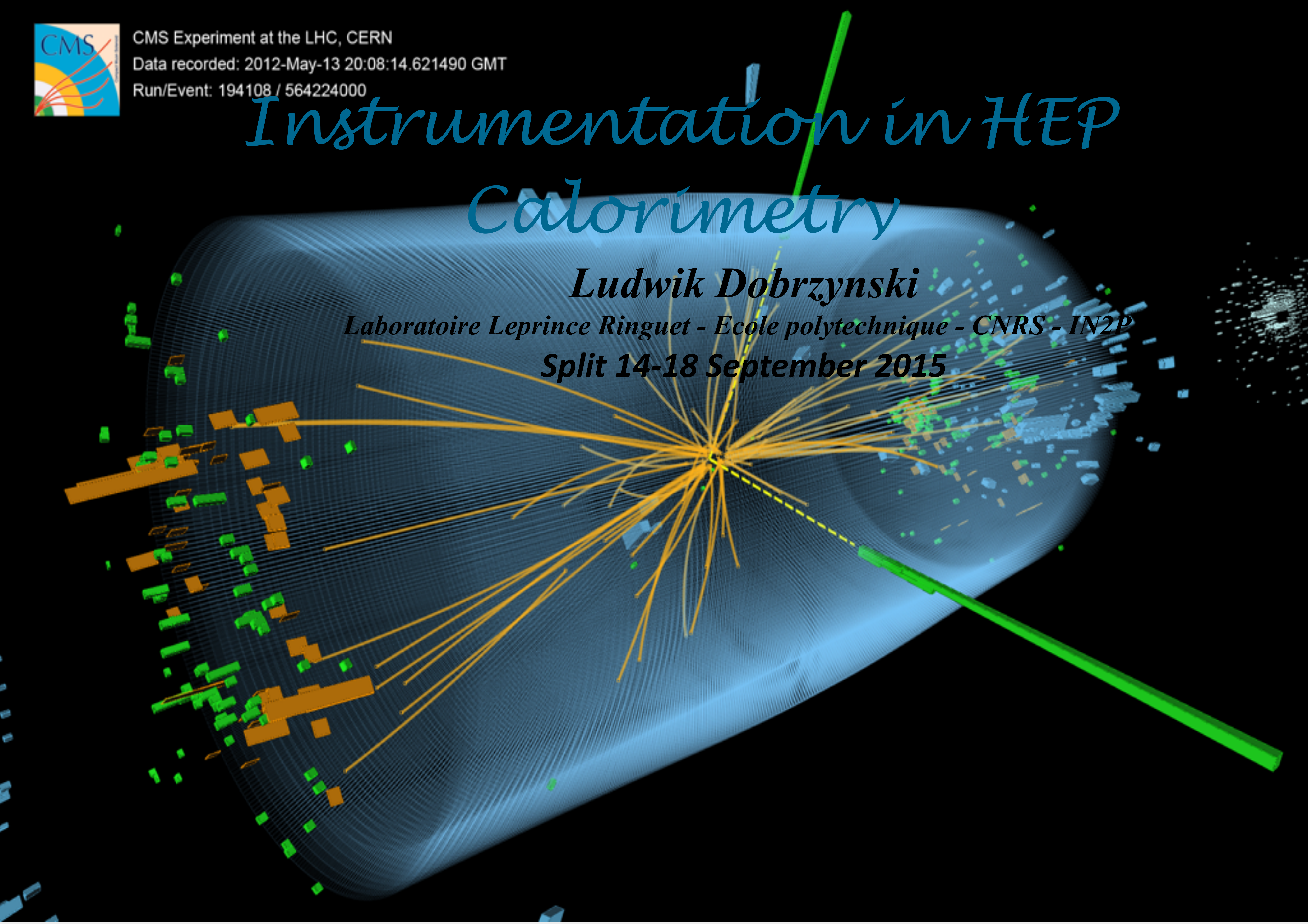
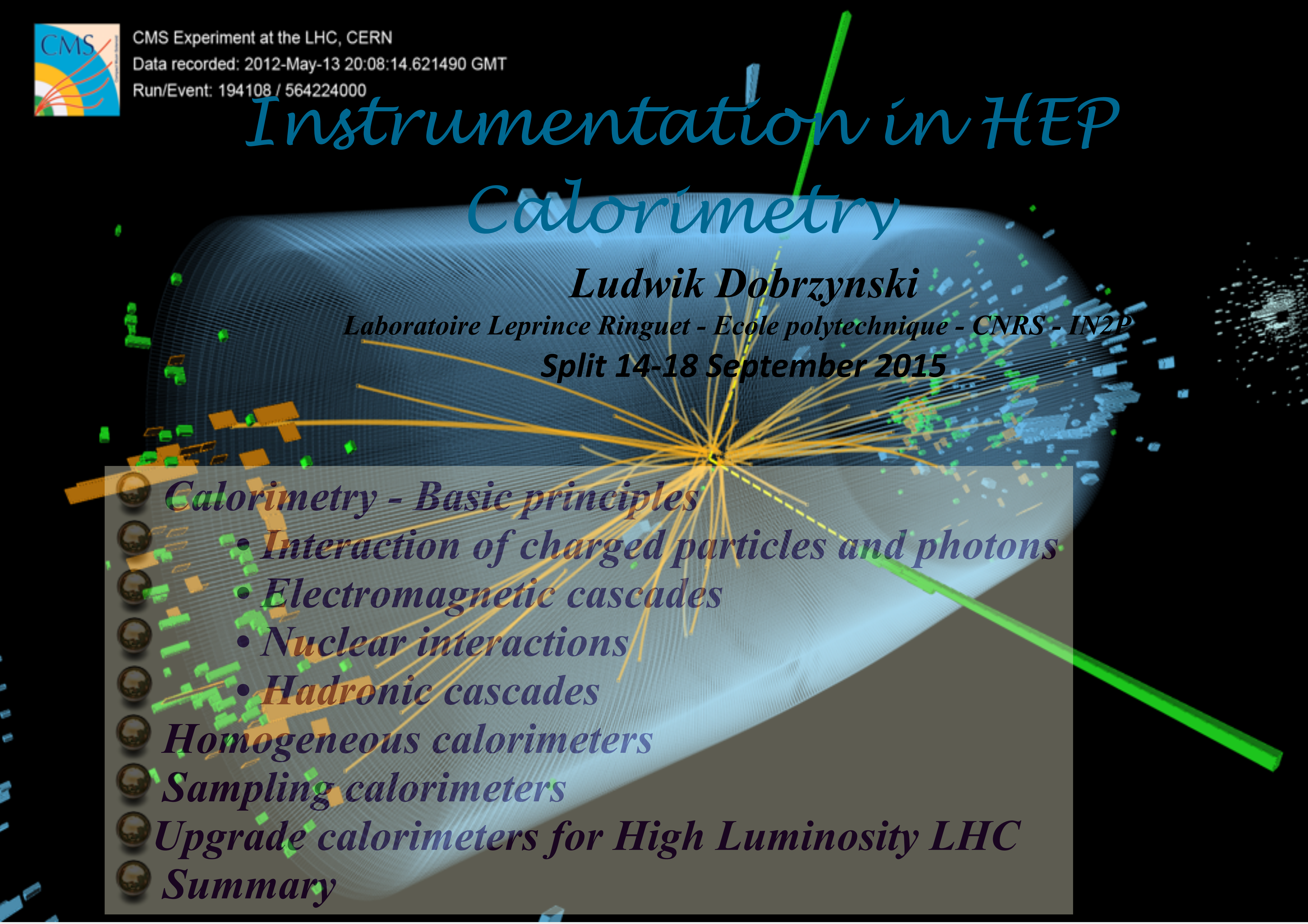


Instrumentation in HEP Calorimetry

Ludwik Dobrzynski

Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P

Split 14-18 September 2015



Instrumentation in HEP
Calorimetry

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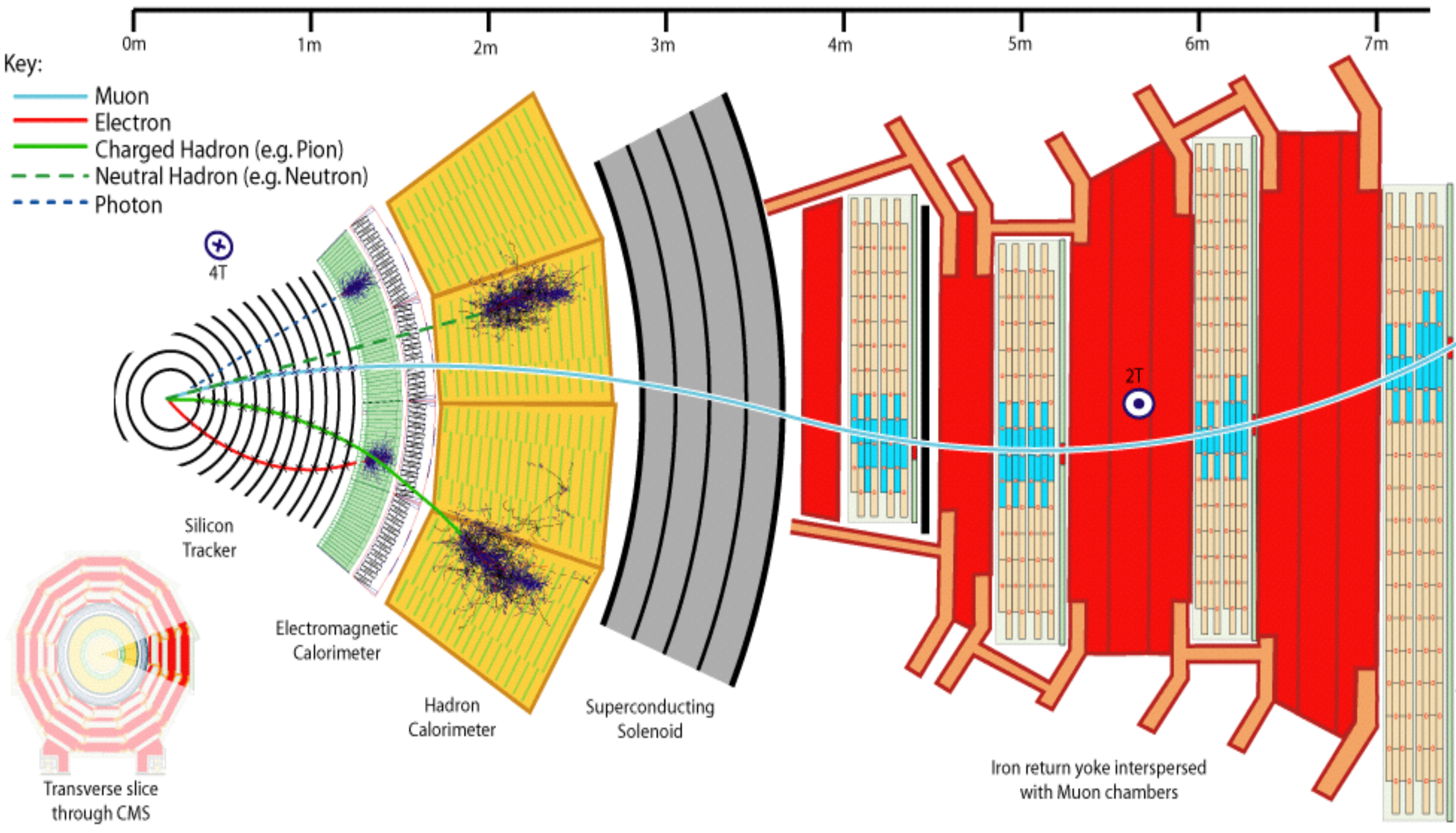
- *Calorimetry - Basic principles*
  - *Interaction of charged particles and photons*
  - *Electromagnetic cascades*
  - *Nuclear interactions*
  - *Hadronic cascades*
- *Homogeneous calorimeters*
- *Sampling calorimeters*
- *Upgrade calorimeters for High Luminosity LHC*
- *Summary*

