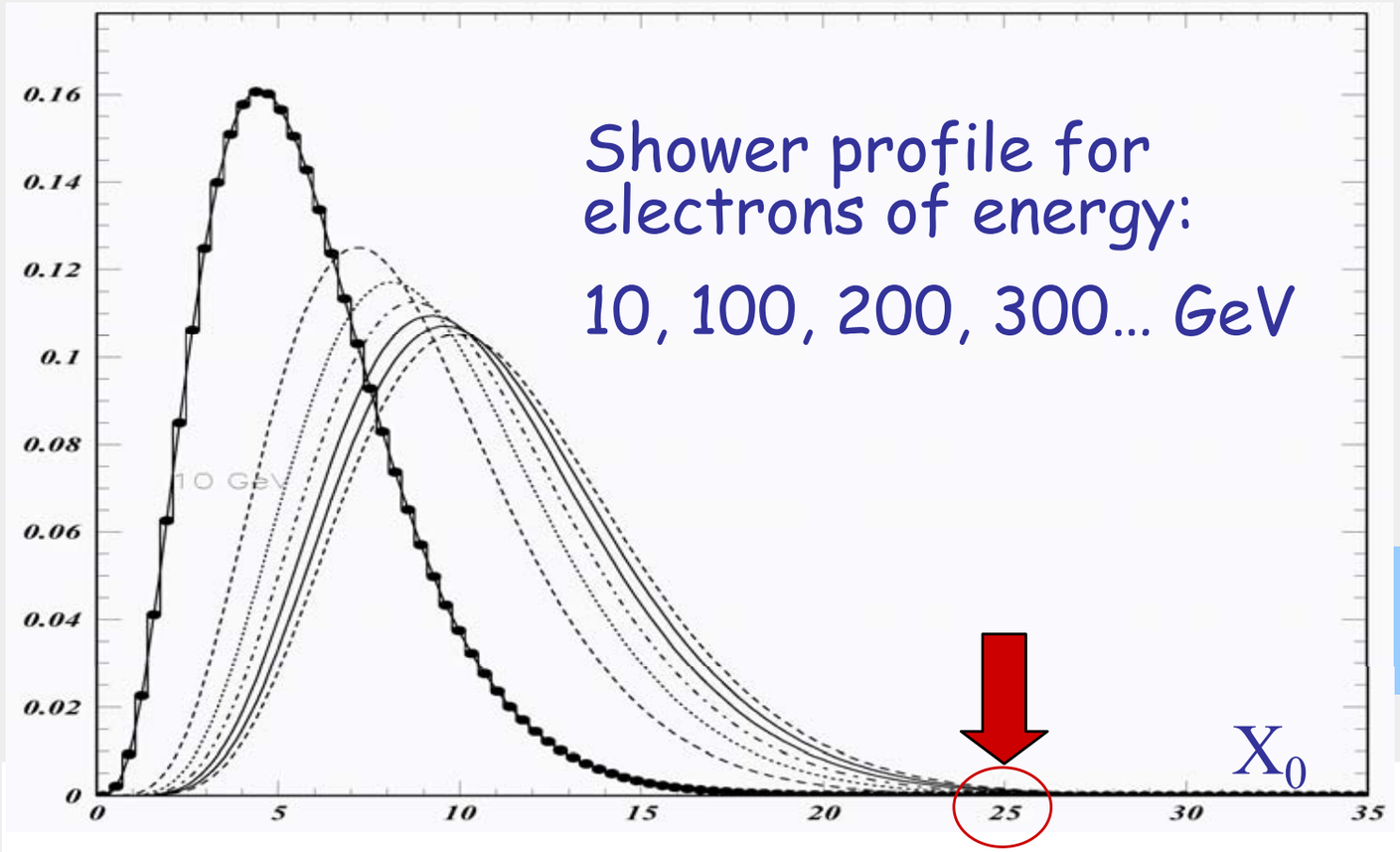
Rayleigh scattering
(no energy loss !)

Compton scattering

pair production



EM showers: longitudinal profile



Shower energy dep parametrization:

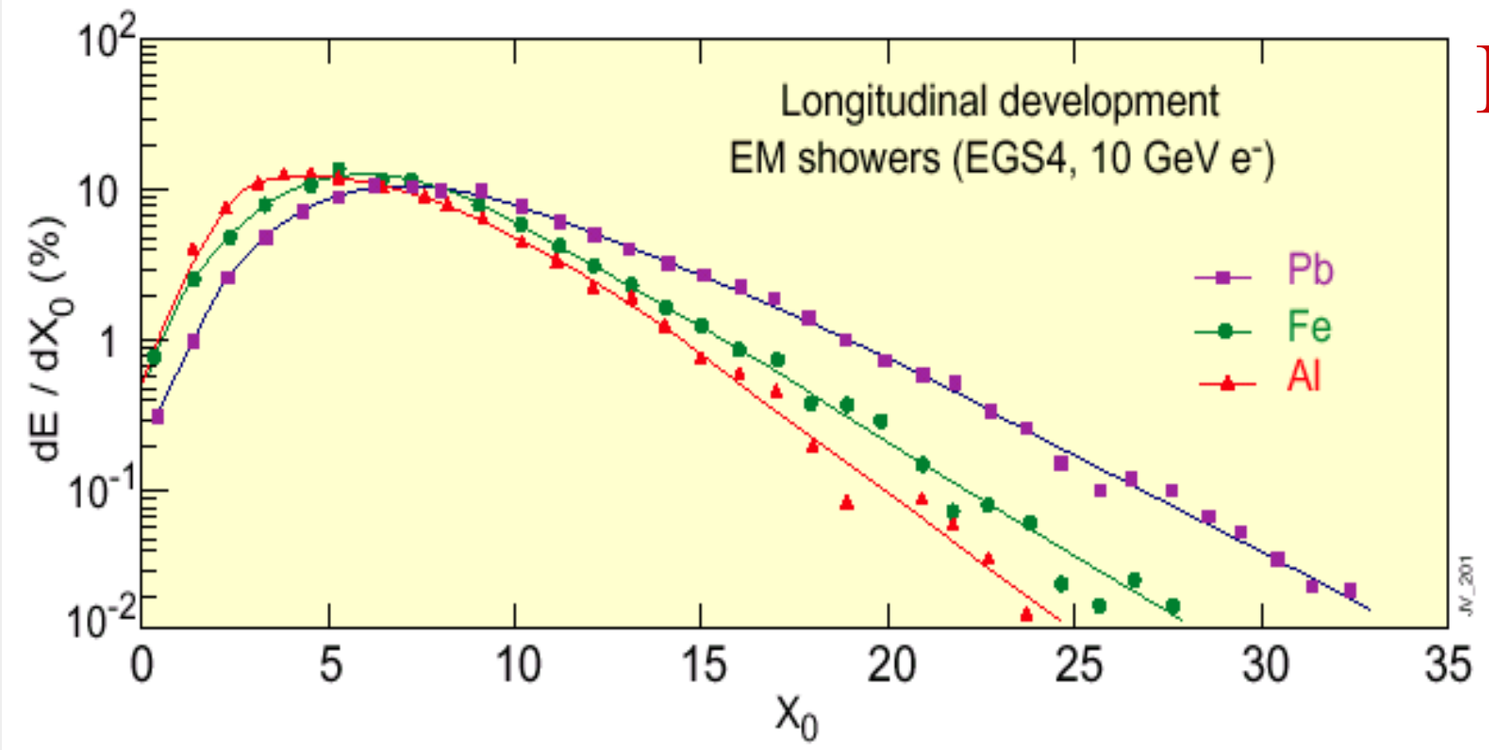
$$\frac{dE}{dt} \propto E_0 t^{\alpha} e^{\beta t}$$

E.Longo & I.Sestili
NIM 128 (1975)

β material dependent

$t_{max} = 1.4 \ln(E_0/E_c)$

$N_{tot} \propto E_0/E_c$



$E_c \alpha 1/Z$ ➡

- shower max
- shower tail

Longitudinal containment:

$t_{95\%} = t_{max} + 0.08Z + 9.6$

EM showers: transverse profile

Transverse shower profile

- Multiple scattering make electrons move away from shower axis
- Photons with energies in the region of minimal absorption can travel far away from shower axis

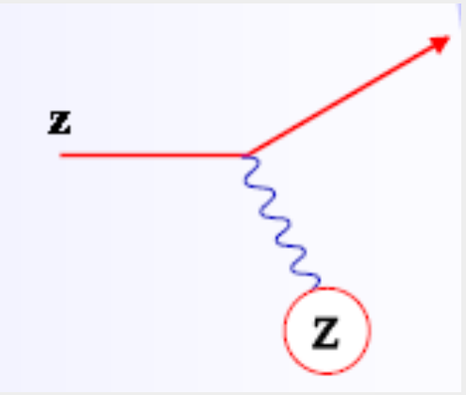
Molière radius sets transverse shower size, it gives the average lateral deflection of critical energy electrons after traversing $1X_0$

$$R_M = \frac{21\text{MeV}}{E_C} X_0 \qquad R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} \left(Z >> 1\right)$$

90% E_0 within $1R_M$, 95% within $2R_M$, 99% within $3.5R_M$

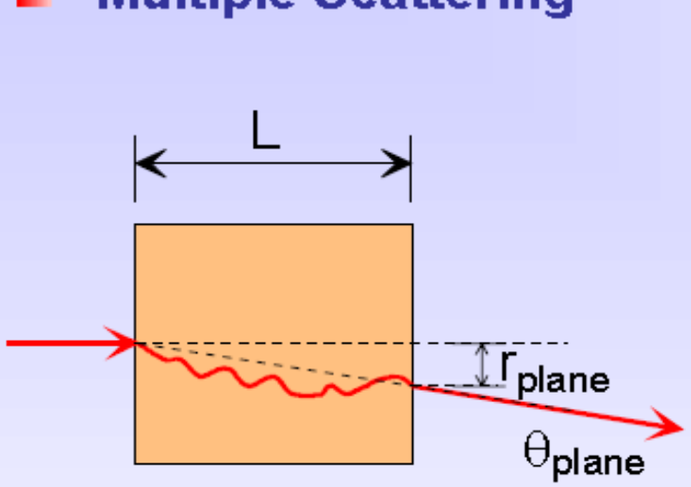
Interaction of charged particles: Multiple Scattering

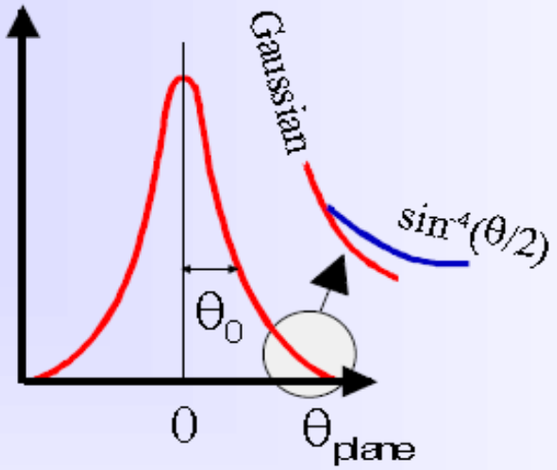
- This process will turn out to be closely related to the transverse profile of electromagnetic showers.
- Coulomb-scattering scales with the squared charges, so scattering in matter is dominated by scattering off nuclei (rather than off electrons), for Z>10. Scattering of spin 0 (Rutherford) and spin 1/2 (Mott) particles are identical in a small-angle approximation.
- Result can be defined in terms of radiation length X_0, to be defined later.



In a sufficiently thick material layer a particle will undergo …

Multiple Scattering

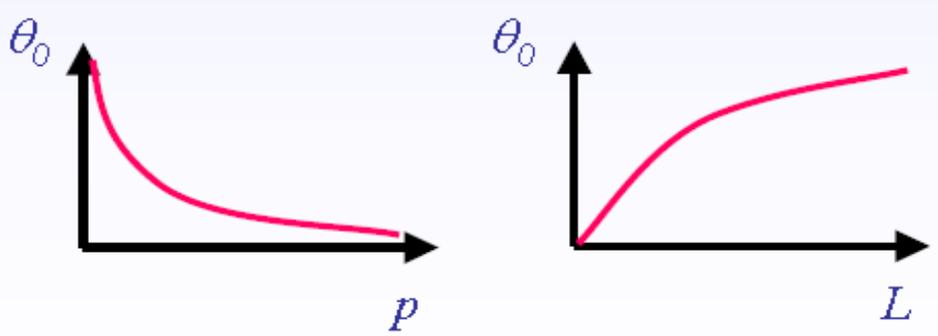




$$\theta_0 = \theta_{plane}^{RMS} = \sqrt{\langle \theta_{plane}^{\ 2} \rangle}$$

$$= \frac{1}{\sqrt{2}} \theta_{space}^{RMS}$$

Approximation $\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$ X_0 is radiation length of the medium (discuss later)



TO BACKUP

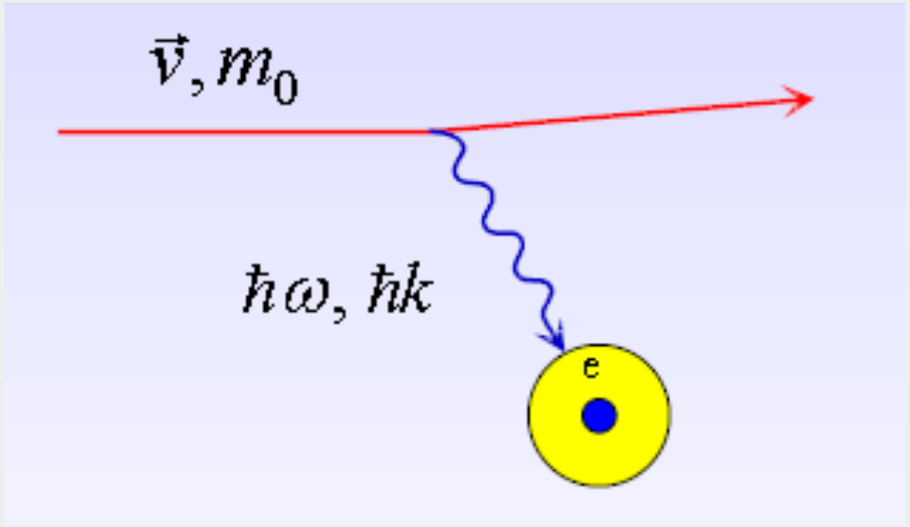
Interaction of charged particles

Detection of charged particles

Particles can only be detected if they deposit energy in matter.

How do they lose energy in matter ?

Discrete collisions with the atomic electrons of the absorber material.



$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE} \hbar \, d\omega$$

N : electron density

Collisions with nuclei not important ($m_e << m_N$) for energy loss.

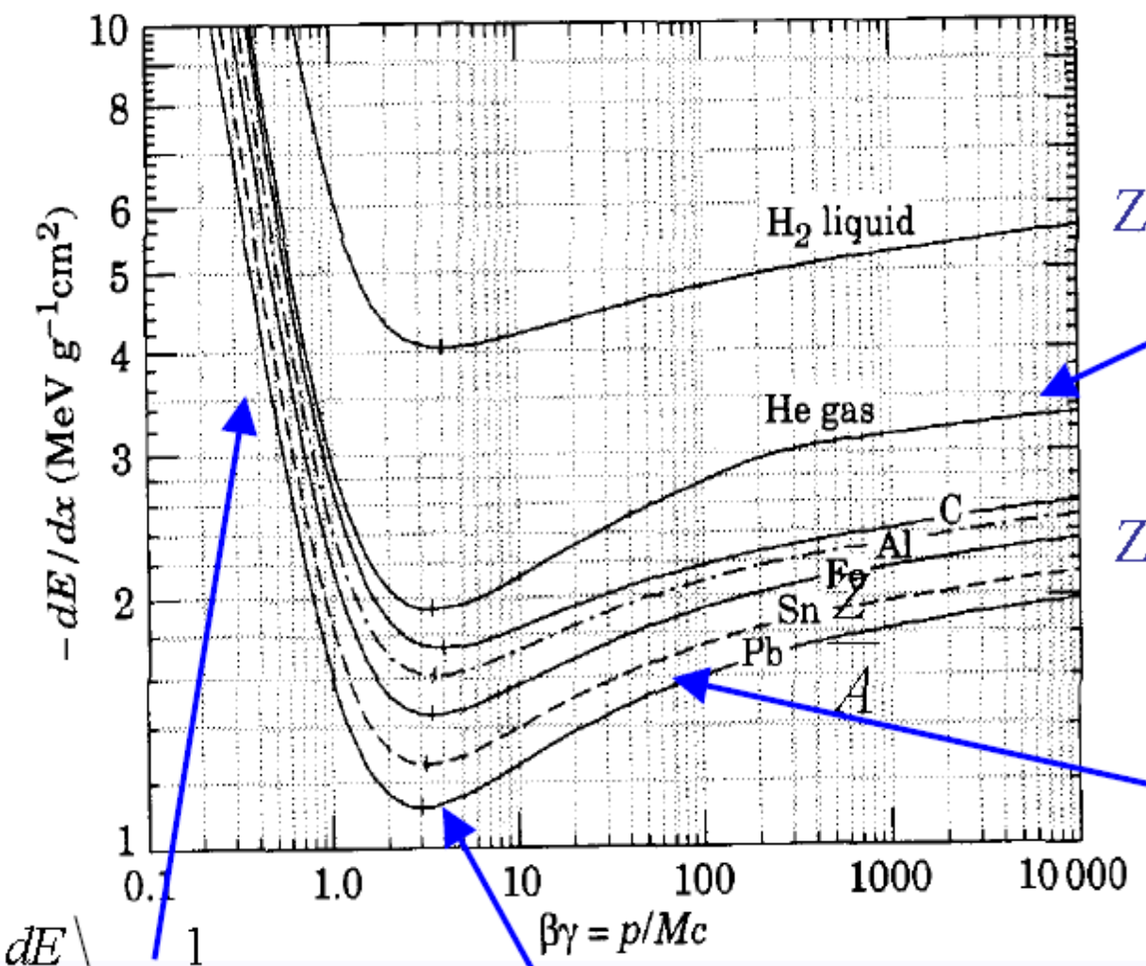
If $\hbar\omega, \hbar k$ are in the right range ⟹ **ionization**.

Interaction of charged particles: Bethe-Bloch formula

- Energy loss by ionization only: **Bethe-Bloch formula**

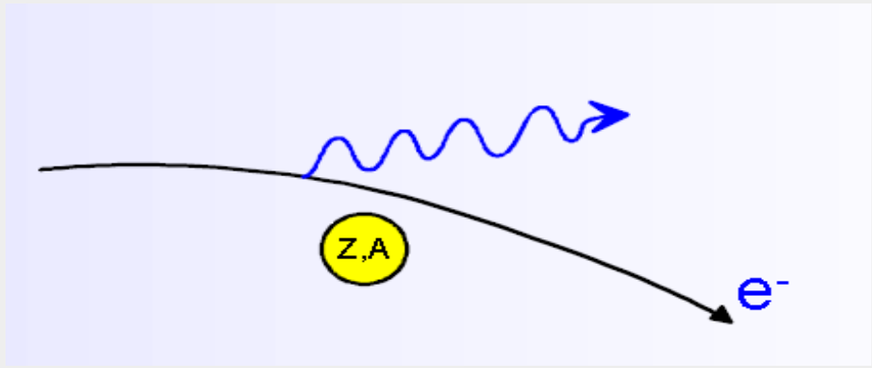
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

- dE/dx in [MeV g^{-1} cm^2]
- Valid for "heavy"particles ($m \geq m_\mu$).
- dE/dx depends only on β, independent of m !
- First approximation: medium simply characterized by Z/A ~ electron density



Interaction of charged particles: Bremsstrahlung

- Energy loss by bremsstrahlung



Radiation of real photons in the Coulomb field
of the nuclei of the absorber medium:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

Effect plays a role only for e± and ultra-relativistic μ (>1000 GeV)

For electrons:
$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \quad \Longrightarrow \quad E = E_0\, e^{-x/X_0}$$

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

radiation length [g/cm^2]

(divide by specific density to get X_0 in cm)

Interaction of charged particles: Critical energy E_c

- Critical energy E_c

$$\left.\frac{dE}{dx}(E_c)\right|_{Brems} = \left.\frac{dE}{dx}(E_c)\right|_{ion}$$

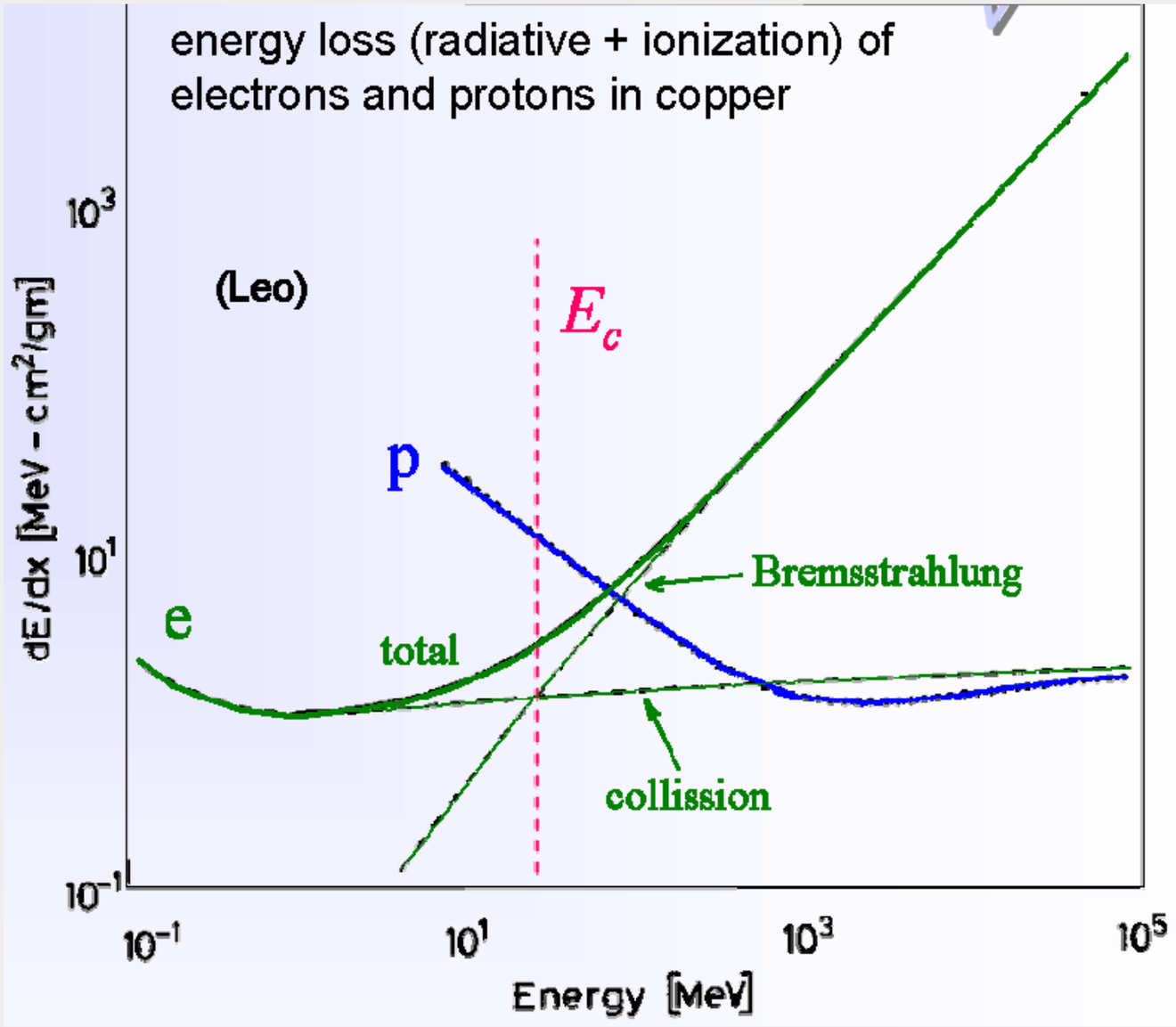
For electrons one finds approximately:

$$E_c^{solid+liq} = \frac{610MeV}{Z+1.24} \qquad E_c^{gas} = \frac{710MeV}{Z+1.24}$$

$E_c(e^-)$ in Cu(Z=29) = 20 MeV

For muons $E_c \approx E_c^{elec}\left(\frac{m_\mu}{m_e}\right)^2$

$E_c(\mu)$ in Cu $\approx$ 1 TeV



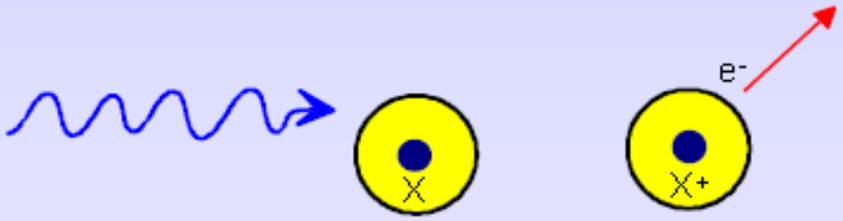
Unlike electrons, muons in multi-GeV range can travers thick layers of dense matter.

Find charged particles traversing the calorimeter? → most likely a muon

Interaction of photons: Photo-electric effect

In order to be detected, a photon has to create charged particles and/or transfer energy to charged particles

Photo-electric effect: (already met in photocathodes of photodetectors)



Only possible in the close neighborhood of a third collision partner → photo effect releases mainly electrons from the K-shell.

$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$

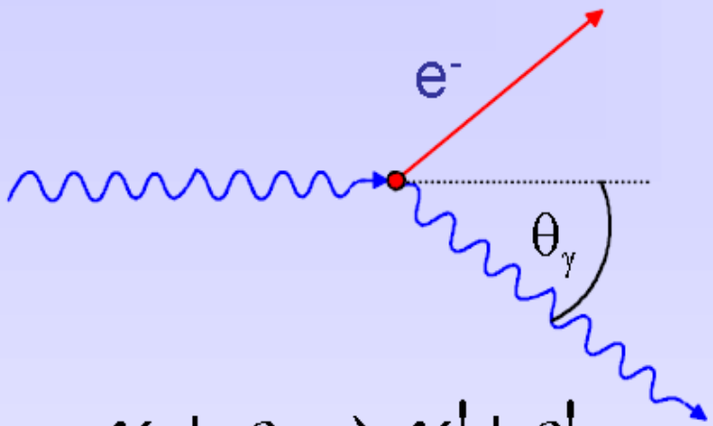
Cross section shows strong modulation if $E_\gamma \approx E_{shell}$

$$\sigma^{K}_{photo} = \left(\frac{32}{\varepsilon^7}\right)^{\frac{1}{2}} \alpha^4 Z^5 \sigma^{e}_{Th} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2} \qquad \sigma^{e}_{Th} = \frac{8}{3}\pi r_e^2 \quad \text{(Thomson)}$$

At high energies ($\varepsilon >> 1$)

$$\sigma^{K}_{photo} = 4\pi r_e^2 \alpha^4 Z^5 \frac{1}{\varepsilon} \qquad \sigma_{photo} \propto Z^5$$

Interaction of photons: Compton scattering

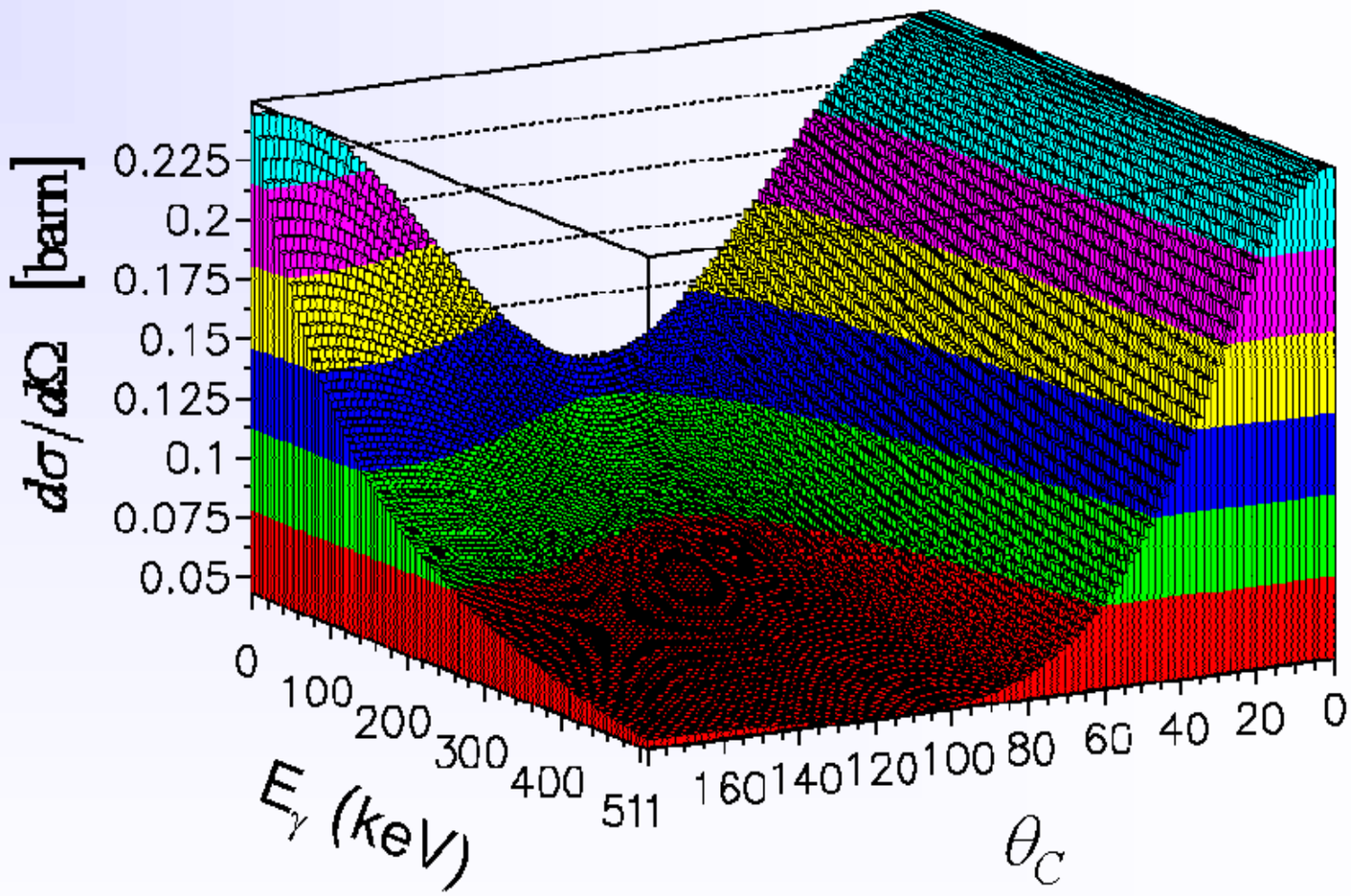


$$\gamma + e \rightarrow \gamma' + e'$$

$$E'_\gamma = E_\gamma \frac{1}{1+\varepsilon\left(1-\cos\theta_\gamma\right)}$$

$$E_e = E_\gamma - E'_\gamma$$

Compton cross-section (Klein-Nishina)



Assume electron as quasi-free.

Klein-Nishina $\frac{d\sigma}{d\Omega}(\theta,\varepsilon)$ →

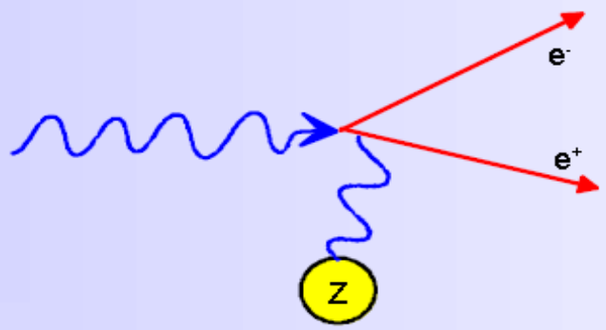
At high energies approximately

$$\sigma_c^e \propto \frac{\ln\varepsilon}{\varepsilon}$$

Atomic Compton cross-section:

$$\sigma_c^{atomic} = Z \cdot \sigma_c^e$$

Interaction of photons: Pair production



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

Only possible in the Coulomb field of a nucleus (or an electron) if $E_\gamma \geq 2m_e c^2$

Cross-section (high energy approximation)

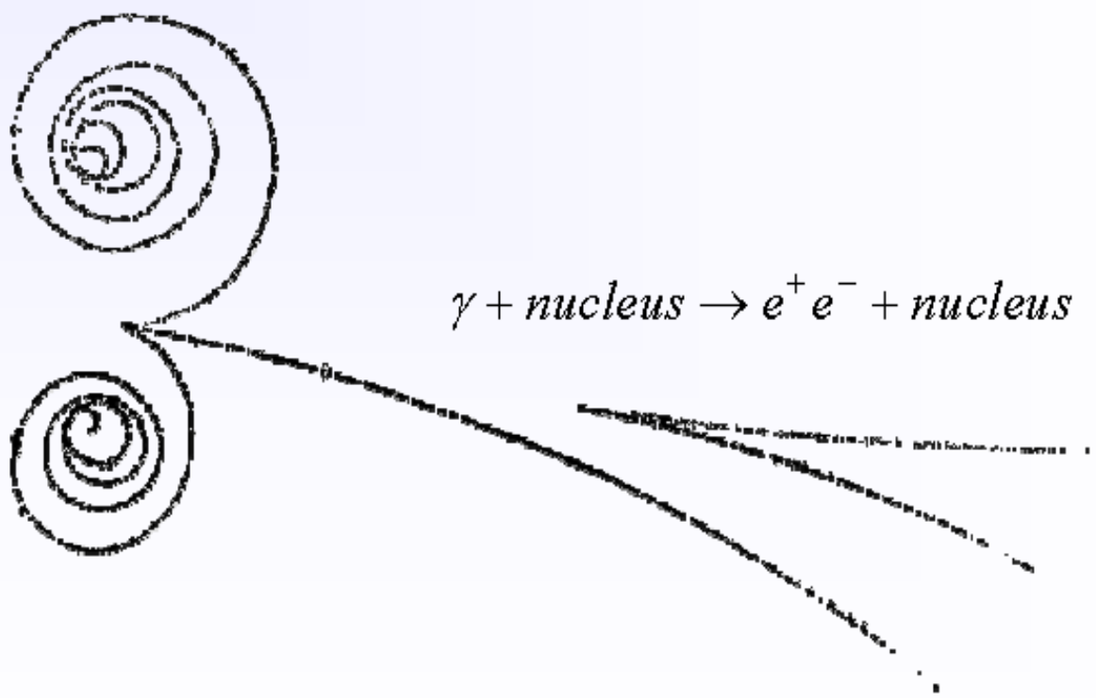
$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9}\ln\frac{183}{Z^{\frac{1}{3}}}\right)$$ independent of energy !

$$\approx \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

$$\approx \frac{A}{N_A}\frac{1}{\lambda_{pair}}$$

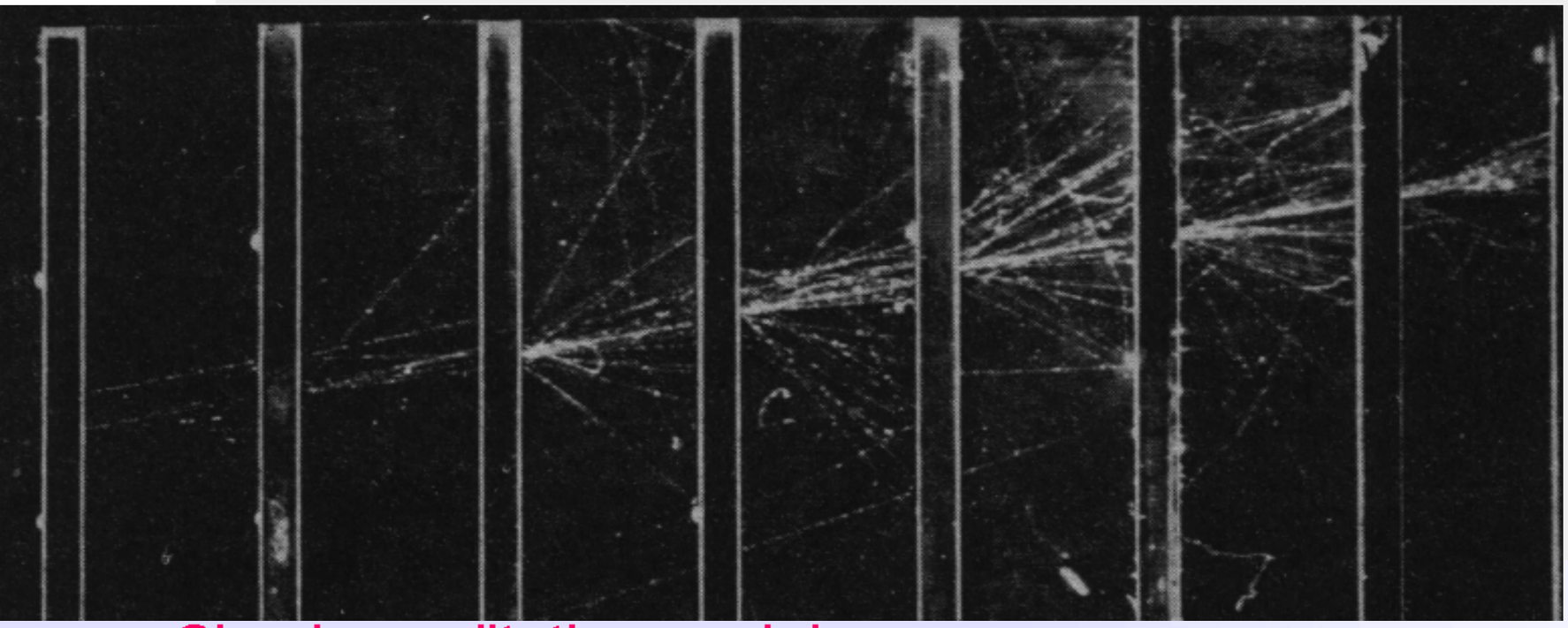
$$\lambda_{pair} = \frac{9}{7}X_0$$

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



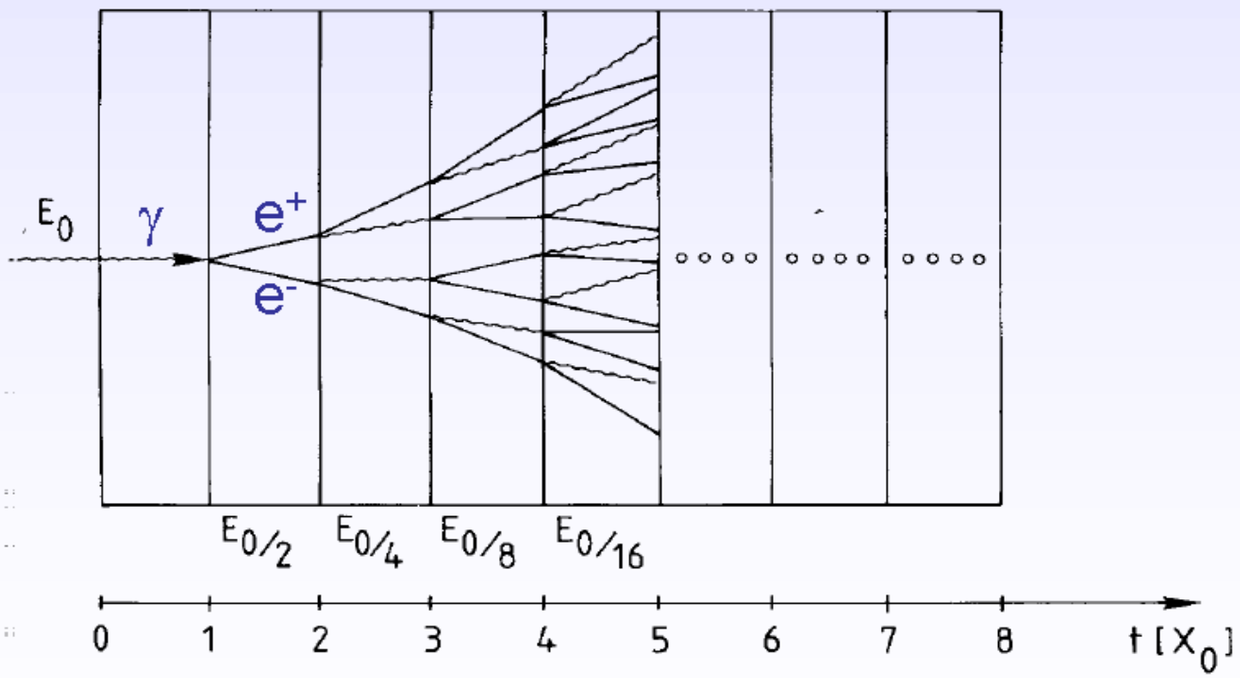
$\gamma + nucleus \rightarrow e^+e^- + nucleus$

Electromagnetic cascades (showers)



Electromagnetic shower in a cloud chamber with lead absorbers

Simple qualitative model



- Consider only Bremsstrahlung and (symmetric) pair production.
- Assume: $X_0 \sim \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t) < E_c$

$$N^{total} = \sum_{t=0}^{t_{max}} 2^t = 2^{(t_{max}+1)} - 1 \approx 2 \cdot 2^{t_{max}} = 2\frac{E_0}{E_c}$$

$$t_{max} = \frac{\ln E_0/E_c}{\ln 2}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect → absorption of energy.

Electromagnetic shower development

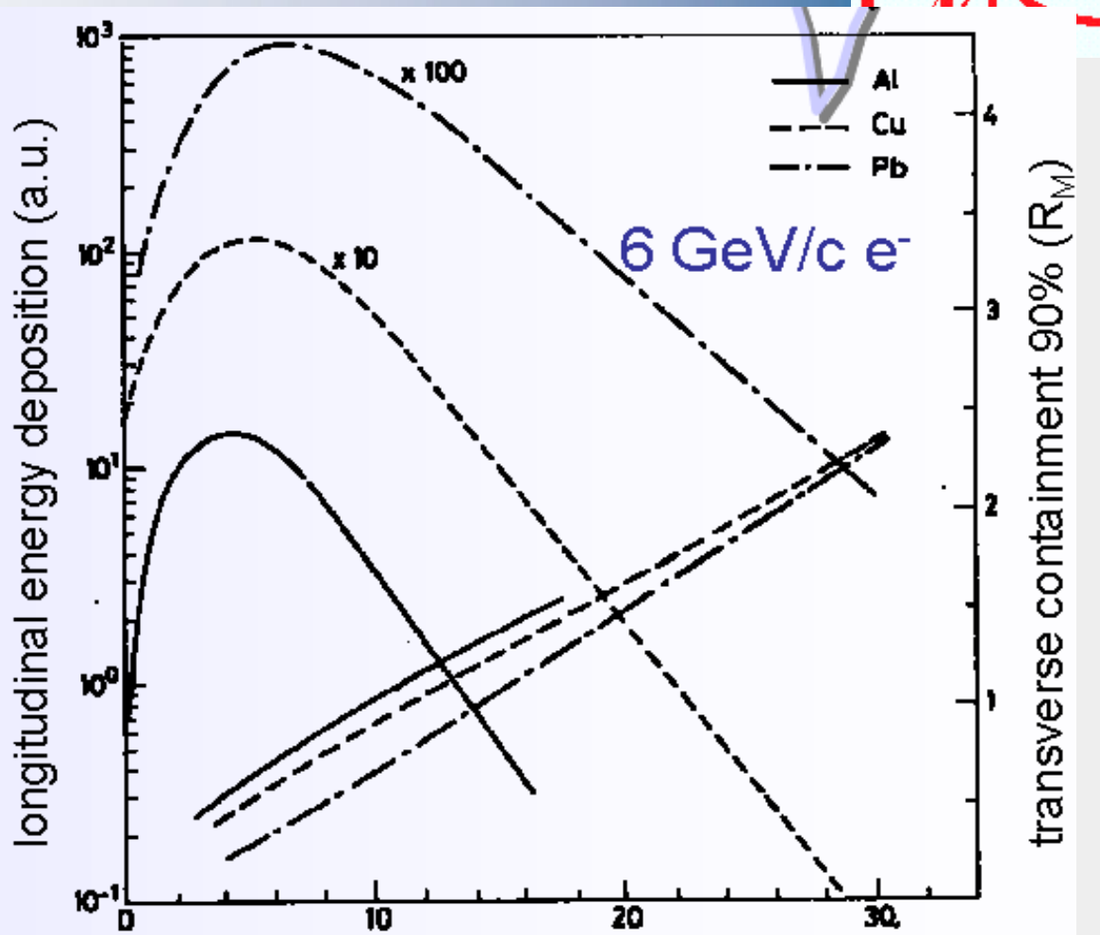
Longitudinal shower development

$$\frac{dE}{dt} \propto t^{\alpha} e^{-t}$$

Shower maximum at $t_{\max} = \ln \frac{E_0}{E_c} \frac{1}{\ln 2}$

95% containment $t_{95\%} \approx t_{\max} + 0.08Z + 9.6$

Size of a calorimeter grows only logarithmically with E_0 ,



(C. Fabjan, T. Ludlam, CERN-EP/82-37)

Transverse shower development

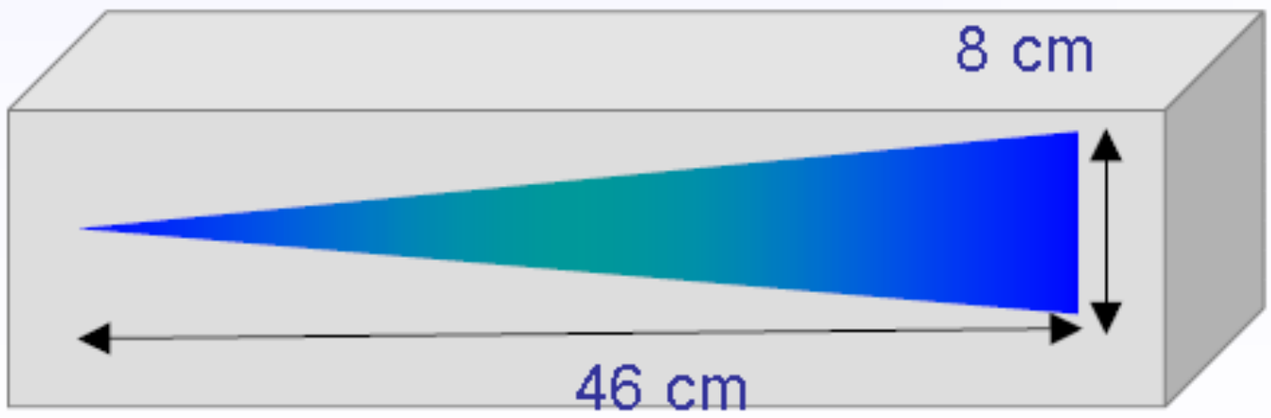
95% of the shower cone is located in a cylinder with radius 2 R_M

Molière radius $R_M = \frac{21\,\text{MeV}}{\ldots} X_0 \quad [g/cm^2]$

Example: E_0 = 100 GeV in lead glass

E_c=11.8 MeV $\rightarrow t_{max} \approx 13$, $t_{95\%} \approx 23$

$X_0 \approx 2$ cm, $R_M = 1.8 \cdot X_0 \approx 3.6$ cm



BACK

Some Useful 'Rules of Thumbs'

Radiation length:

$$X_0 = \frac{180A}{Z^2}\ \frac{\mathrm{g}}{\mathrm{cm}^2}$$

Critical energy:
[Attention: Definition of Rossi used]

$$E_c = \frac{550\ \mathrm{MeV}}{Z}$$

Shower maximum:

$$t_{\max} = \ln\frac{E}{E_c} - \begin{cases} 1.0 & e^- \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

Problem:
Calculate how much Pb, Fe or Cu is needed to stop a 10 GeV electron.

Pb : Z=82 , A=207, ρ=11.34 g/cm^3
Fe : Z=26 , A=56, ρ=7.87 g/cm^3
Cu : Z=29 , A=63, ρ=8.92 g/cm^3

Longitudinal
energy containment:

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

Transverse
Energy containment:

$$R(90\%) = R_M$$
$$R(95\%) = 2R_M$$

Position resolution - EM

- Reconstruction of invariant masses of particles decaying into photons, electron identification using match with track measured in tracking devices
- Impact position of showers is determined using the transverse (and longitudinal) energy distribution in calorimeter cells
- Method based on center of gravity (COG) calculation
  - works for projective geometry and particles coming from the interaction vertex
  - calorimeter cell size d $\leq 1R_M$
- Typical resolutions: few mm/$\sqrt{E}$

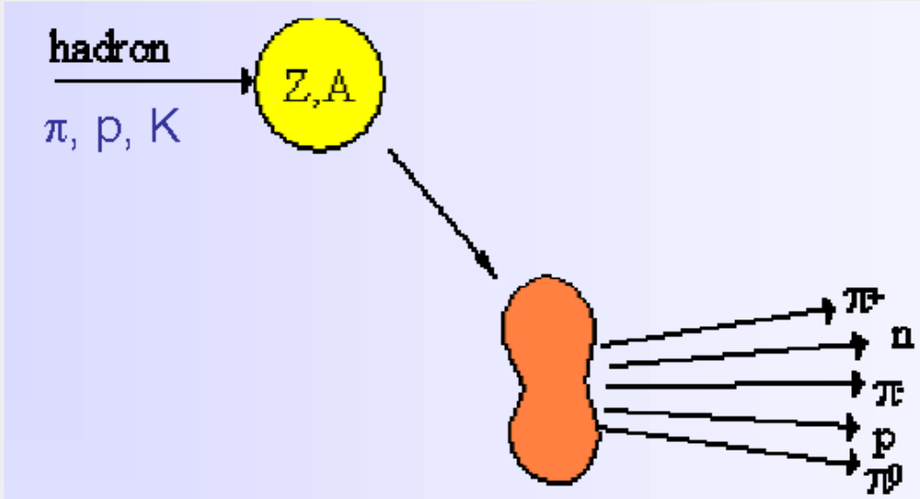
TO BACKUP

Nuclear Interactions

BACK

The interaction of energetic hadrons (charged or neutral) with matter is determined by inelastic nuclear processes.

Excitation and finally break-up of nucleus
→ nucleus fragments
+ production of secondary particles.



multiplicity $\propto \ln(E)$

$p_t \approx 0.35$ GeV/c

For high energies (>1 GeV) the cross-sections depend only little on the energy and on the type of the incident particle (π, p, K…).

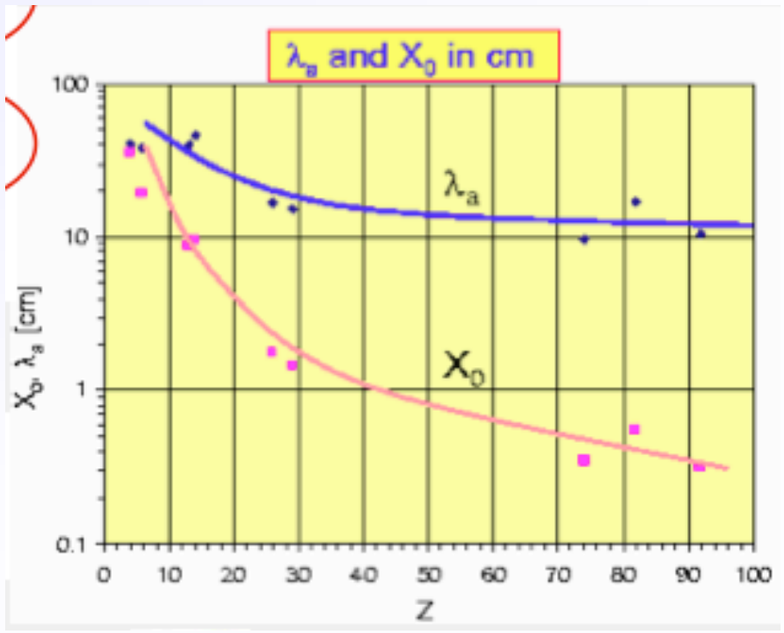
$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \approx 35\,mb$$

In analogy to X_0 a hadronic absorption length can be defined

$$\lambda_a = \frac{A}{N_A \sigma_{inel}} \propto A^{\frac{1}{4}} \quad \text{because} \quad \sigma_{inel} \approx \sigma_0 A^{0.7}$$

similarly a hadronic interaction length

$$\lambda_I = \frac{A}{N_A \sigma_{total}} \propto A^{\frac{1}{3}} \qquad \lambda_I < \lambda_a$$



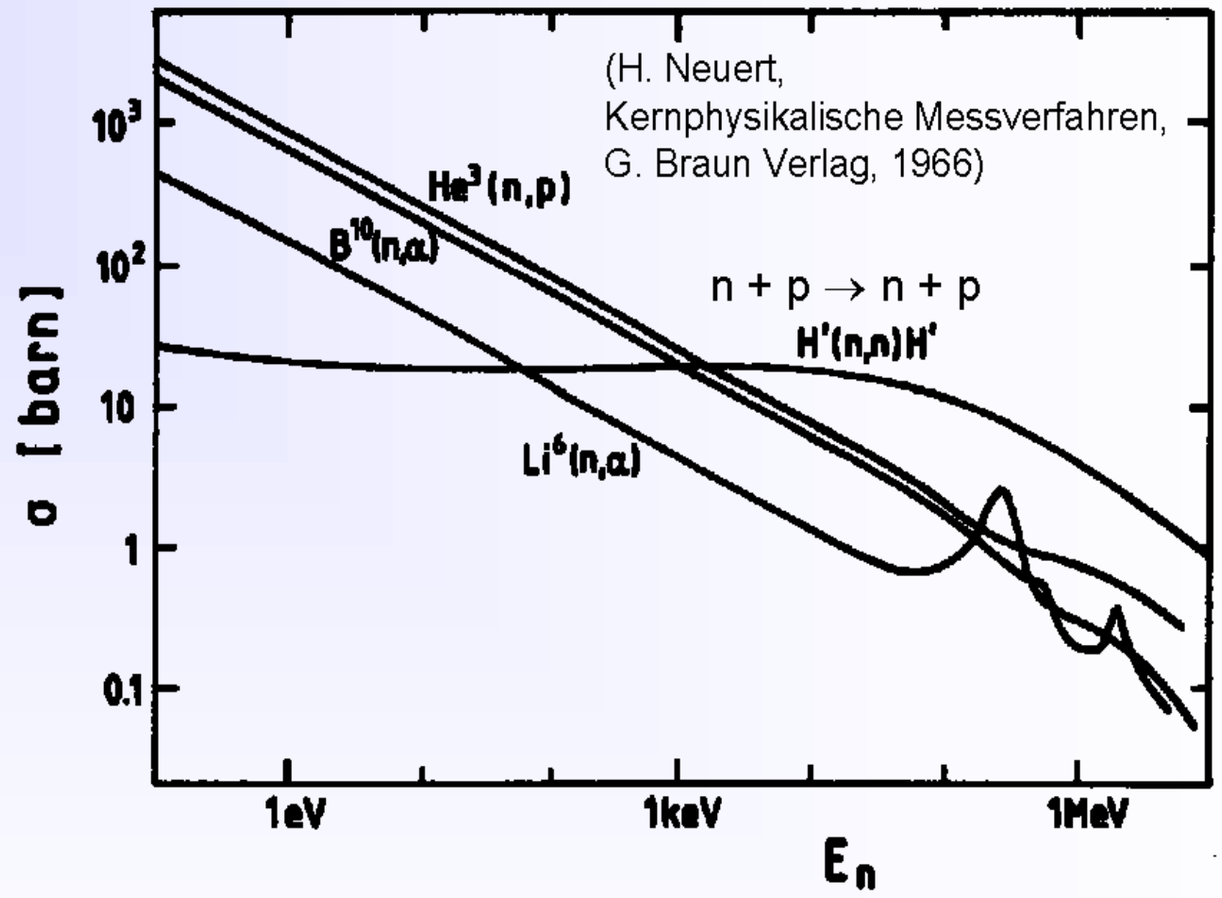
TO BACKUP

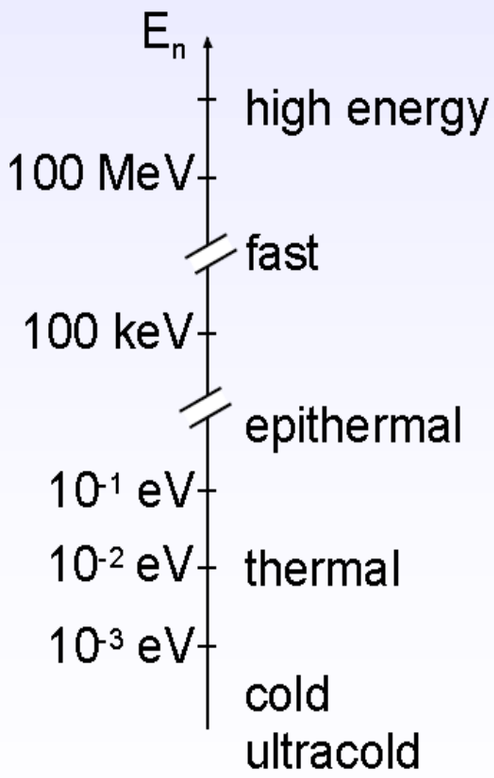
Interaction of neutrons

Neutrons have no charge, i.e. their interaction is based only on strong (and weak) nuclear force. To detect neutrons, we have to create charged particles.
Possible neutron conversion and elastic reactions …

$n + {}^{6}Li \rightarrow \alpha + {}^{3}H$
$n + {}^{10}B \rightarrow \alpha + {}^{7}Li$
$n + {}^{3}He \rightarrow p + {}^{3}H$
} $E_n < 20$ MeV

$n + p \rightarrow n + p$ $E_n < 1$ GeV





In addition there are …

- neutron induced fission $E_n \approx E_{th} \approx 1/40$ eV
- inelastic reactions → hadronic cascades (see below) $E_n > 1$ GeV

Interaction neutrinos

Neutrinos interact only weakly → tiny cross-sections. For their detection we need again first a charged particle. Possible detection reactions:

$$\nu_\ell + n \rightarrow \ell^- + p \qquad \ell = e, \mu, \tau$$
$$\bar{\nu}_\ell + p \rightarrow \ell^+ + n \qquad \ell = e, \mu, \tau$$

The cross-section for the reaction $\nu_e + n \rightarrow e^- + p$ is of the order of 10^{-43} cm^2 (per nucleon, $E_\nu \approx$ few MeV).

→ detection efficiency $\varepsilon_{\text{det}} = \sigma \cdot N^{surf} = \sigma \cdot \rho \frac{N_A}{A} d$

1 m Iron: $\varepsilon_{\text{det}} \approx 5 \cdot 10^{-17}$

1 km water: $\varepsilon_{\text{det}} \approx 6 \cdot 10^{-15}$

Neutrino detection requires big and massive detectors (ktons - Mtons) and very high neutrino fluxes (e.g. 10^{20} ν / yr).

In collider experiments fully hermetic detectors allow to detect neutrinos indirectly:

- sum up all visible energy and momentum.
- attribute missing energy and momentum to neutrino.

Hadron showers

All the fluctuations described in em case plus more and more significant

- Breakdown of ***non-em*** energy deposit in lead absorber:
  - *Ionizing particles* *56%* (2/3 from spallation protons)
  - *Neutrons* *10%* (37 neutrons per GeV!)
  - *Invisible* *34%*

Spallation protons carry typically 100 MeV,
Evaporation neutrons 3 MeV

An important fraction of energy goes in nuclear binding: not detectable!

FLUCTUATIONS OF E_{vis} : INTRINSIC LIMIT TO HADRONIC ENERGY MEASUREMENT

- Hadron showers contain em component (π^o, η)
- Size of em component F_{em} is mainly determined by the first interaction
- On average 1/3 of mesons produced in the 1° interaction will be a π^o, this fraction fluctuates in a significant way
- The 2° generation $\pi^{\pm}$ will produce π^o if enough energetic

An important fraction of energy goes in em deposits and strongly varies

Hadronic Showers

Hadronic interaction:

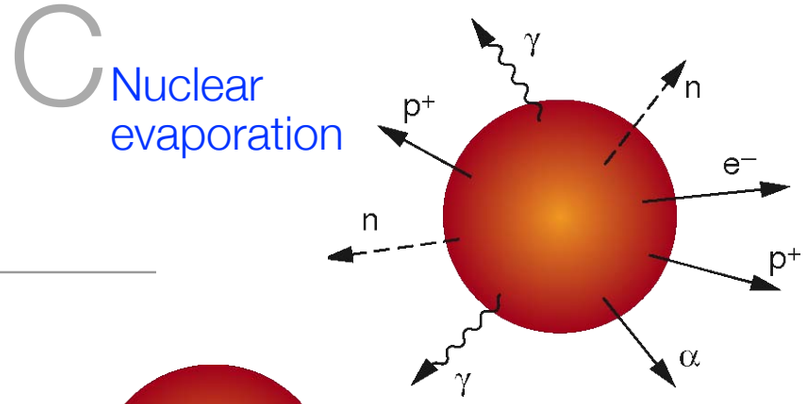
Elastic:

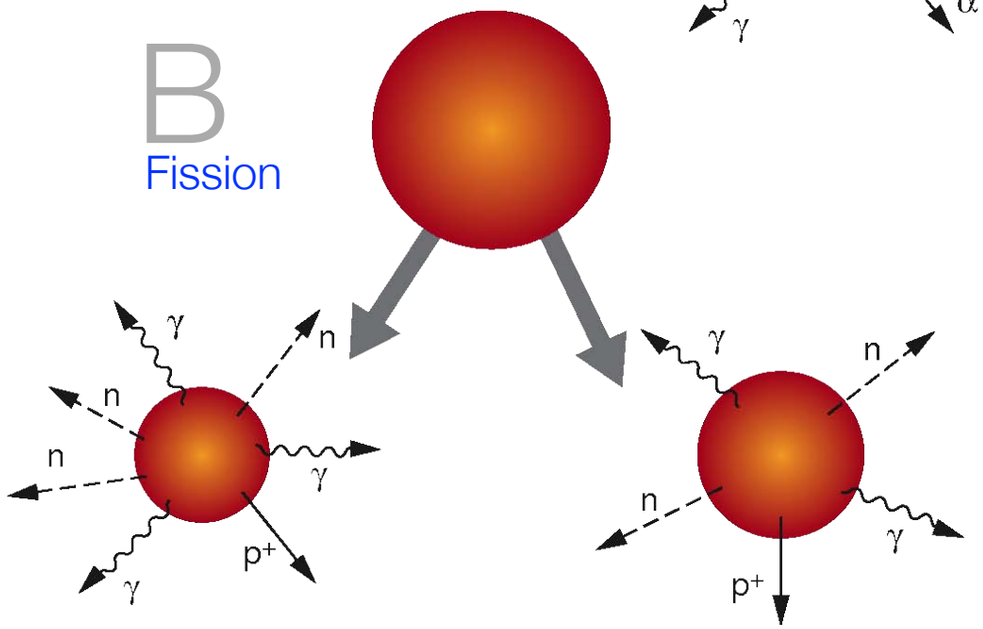
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

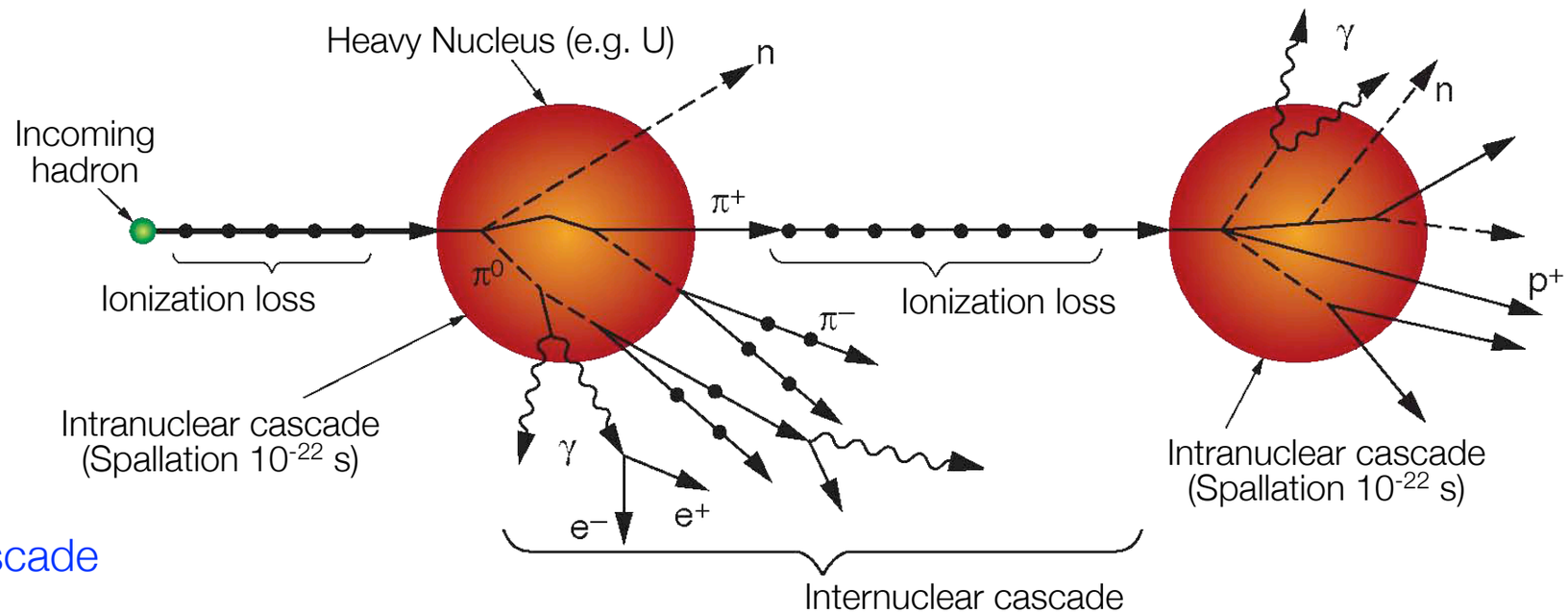
Inelastic:

$$p + \text{Nucleus} \rightarrow \pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ \qquad\quad \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ \qquad\quad \rightarrow \text{Nuclear fission} \end{array}\right]$$







A
Inter- and intranuclear cascade

TO BACKUP

Hadronic Showers

Hadronic interaction:

Cross Section:

at high energies
also diffractive contribution

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$

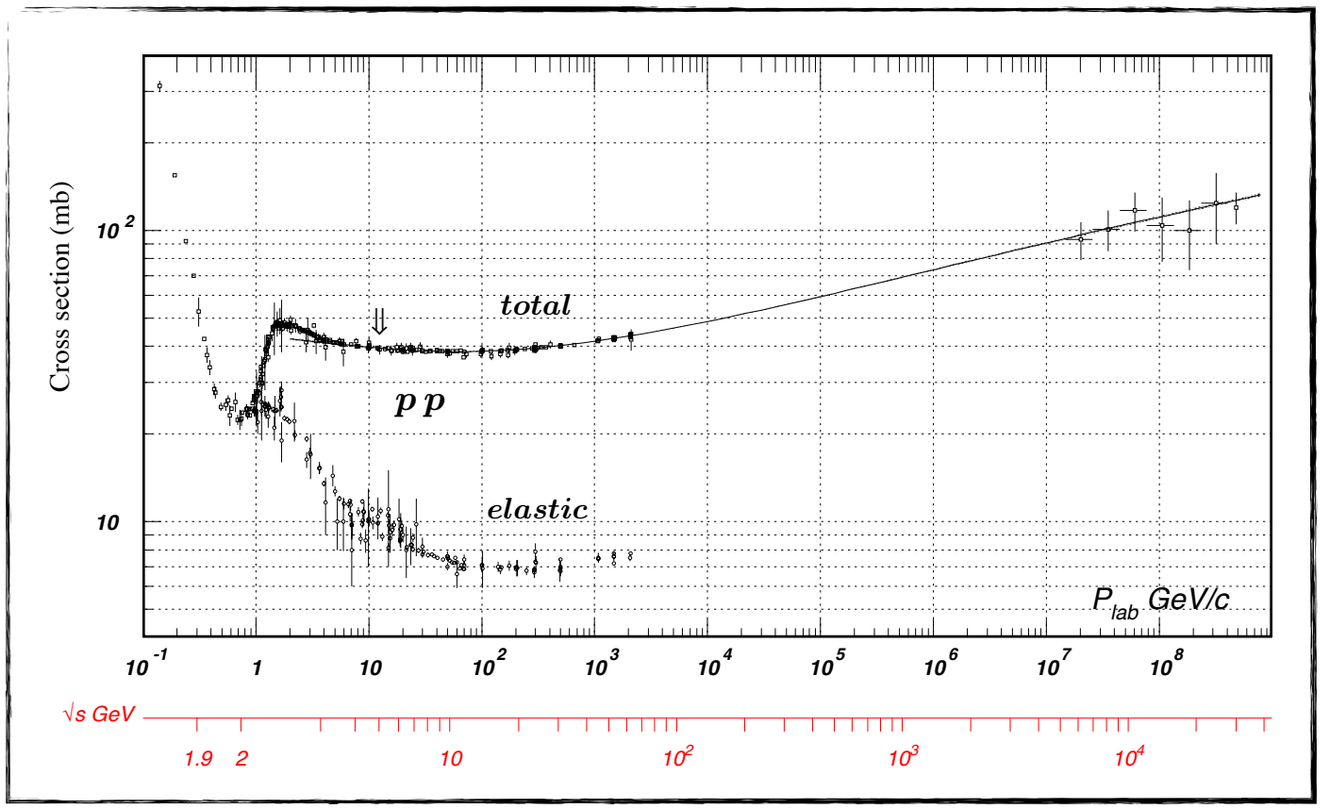
For substantial energies
σ_{inel} dominates:

$$\sigma_{\text{el}} \approx 10 \text{ mb}$$

$$\sigma_{\text{inel}} \propto A^{2/3}$$ [geometrical cross section]

$$\therefore \ \sigma_{\text{tot}} = \sigma_{\text{tot}}(pA) \approx \sigma_{\text{tot}}(pp) \cdot A^{2/3}$$

[σ_{tot} slightly grows with $\sqrt{s}$]



Total proton-proton cross section
[similar for p+n in 1-100 GeV range]

Hadronic interaction length:

$$\lambda_{\text{int}} = \frac{1}{\sigma_{\text{tot}} \cdot n} = \frac{A}{\sigma_{pp}\, A^{2/3} \cdot N_A \rho} \sim A^{1/3}$$ [for $\sqrt{s} \approx 1 - 100$ GeV]

$$\approx 35 \text{ g/cm}^2 \cdot A^{1/3}$$

which yields:

$$N(x) = N_0 \exp(-x/\lambda_{\text{int}})$$

Remark: In principle one should distinguish between collision length $\lambda_W \sim 1/\sigma_{\text{tot}}$ and interaction length $\lambda_{\text{int}} \sim 1/\sigma_{\text{inel}}$ where the latter considers inelastic processes only (absorption) ...

Interaction length characterizes both, longitudinal and transverse profile of hadronic showers ...

Hadronic Showers

Hadronic vs. electromagnetic interaction length:

$$\left.\begin{aligned} X_0 &\sim \frac{A}{Z^2} \\ \lambda_{\mathrm{int}} &\sim A^{1/3} \end{aligned}\right] \rightarrow \quad \frac{\lambda_{\mathrm{int}}}{X_0} \sim A^{4/3}$$

$$\lambda_{\mathrm{int}} \gg X_0$$

[$\lambda_{int}/X_0 > 30$ possible; see below]

Typical
Longitudinal size: 6 ... 9 λ_{int} [95% containment] [EM: 15-20 X_0]

Typical
Transverse size: one λ_{int} [95% containment] [EM: 2 R_M; compact]

Hadronic calorimeter need more depth than electromagnetic calorimeter ...

Some numerical values for materials typical used in hadron calorimeters

	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

Hadronic Showers

Hadronic shower development:

[estimate similar to e.m. case]

Depth (in units of λ_{int}):

$$t = \frac{x}{\lambda_{\mathrm{int}}}$$

Energy in depth t:

$$E(t) = \frac{E}{\langle n \rangle^t} \quad \& \quad E(t_{\max}) = E_{\mathrm{thr}}$$

[with $E_{thr} \approx 290$ MeV]

$$E_{\mathrm{thr}} = \frac{E}{\langle n \rangle^{t_{\max}}}$$

Shower maximum:

$$\langle n \rangle^{t_{\max}} = \frac{E}{E_{\mathrm{thr}}}$$

Number of particles lower by factor E_{thr}/E_c compared to e.m. shower ...

Intrinsic resolution: worse by factor $\sqrt{E_{thr}/E_c}$

$$t_{\max} = \frac{\ln\left(E/E_{\mathrm{thr}}\right)}{\ln\langle n \rangle}$$

But:

Only rough estimate as ...

energy sharing between shower particles fluctuates strongly ...

part of the energy is not detectable (neutrinos, binding energy); partial compensation possible (n-capture & fission)

spatial distribution varies strongly; different range of e.g. $\pi^{\pm}$ and π^0 ...

electromagnetic fraction, i.e. fraction of energy deposited by $\pi^0 \rightarrow \gamma\gamma$ increases with energy ...

$$f_{\mathrm{em}} \approx f_{\pi^0} \sim \ln E/(1\ \mathrm{GeV})$$

Explanation: charged hadron contribute to electromagnetic fraction via $\pi^- p \rightarrow \pi^0 n$; the opposite happens only rarely as π^0 travel only 0.2 μm before its decay ('one-way street') ...