The CMS detector: transverse



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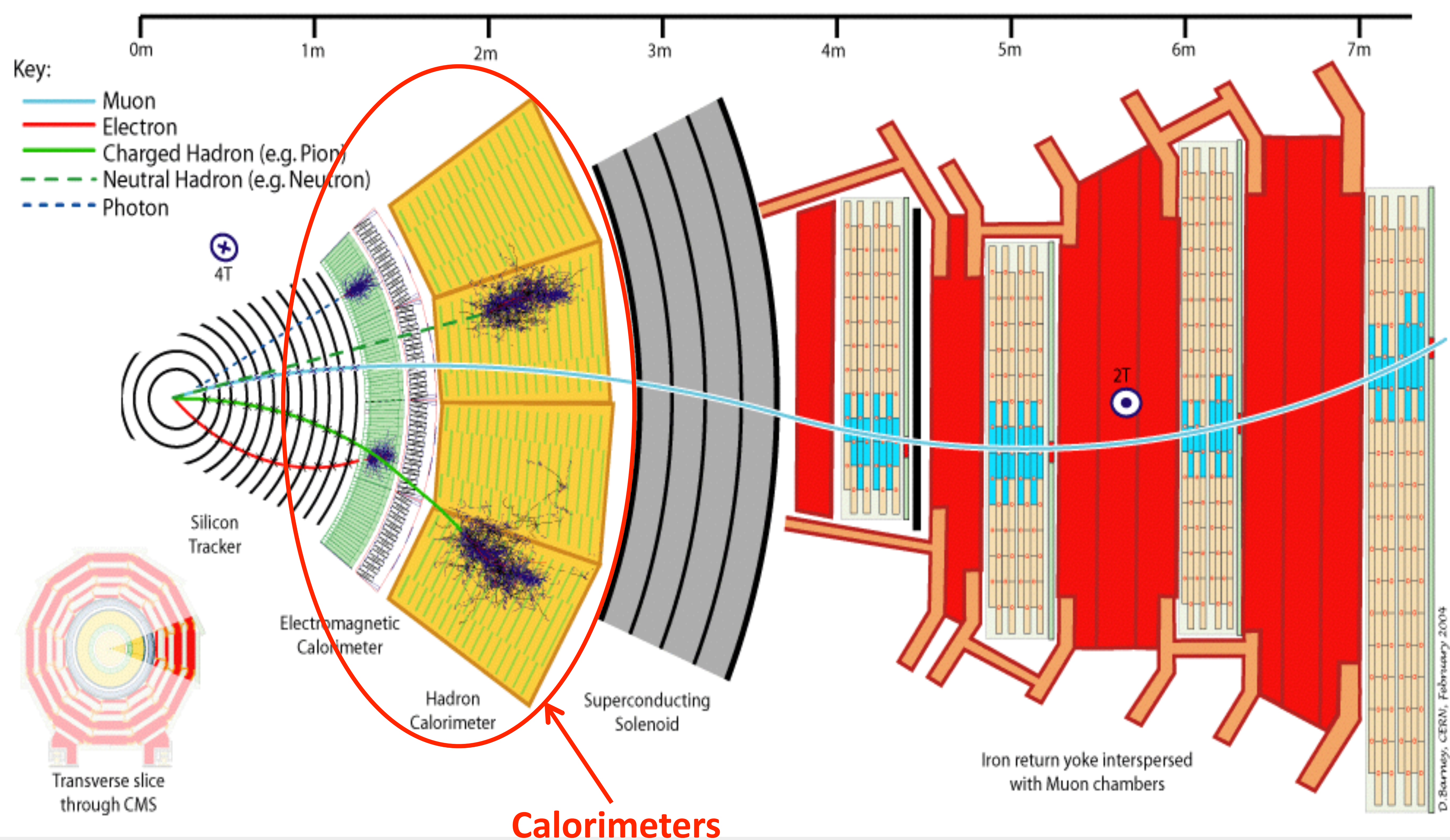

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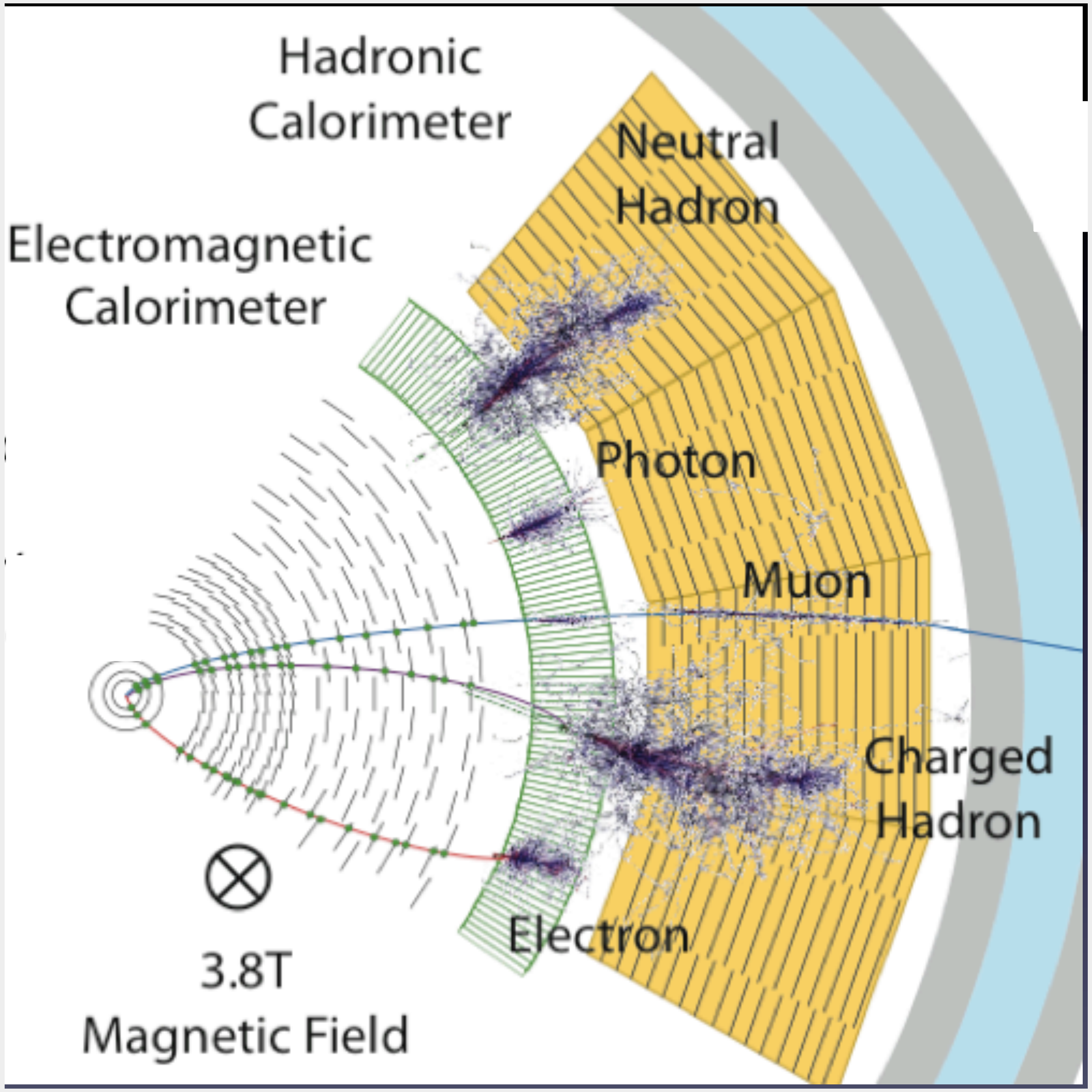
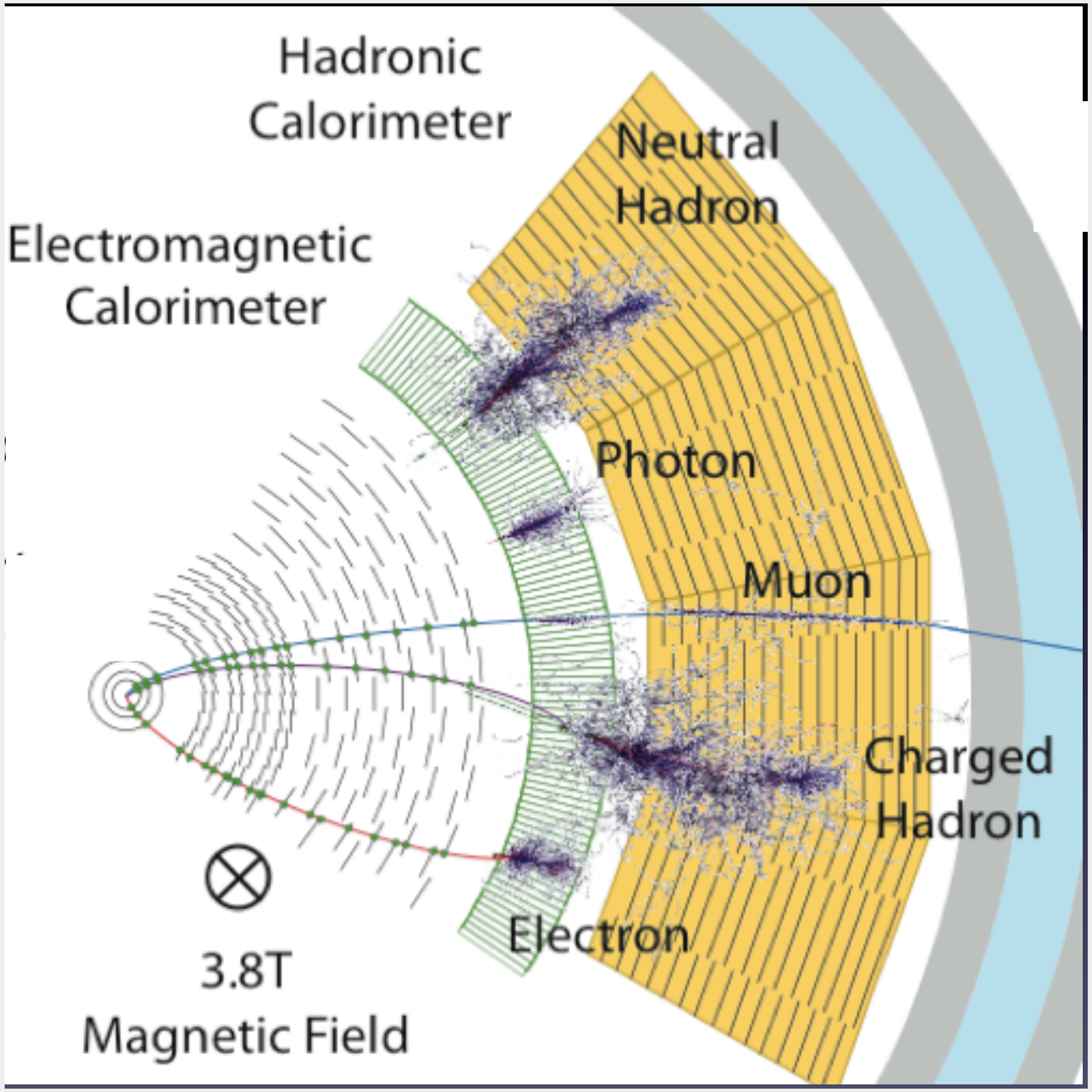


What is a Calorimeter?

- In nuclear and particle physics calorimetry refers to the detection of particles through total absorption in a block of matter
  - The measurement process is destructive for almost all particle
  - The exception are muons (and neutrinos) → identify muons easily since they penetrate a substantial amount of matter



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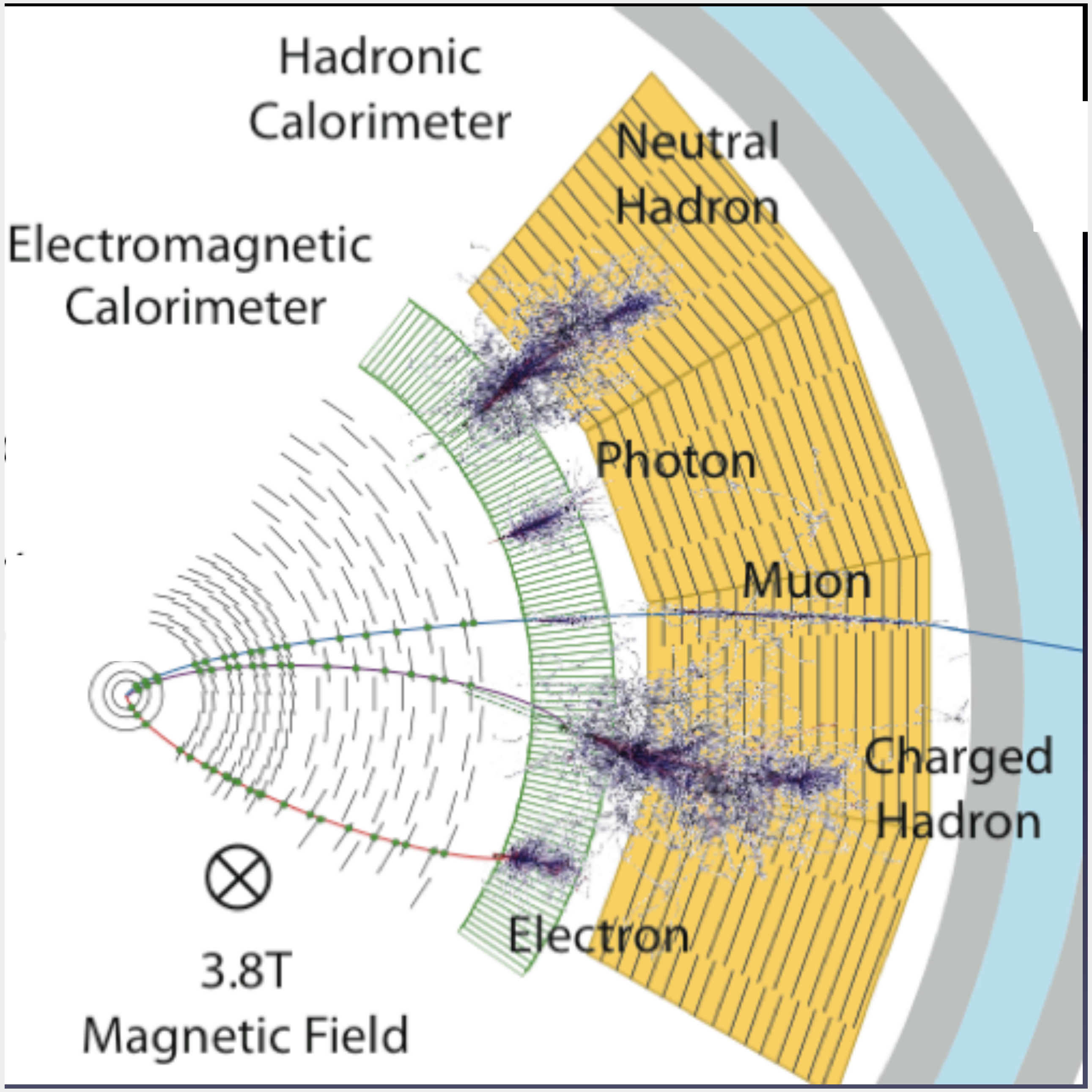