At energies below 1 GeV hadrons loose their energy via ionization only ...

Thus: need Monte Carlo (GEISHA, CALOR, ...) to describe shower development correctly ...

Hadronic Showers

Transverse shower profile

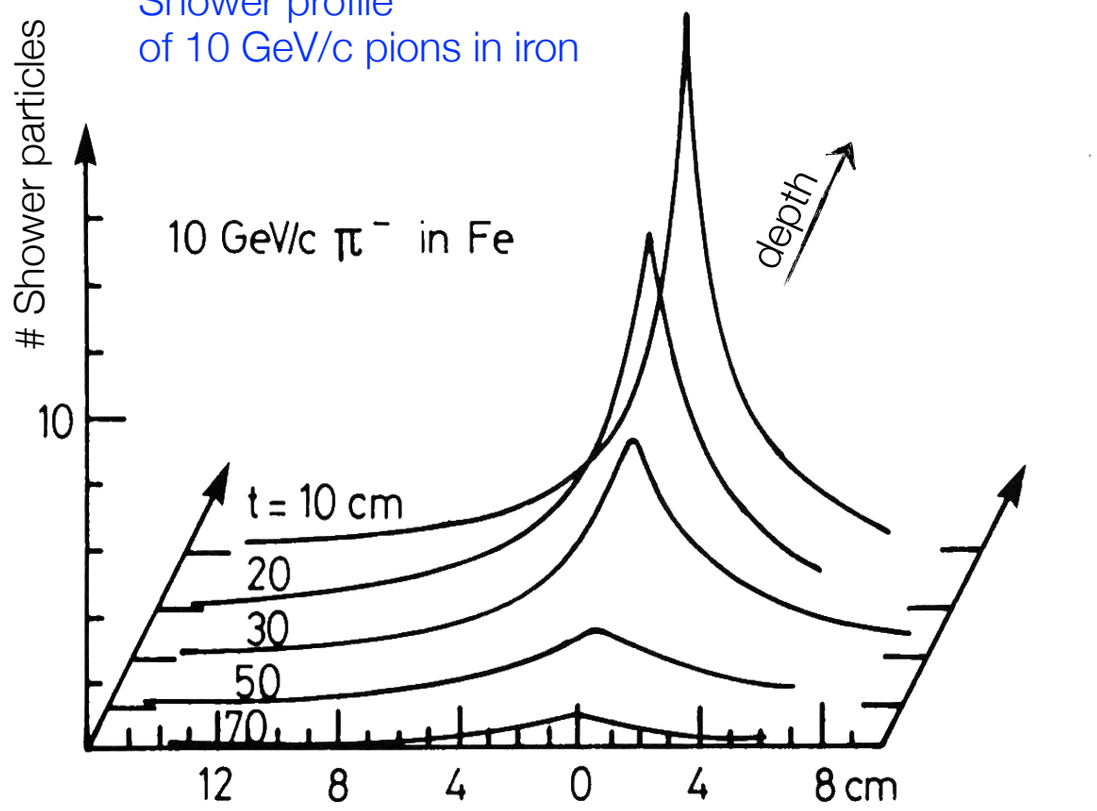
Typical transverse momenta of secondaries: $\langle p_t \rangle \simeq 350\mathrm{MeV}/c$ ...

Lateral extend at shower maximum: $R_{95\%} \approx \lambda_{int}$ ...

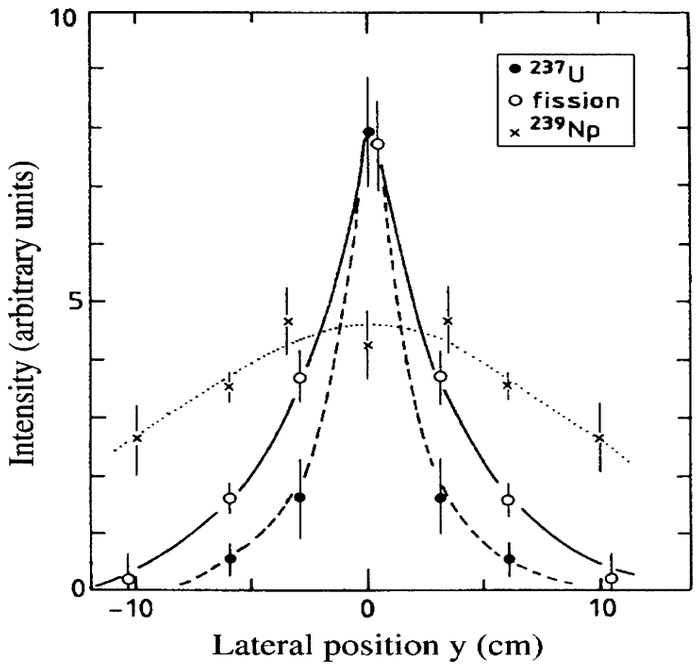
Electromagnetic component leads to relatively well-defined core: $R \approx R_M$ ...

Exponential decay after shower maximum ...

Shower profile of 10 GeV/c pions in iron



Lateral shower position [cm]



Lateral profile for 300 GeV π^-

[target material ^{238}U]
[measured at depth 4 λ_{int}]

More π^0's and γ in core
Energetic neutrons and charged pions form a wider core
Thermal neutrons generate broad tail

Measurement from induced radioactivity:

^{99}Mo (fission): neutron induced ...
[energetic neutron component]

^{237}U: mainly produced via $^{238}U(\gamma,n)^{237}U$ ...
[electromagnetic component]

^{239}Np: from ^{239}U decay ...
[thermal neutrons]

Ordinate indicates decay rate of different radioactive nuclides ...

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Fluctuations:

- Sampling fluctuations
- Leakage fluctuations
- Fluctuations of electromagnetic fraction
- Nuclear excitations, fission, binding energy fluctuations ...
- Heavily ionizing particles

Typical:

A: 0.5 – 1.0 [Record:0.35]

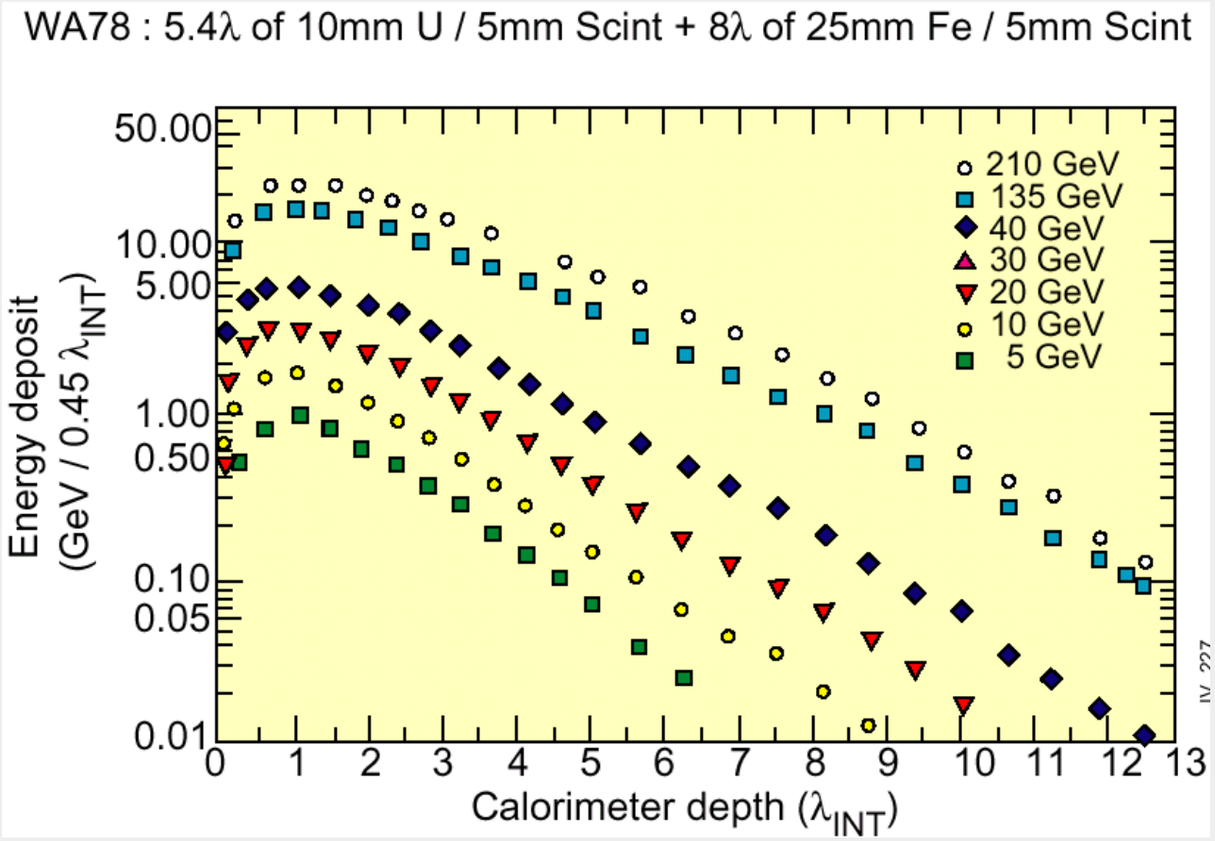
B: 0.03 – 0.05

C: few %

Hadron shower profile

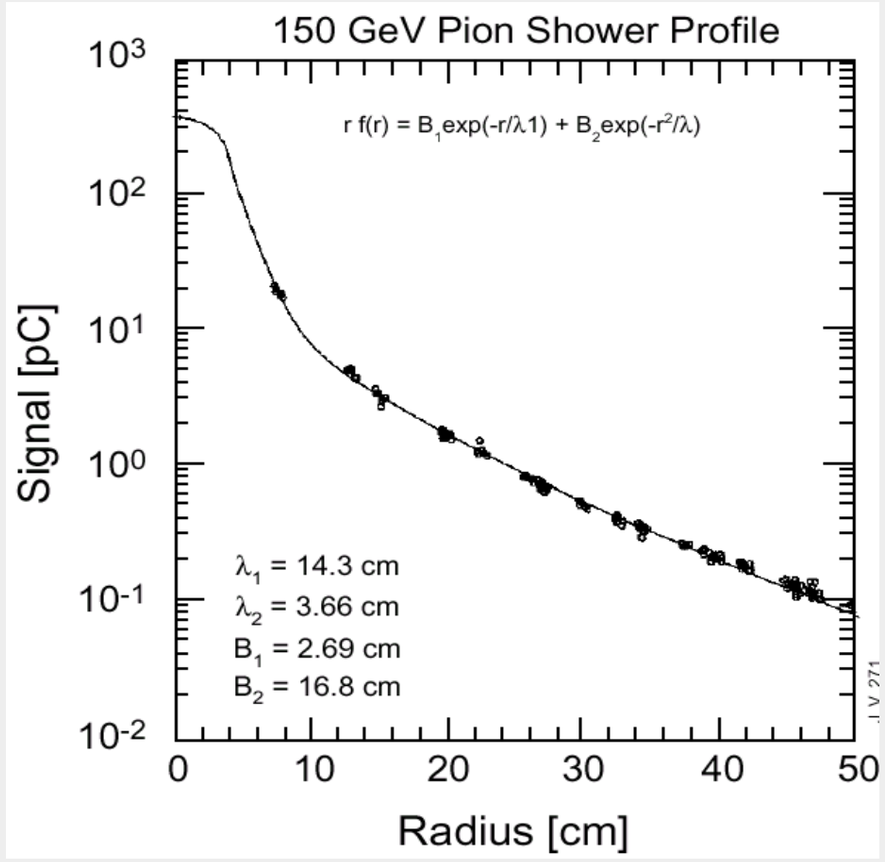
LONGITUDINAL

- **Sharp peak from π^o from the 1° interaction**
- **Gradual extinction with typical scale λ_{int}**



LATERAL

- **Average p_t secondaries ~ 300 MeV**
- **Typical transverse scale λ_{int}**
- **Dense core due to π^o**



~10 λ needed to contain 99% E of 200 GeV π (about 1 – 2 m of heavy absorber)

Transverse radius for 95%E containment ~1λ

Need to sample

BACK

Calorimeter energy resolution determined by fluctuations ...

Homogeneous calorimeters:

- Shower fluctuations
- Photo-electron statistics
- Shower leakage

] Quantum fluctuations

- Instrumental effects (noise, light attenuation, non-uniformity)

In addition for

Sampling calorimeters:

- Sampling fluctuations
- Landau fluctuations
- Track length fluctuations

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Quantum fluctuations	$\sim 1/\sqrt{E}$
Electronic noise	$\sim 1/E$
Shower leakage*	$\approx \text{const}$
Sampling fluctuations	$\sim 1/\sqrt{E}$
Landau fluctuations	$\sim 1/\sqrt{E}$
Track length fluctuations	$\sim 1/\sqrt{E}$

* Different for longitudinal and lateral leakage ...
Complicated; small energy dependence ...

TO BACKUP

Energy resolution

Shower fluctuations:
[intrinsic resolution]

Ideal (homogeneous) calorimeter without leakage: energy resolution limited only by statistical fluctuations of the number N of shower particles ...

i.e.:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} \qquad \text{with } N = \frac{E}{W}$$

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{W}{E}}$$

E : energy of primary particle

W : mean energy required to produce 'signal quantum'

Examples:

Silicon detectors	:	W ≈ 3.6 eV
Gas detectors	:	W ≈ 30 eV
Plastic scintillator	:	W ≈ 100 eV

Resolution improves due to correlations between fluctuations (Fano factor; see above) ...

$$\frac{\sigma_E}{E} \propto \sqrt{\frac{FW}{E}}$$

[F: Fano factor]

Energy resolution

Photo-electron statistics:

For detectors for which the deposited energy is measured via light detection inefficiencies converting photons into a detectable electrical signal (e.g. photo electrons) contribute to the measurement uncertainty ...

i.e.:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_{N_{\mathrm{pe}}}}{N_{\mathrm{pe}}} \approx \frac{1}{\sqrt{N_{\mathrm{pe}}}}$$

N_{pe}: number of photo electrons

This contribution is present for calorimeters based on detecting scintillation or Cherenkov light; important in this context are quantum efficiency and gain of the used photo detectors (e.g. Photomultiplier, Avalanche Photodiodes ...)

Also important: losses in light guides and wavelength shifters ....

Energy resolution

Shower leakage:

Fluctuations due to finite size of calorimeter; shower not fully contained ...

Lateral leakage: limited influence
Longitudinal leakage: strong influence

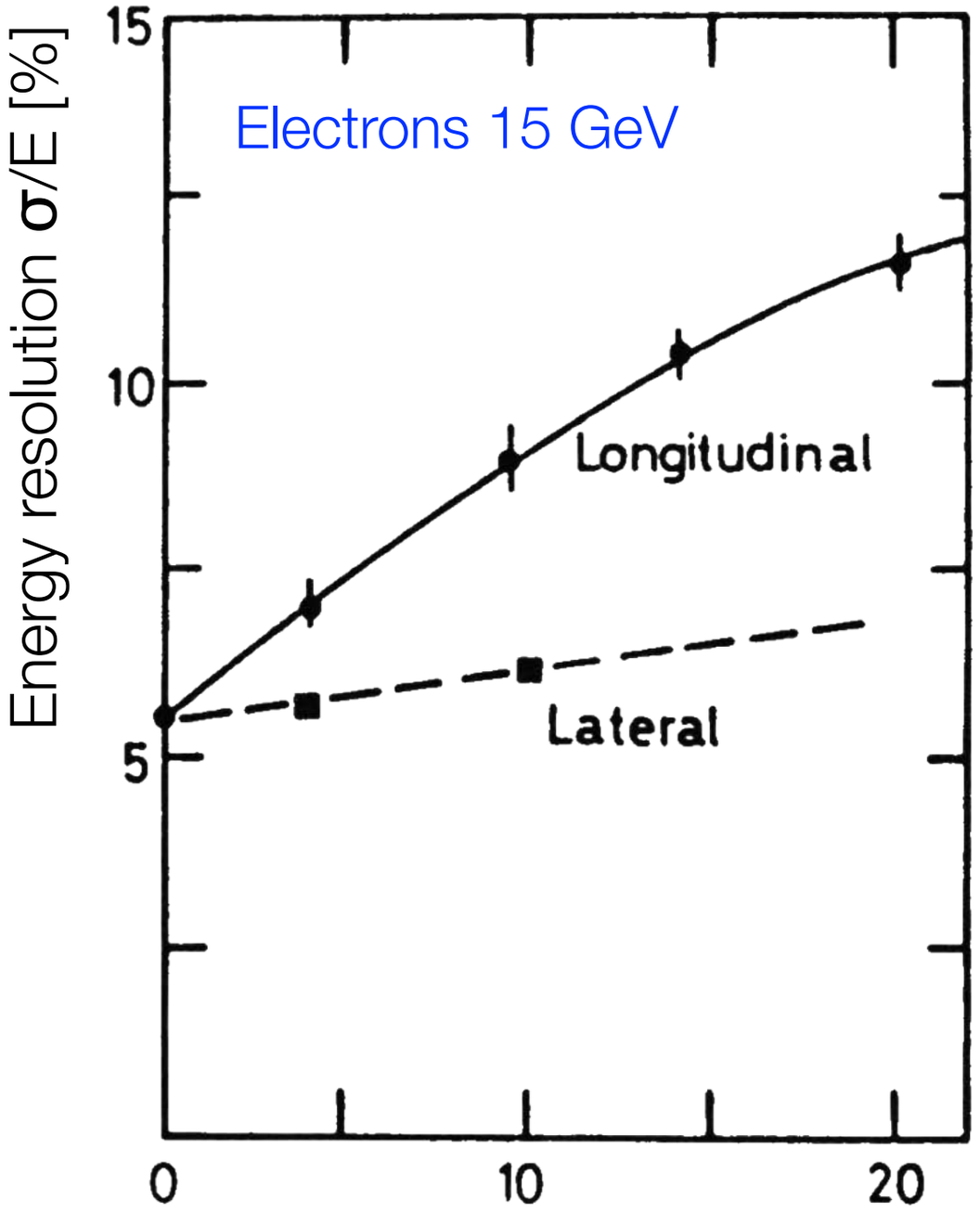
Typical expression when including leakage effects:

$$\frac{\sigma_E}{E} \propto \left(\frac{\sigma_E}{E}\right)_{f=0} \cdot \left[1 + 2f\sqrt{E}\right]$$

[f : average fraction of shower leakage]

Remark: other parameterizations exist ...

Marmor Calorimeter
[CHARM Collaboration]



Energy resolution

Sampling fluctuations:

Additional contribution to energy resolution in sampling calorimeters due to fluctuations of the number of (low-energy) electrons crossing active layer ...

Increases linearly with energy of incident particle and fineness of the sampling ...

$$N_{\mathrm{ch}} \propto \frac{E}{E_c\, t_{\mathrm{abs}}}$$

N_{ch} : charged particles reaching active layer
N_{max} : total number of particles = E/E_c
t_{abs} : absorber thickness in X_0

Reasoning: Energy deposition dominantly due to low energy electrons; range of these electrons smaller than absorber thickness t_{abs}; only few electrons reach active layer ...
Fraction $f \sim 1/t_{abs}$ reaches the active medium ...

Resulting
energy resolution:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_{N_{\mathrm{ch}}}}{N_{\mathrm{ch}}} \propto \sqrt{\frac{E_c\, t_{\mathrm{abs}}}{E}}$$

Choose: E_c small (large Z)
t_{abs} small (fine sampling)

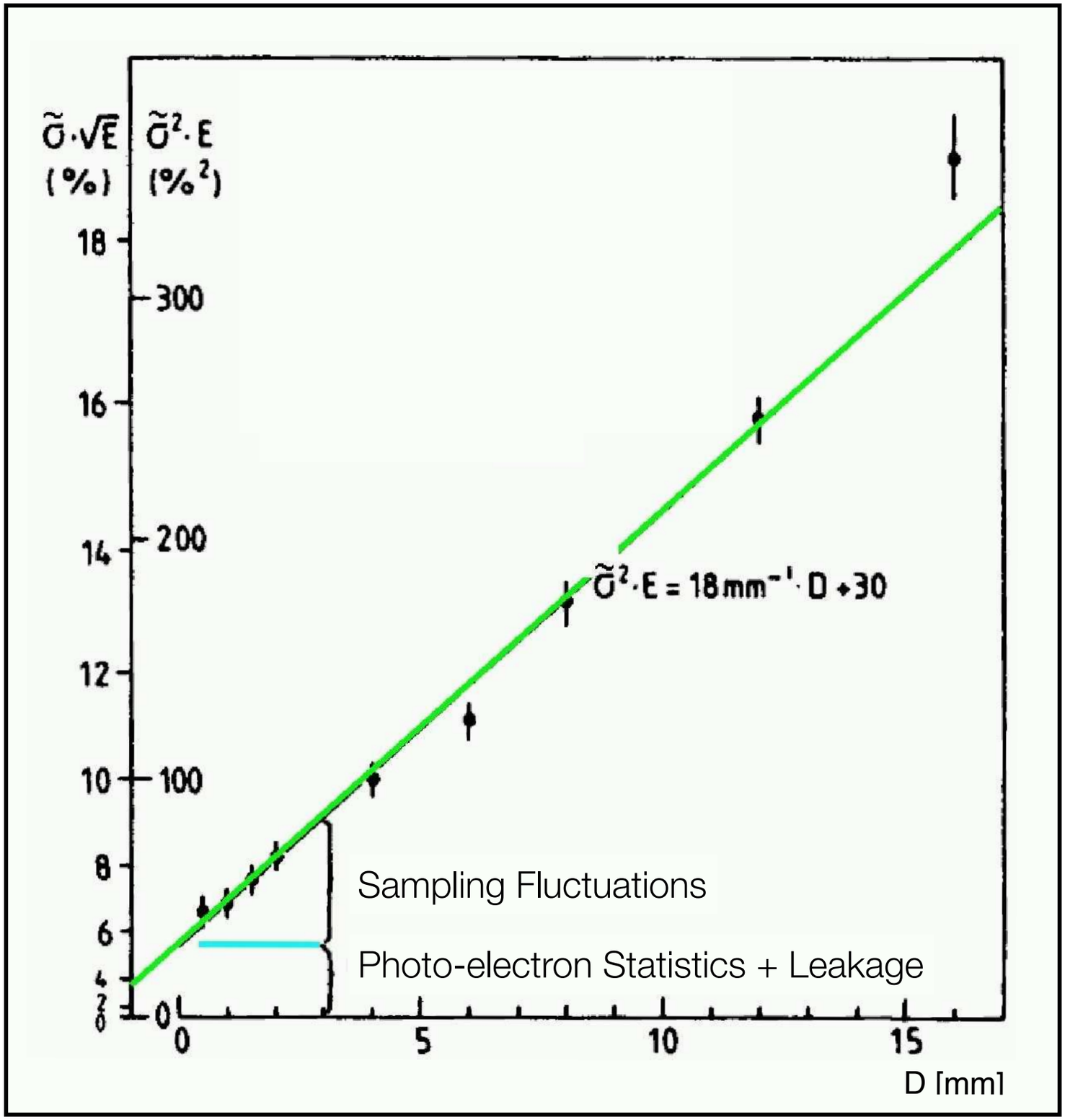
Semi-empirical:

$$\frac{\sigma_E}{E} = 3.2\% \sqrt{\frac{E_c\ [\mathrm{MeV}] \cdot t_{\mathrm{abs}}}{F \cdot E\ [\mathrm{GeV}]}}$$

where F takes detector threshold effects into account ...

Energy resolution

Measure energy resolution of a sampling calorimeter for different absorber thicknesses



Sampling contribution:

$$\frac{\sigma_E}{E} = 3.2\%\sqrt{\frac{E_c\ [\mathrm{MeV}]\cdot t_{\mathrm{abs}}}{F\cdot E\ [\mathrm{GeV}]}}$$

Energy resolution

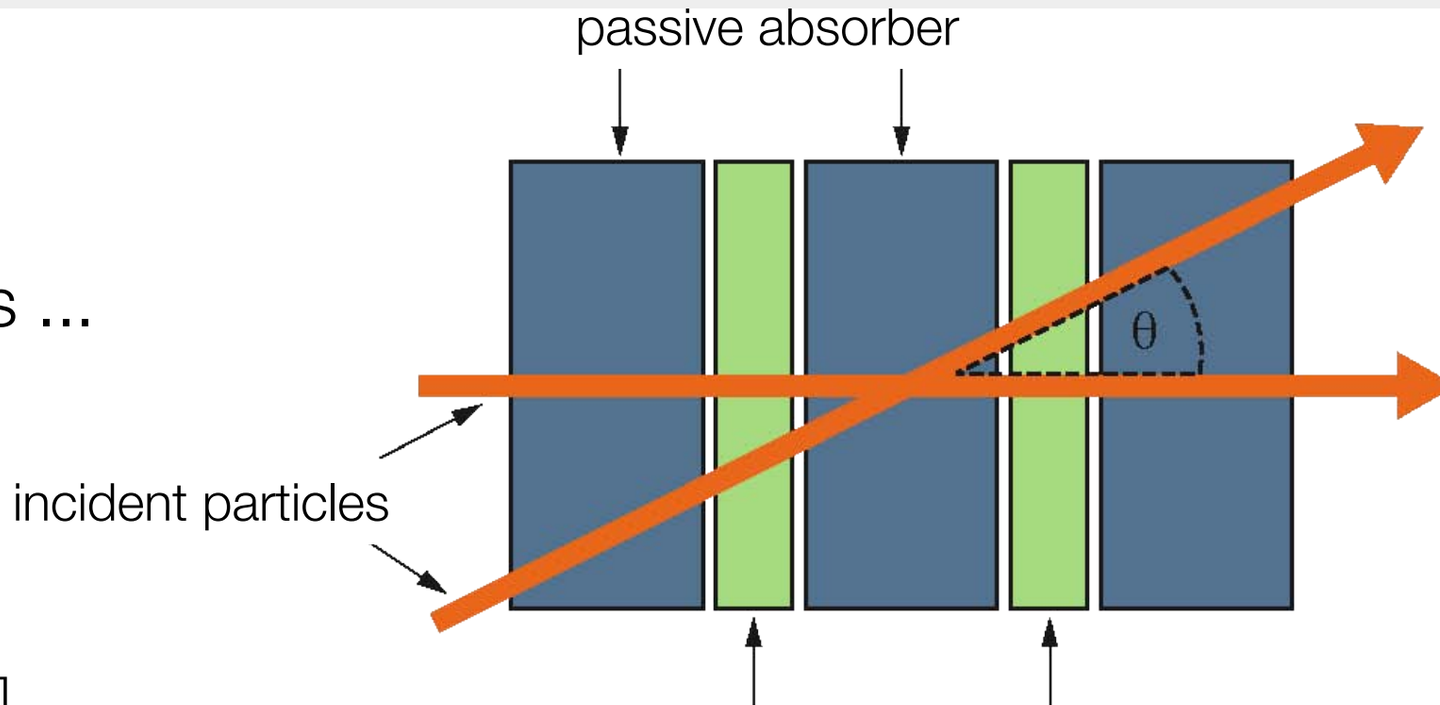
Track length fluctuations:

Due to multiple scattering particles traverse absorber at different angles ...

→ Different effective absorber thickness:

$$t_{\mathrm{abs}} \rightarrow t_{\mathrm{abs}} / \cos\theta$$

[Enters sampling (and Landau) fluctuations]



Landau fluctuations:

Asymmetric distribution of energy deposits in thin active layers yields correction [Landau instead of Gaussian distribution]:

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{N_{\mathrm{ch}}}} \cdot \frac{3}{\ln(k \cdot \delta)}$$

[semi-empirical]

with:

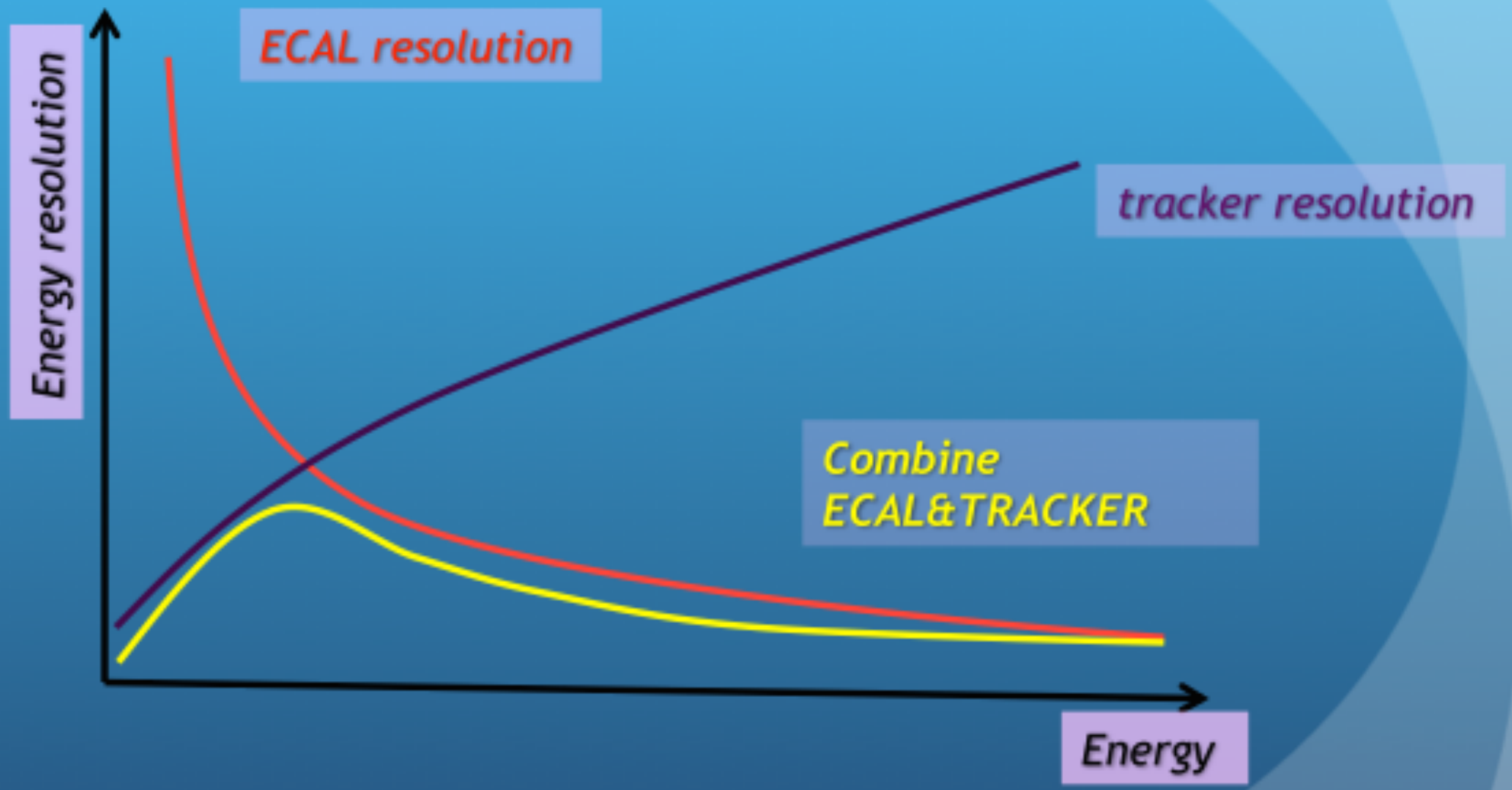
k : constant; k = $1.3 \cdot 10^4$ if **δ** measured in MeV

δ : average energy loss in active layer ('thickness')

BACK

Particle Flow Calorimeter

Particle flow principle: being able to reconstruct every individual particle in a collision event (or else) by combining efficiently subdetectors information
Requirements: good tracking ability, ECAL segmented, HCAL for ID..



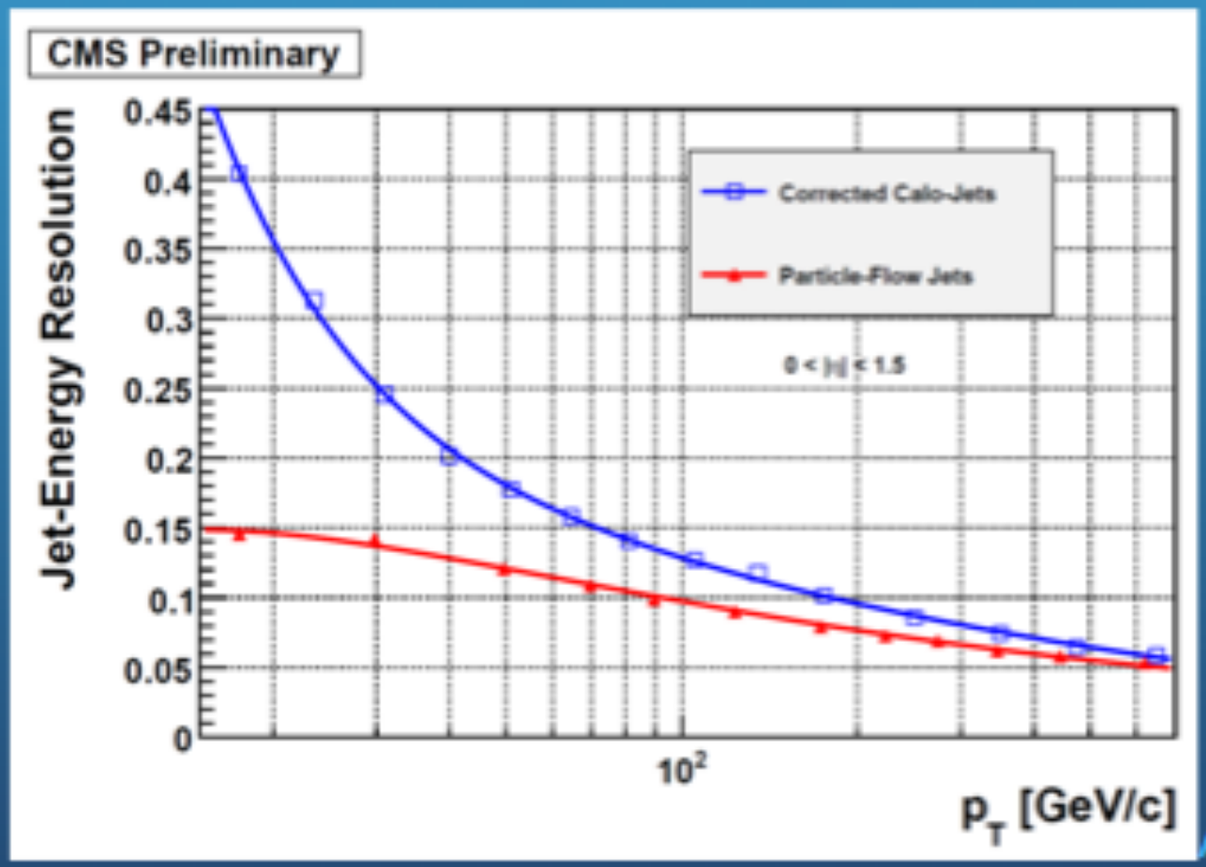
Combining subdetectors info: get a much better resolution on single object

TO BACKUP

Particle Flow Calorimeter

Particle flow algorithm: with an access to single particle 4-vectors

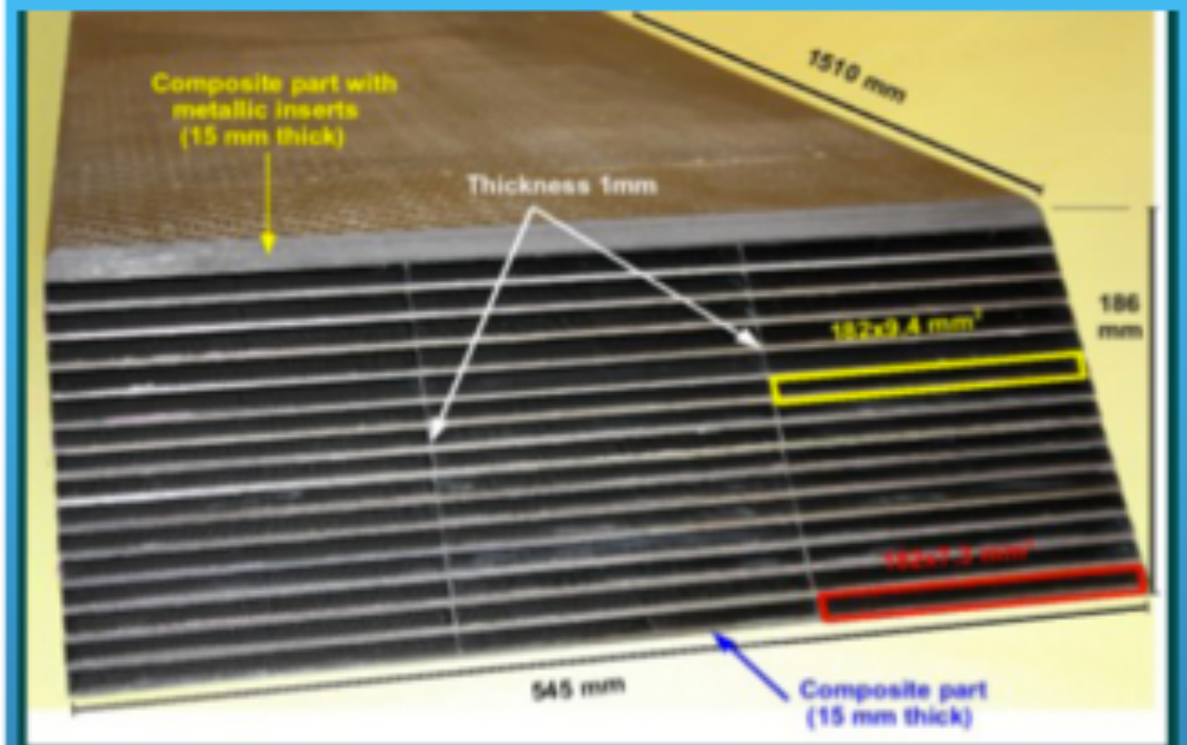
- Use **adapted calibration** for each objects electrons/photons/jets (avoid bias in energy response)
- Get the **best resolution from track** on charged particles (65% of a jet!)
- EM part measured **precisely by the ECAL** (neutral pions = 25% of jet)
- **Deduce neutral energy** from previous info (neutrals = 10% of a jet)
- Significant improvement **angular resolution**
- Correct **evaluation of missing ET** by including spiraling low energy particles



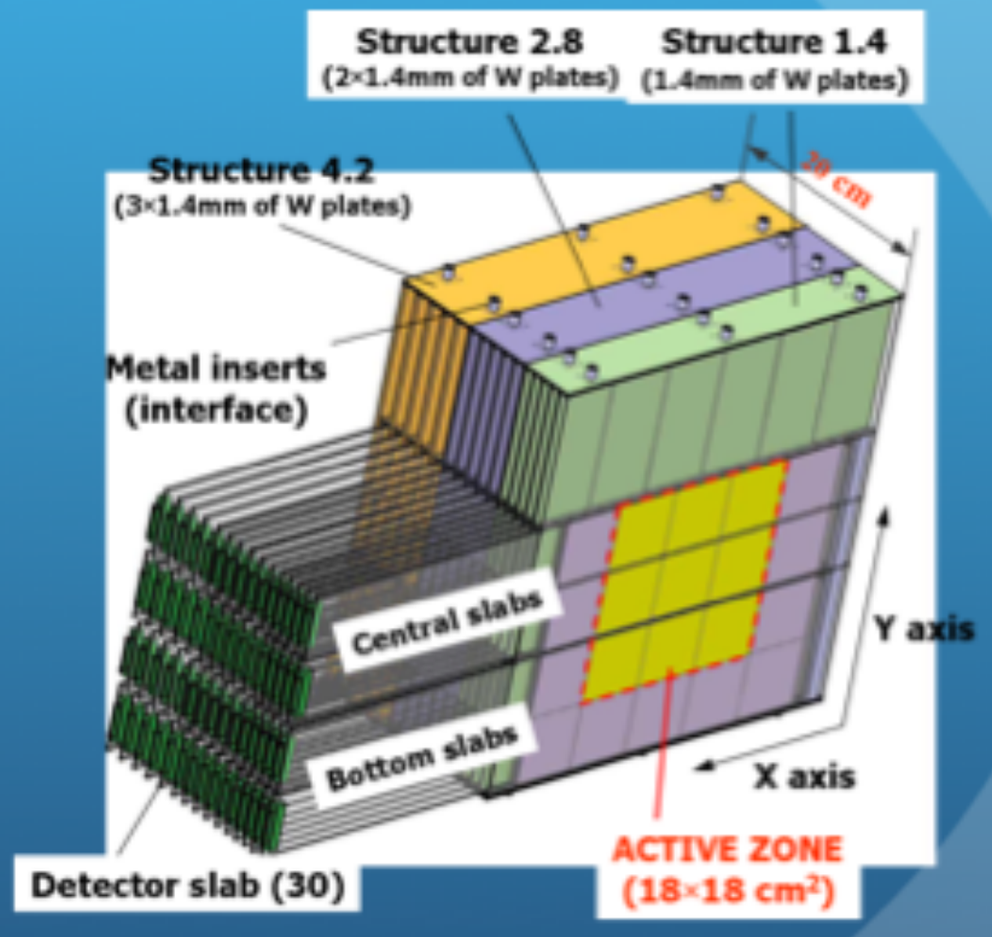
Example of performance on CMS jet energy resolution

Can you make a PF detector?
Can you import tracking techniques into calorimetry?