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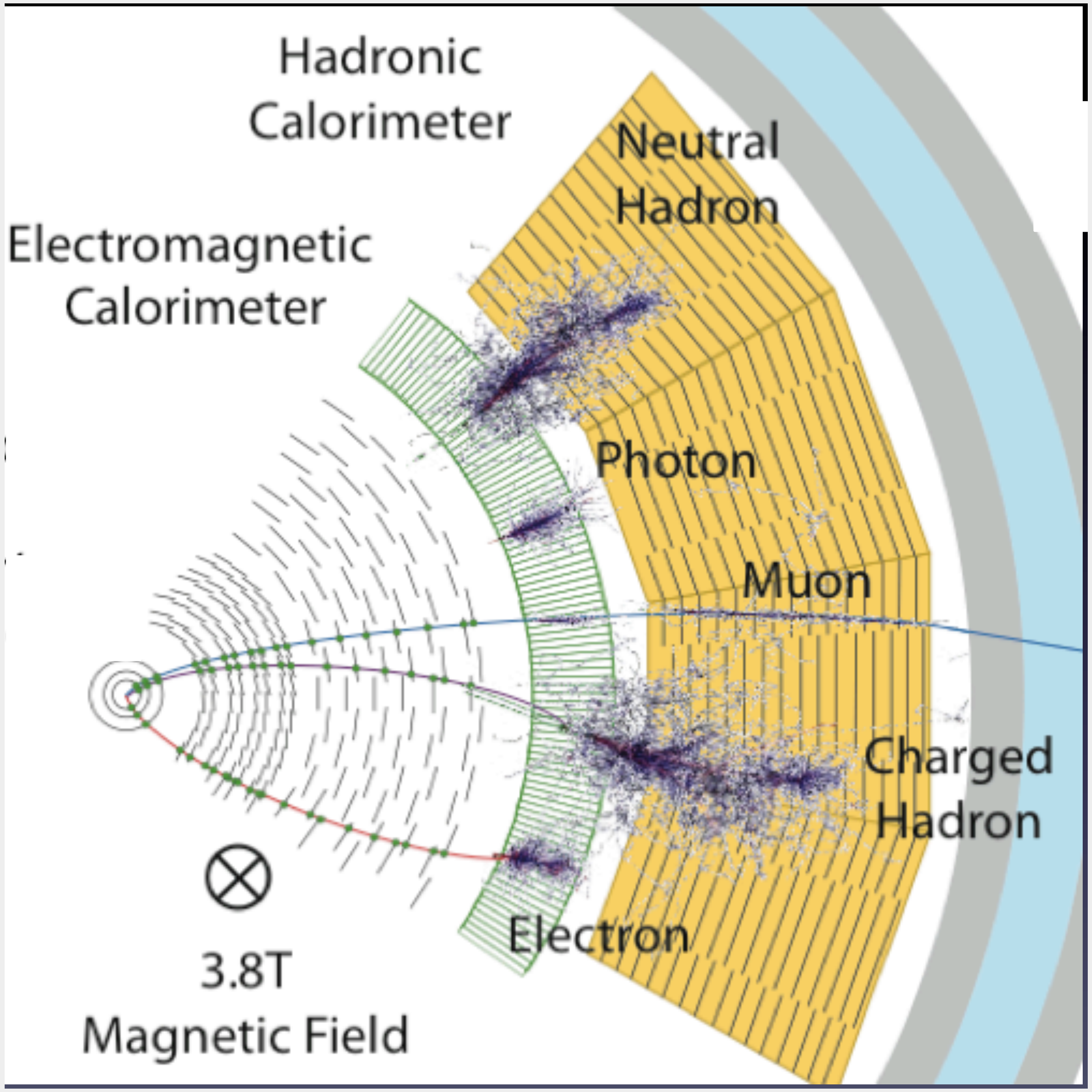

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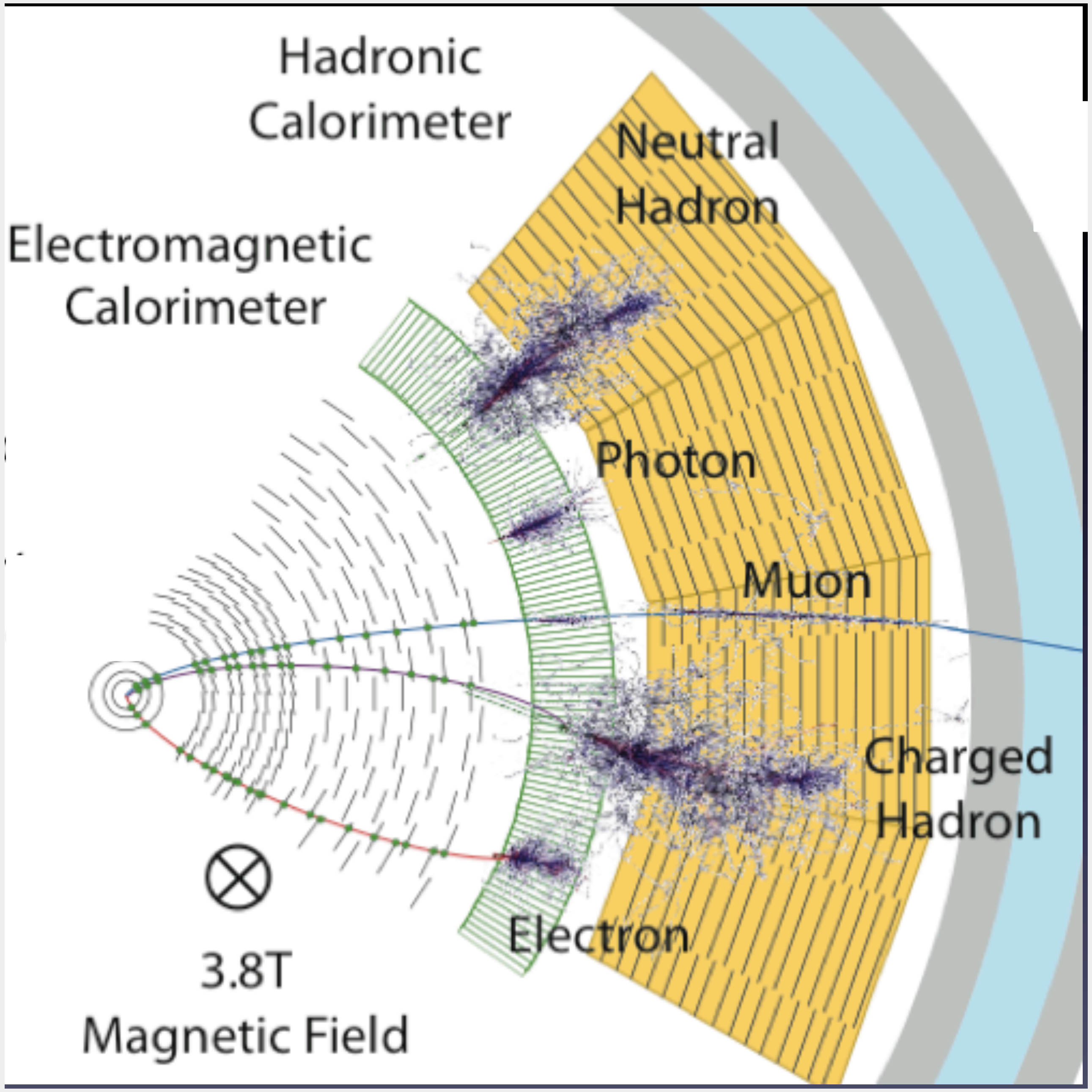

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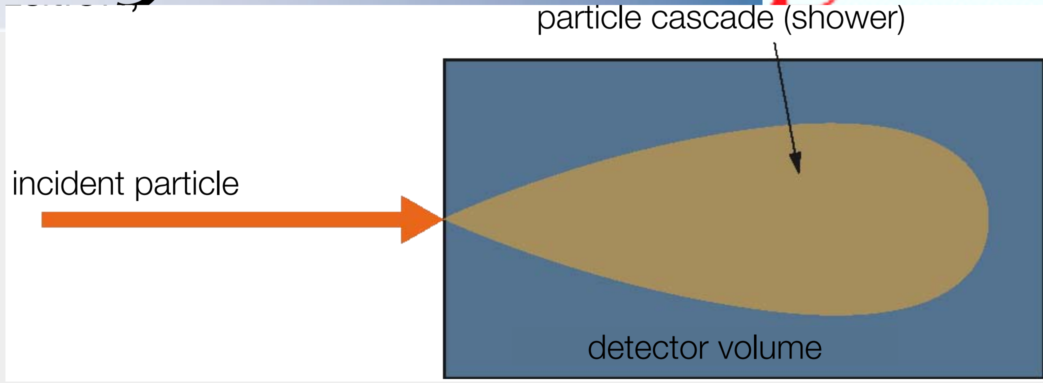
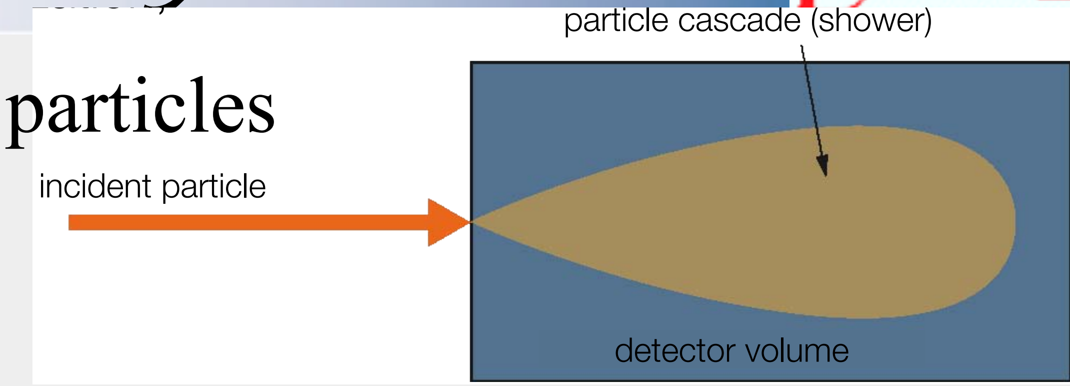


Why calorimetry?

- Measure the energy for both ***charged + neutral*** particles



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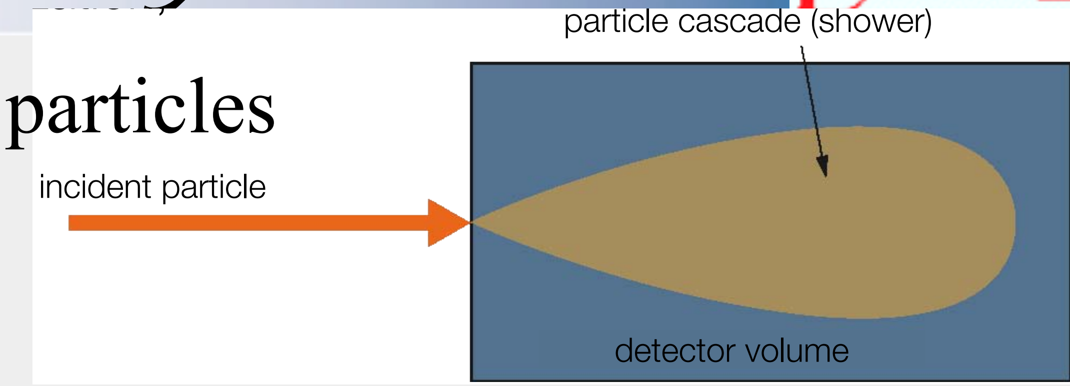

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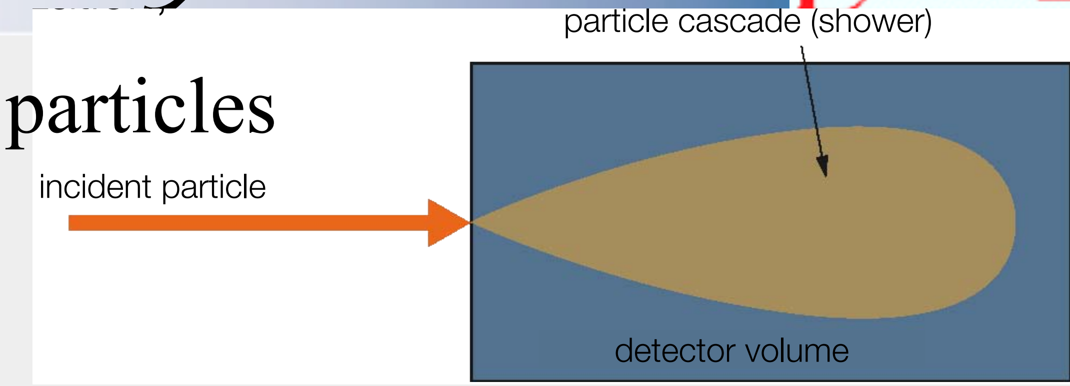

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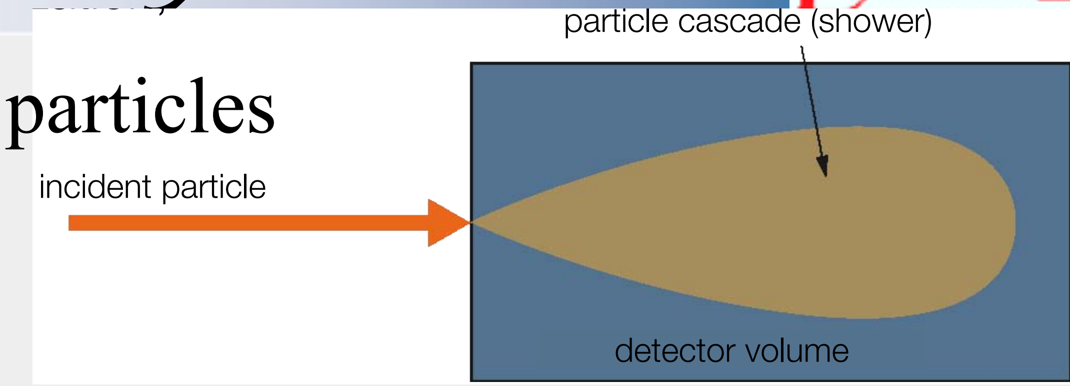

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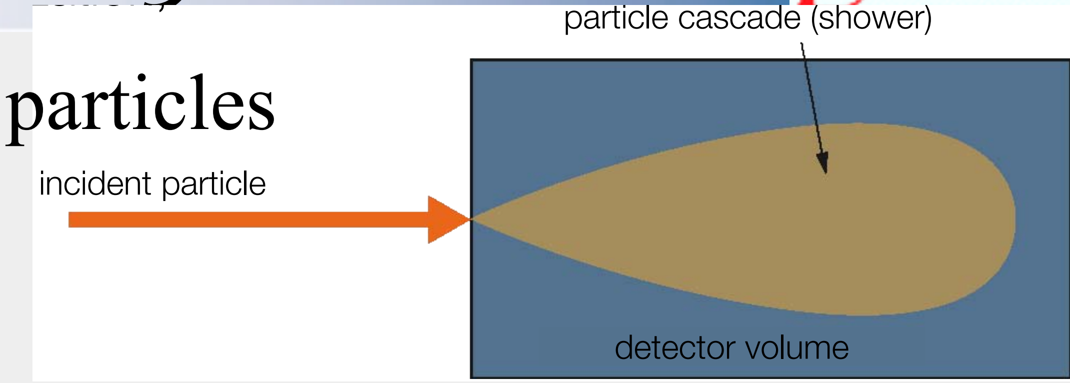

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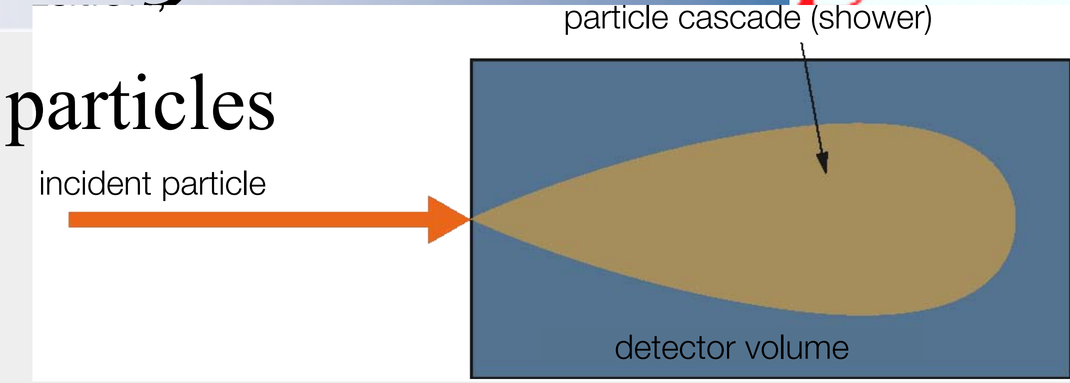

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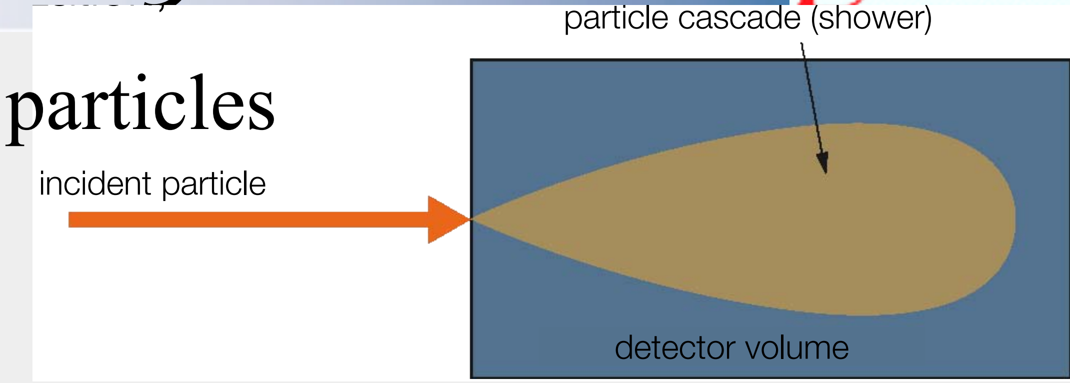

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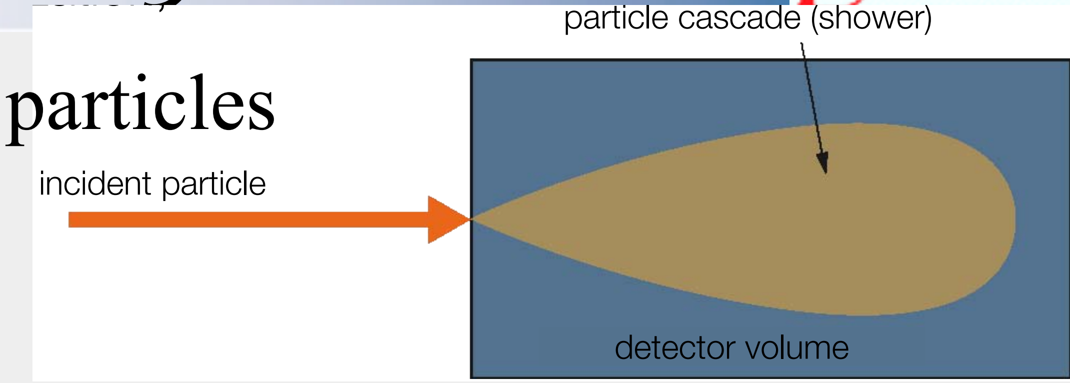

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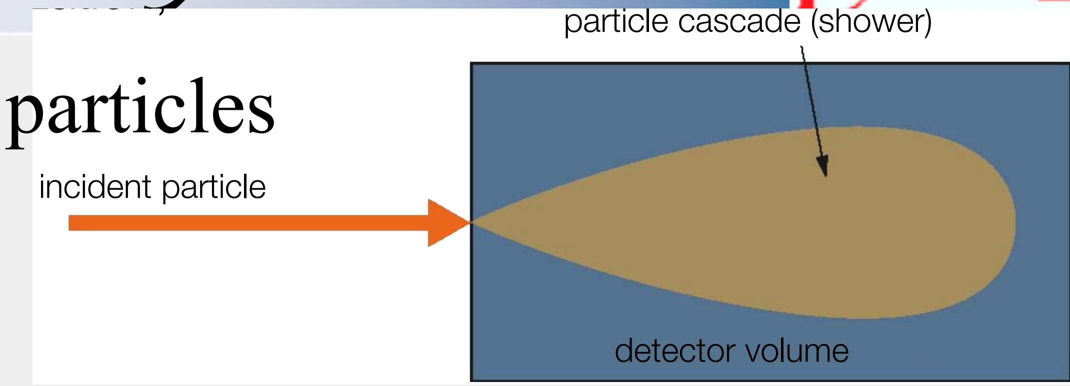

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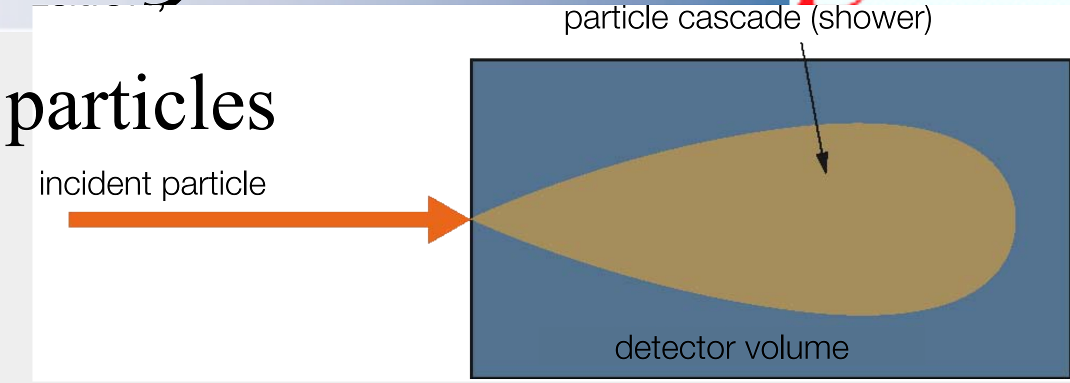

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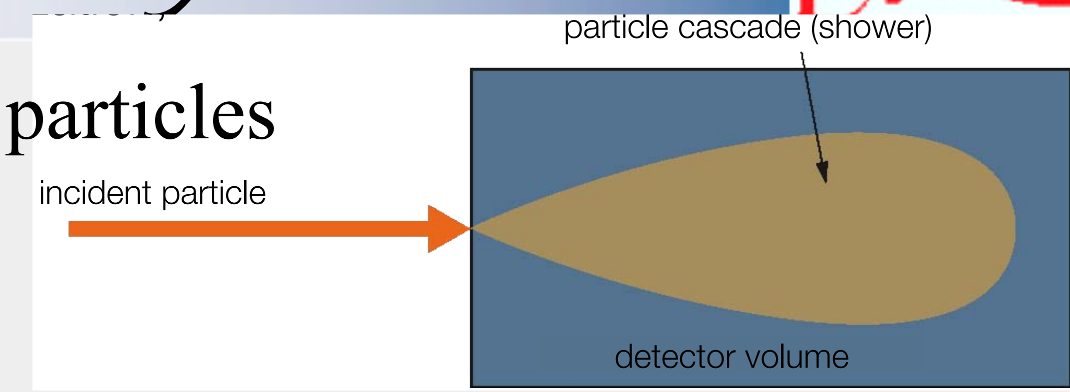

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recognize and select interesting events in real time ***(trigger)***