Particle Flow Calorimeter: ILC



SiW Silicon Tungstate calorimeter
Single cell 1x1cm^2
20 cm depth for 24 X_o



Carbon-fibre/tungsten mechanical strcuture

Active Sensor Unit (1024 readout channels)
- 18X18 cm^2 PCB
- 16 readout ASICs
- 4 silicon sensors
  - (each with 256 5x5mm^2 pads)

Dynamic range: single MIP to
- EM shower core @ 100s GeV

From D. Jeans CHEF2013

Hadronic cascades: the concept of compensation

A hadron calorimeter shows in general different efficiencies for the detection of the hadronic and electromagnetic components ε_h and ε_e.

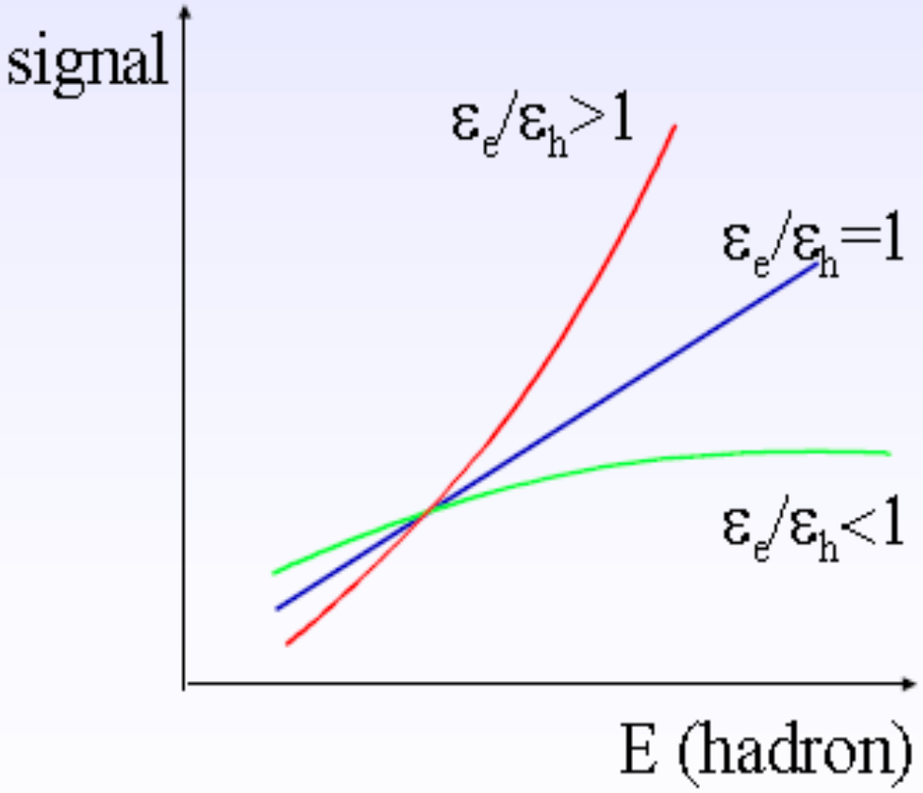
$$R_h = \varepsilon_h E_h + \varepsilon_e E_e$$

ε_h: hadron efficiency
ε_e: electron efficiency

The fraction of the energy deposited hadronically depends on the energy (remember $n(\pi^0)$)

$$\frac{E_h}{E} = 1 - f_{\pi^0} = 1 - k \ln E \ \ (GeV) \qquad k \approx 0.1$$

→ Response of calorimeter to hadron shower becomes non-linear



(Schematically after Wigmans R. Wigmans NIM A 259 (1987) 389)

Energy resolution degraded !

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b \cdot \left| \frac{\varepsilon_e}{\varepsilon_h} - 1 \right|$$

TO BACKUP

BACK

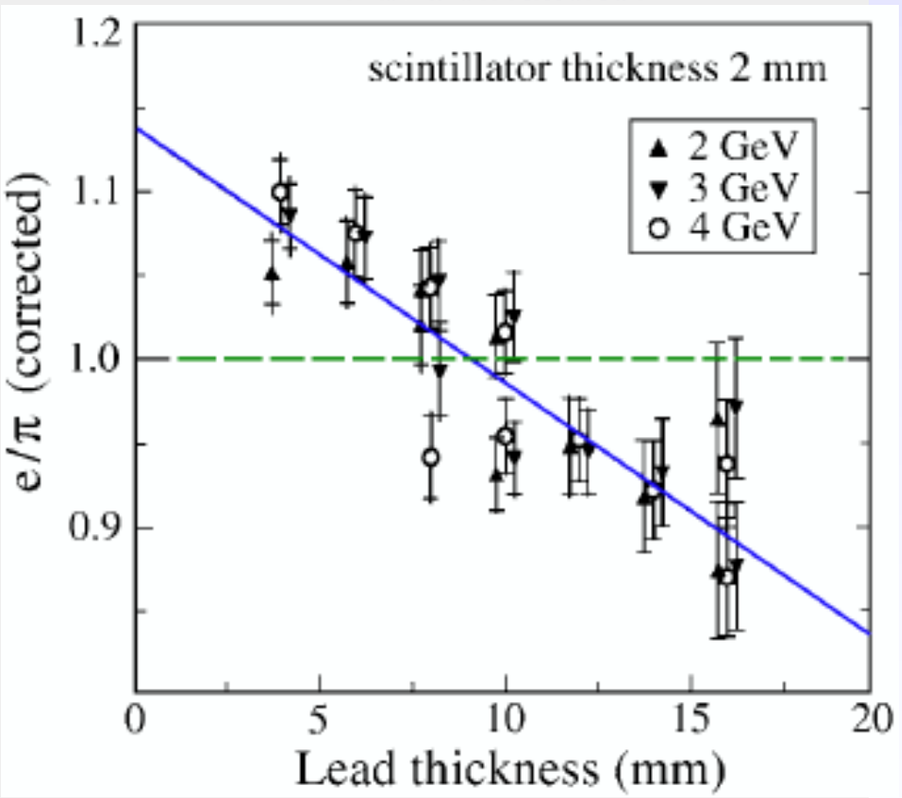
Hadronic cascades: How to achieve compensation?

increase ε_h : use Uranium absorber → amplify neutron and soft γ component by fission + use hydrogeneous detector → high neutron detection efficiency

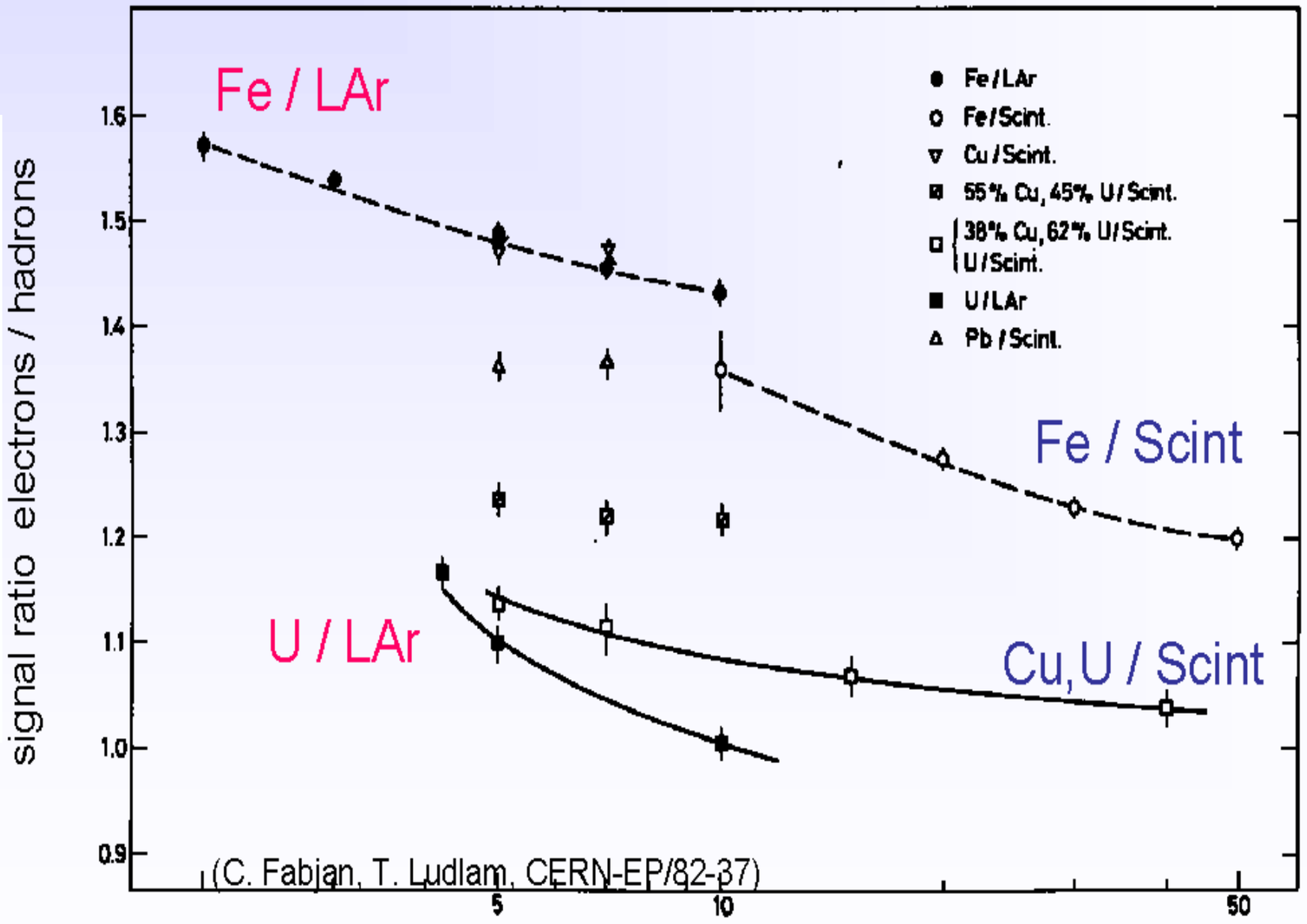
decrease ε_e : combine high Z absorber with low Z detectors. Suppressed low energy γ detection ($\sigma_{photo} \propto Z^5$)

offline compensation : requires detailed fine segmented shower data → event by event correction.

Pb/Scintillator



Sampling fraction can be tuned to achieve compensation

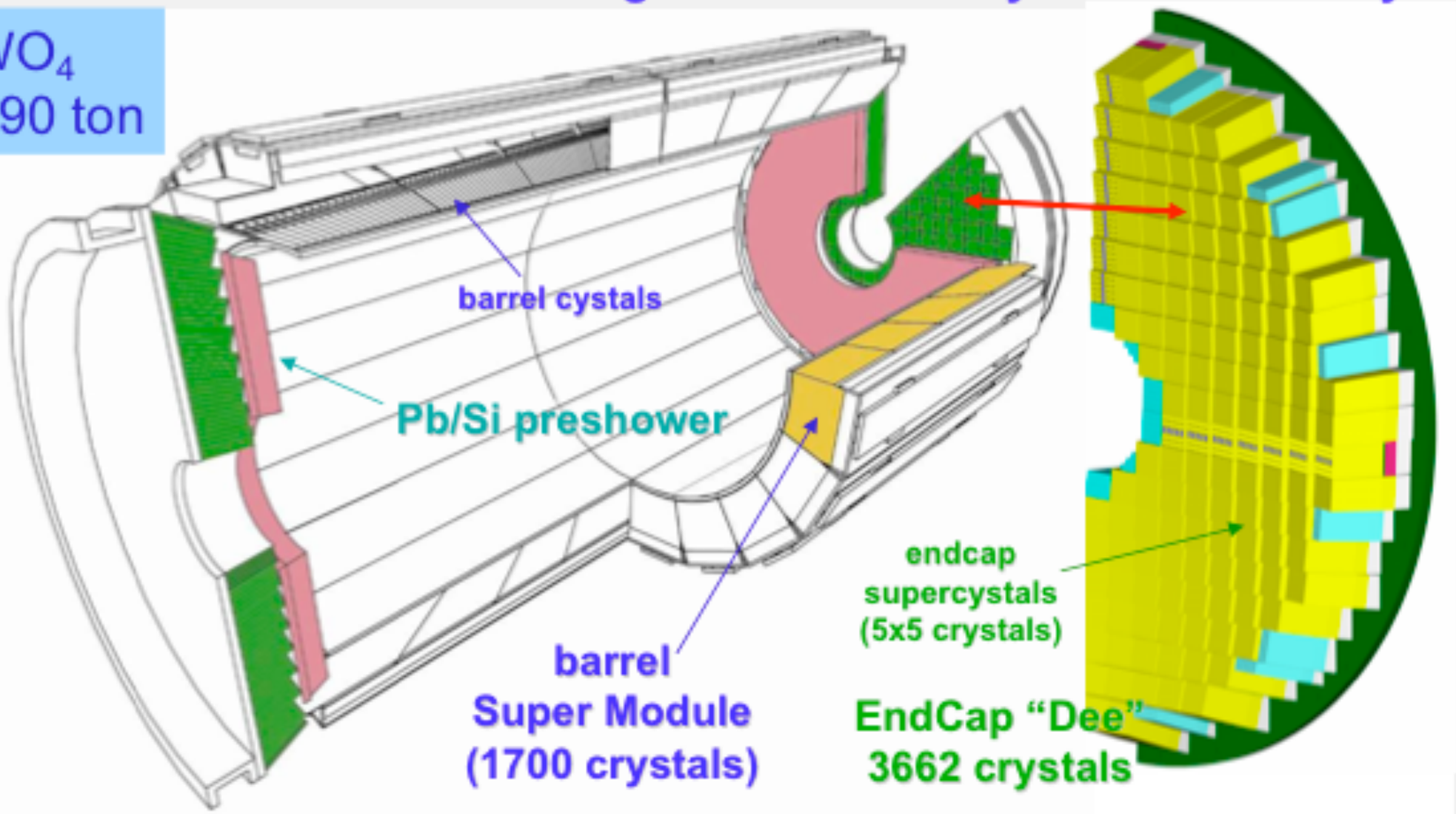


CMS ECAL

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m^3, 90 ton

Previous Crystal calorimeters: max 1m^3



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2x2x23cm^3$)

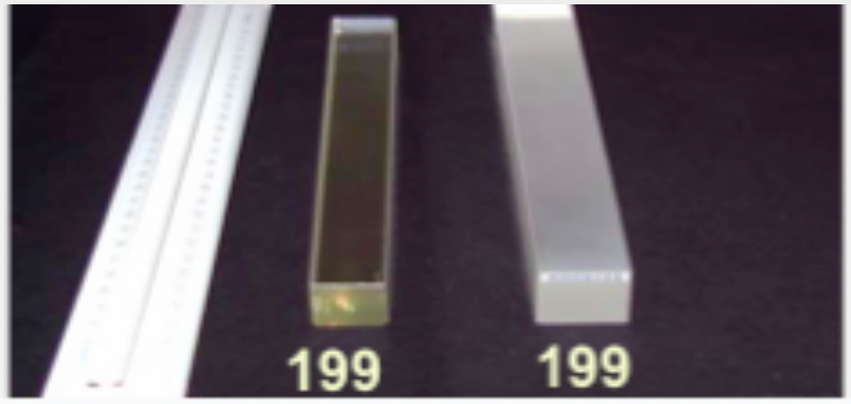
EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3x3x22cm^3$)

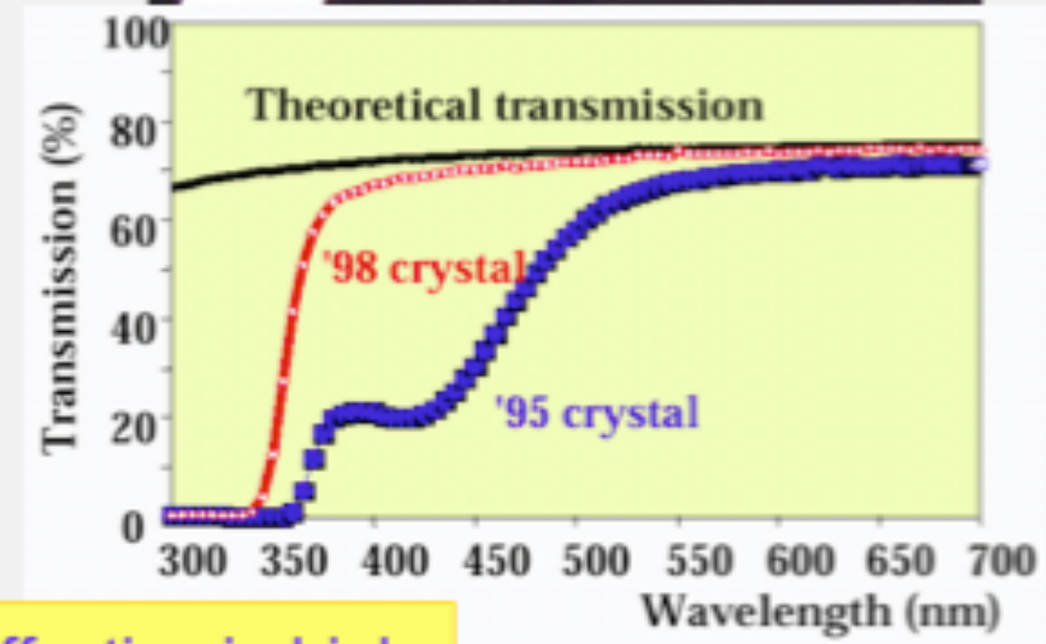
TO BACKUP BACK

CMS developed a new crystal

Lead Tungstate Crystals (PWO) for CMS

Parameter		Value
Radiation length	cm	0.89
Moliere radius	cm	2.2
Hardness	Moh	4
Refractive index		2.3
Peak emission	nm	440
% of light in 25 ns		80%
Light yield (23 cm)	γ/MeV	100



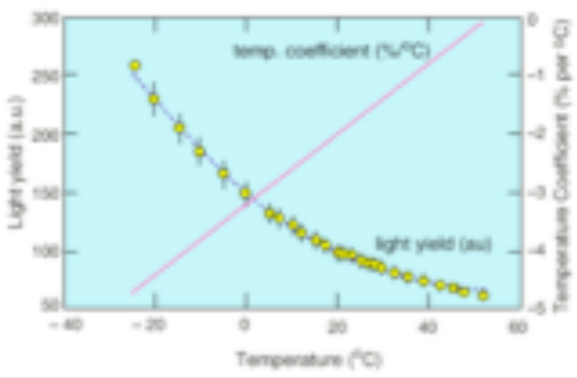


Very low light output

Hard light extraction

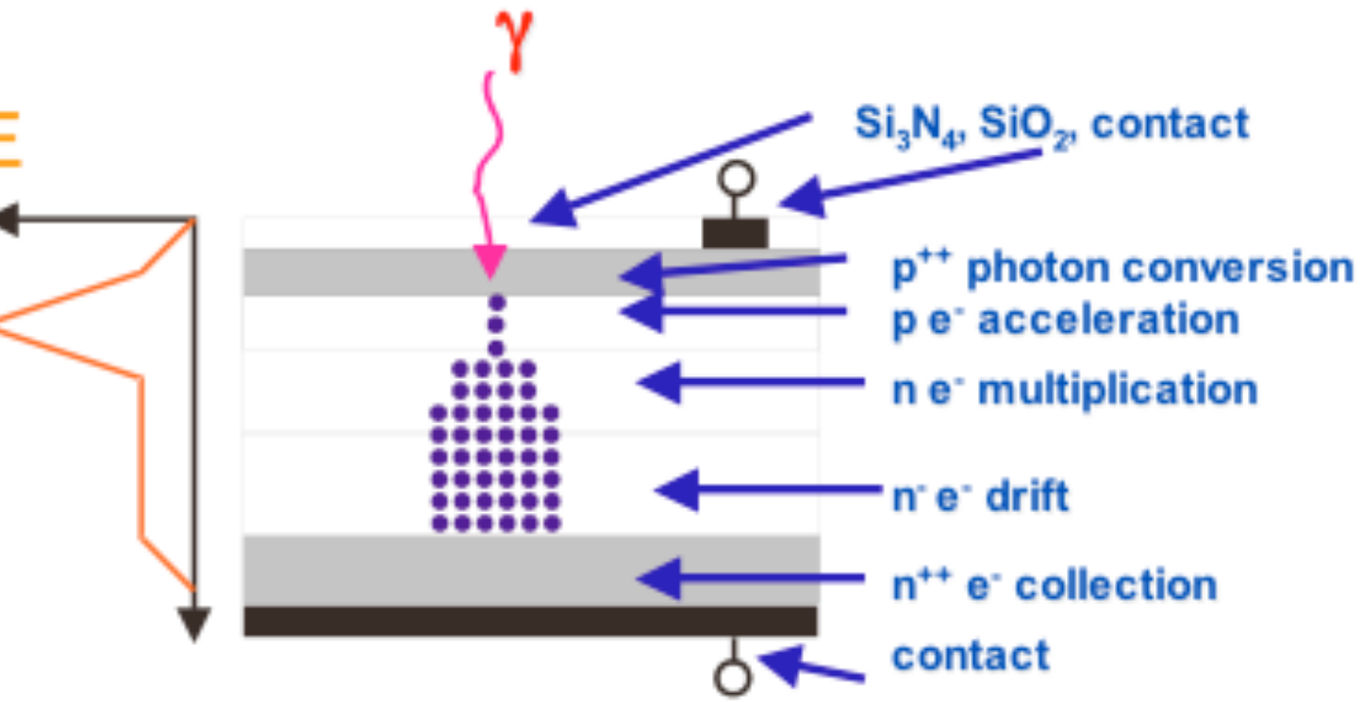
Very effective in high energy γ containment

T dependent: -2%/°C

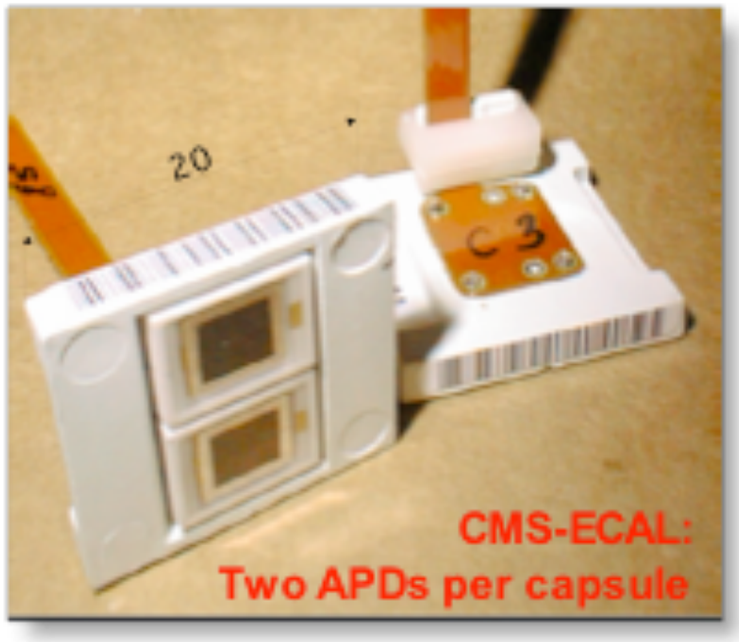


23 cm to contain em showers!

Avalanche Photo Diodes



Internal gain=50 for V=380 V



$N_{photons}$/MeV x Light-collection-efficiency (2 APDs) x QE
≈ 5 photo-electrons/MeV (in CMS-ECAL)

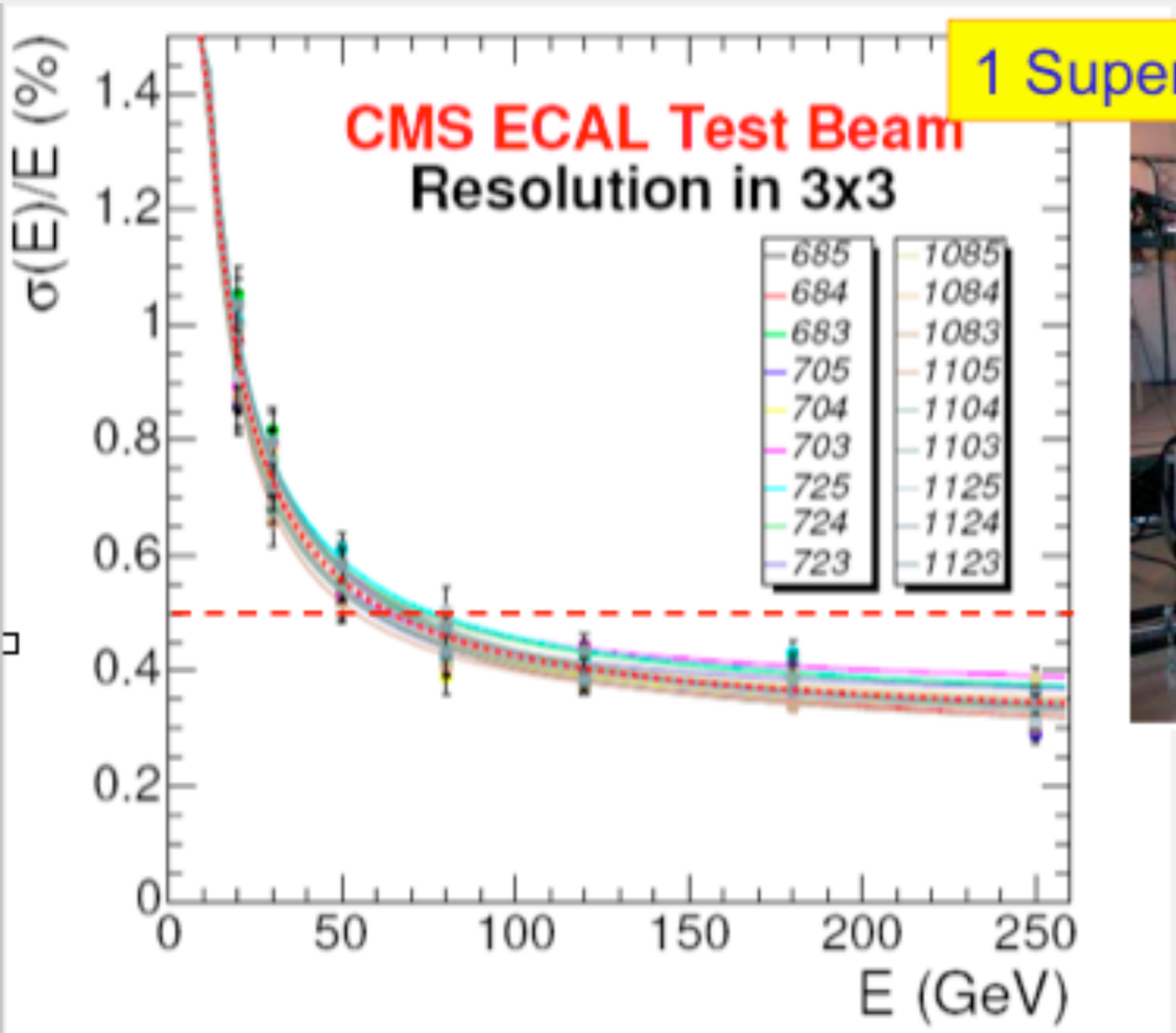
- Drawback of $PbWO_4$: Low light yield
  - → Need photodetectors **with intrinsic gain** (+radiation hard, +insensitive to magnetic field)

- Choice for CMS-ECAL Barrel and ALICE PHOS: **Avalanche Photo Diodes (APD**
  - rad. hard, fast (few ns)
  - Quantum efficiency (QE, photon conversion into electrons) : ~75% at 430 nm
  - Active Area : 25 mm^2
  - Excess noise factor F≈2

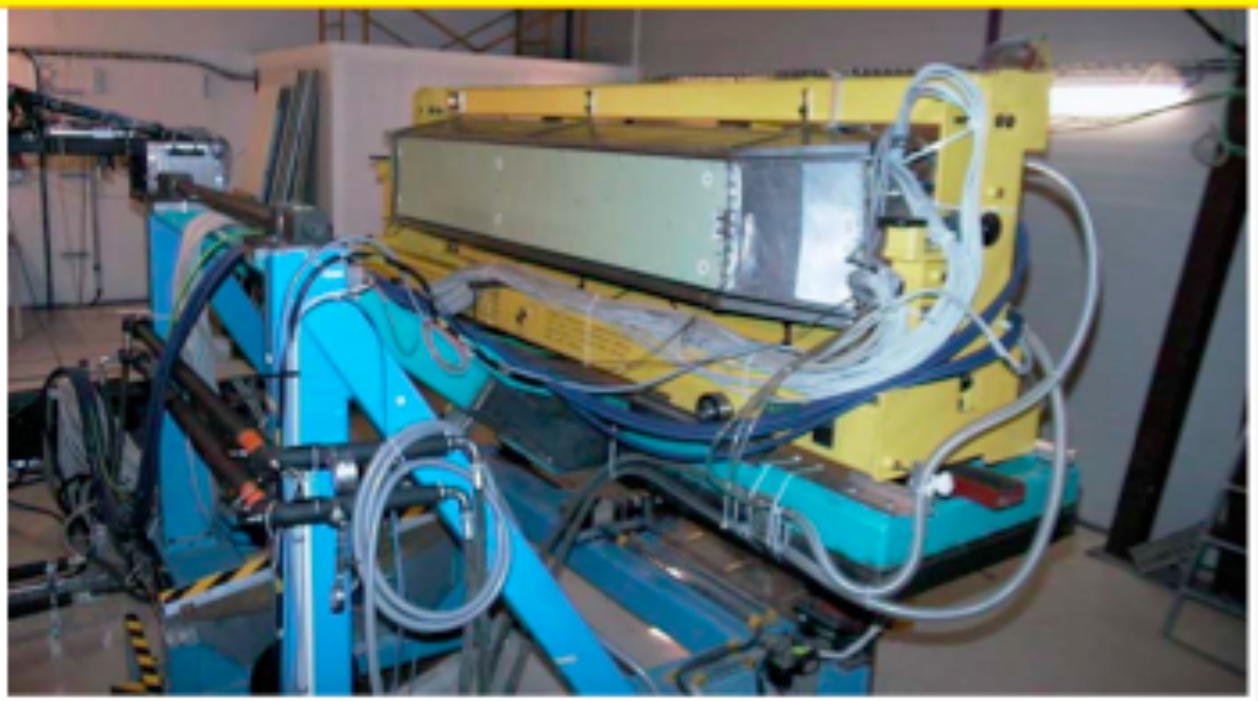
- **But :** strong sensitivity of gain to voltage and temperature variations!

  → Good stability needed!

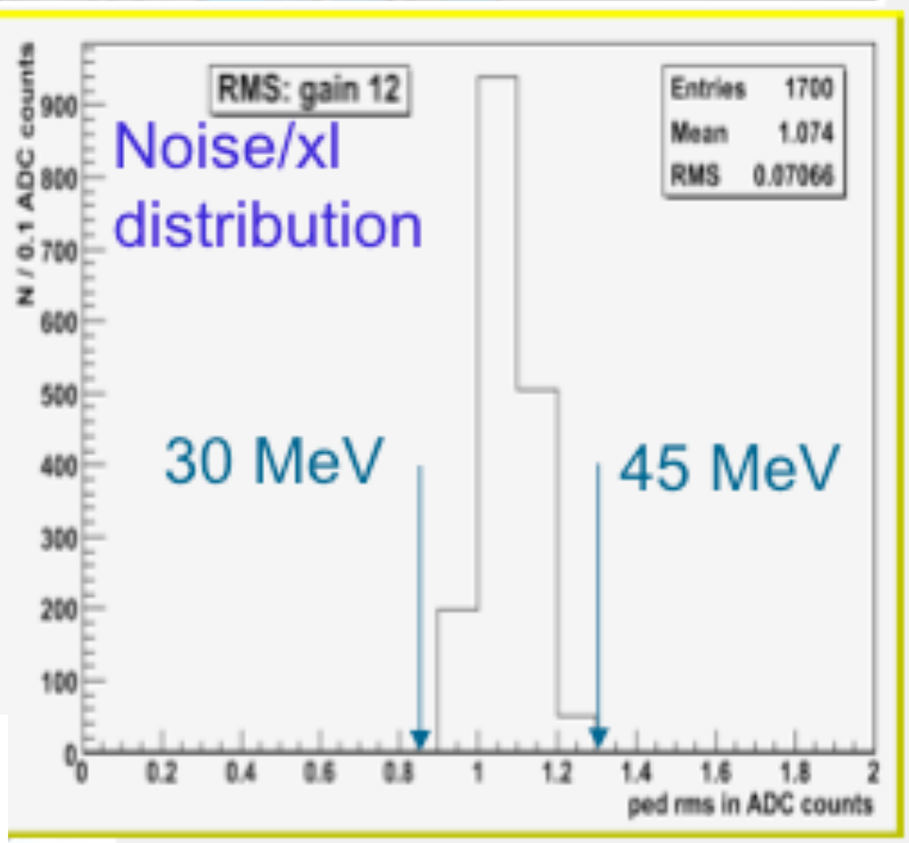
Performance of the CMS ECAL



1 Super Module 1700 xl on test beam in 2004



$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$



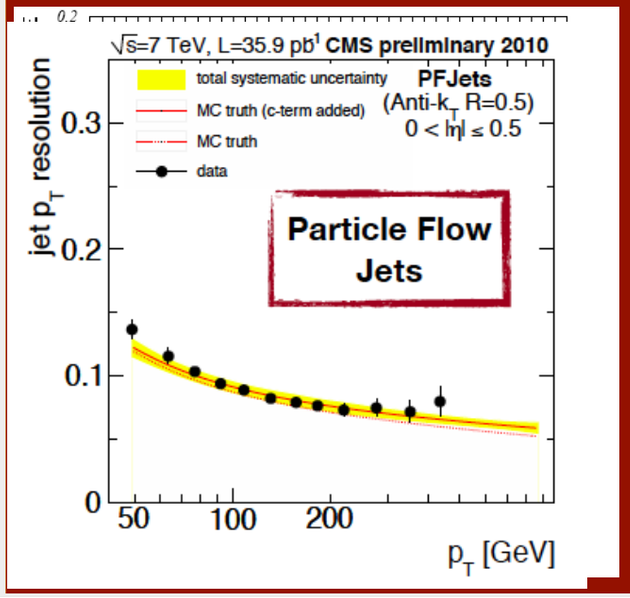
CMS Hadron Calorimeter

5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

14 mm iron / 3 mm scint.
sci. fibres, read out by phototubes

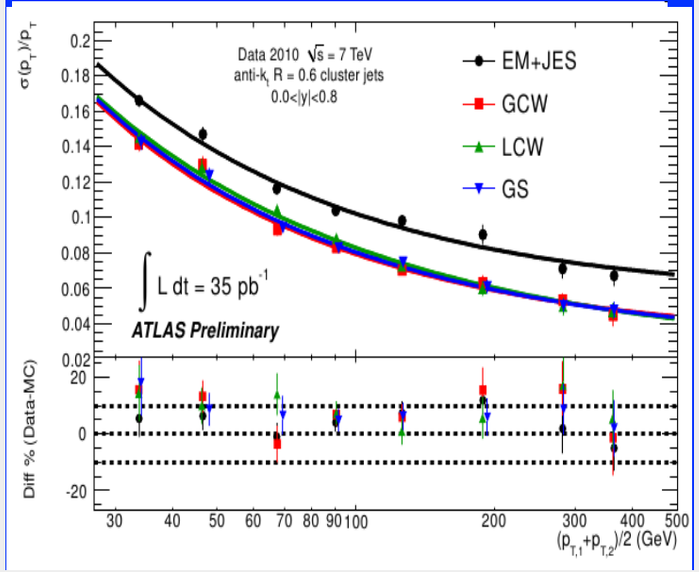
CMS

- HCAL only
  $\sigma/E = (93.8)\%/\sqrt{E} \oplus (7.4)\%$
- ECAL+HCAL
  $\sigma/E = (82.6)\%/\sqrt{E} \oplus (4.5)\%$



ATLAS

- Standalone tile calorimeter
  $\sigma/E = (52.9)\%/\sqrt{E} \oplus (5.7)\%$
- Improved resolution using full calorimetric system (ECAL+HCAL)
  $\sigma/E = (42)\%/\sqrt{E} \oplus (2)\%$

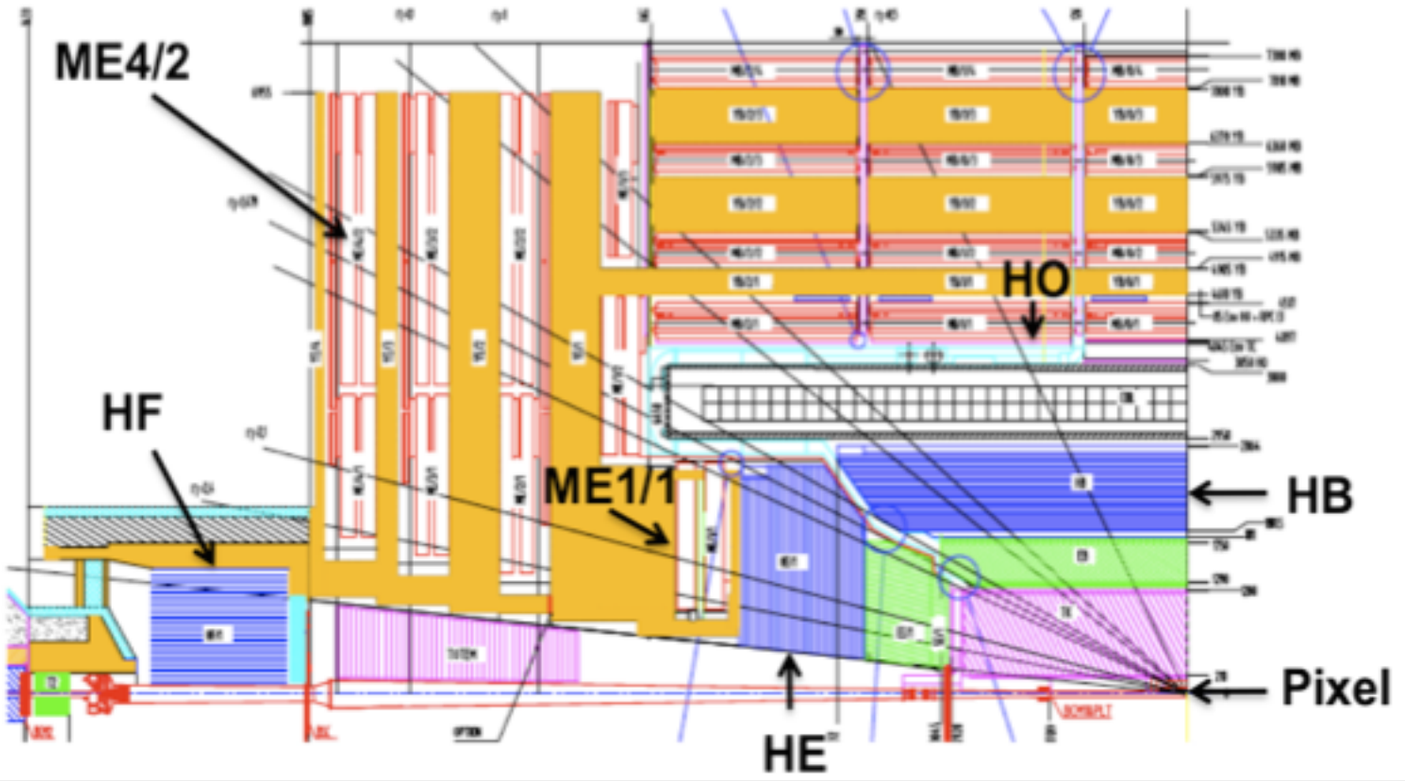


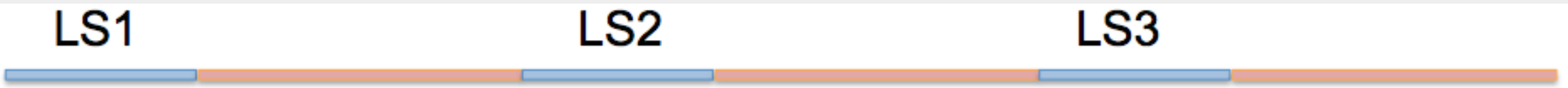
Phases of the CMS upgrade

LS1 Projects: in production

Now

- Completes muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPM)
- DAQ1 → DAQ2



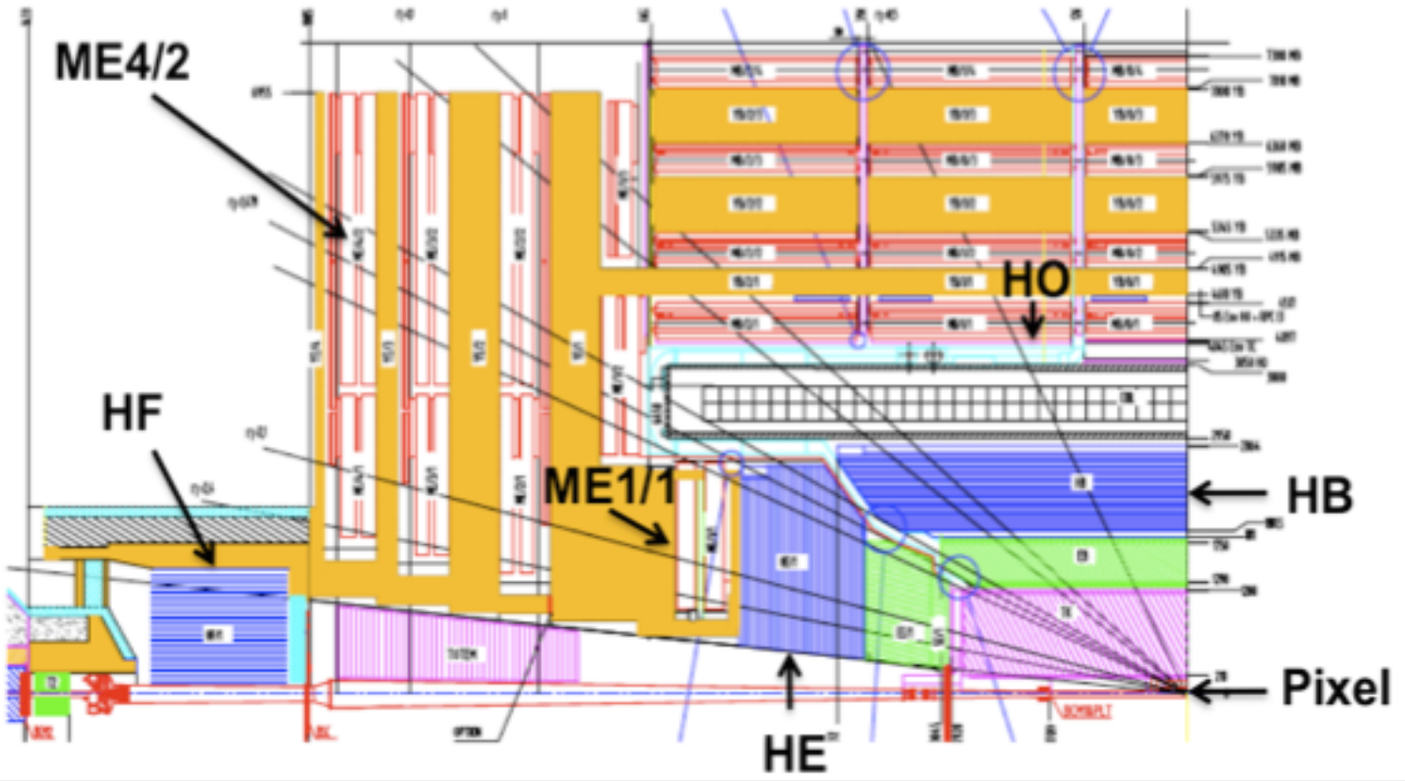


Phases of the CMS upgrade

LS1 Projects: in production

Now

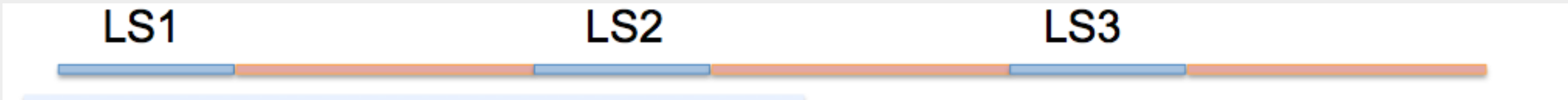
- Completes muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPM)
- DAQ1 → DAQ2



Phase 1 Upgrades (TDRs)

LS2 - 2019

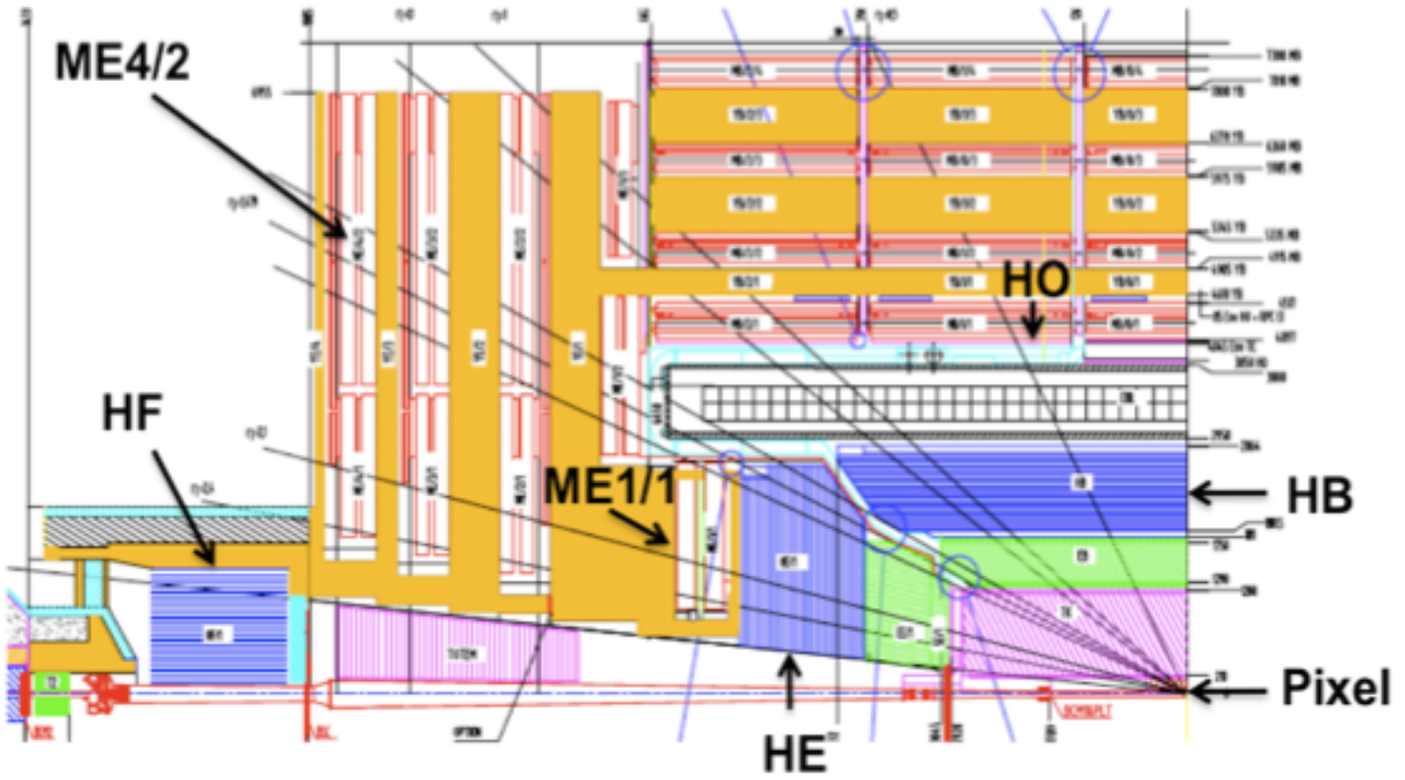
- New Pixels, HCAL electronics and L1-Trigger
- GEM under cost review
- Preparatory work during LS1
  - New beam pipe
  - Install test slices (*Pixel (cooling), HCAL, L1-trigger)*
  - Install ECAL optical splitters
    - *L1-trigger upgrade, transition to operations*



Phases of the CMS upgrade

LS1 Projects: in production *Now*

- Completes muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPM)
- DAQ1 → DAQ2



Phase 1 Upgrades (TDRs) *LS2 - 2019*

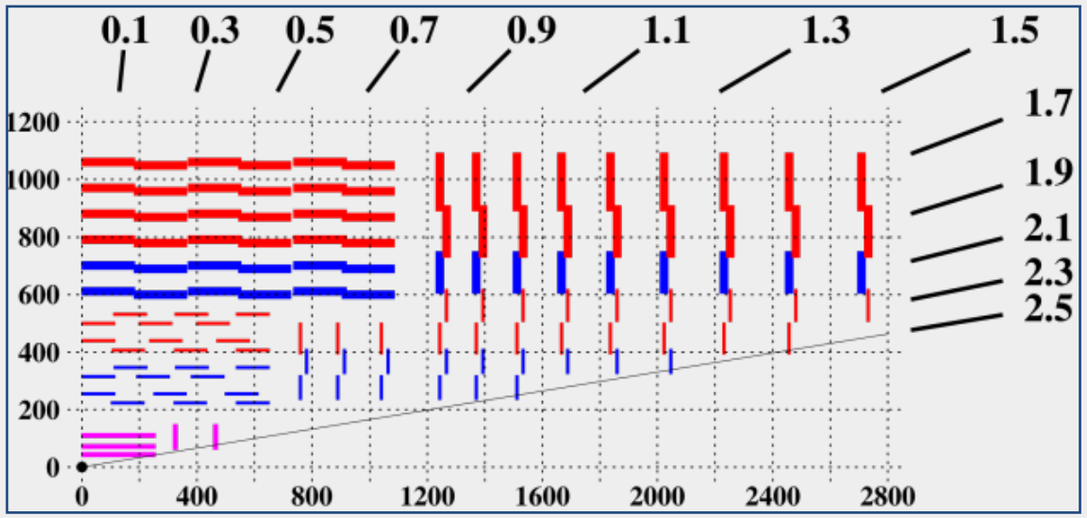
- New Pixels, HCAL electronics and L1-Trigger
- GEM under cost review
- Preparatory work during LS1
  - New beam pipe
  - Install test slices (*Pixel (cooling), HCAL, L1-trigger)*
  - Install ECAL optical splitters
    - *L1-trigger upgrade, transition to operations*

Phase 2: HL-LHC *LS3 - 2023*

- Tracker Replacement, Track Trigger
- Forward : Calorimetry and Muons and tracking
- Further Trigger upgrade
- Further DAQ upgrade
- Shielding/beampipe for higher aperture

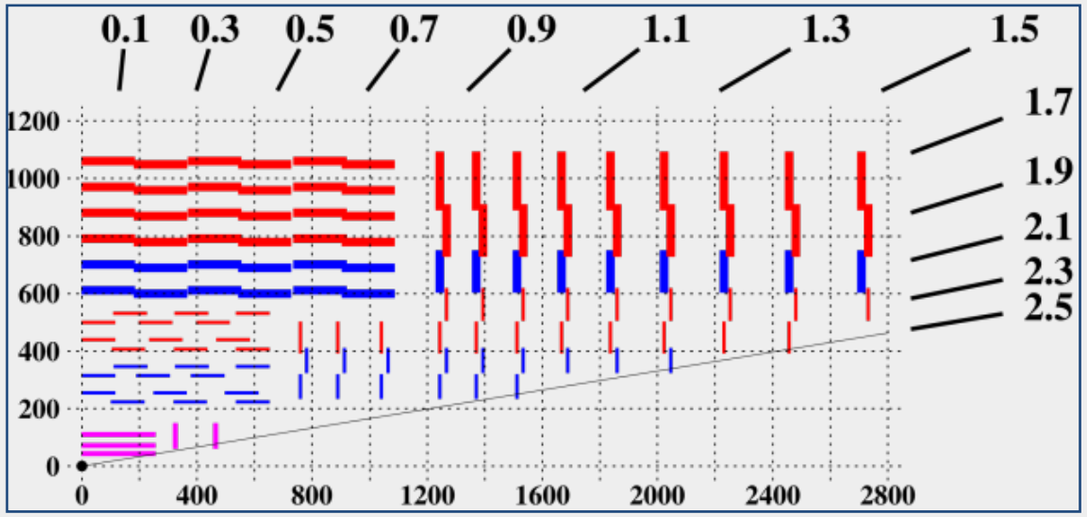
LS1 LS2 LS3

From Current to Phase 2 Tracker



Current CMS Silicon Tracker

From Current to Phase 2 Tracker



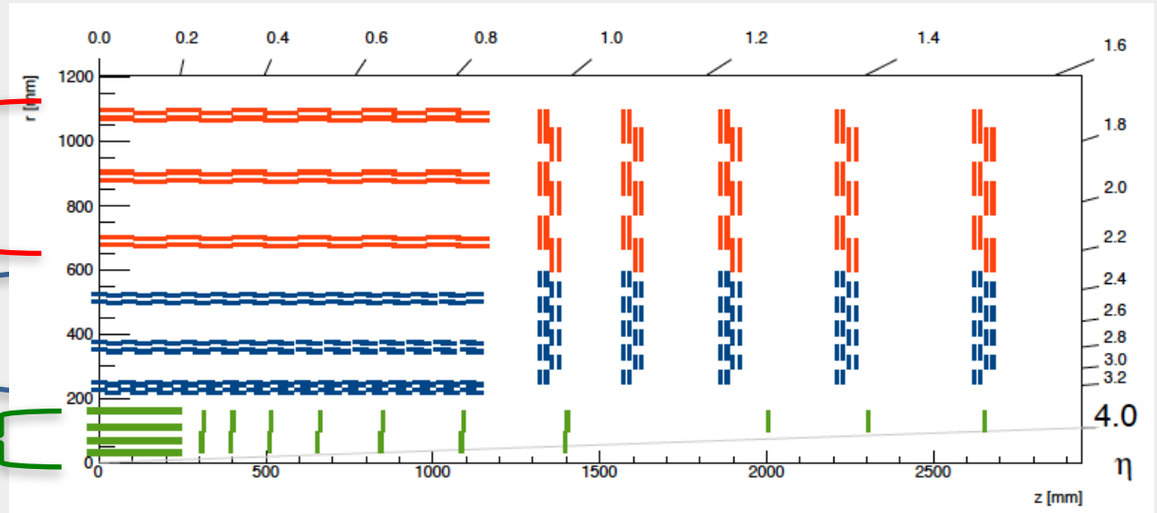
Current CMS Silicon Tracker

Proposed CMS Phase 2 tracker for 2015

Strip/Strip modules SS (pairs of strip sensors)

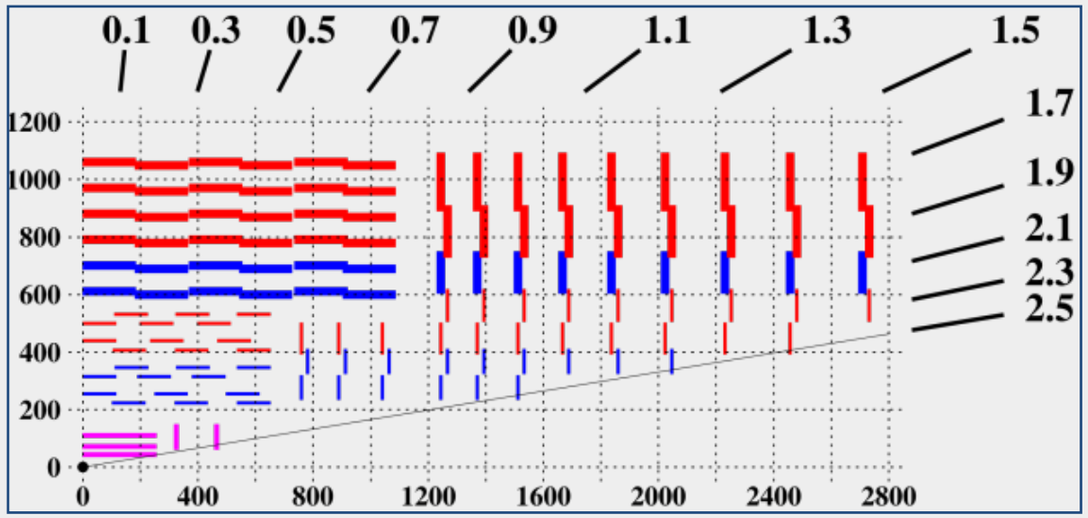
Strip/Pixel modules PS

Pixel modules



Inner Tracker, new Disks to η=4

From Current to Phase 2 Tracker



Current CMS Silicon Tracker

Requirements

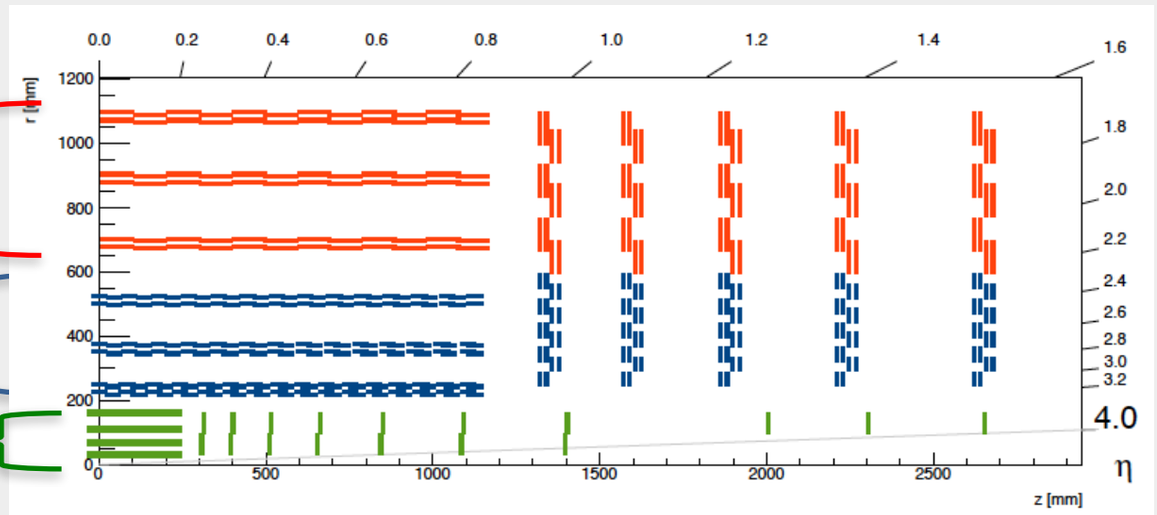
- Radiation tolerance
- Increased granularity
- Improved 2-track separation
- Reduced material
- Robust pattern recognition
- Support for L1 trigger upgrade
- Extended tracking acceptance

Proposed CMS Phase 2 tracker for 2015

Strip/Strip modules SS (pairs of strip sensors)

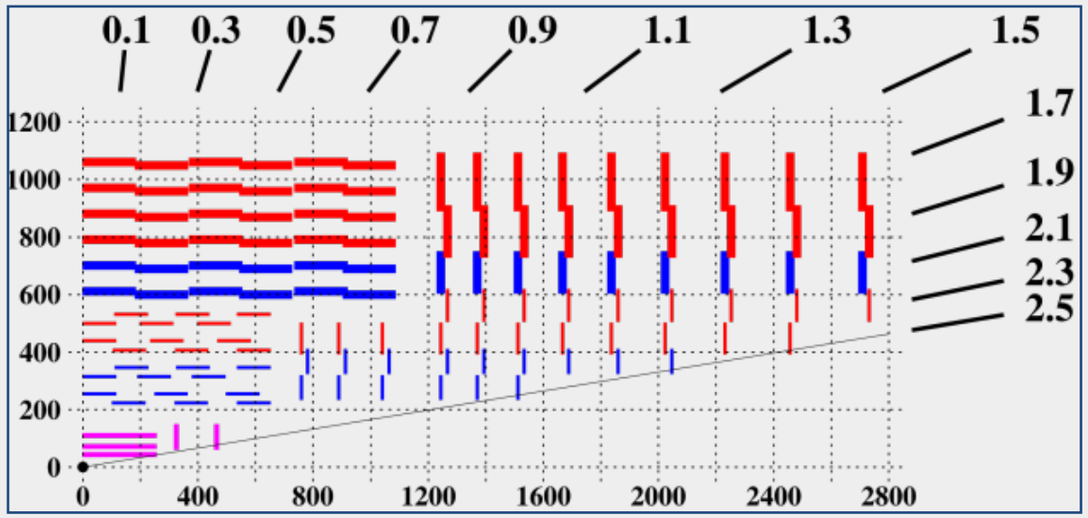
Strip/Pixel modules PS

Pixel modules

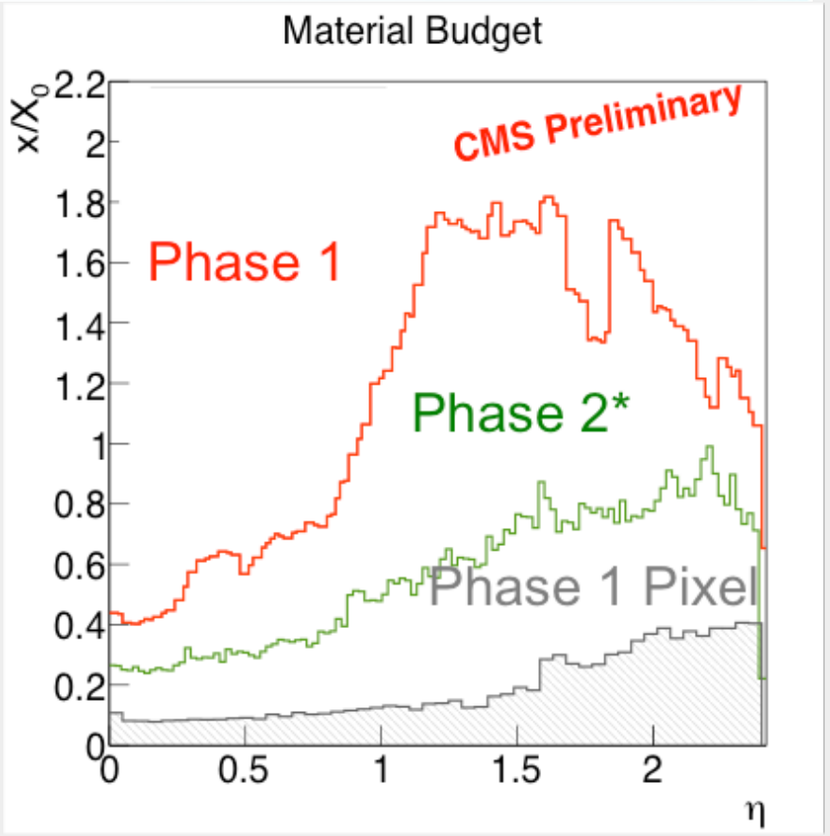


Inner Tracker, new Disks to η=4

From Current to Phase 2 Tracker



Current CMS Silicon Tracker



Requirements

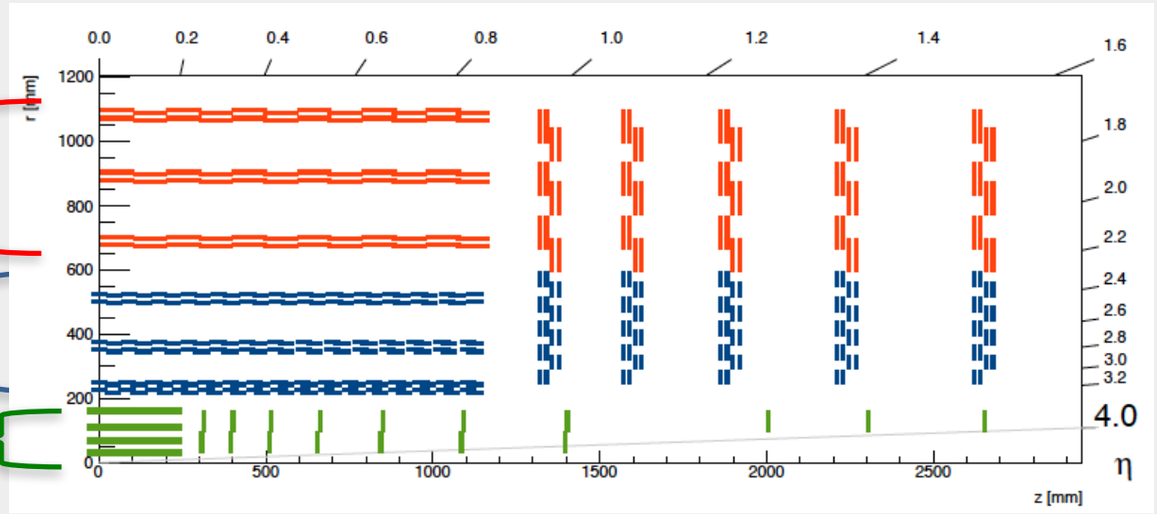
- Radiation tolerance
- Increased granularity
- Improved 2-track separation
- Reduced material
- Robust pattern recognition
- Support for L1 trigger upgrade
- Extended tracking acceptance

Proposed CMS Phase 2 tracker for 2015

Strip/Strip modules SS (pairs of strip sensors)

Strip/Pixel modules PS

Pixel modules

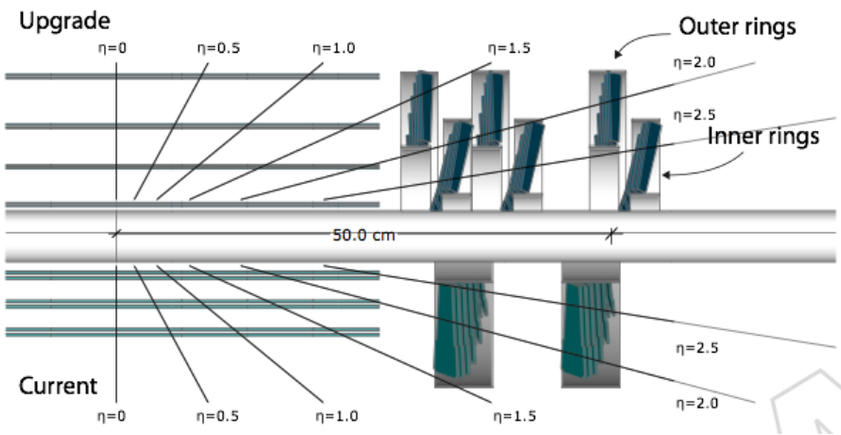


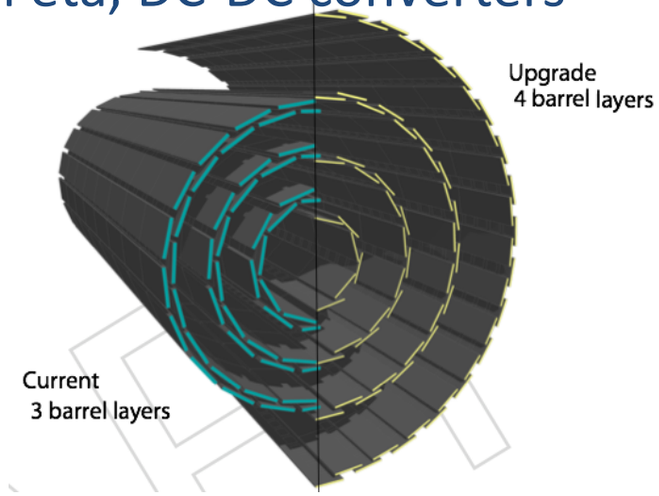
Inner Tracker, new Disks to η=4

New pixel detector (EYETS)

Features of New Design

- Robust design: 4 barrel layers and 3 endcap disks at each end
- Smaller inner radius (new beampipe), large outer
- New readout chip with expanded buffers, embedded digitization and high speed data link
- Reduced mass with 2-phase CO_2 cooling, electronics moved to high eta, DC-DC converters

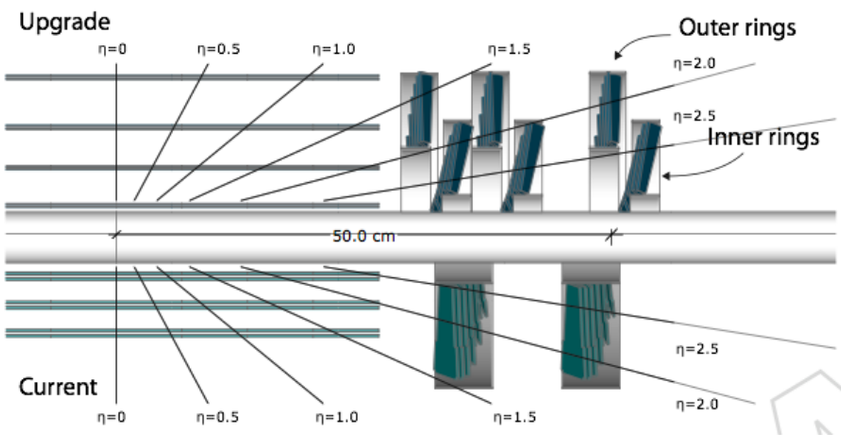




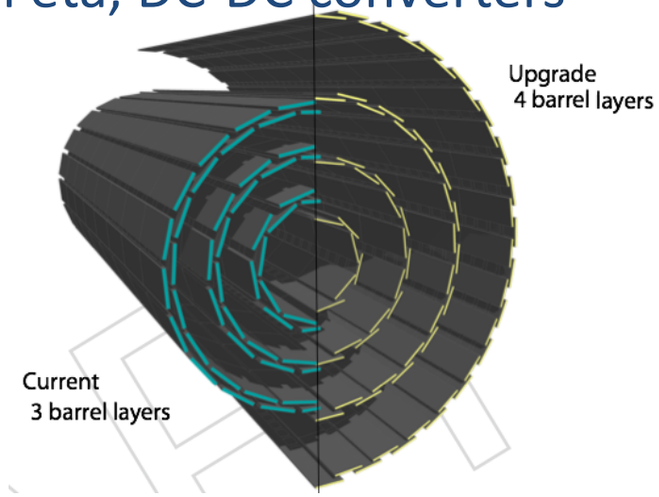
New pixel detector (EYETS)