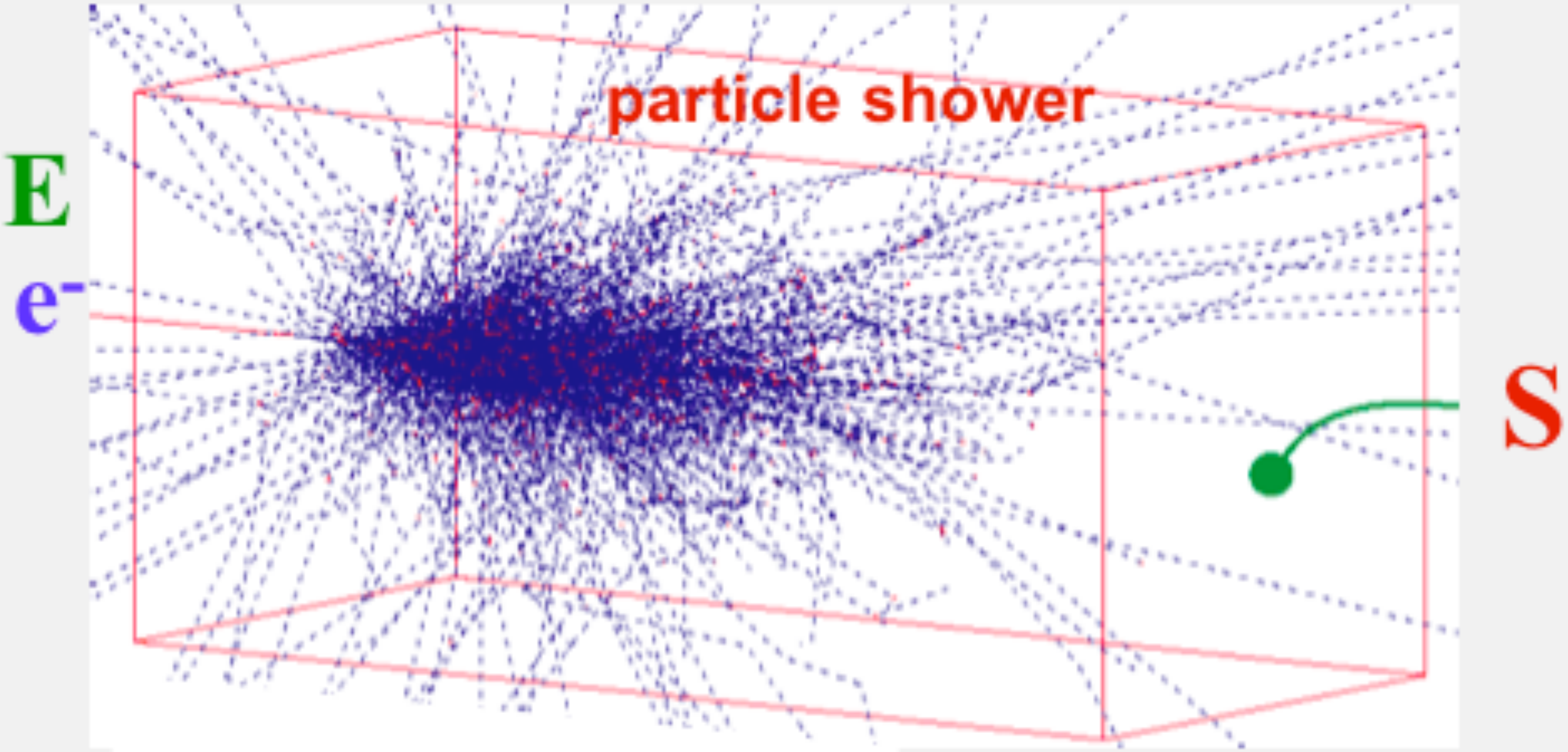
• Performance of calorimeters ***improves with energy***

(~$E^{-1/2}$ if statistical processes are the limiting factor)

Important calorimeter features

- Energy resolution
- Good shower position resolution (gives 4-vectors for physics)
- Signal response is fast
- Particle ID capability

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: Basic Principle (1)

Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

Basic mechanism for calorimetry in particle physics is the formation of

⟹ electromagnetic showers

⟹ and/or hadronic showers.

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

→ Charge

→ Cherenkov light

→ Scintillation light

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

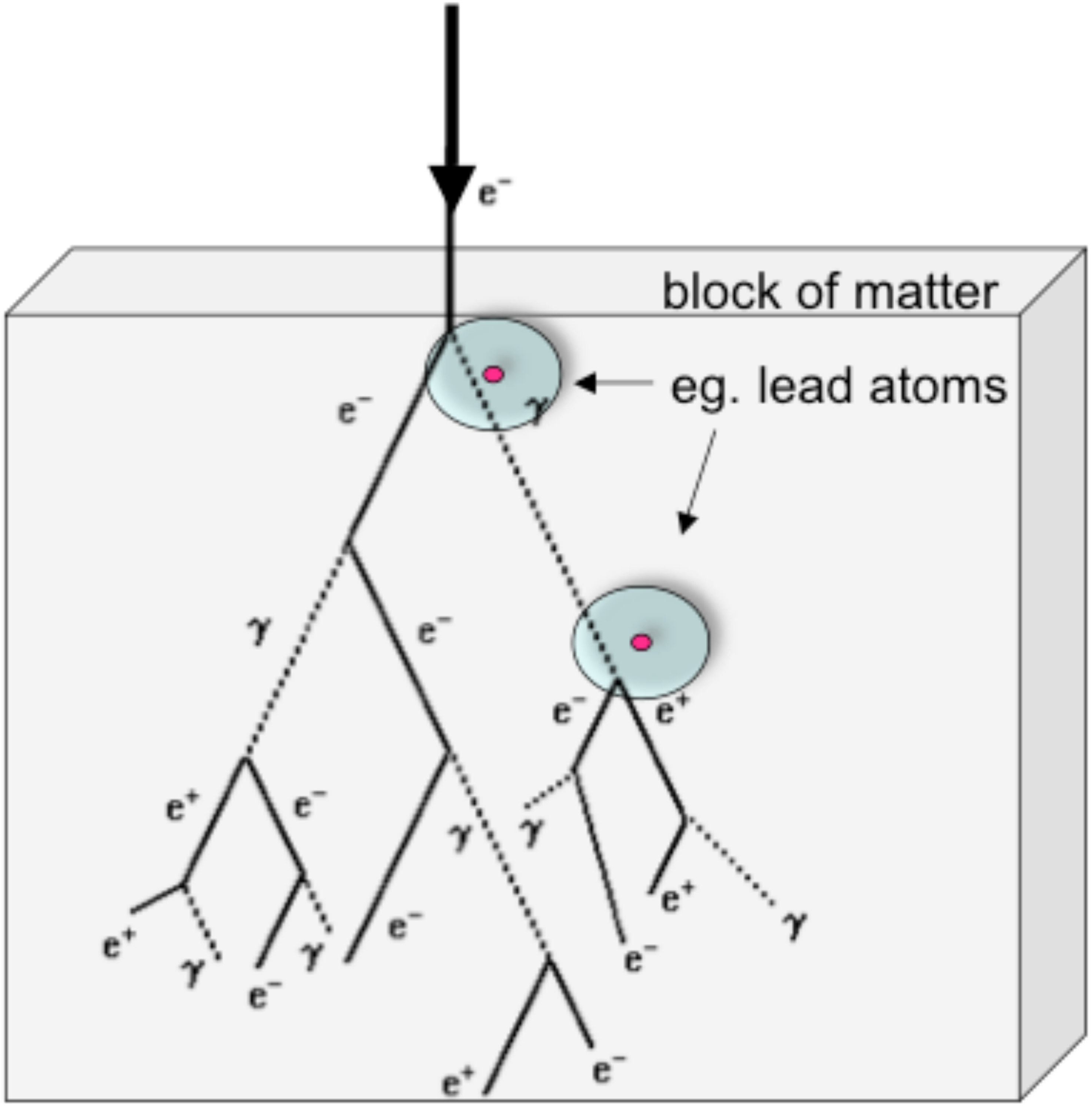
• Detector response ∝ E

• Calorimetry works both for:

⟹ charged (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 Principles (2)



Ionization, scintillation, Cherenkov light

- Relevant quantities:

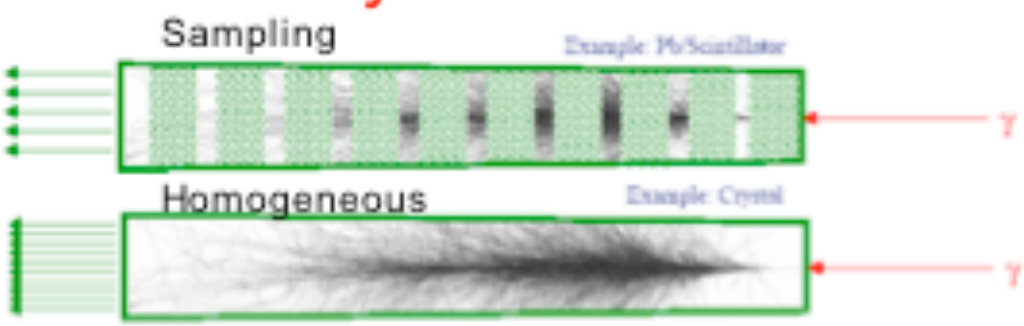
Radiation length X_0:

- 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:

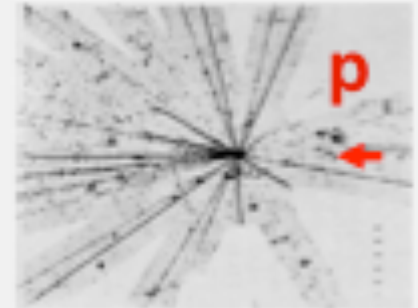
- Measure for the lateral shower size
- On average, 90% of shower is contained within cylinder of radius ρ_M around the shower axis.

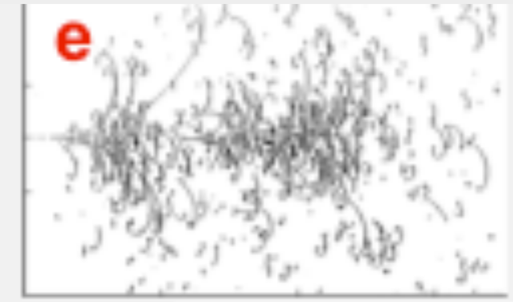
- Detector layout

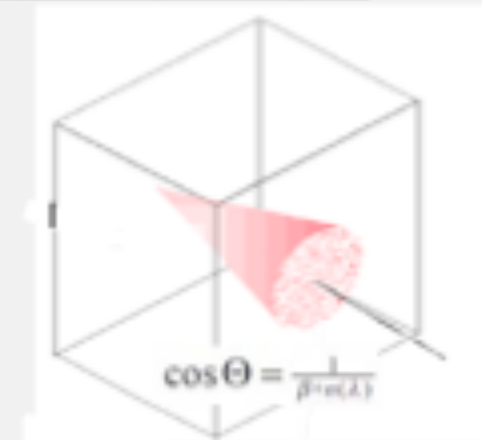


Calorimetry in four steps

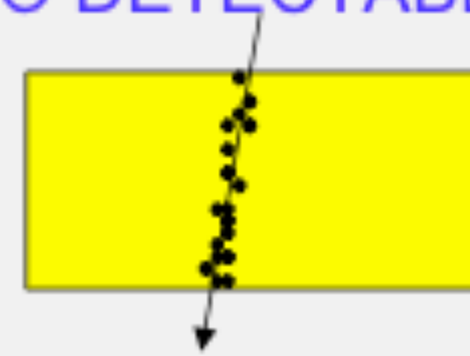
PARTICLE INTERACTION IN MATTER (depends on the impinging particle and on the kind of material)

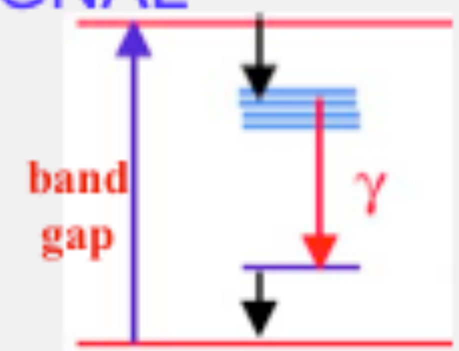




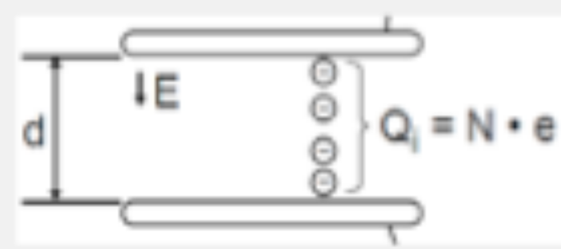


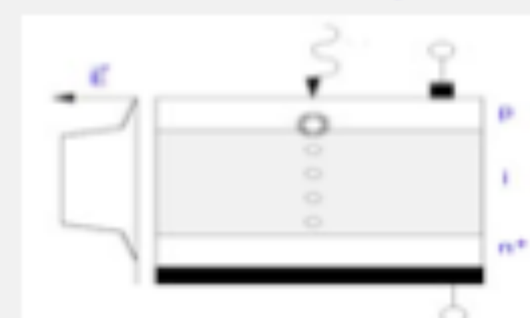
ENERGY LOSS TRANSFER TO DETECTABLE SIGNAL (depends on the material)