Features of New Design

- Robust design: 4 barrel layers and 3 endcap disks at each end
- Smaller inner radius (new beampipe), large outer
- New readout chip with expanded buffers, embedded digitization and high speed data link
- Reduced mass with 2-phase CO_2 cooling, electronics moved to high eta, DC-DC converters



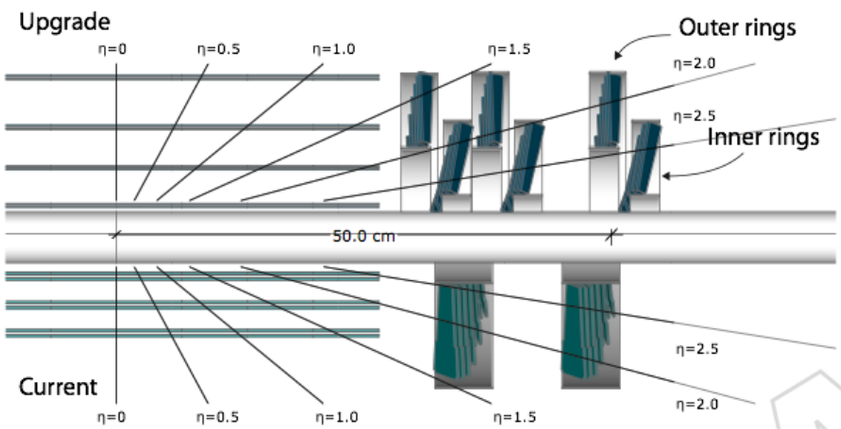
Will be installed (2016-2017)



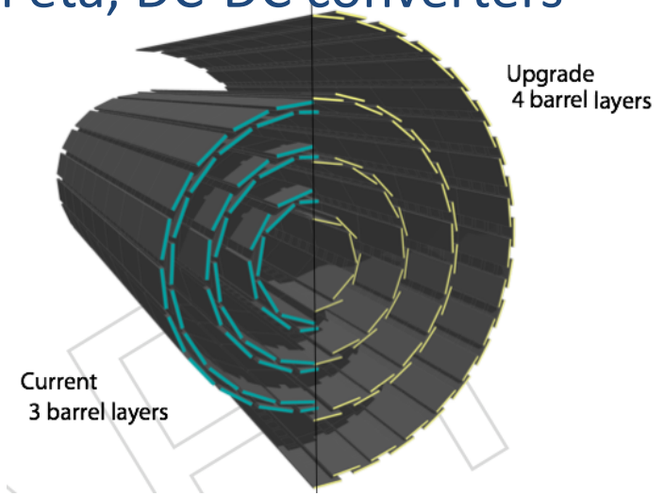
New pixel detector (EYETS)

Features of New Design

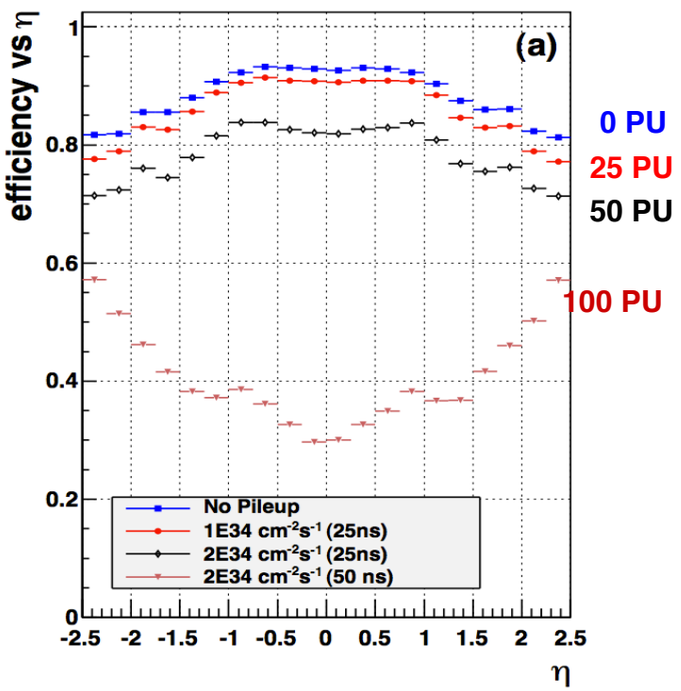
- Robust design: 4 barrel layers and 3 endcap disks at each end
- Smaller inner radius (new beampipe), large outer
- New readout chip with expanded buffers, embedded digitization and high speed data link
- Reduced mass with 2-phase CO_2 cooling, electronics moved to high eta, DC-DC converters



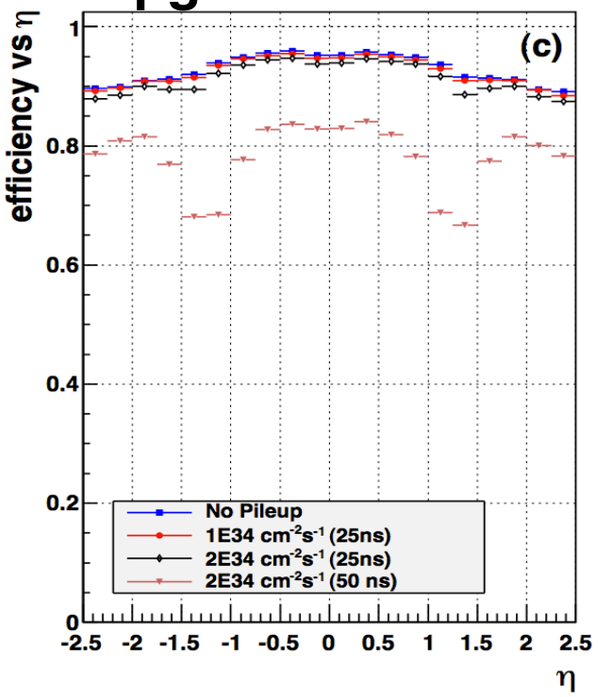
Will be installed (2016-2017)



current detector



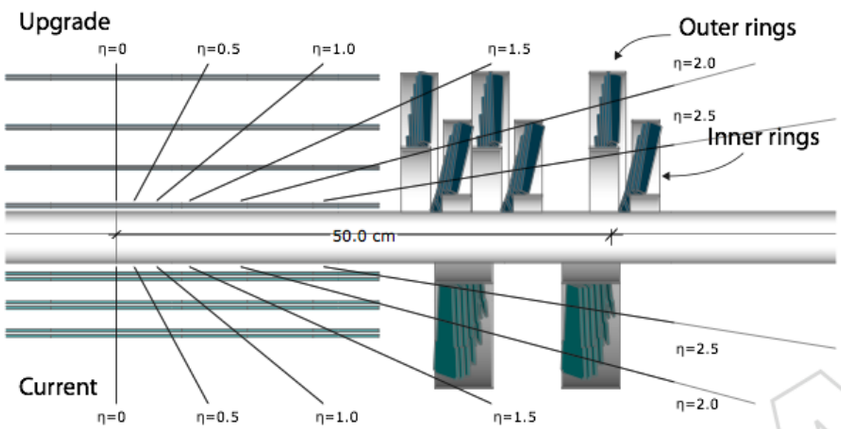
upgrade detector



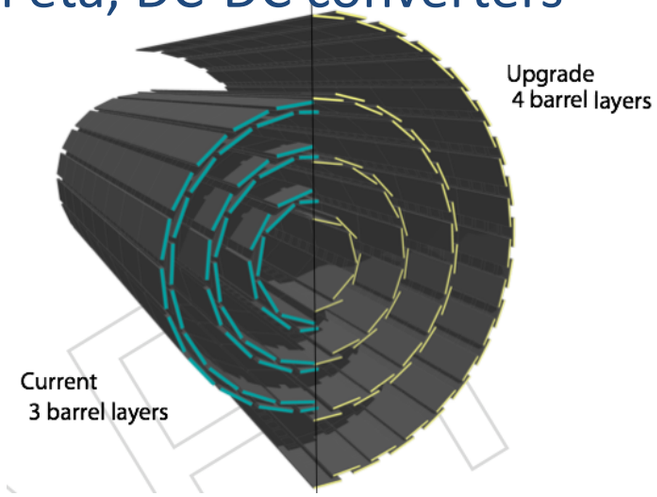
New pixel detector (EYETS)

Features of New Design

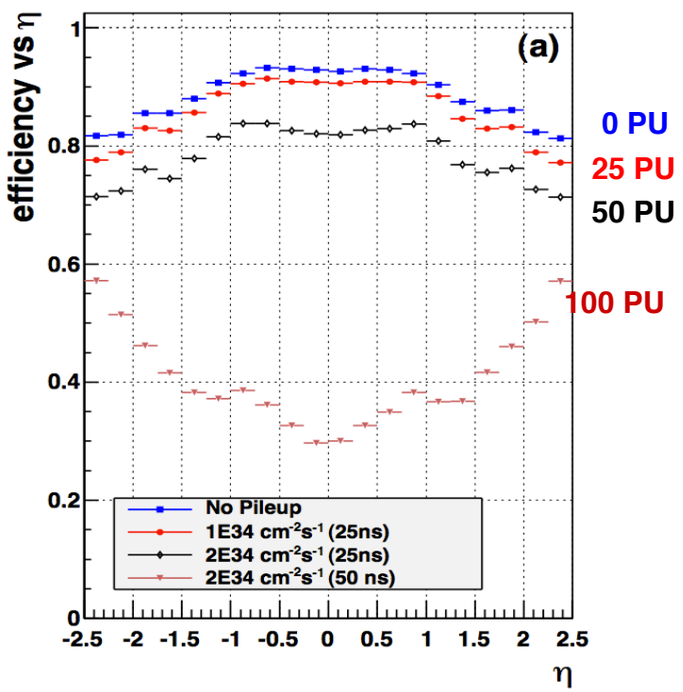
- Robust design: 4 barrel layers and 3 endcap disks at each end
- Smaller inner radius (new beampipe), large outer
- New readout chip with expanded buffers, embedded digitization and high speed data link
- Reduced mass with 2-phase CO_2 cooling, electronics moved to high eta, DC-DC converters



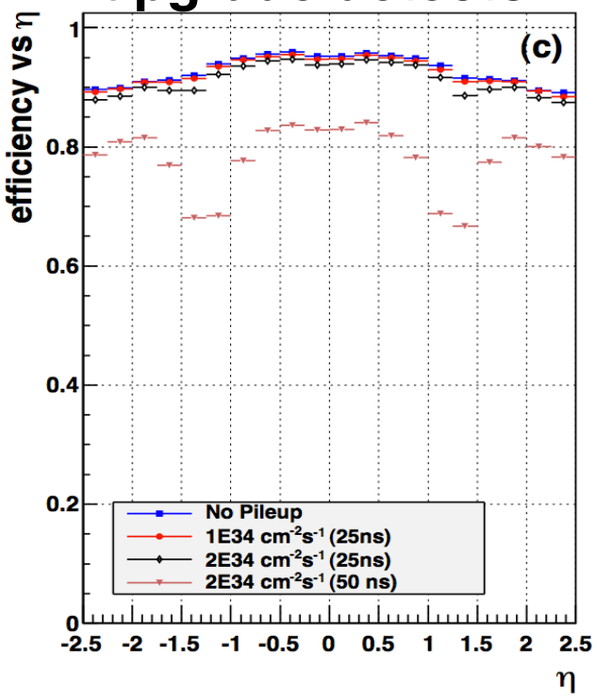
Will be installed (2016-2017)



current detector



upgrade detector



Using same Higgs selections as 2012

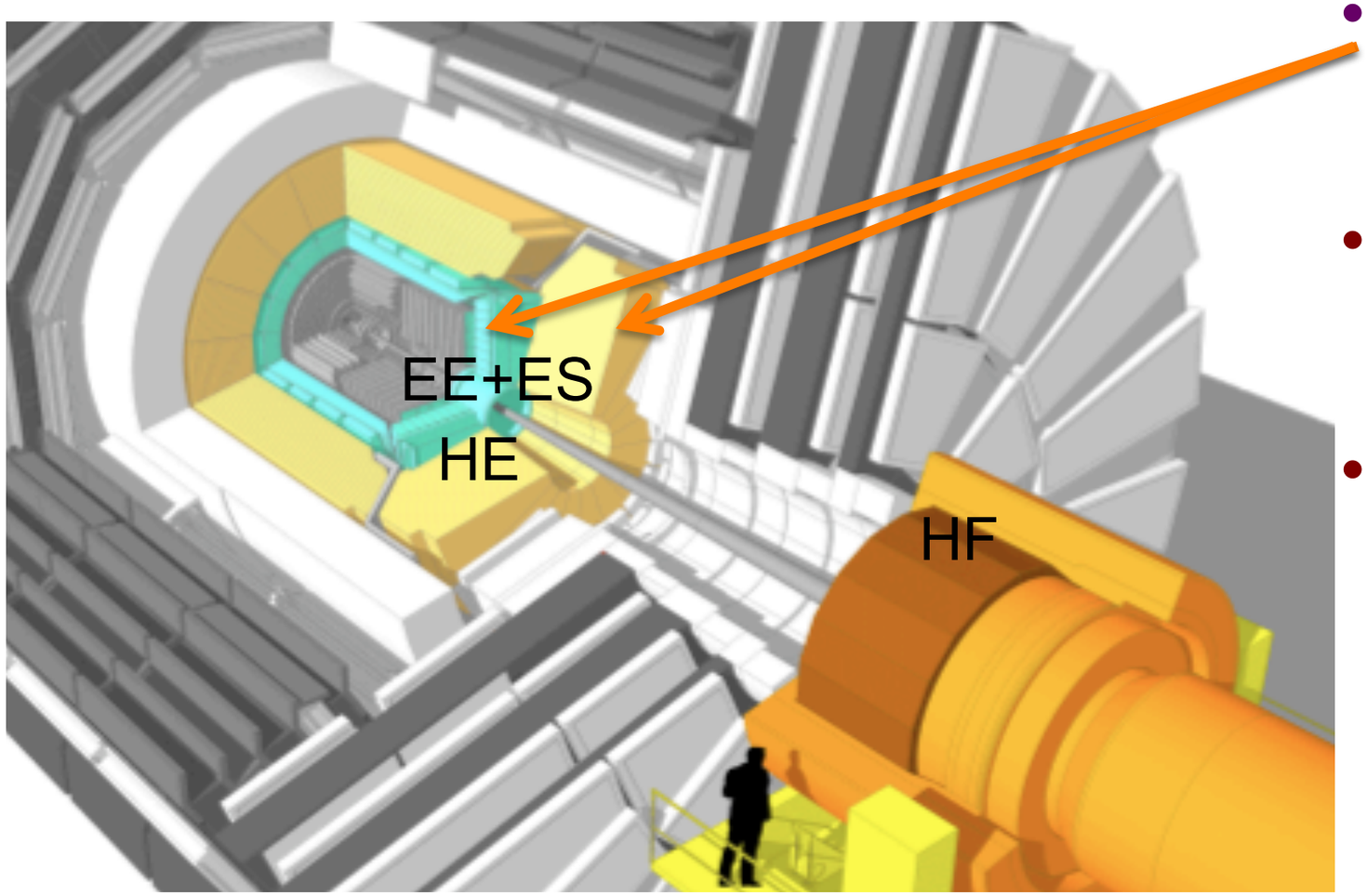
Significant gain in signal reconstruction efficiency:

H→	4μ	+41%
H→	2μ2e	+48%
H→	4e	+51%

Primary vertex resolution improved by ~1.5 - 2

Endcap calorimeters: longevity appraisal and upgrade plan

- *Substantial* performance degradation in the ECAL and HCAL endcaps
- *Moderate* damage in the ECAL and HCAL barrel
  - Increase of APD dark current in ECAL will require mitigation
- Moderate degradation in HF (operable throughout Phase II)



- **Replacement/upgrade of both ECAL and HCAL endcaps in LS3**
- **Upgrade of the ECAL FE electronics: 40 MHz data stream (barrel)**
- Mitigation of the APD current noise **needed**
  - FE with faster shaping time (also, improved timing, spike rejection)
  - Cooling of the barrel

ECAL: $PbWO_4$ crystals **HB/HE: Sci Tiles/WLS**
HF: Quartz fibre Calo

High Granularity Calorimeter (HGCAL)

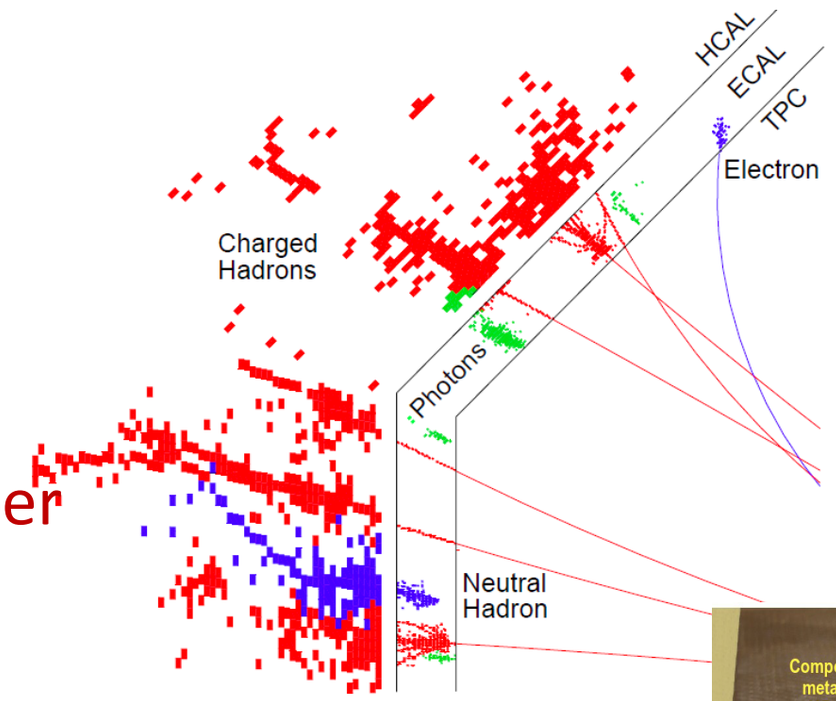
- High Granularity Calorimeter
  - Fine depth segmentation

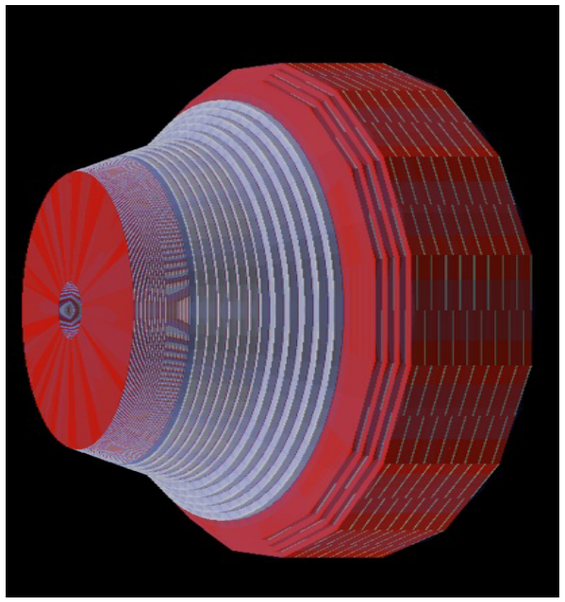
    ECAL: ~33 cm, 25 X_0, 1 λ

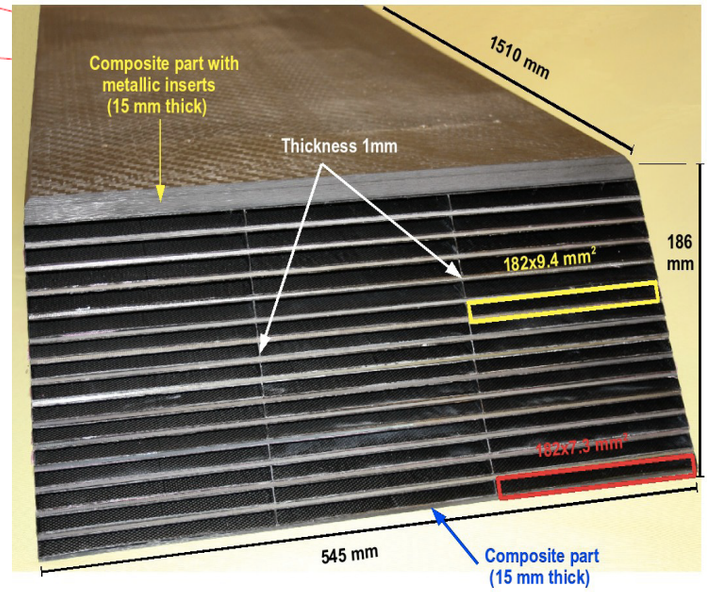
    30 layers Si separated by lead/Cu

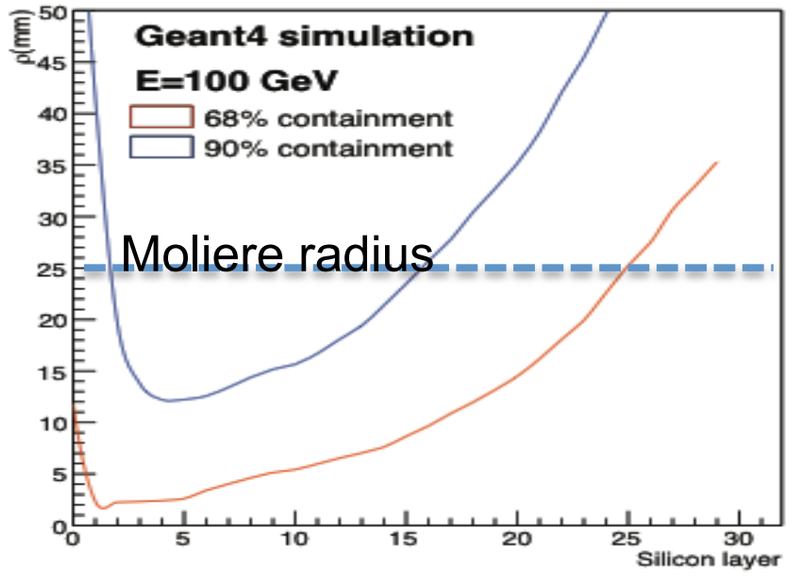
    HCAL: ~66 cm, 3.5 λ

    12 planes of Si separated by absorber
  - 9 Mch & 660 m^2 Si
- Back HCAL as HE re-build 5λ
  - With increased transverse granularity
- 3D measurement of the shower topology
  - 25 mm Moliere radius (shower narrower before max)
  - **Expected e/γ resolution ~ 20%/sqrt(E) + ≤ 1%**
- Studies and R&D



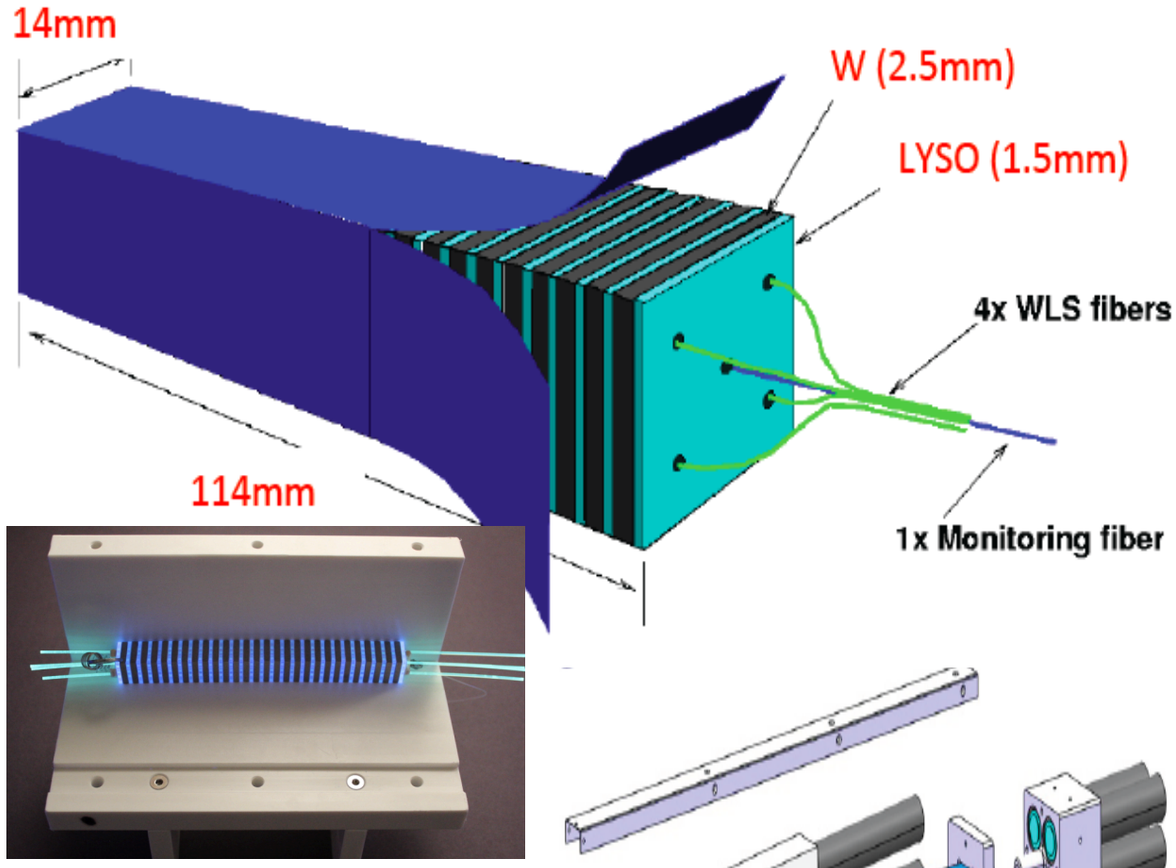


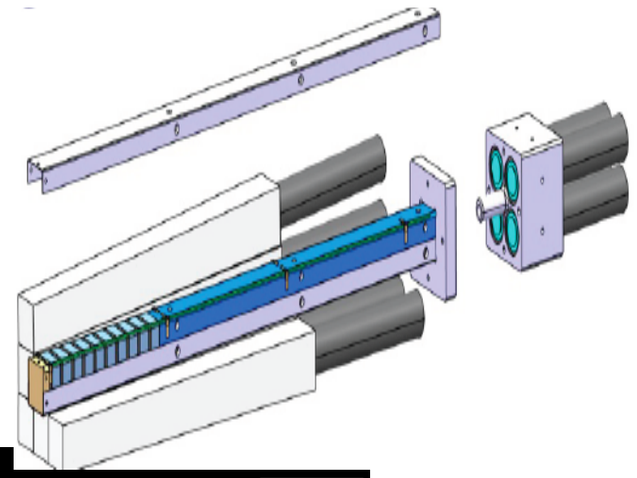


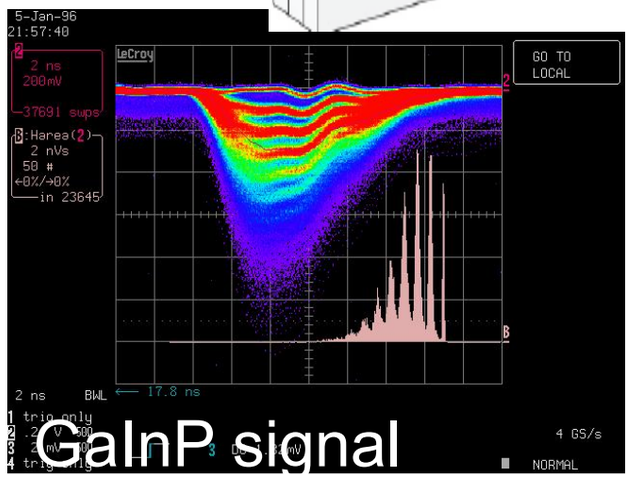


EE Shashlik – Test beam ongoing

- EE Shashlik:
  - W-absorber and Crystals LYSO (CeF_3 alternative) - 28 plates
    → Very compact (11 cm), small Moliere radius (14 mm) and fine granularity (14 mm^2) to mitigate pile-up
    → high light yield for good e/γ
    energy resolution ~ 10%/sqrt(E) + 1%
  - Readout with:
    - 4 WLS Capillaries (scintillating fibers CeF_3)
    - Calibration Fiber (1 per module)
    - GaInP(SiPM) Photosensors (4 per module)
  - No depth segmentation but investigating:
    - Extraction of a signal near shower max with precise timing - WLS with scintillating dye on quartz core







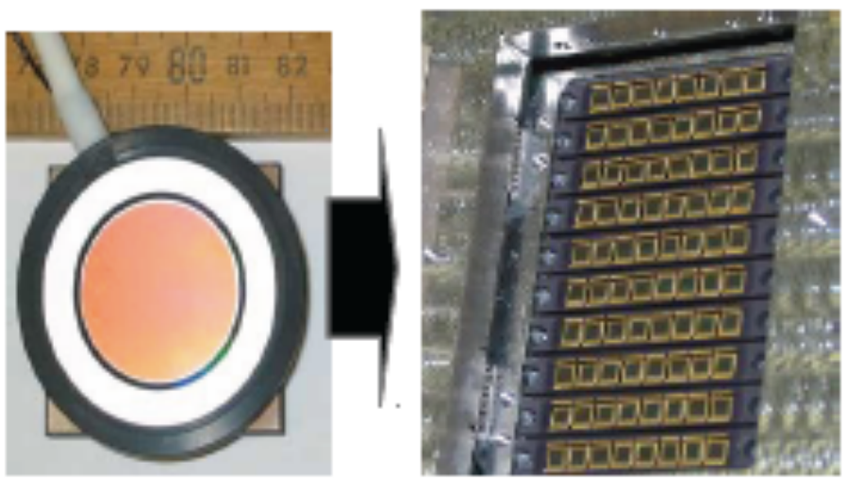
GaInP signal

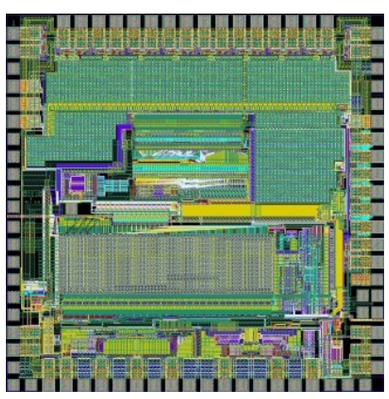
CMS HCAL Read-Out Upgrades

Installation during LS1(HO)/LS2(HB/HE)

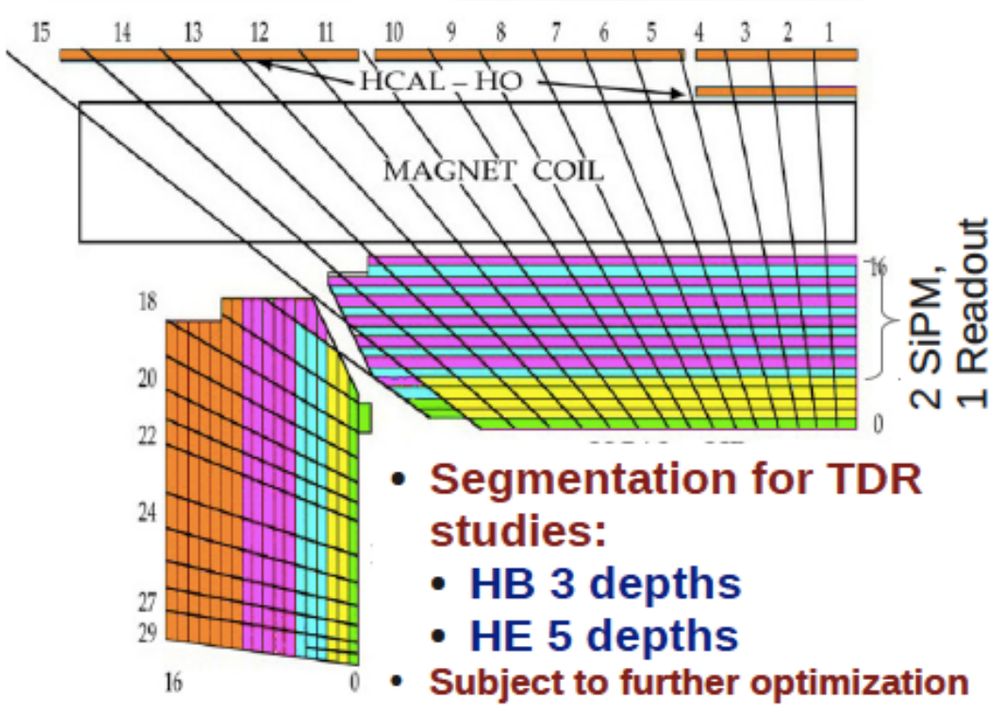
HB/HE/HO

From HPD to SiPM's





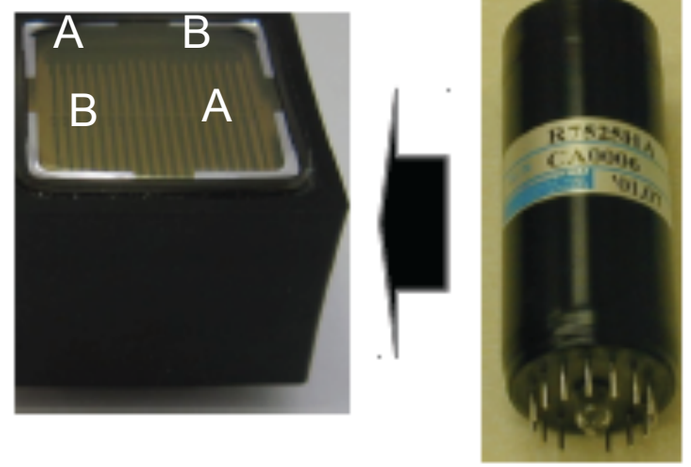
- Use SiPM's to increase HB/HE Depth Segmentation
- Improved PF Hadronic shower localization
- Provides effective tool for pile-up mitigation at high luminosity
- Mitigate radiation damage to scintillator & WLS fibers



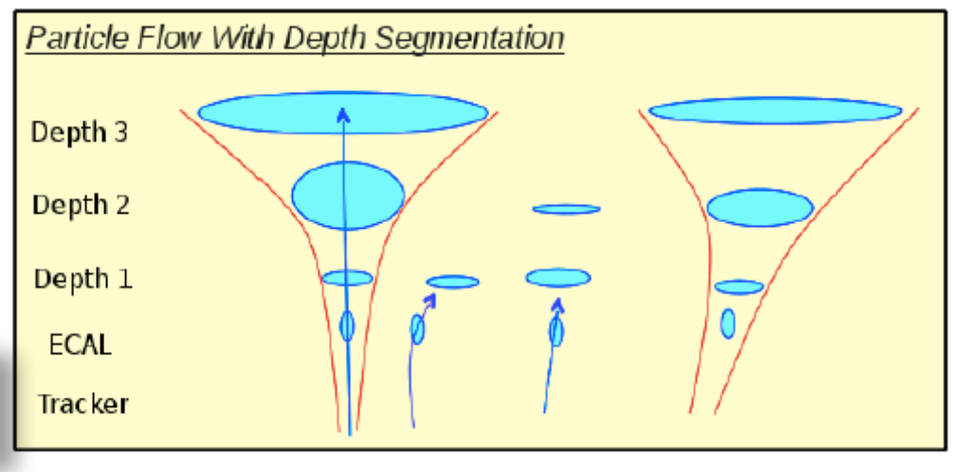
Installation during LS1

HF

From single to multi-anode PMT's



Depth segmentation: mitigate high pileup



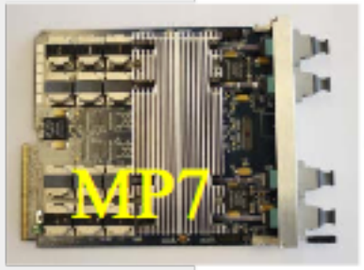
Level - 1 Trigger upgrade

CERN-LHCC-2013-011
(CMS-TDR-012)

New hardware!

Limited number of boards.

Ambitious plan assume parallel running of a (part of) new system in 2015. Full replacement 2015/16 YEST

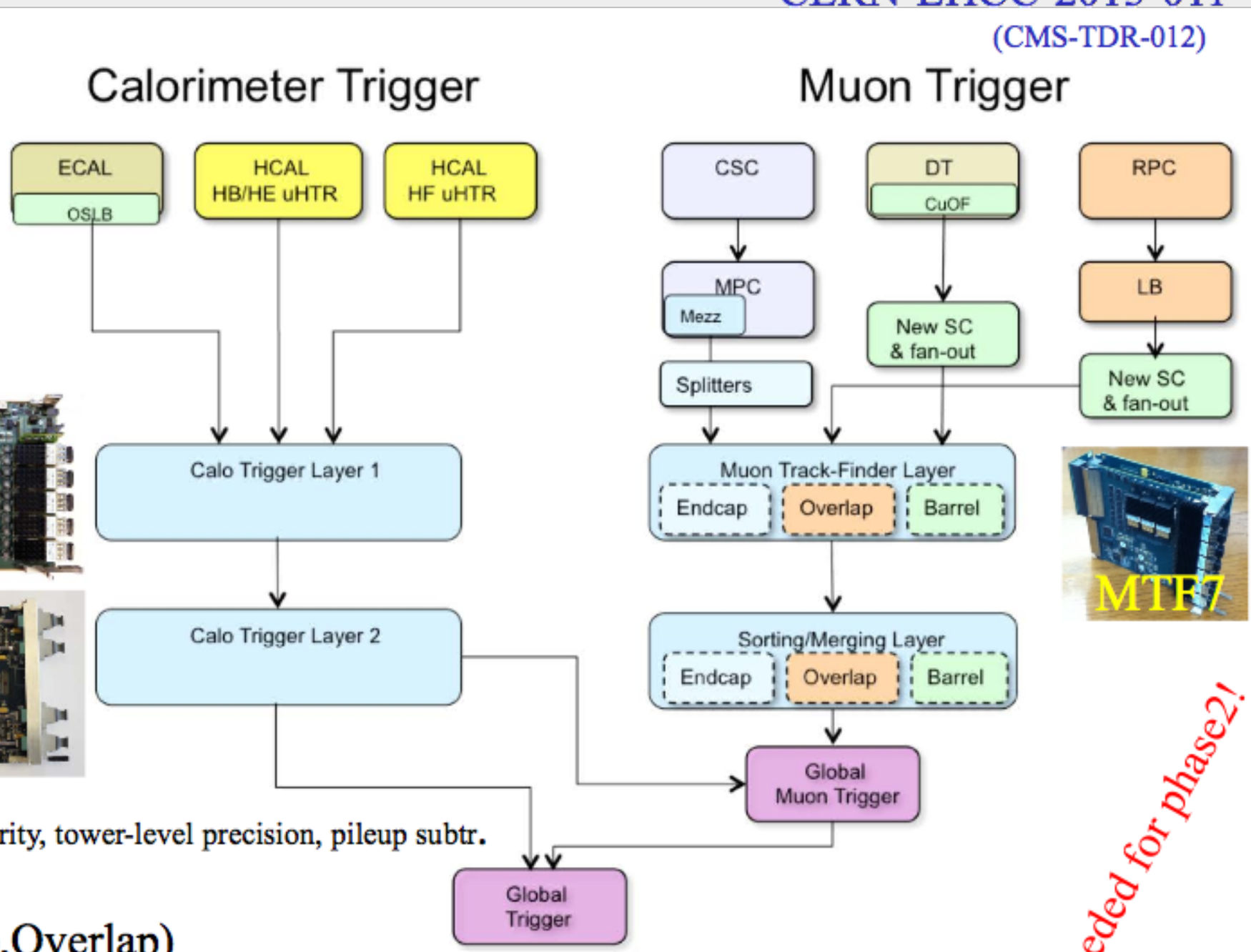


Global Trigger:
- more algorithms,
- flexibility

Calorimetry:
- improved algorithms, granularity, tower-level precision, pileup subtr.

Muons:
- 3 partitions (Barrel,Endcap,Overlap)
- explore the available information at early step of triggering.

Currently independent candidates from DTTF, CSCTF, PACT merged at GMT



More needed for phase2!

L1 Trigger upgrade

- **Level-1 trigger rate** limited to **1kHz**, 4μs latency by detector readout.
- Mitigate through improved:
  - **muon triggers**: improved μ p_T resolution w/ full information from 3 systems in track finding, more processing
  - **calorimeter triggers**: finer granularity, more processing means better e/γ/μ isolation & jet/τ resolution w/ PU subtraction
- Increased system flexibility and algorithm sophistication
- Build/commission in parallel with current system – staged installation, will benefit already at start of Run 2

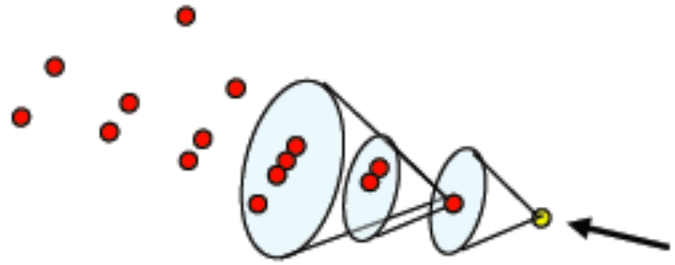
Larger FPGAs, finer granularity input, high speed optical links

Trigger efficiency @ 2e34 $cm^{-2}s^{-1}$

Channel	Current	Upgrade
W(eν),H(bb)	37.5%	71.5%
W(μν),H(bb)	69.6%	97.9%
VBF H(ττ(μτ))	19.4%	48.4%
VBF H(ττ(ετ))	14.0%	39.0%
VBF H(ττ(ττ))	14.9%	50.1%
H(WW(eeνν))	74.2%	95.3%
H(WW(μμνν))	89.3%	99.9%
H(WW(eμνν))	86.9%	99.3%
H(WW(μeνν))	90.7%	99.7%

Particle Flow

Mark Thomson



ConeClustering Algorithm

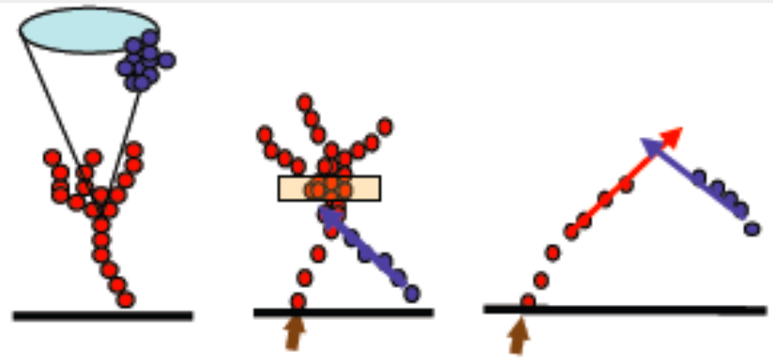
Topological Association Algorithms

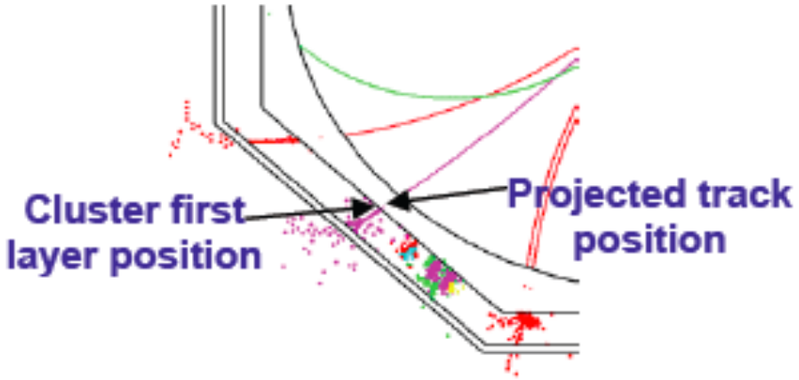
Track-Cluster Association Algorithms

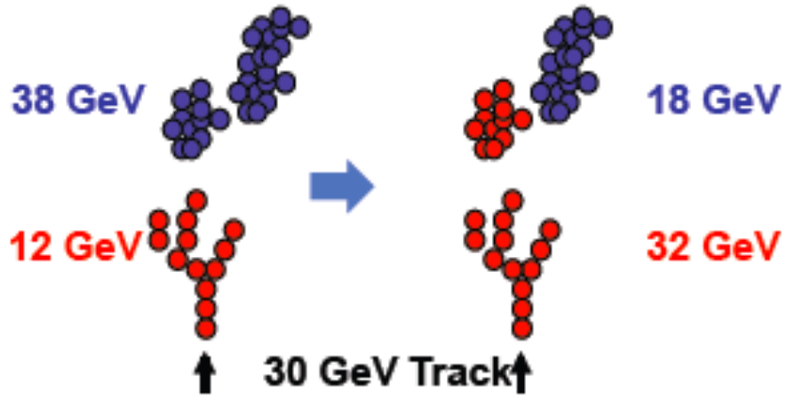
Reclustering Algorithms

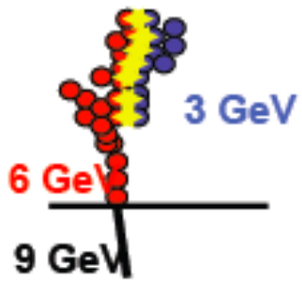
Fragment Removal Algorithms

PFO Construction Algorithms

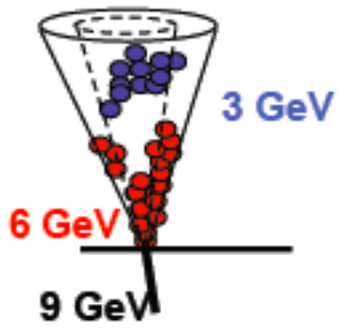




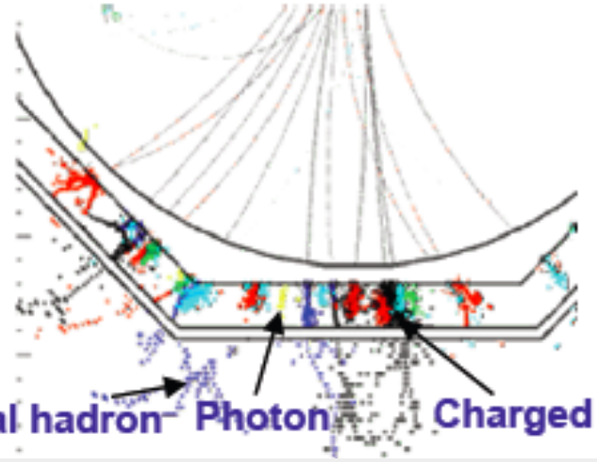




Layers in close contact



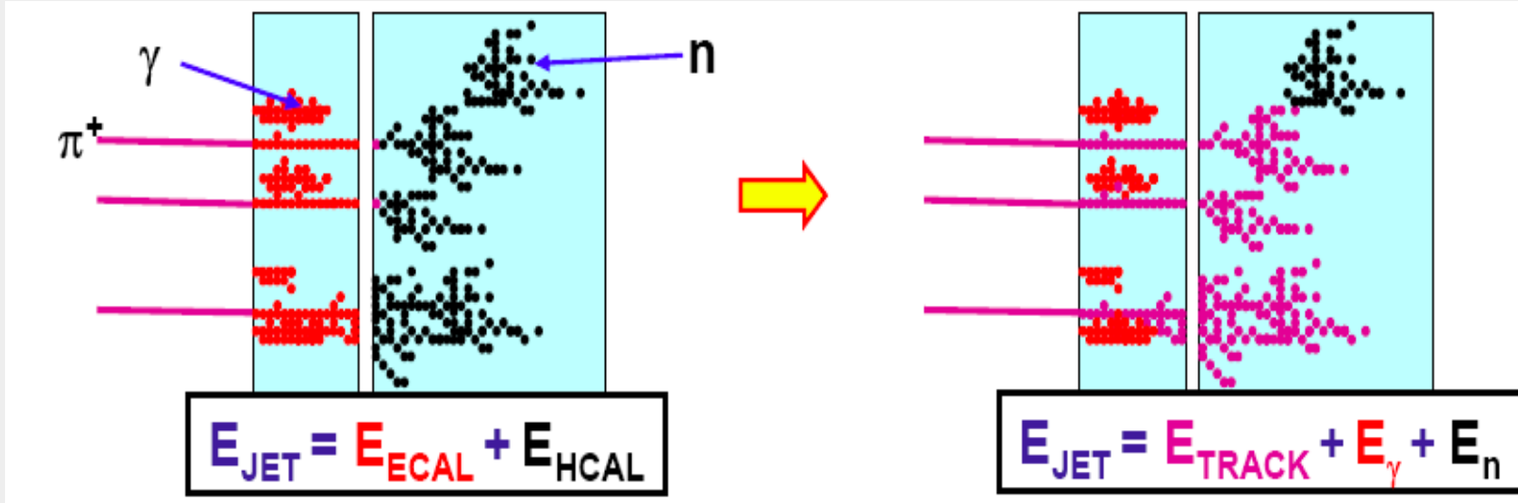
Fraction of energy in cone

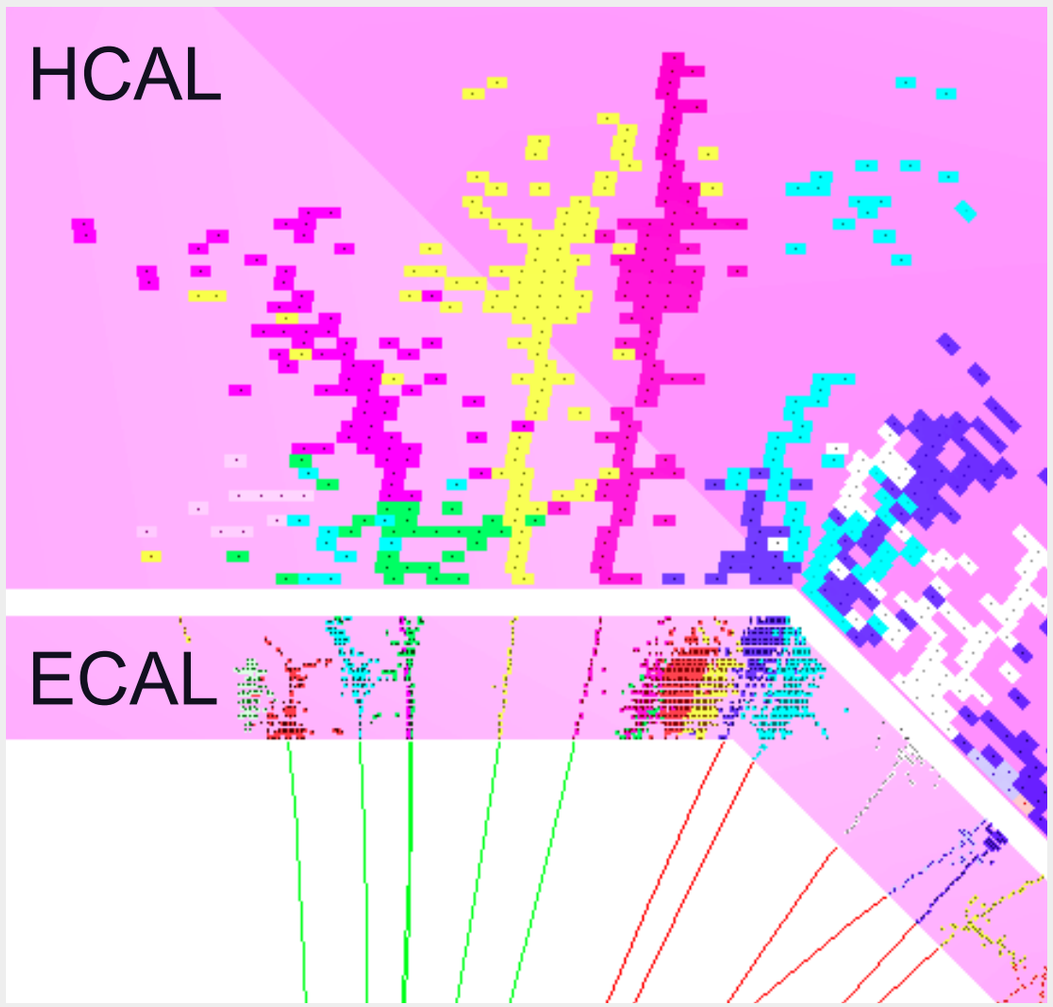


PF calorimetry (CALICE)

Design detectors for Pflow

- ECAL and HCAL: inside solenoids
- Low mass tracker
- High granularity for imaging calorimetry
- It also require sophisticated software





Two proto-collaborations for ILC (ILD and SLD)

- ECAL: Highly segmented $S_I W$ or Scintillator-W sampling calorimeters
  - Transverse segmentation: ~5 x 5 mm^2
  - ~30 longitudinal sampling layers
- HCAL: Highly segmented sampling calorimeters Steel or W absorber+ active material (RPC, GEM)
  - Transverse segmentation: 1x1 cm^2 – 3x3 cm^2
  - ~50 Longitudinal sampling layers !
- ***Aiming at*** $\sigma_E / E < 3.5\%$

The CMS Phase II Upgrades

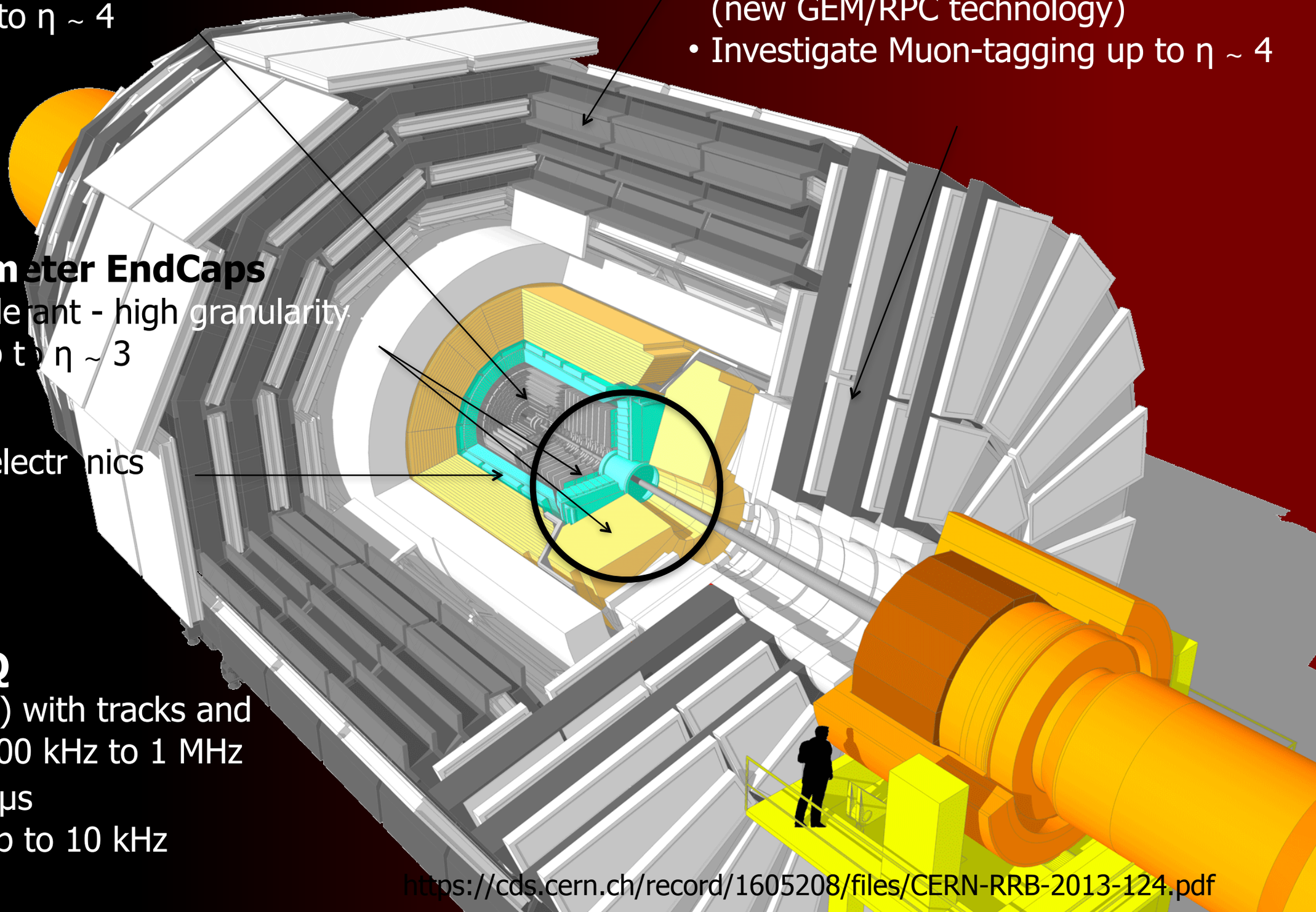
New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 4

New Calorimeter EndCaps
- Radiation tolerant - high granularity
- Coverage up to η ~ 3

Barrel ECAL
- Replace FE electronics

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
- Latency ≥ 10μs
- HLT output up to 10 kHz



https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

Why HGCAL?

- A dense, highly granular 3D sampling calorimeter provides
  - unprecedented topological information and shower tracking capability
- together with
  - energy resolution well matched to boosted kinematics of particles and jets in the End-Cap acceptance
- Aim to exploit these for feature extraction and and precision calorimetry, both at L1 and offline, with Particle Flow reconstruction in the high occupancy environment of the HL-LHC

TO BACKUP

Why HGC?

- Leptons, electrons and photons, will remain a key physics signature for the HL-LHC
- Hadronic tau decays and jets will play a central role in much of the HL-LHC physics program
  - VBF H-> $\tau\tau$ => precision Higgs
  - VBF H -> Invisible => Dark Matter
  - VBS, EWSB, resonances etc
  - VBF SUSY => EWK SUSY sector, charginos, neutralinos
    - Require good MET resolution and clean tails, in presence of high p_T VBF jets in EndCap!

Why HGC?

- Tracking e/γ shower development as function of depth in order to
  - Unfold the effect of non-projective geometry
  - Apply PU subtraction & measure the energy of the electron shower using dynamic clustering
    - Layer-by-layer using knowledge of lateral and longitudinal EM shower shapes and longitudinal PU development
    - Update and new results see Pedro's talk
  - Use 3D shower development to further improve e/γ identification
  - Measure high energy electron/photon shower directions to a few mrad.

Why HGC?

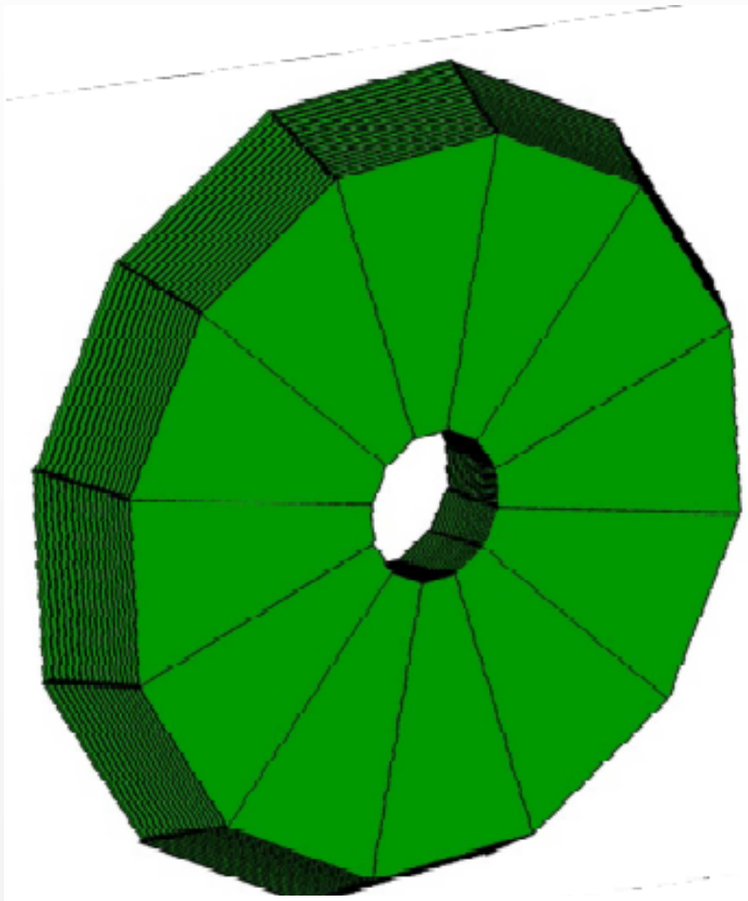
- Tracking Jet shower development as function of depth in order to
  - Unfold the effect of non-projective geometry
  - Apply PU subtraction, identify and measure the energy of (VBF) Jets using narrow cones
    - Layer-by-layer using knowledge of lateral and longitudinal Jet shapes and longitudinal PU development
    - First results see Pedro's talk
  - Use 3D Jet development to discriminate against QCD jets "promoted" by PU
  - Provide L1 Jet trigger and improve PF Jet reconstruction

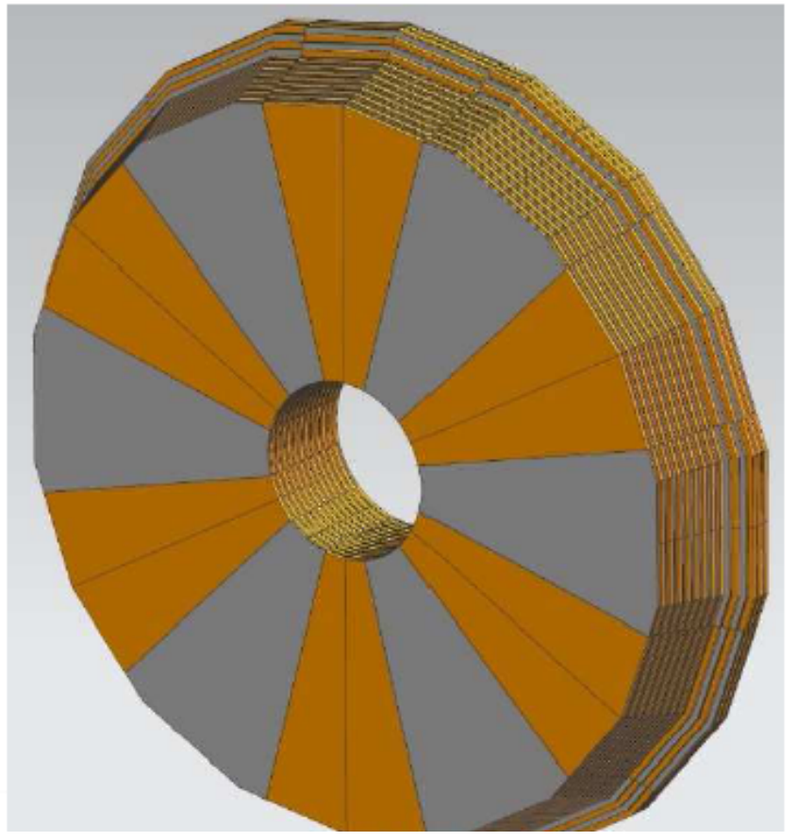
HGCAL Mechanical Design

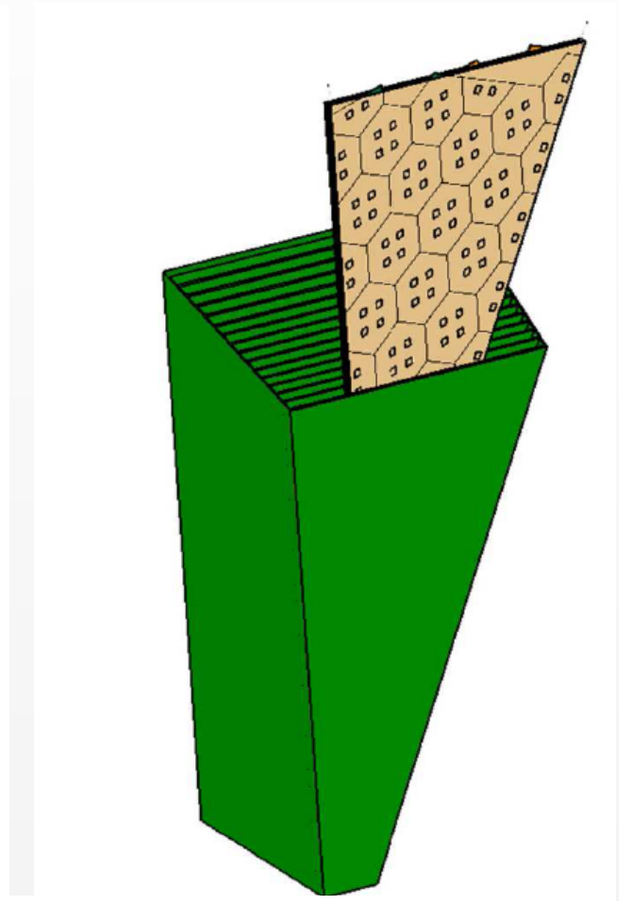
- Developed viable mechanical design, with independent Cassettes inserted into Alveolar support structures
  - Cassettes: Modules mounted on both sides of 6mm thick Cu plate, which integrates CO_2 capillary and cooling pipes
  - EE CF/W composite Alveolar structure based on CALICE design
    - Geometry adapted to integrate into CMS End-Cap, and mitigate effect of inhomogeneity at Cassette boundaries
  - FH Brass Alveolar structure based on HE

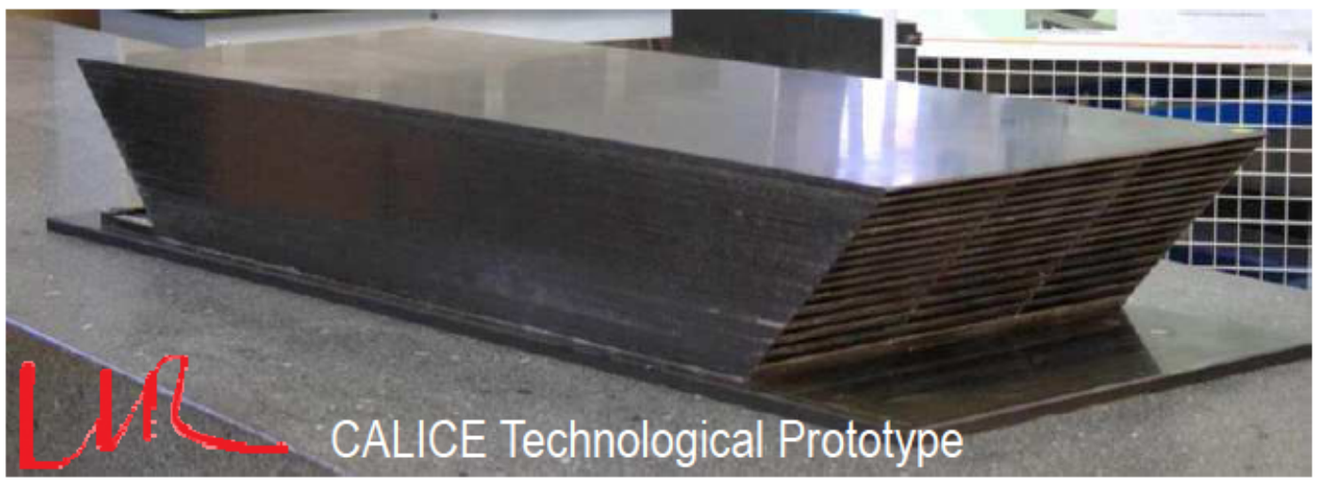
TO BACKUP

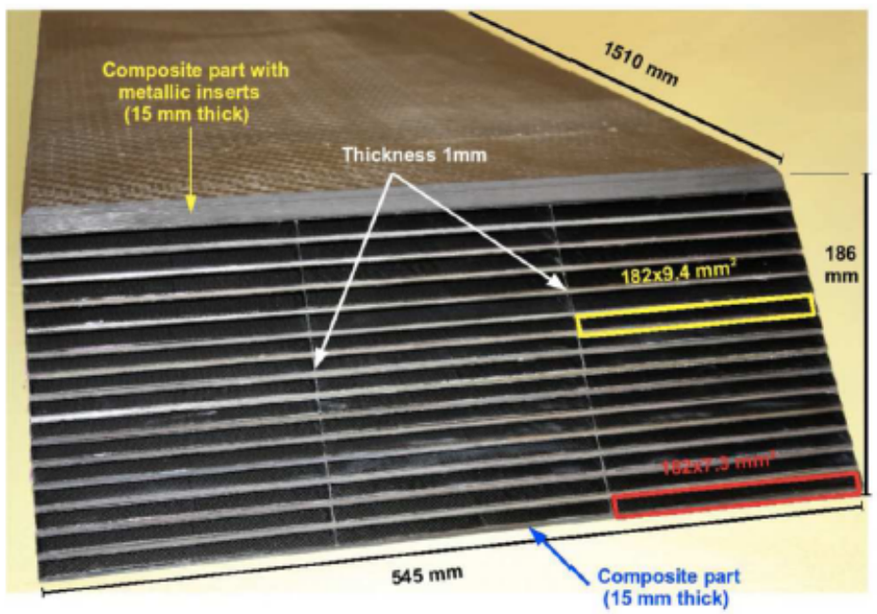
HGC Mechanical Design





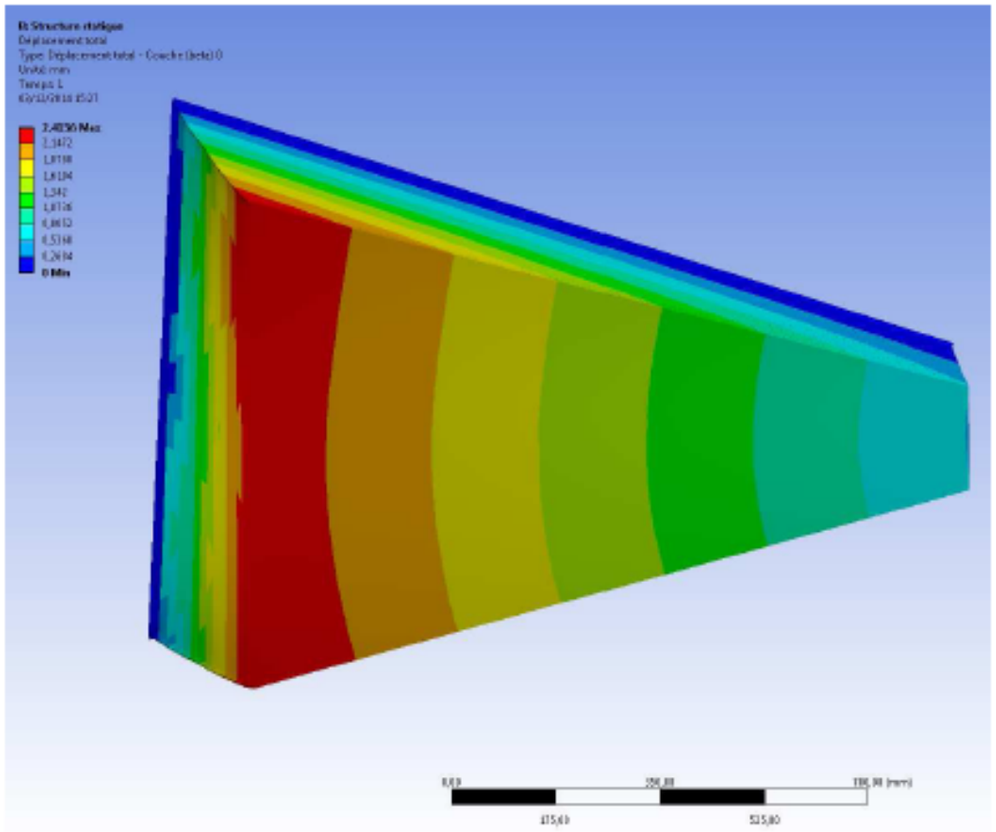




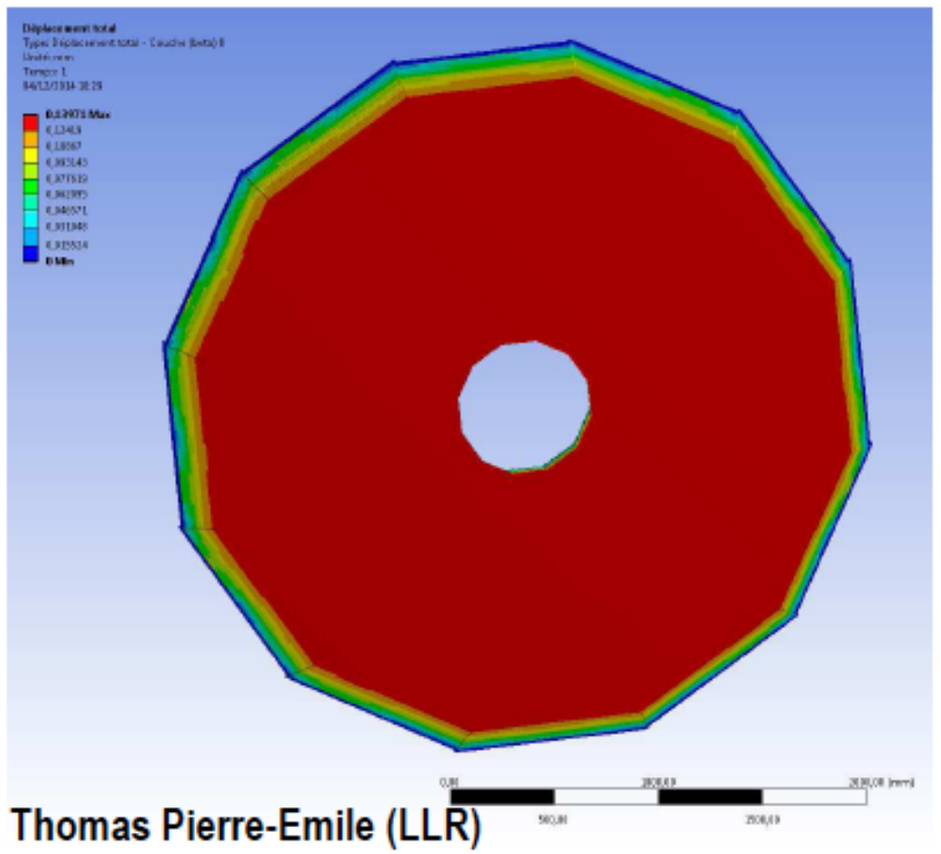


HGC Mechanical Design

Standalone wedge (at 270°)