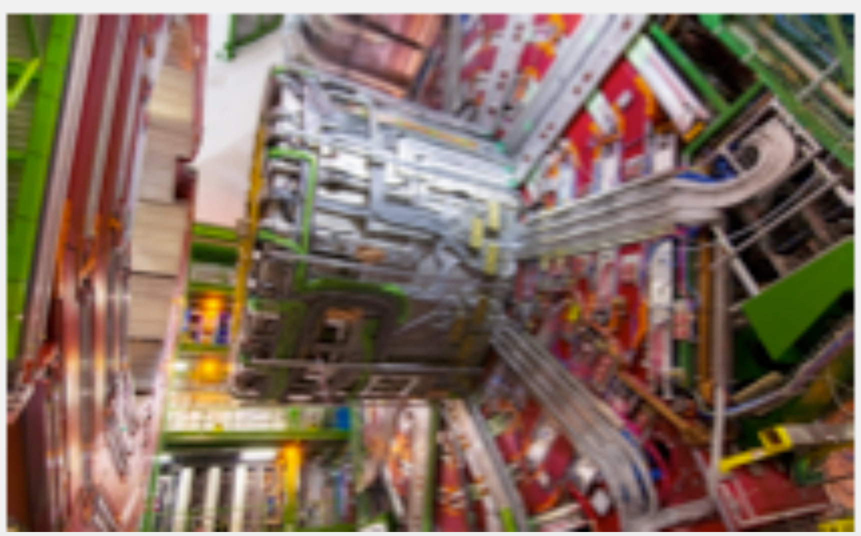


SIGNAL COLLECTION (depends on signal, many techniques of collection)

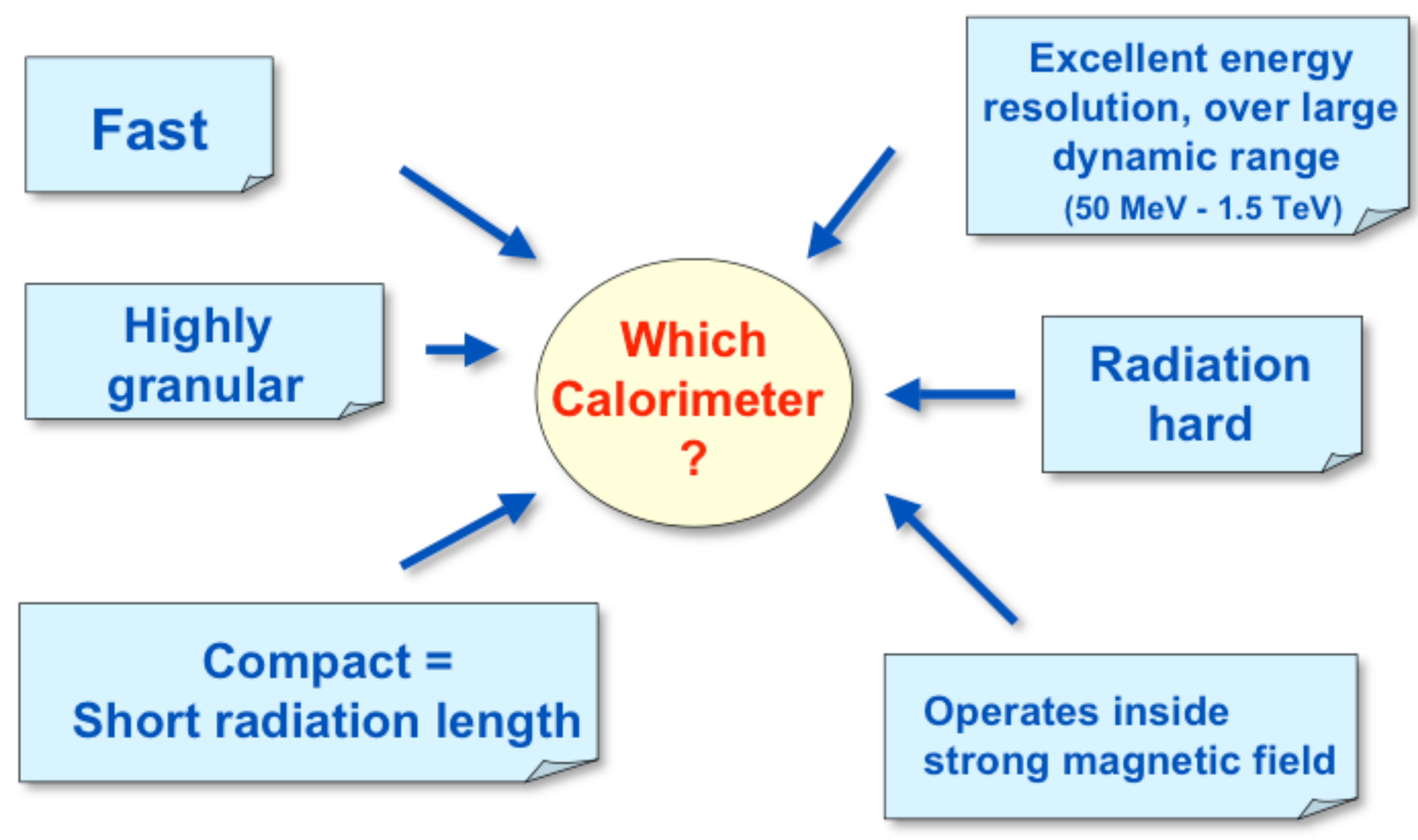




BUILD A SYSTEM



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

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

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 can also be ~ E-1/4)
- fluctuations in energy lost in dead material before or within the calorimeter

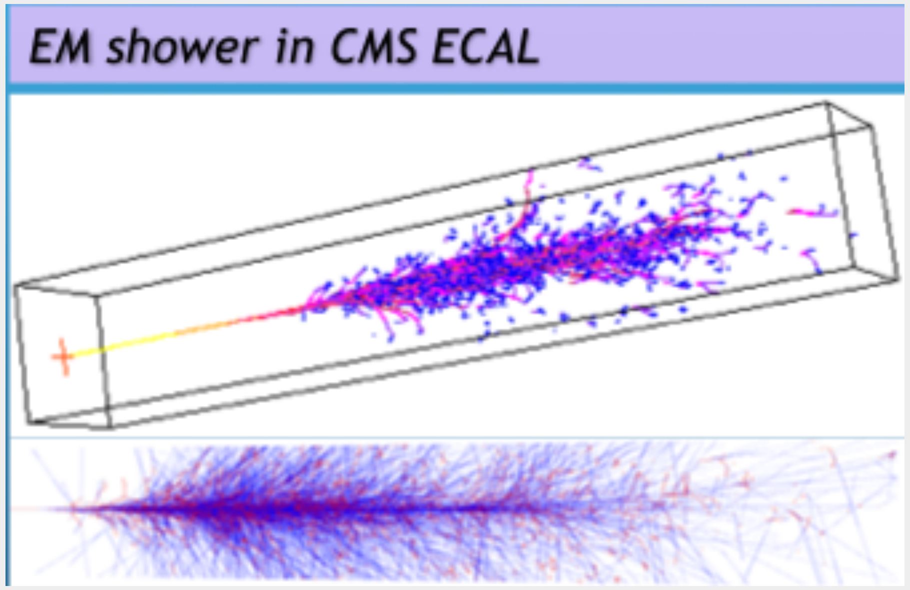
c: noise term

- readout electronic noise
- Radio-activity, pile-up fluctuations

More

Calorimeter Types

- Homogeneous



- Sampling

Calorimeter Types

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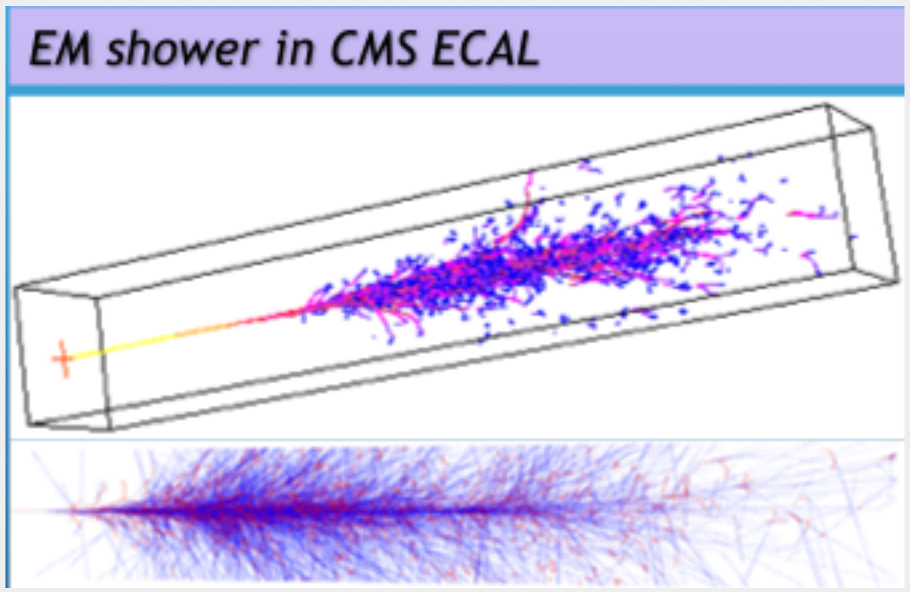

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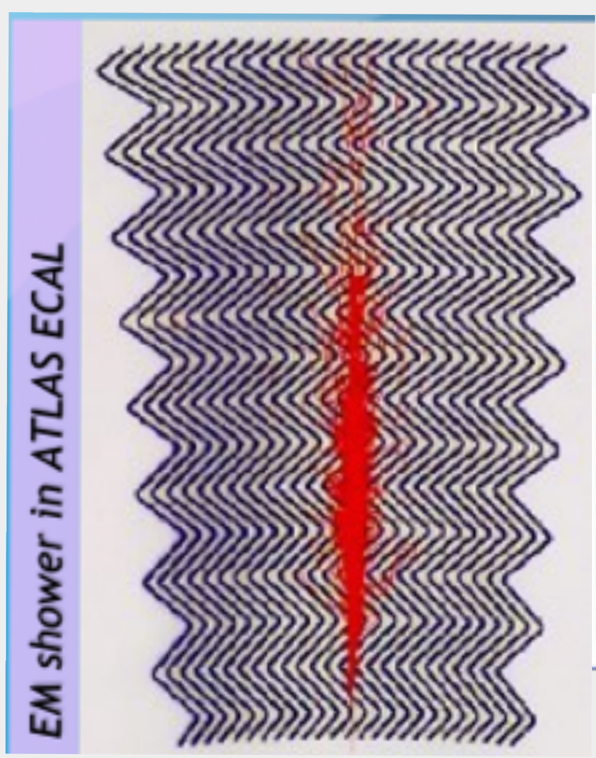

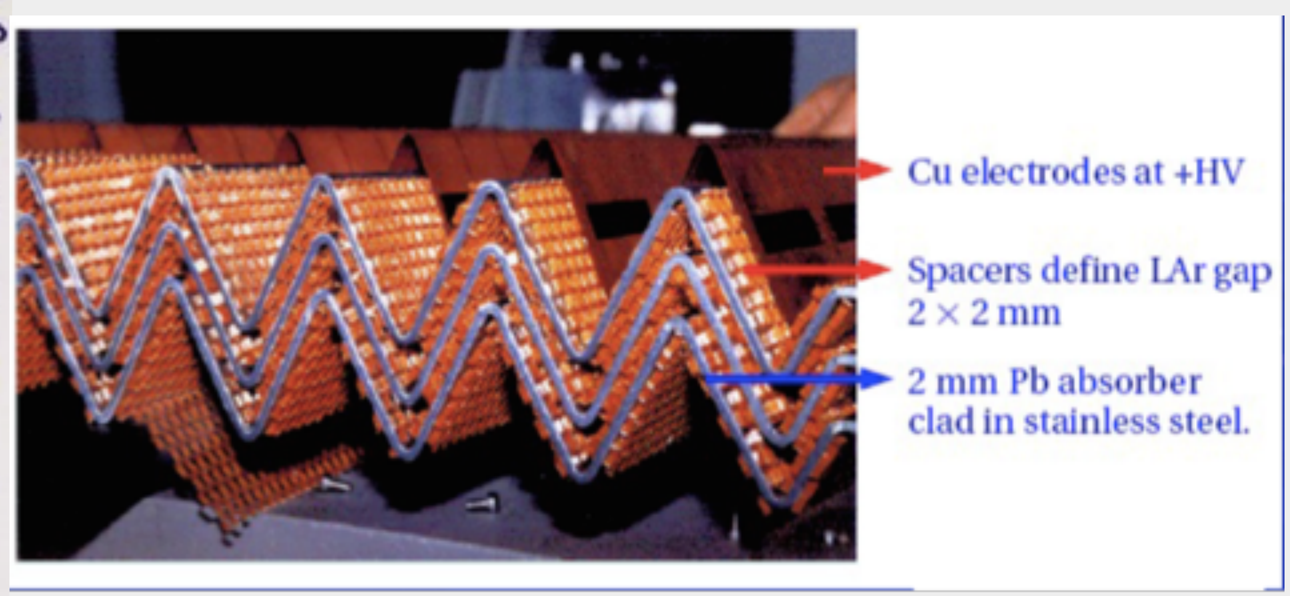

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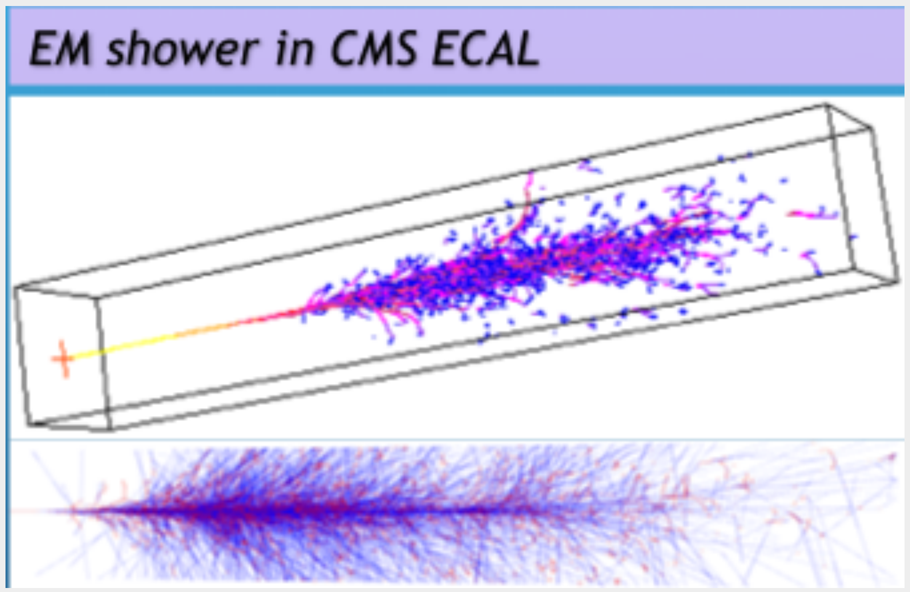