Full “wheel”



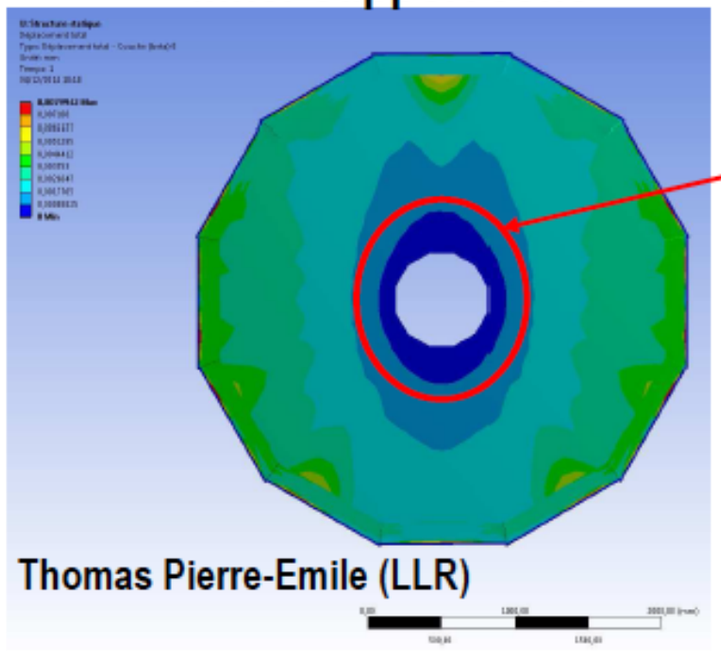
Thomas Pierre-Emile (LLR)

	Standalone (270°)	Full wheel
Displacement (max)	2.4 mm	**0.14 mm**
Failure criteria F (max)	~0.3	**~ 0.10**
Margin of Safety	85 %	**210 %**

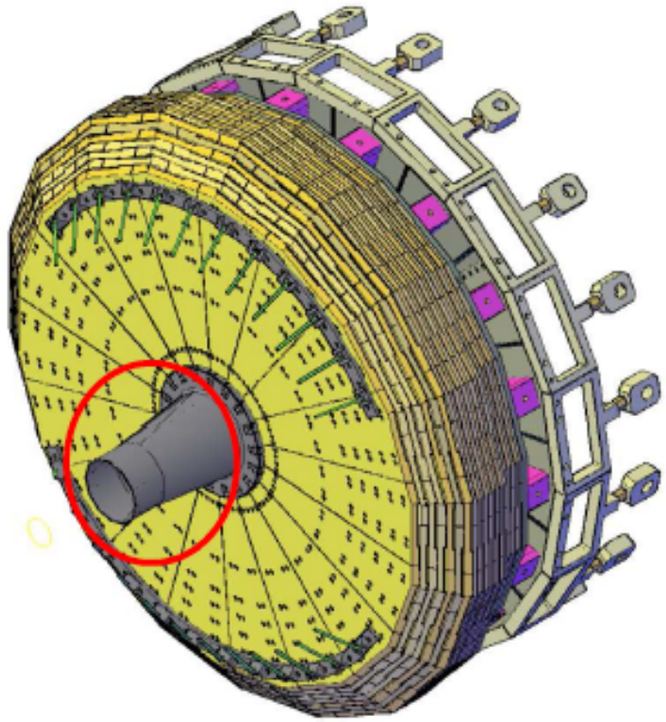
- **Failure occurs when failure criteria F ≥ 1**
- Margin of Safety $\propto (1/\sqrt{F} - 1)$,
  - **200% is reasonable from engineering point of view**

HGC Mechanical Design

Full "wheel"
+ inner support cone



First look at:
Fix node on the edges to simulate an attachment to a infinitely rigid
inner support cone
(optimistic, for illustration)



	Standalone (270°)	Full wheel	Full wheel + support cone
Displacement (max)	2.4 mm	0.14 mm	**0.008 mm**
Failure criteria F (max)	~0.3	~ 0.10	**0.008**
Margin of Safety	85 %	210 %	**1000 % !**

- **User of an inner support cone allows additional handle to better distribute the load.**
  - Would help reducing the side walls thickness
  - May lead to further design optimization and alternatives
- **All these studies have to be verified with destructive tests** on small samples or demonstrator (**on-going**)

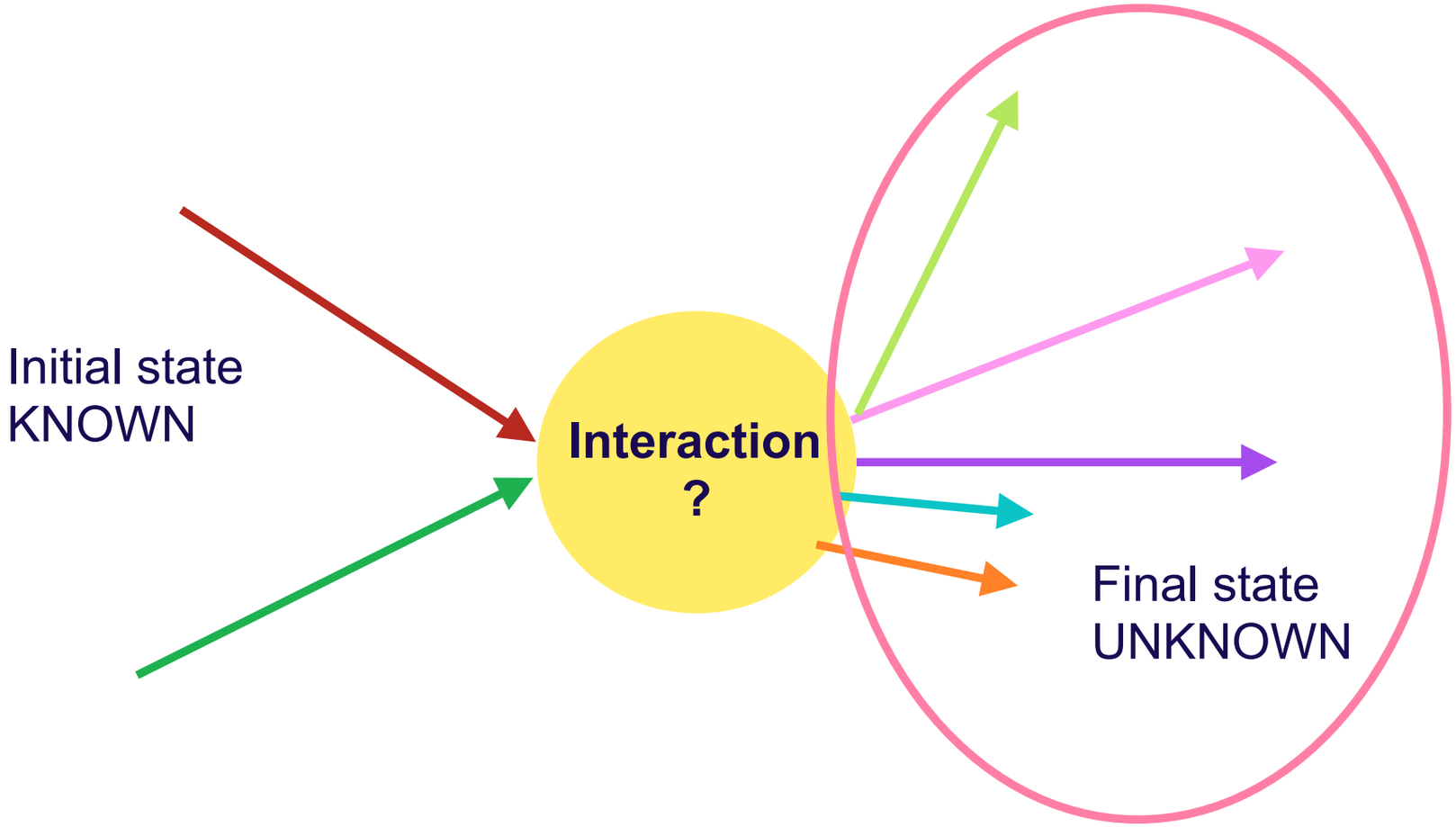
WHY DO WE NEED PARTICLE DETECTORS ?

WHY DO WE NEED PARTICLE DETECTORS ?

- An astronomer uses a telescope
- A biologist uses a microscope
- We (a lot of us at least) use a camera to take a snapshot of reality
- Particle physicists invent, build and operate detectors to record the products of initial particles interactions:

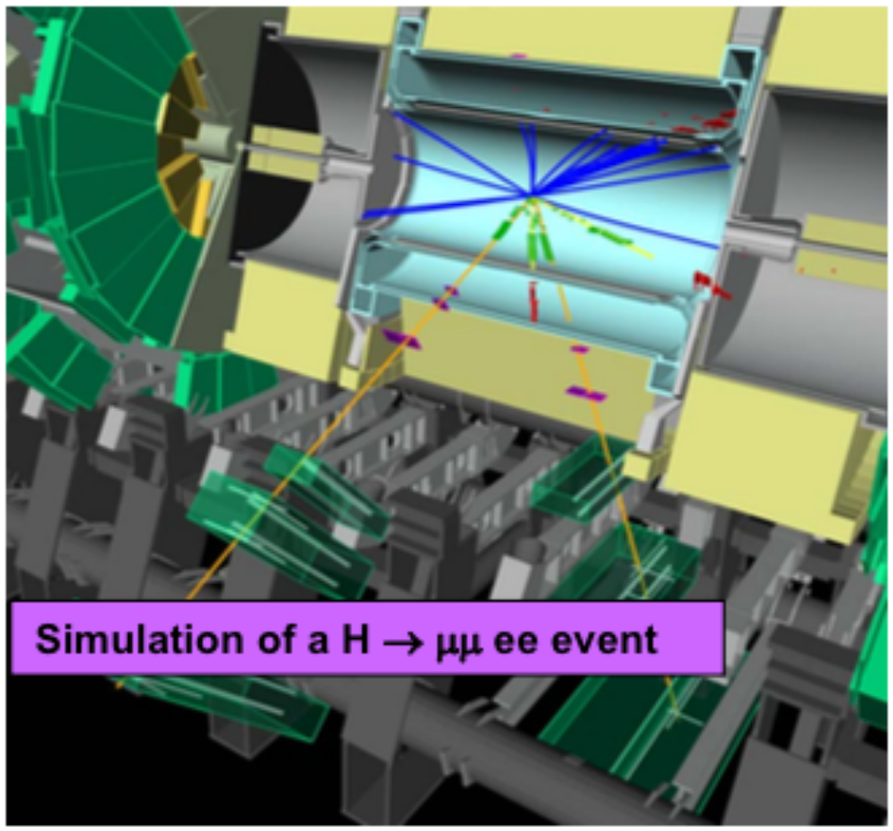
WHY DO WE NEED PARTICLE DETECTORS ?

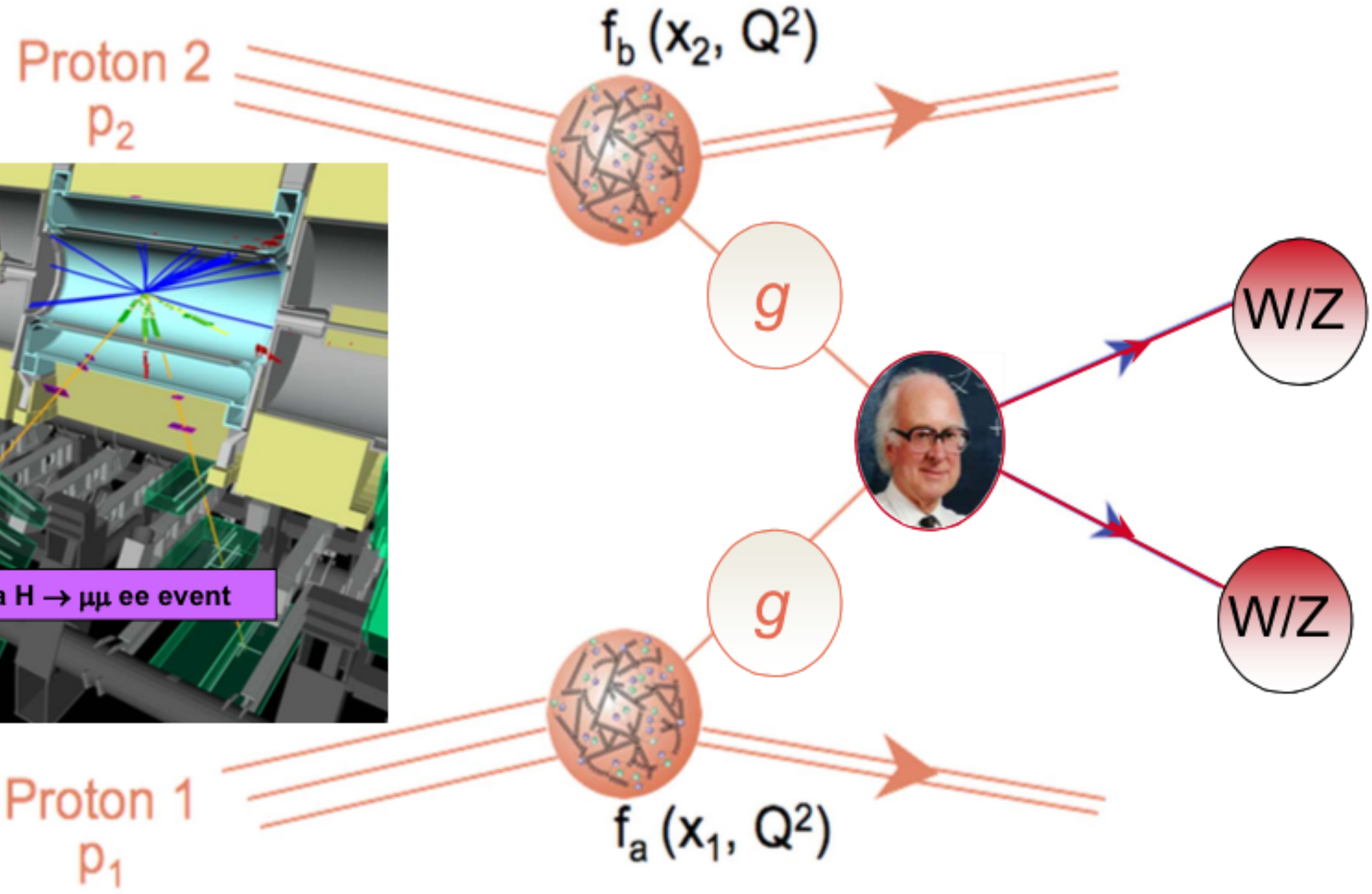
- An astronomer uses a telescope
- A biologist uses a microscope
- We (a lot of us at least) use a camera to take a snapshot of reality
- Particle physicists invent, build and operate detectors to record the products of initial particles interactions:



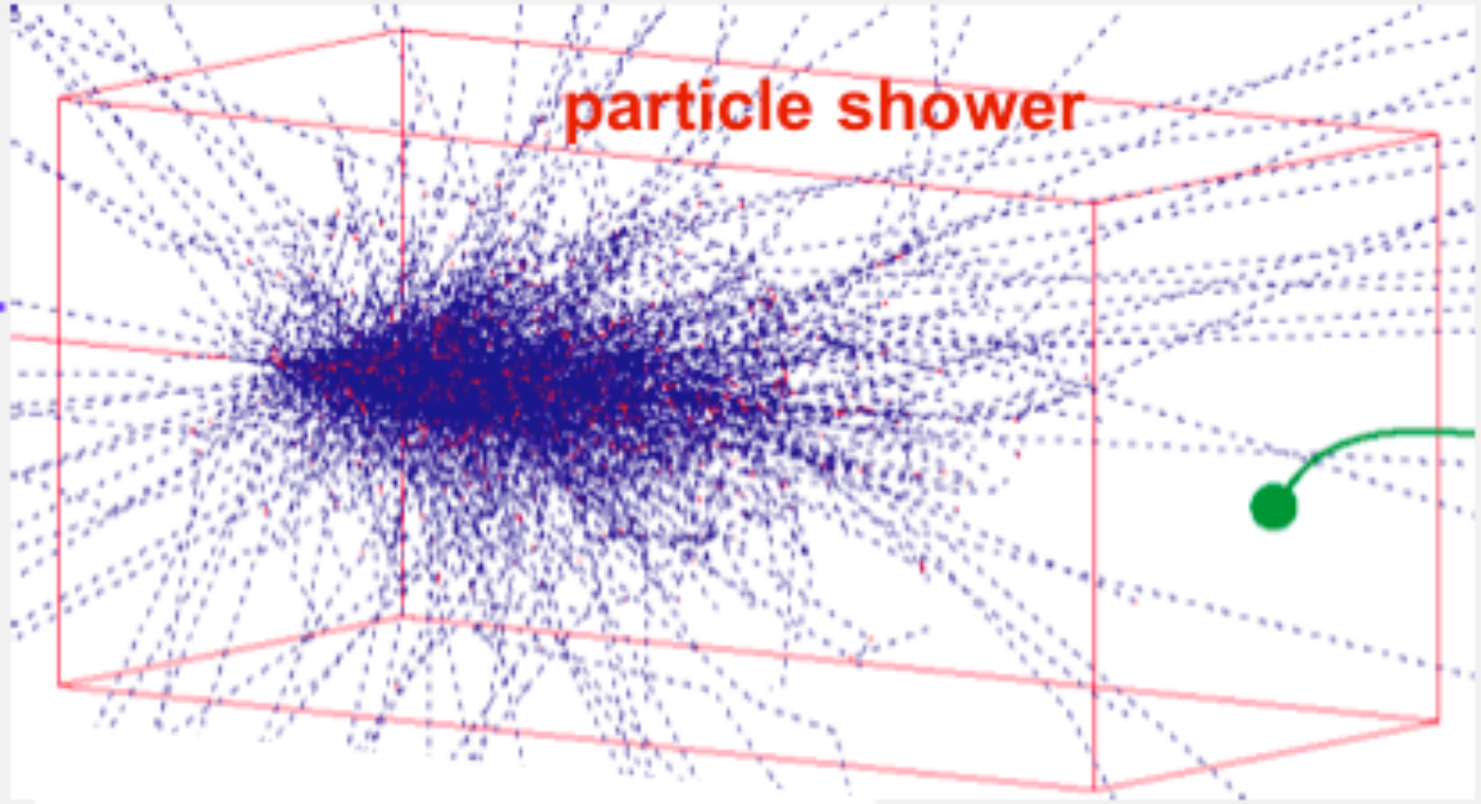
DETECTOR
to record the final state for physicists to interpret nature of the interaction

WHAT ARE WE LOOKING FOR ?





Calorimeter's Concept



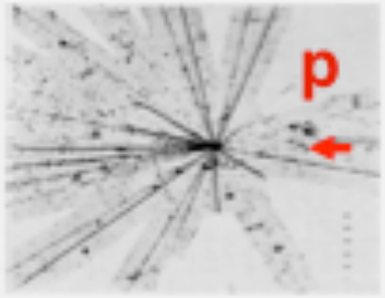
Converts energy **E** of incident particles to detector response **S**:

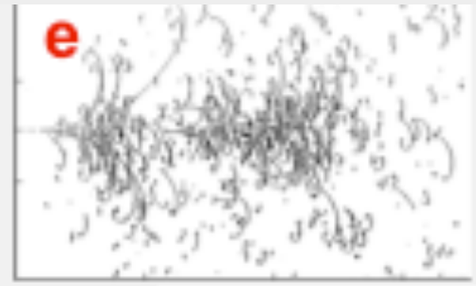
$$S \propto E$$

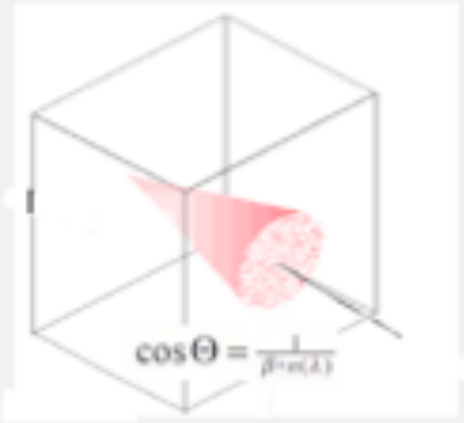
Calorimetry is a "destructive" method. Energy and particle get absorbed !

Calorimetry in four steps

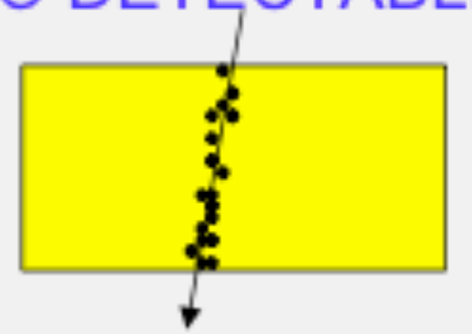
PARTICLE INTERACTION IN MATTER (depends on the impinging particle and on the kind of material)

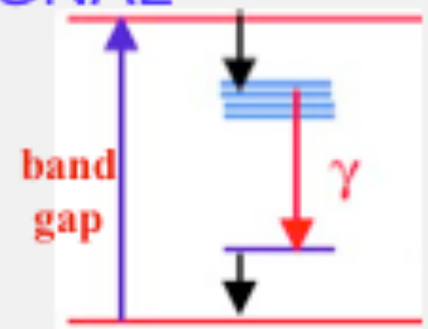




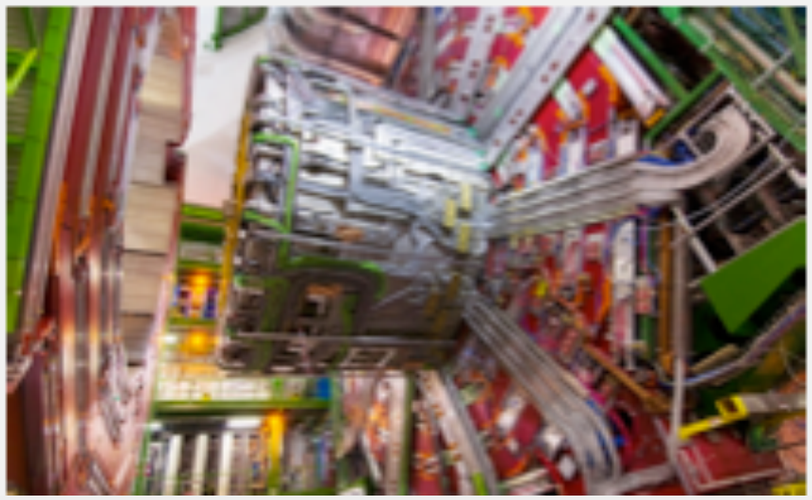


ENERGY LOSS TRANSFER TO DETECTABLE SIGNAL (depends on the material)

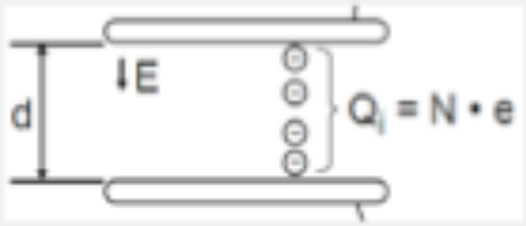


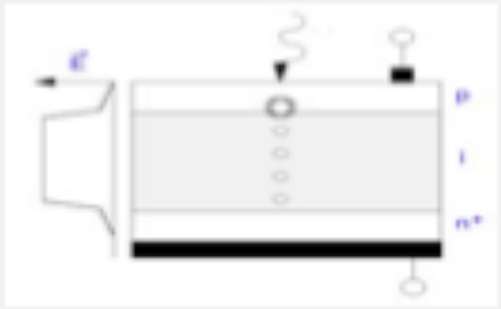


BUILD A SYSTEM



SIGNAL COLLECTION (depends on signal, many techniques of collection)





Homogeneous calorimeters

- **Homogeneous calorimeters: Detector = absorber**
  - ⇨ good energy resolution
  - ⇨ limited spatial resolution (particularly in longitudinal direction)
  - ⇨ only used for electromagnetic calorimetry

Two main types:

1. Scintillators →

2. Cherenkov devices →

In both cases the signal consists of photons. Readout via photomultiplier -diode/triode, APD, HPD

Scintillator	Density [g/cm^3]	X_0 [cm]	Light Yield γ/MeV (rel. yield*)	τ_1 [ns]	λ_1 [nm]	Rad. Dam. [Gy]	Comments
NaI (Tl)	3.67	2.59	4×10^4	230	415	≥10	hydroscopic, fragile
CsI (Tl)	4.51	1.86	5×10^4 (0.49)	1005	565	≥10	Slightly hygroscopic
CSI pure	4.51	1.86	4×10^4 (0.04)	10 36	310 310	10^3	Slightly hygroscopic
BaF_2	4.87	2.03	10^4 (0.13)	0.6 620	220 310	10^5	
BGO	7.13	1.13	8×10^3	300	480	10	
$PbW0_4$	8.28	0.89	≈100	440 broad band 530 broad band		10^4	light yield =f(T)

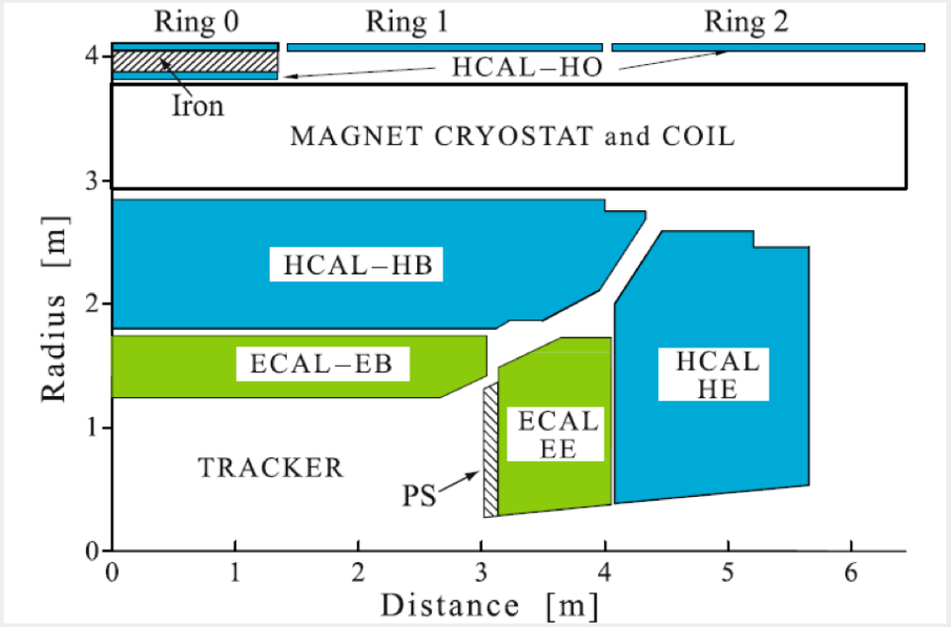
* Relative light yield: rel. to NaI(Tl) readout with PM (bialkali PC)

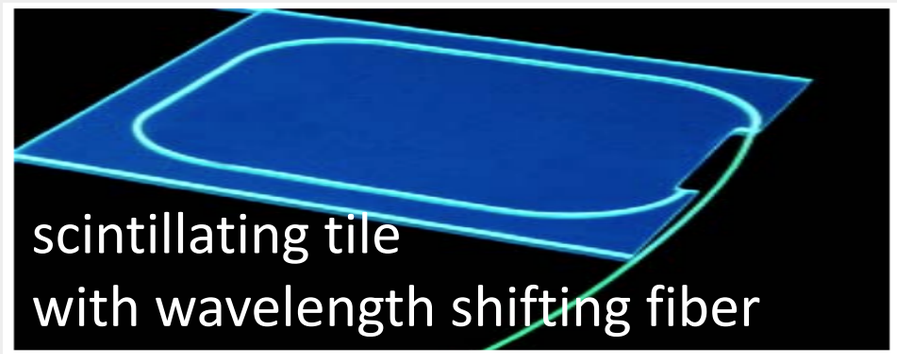
Material	Density [g/cm^3]	X_0 [cm]	n	Light yield [p.e./GeV] (rel. p.e.*)	λ_{cut} [nm]	Rad. Dam. [Gy]	Comments
SF-5 Lead glass	4.08	2.54	1.67	600 (1.5×10^{-4})	350	10^2	
SF-6 Lead glass	5.20	1.69	1.81	900 (2.3×10^{-4})	350	10^2	
PbF_2	7.66	0.95	1.82	2000 (5×10^{-4})		10^3	Not available in quantity

Hadron calorimeter

- HCAL Barrel (HB) 0<|η|<1.3 and Endcap (HE) 1.3<|η|<3
  - Sampling calorimeter, alternating layers of brass absorber and plastic scintillator tiles.
  - Hybrid photo-detector (HPD) readout

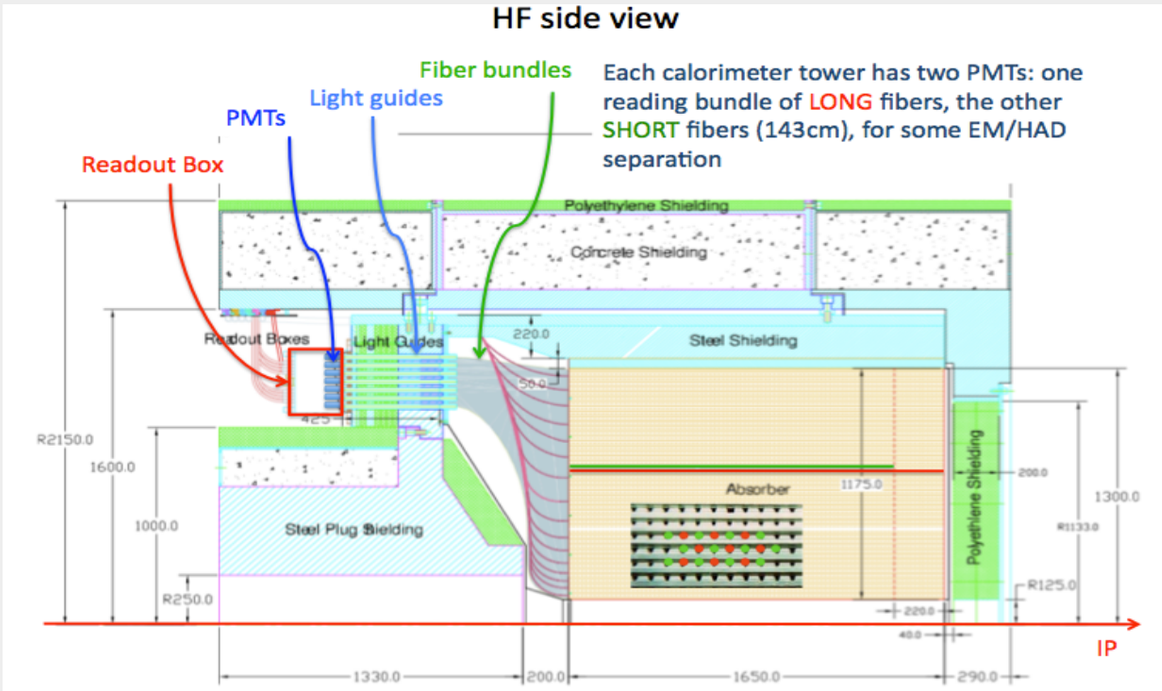
- Outer (HO): Outside solenoid
  - Tail catcher with scintillator layers
  - HPD readout





- Forward (HF) at |z|=11 m: 2.9<|η|<5
  - Cherenkov light from scintillating quartz fibers in steel absorber
  - read out with conventional PMTs

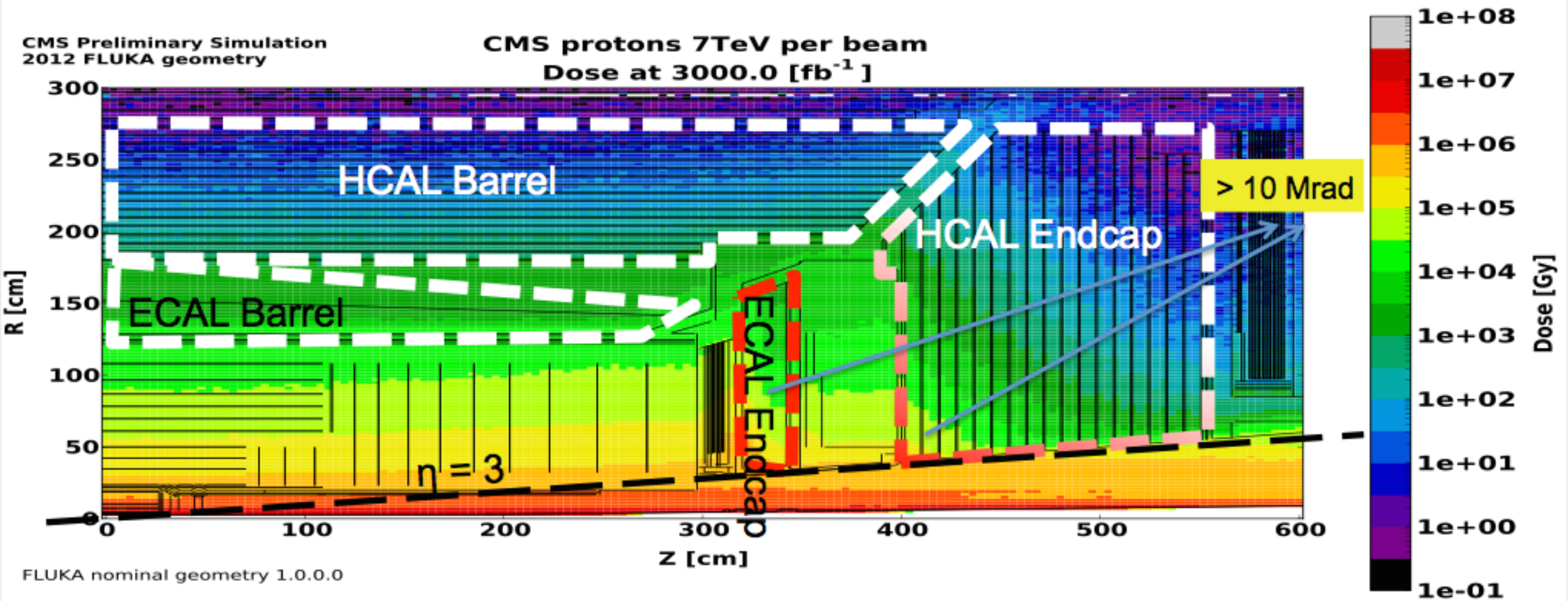
- Stability of photo-detector gains monitored using LED system
- Pedestals, and signal synchronization (timing) monitored using Laser data



Silvia Goy Lopez (CIEMAT) ICHEP, 3 July 2014

PHASE 2 - Concequence of Radiation and Pile-up environment

- Radiation six times higher than nominal LHC design
- 5(7)E34 Hz/cm² ➔ ~ 140 (200) collisions/bunch crossing



Longevity studies and simulation for 300 fb^{-1}/y ➔ 3000 fb^{-1} total

Phase 2 Upgrades Strategy:

- **Maintain performance at extreme <PU>**
- **Sustain rates and radiation doses**