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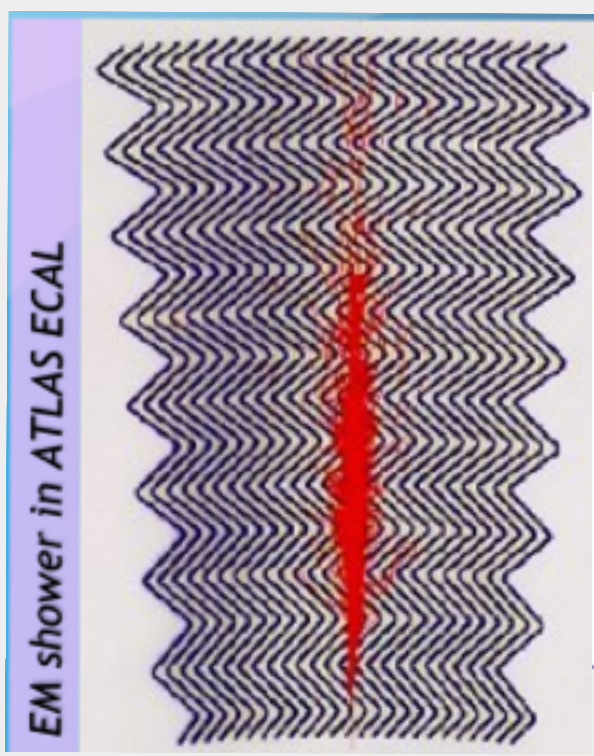
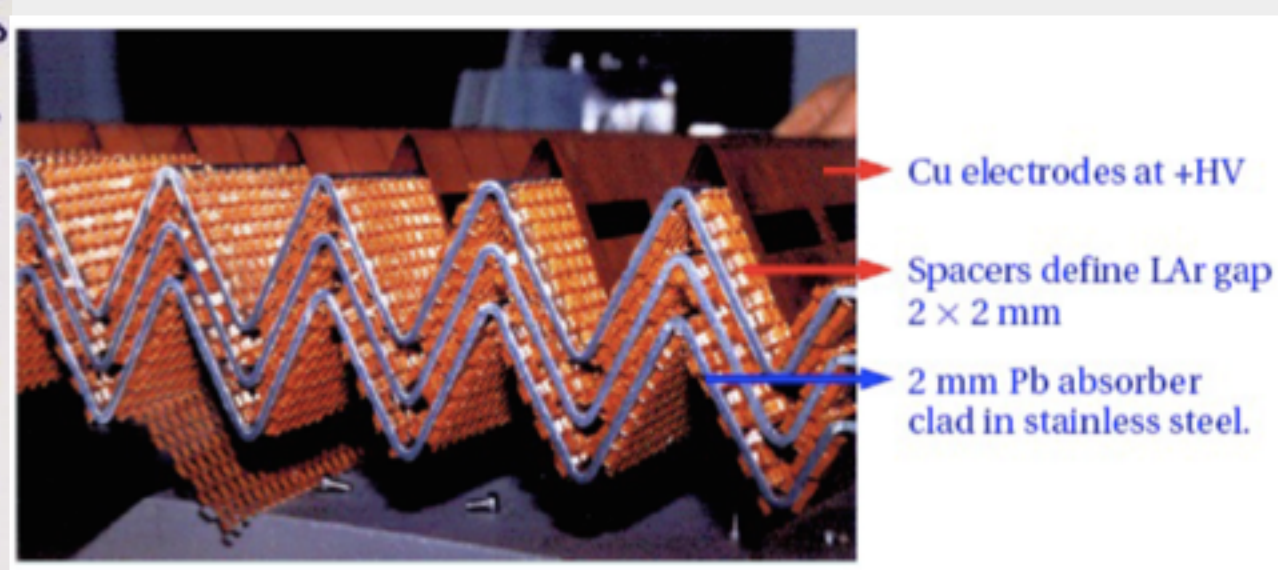
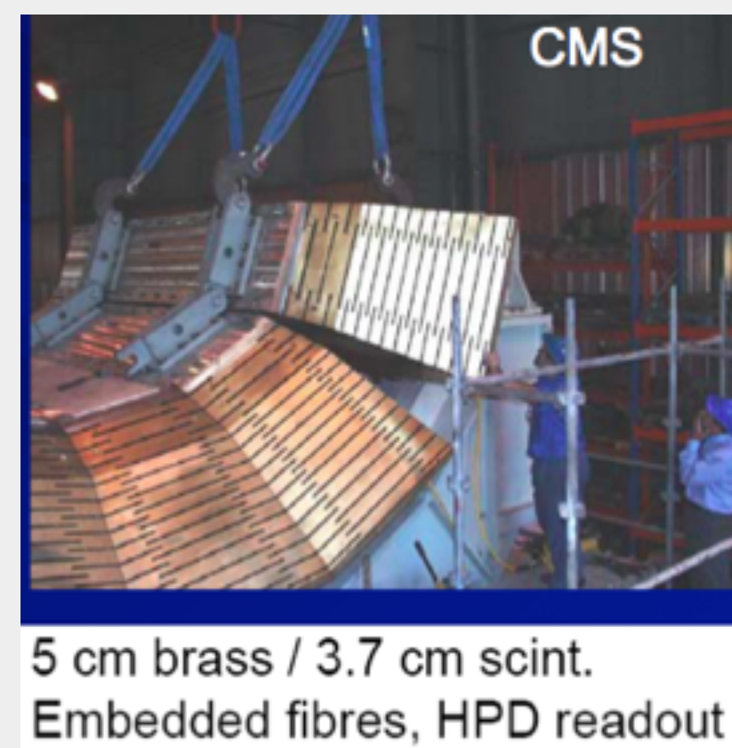






Homogeneous calorimeters

Homogeneous calorimeters: Detector = absorber

- ⇨ good energy resolution
- ⇨ limited spatial resolution (particularly in longitudinal direction)
- ⇨ only used for electromagnetic calorimetry

Two main types:

1. Scintillators

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)

2. Cherenkov devices

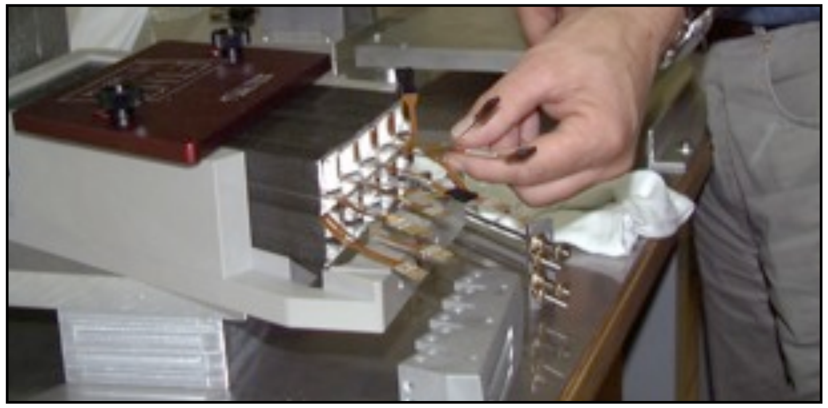
Material	Density [g/cm^3]	X_0 [cm]	n	Light yield [p.e./GeV] (rel. p.e.*)	λ_{cut} [nm]	Rad. Dam. [Gy]	Comments
SF-5 Lead glass	4.08	2.54	1.67	600 (1.5×10^{-4})	350	10^2	
SF-6 Lead glass	5.20	1.69	1.81	900 (2.3×10^{-4})	350	10^2	
PbF_2	7.66	0.95	1.82	2000 (5×10^{-4})		10^3	Not available in quantity

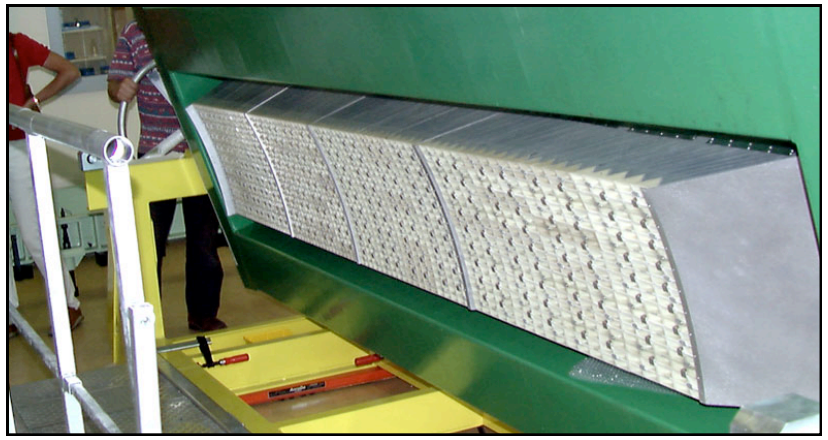
In both cases the signal consists of photons. Readout via photomultiplier, -diode/triode, APD, HPD

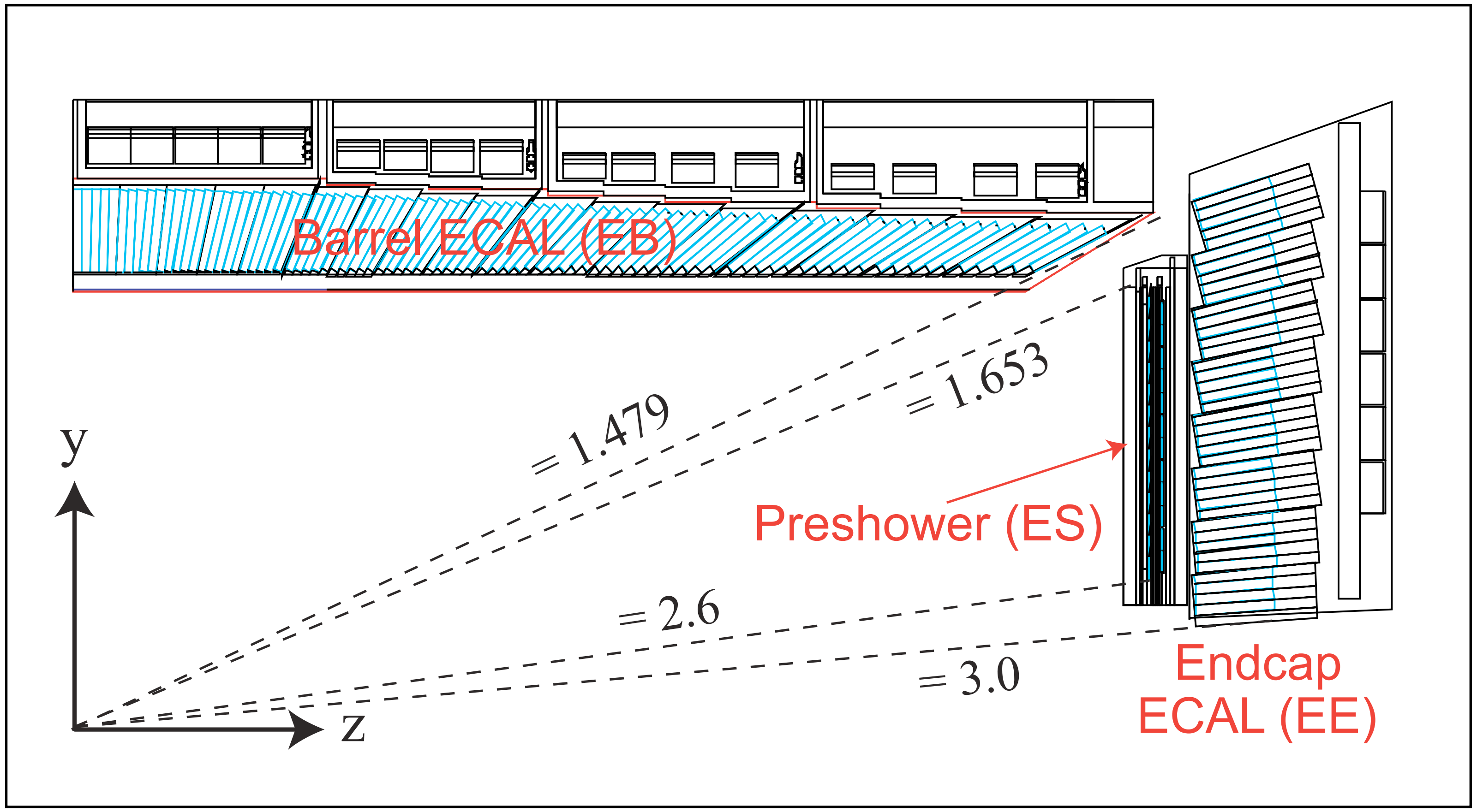
Homogeneous Calorimeters

Scintillator : PBW04 [Lead Tungsten]
Photosensor : APDs [Avalanche Photodiodes]

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





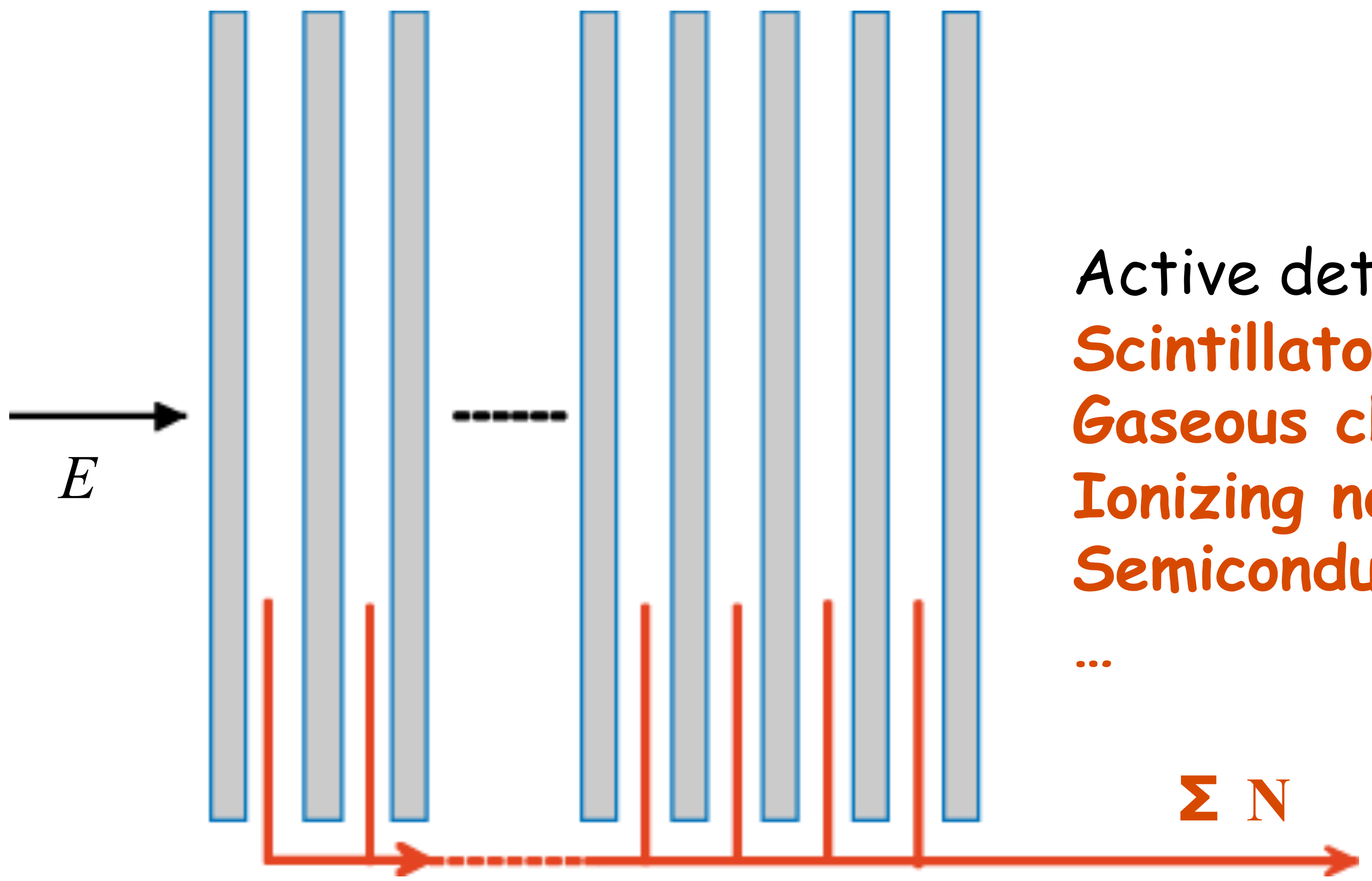


Sampling Calorimeter

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

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

Particle absorption and Shower sampling are separated.



Active detector:
Scintillators
Gaseous chambers
Ionizing noble liquid
Semiconductors
...

Resolution is better, smaller is the detection gap and larger the sampling fraction (up to some limitations…). Easy for longitudinal segmentation

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 ...

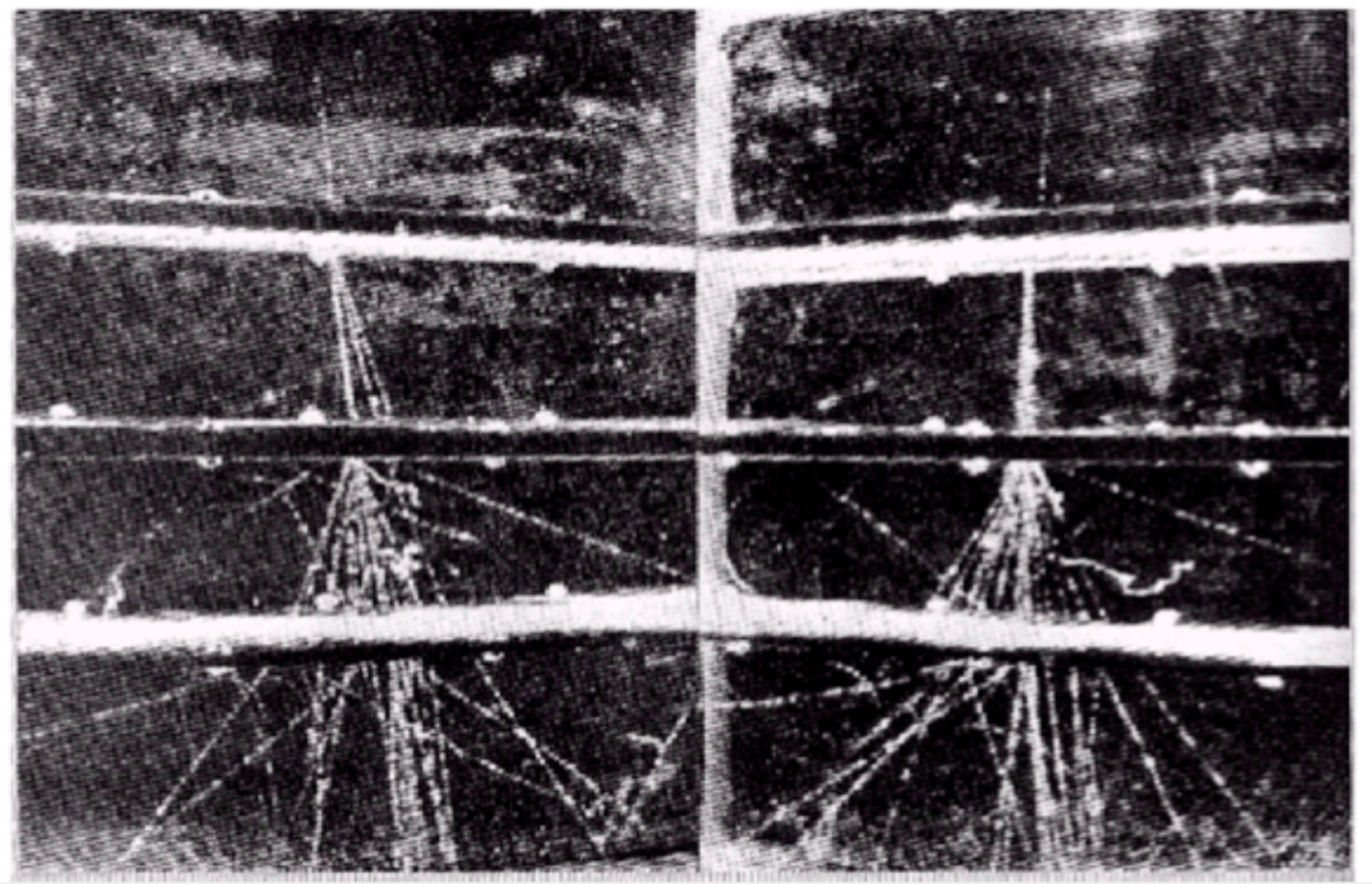
Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters ...

★ 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 typically result in a reduced energy resolution for sampling calorimeters ...

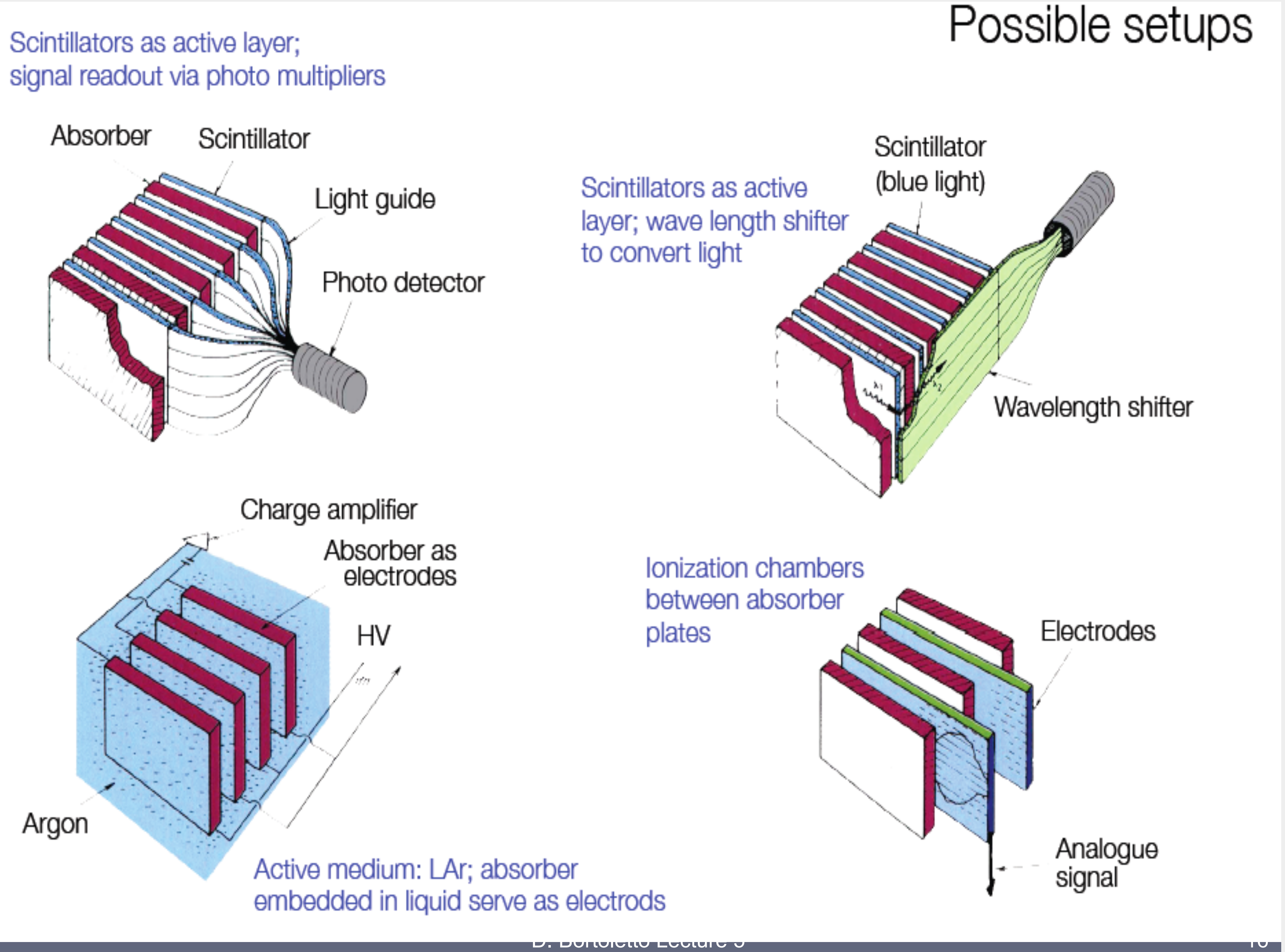
Sampling electromagnetic shower

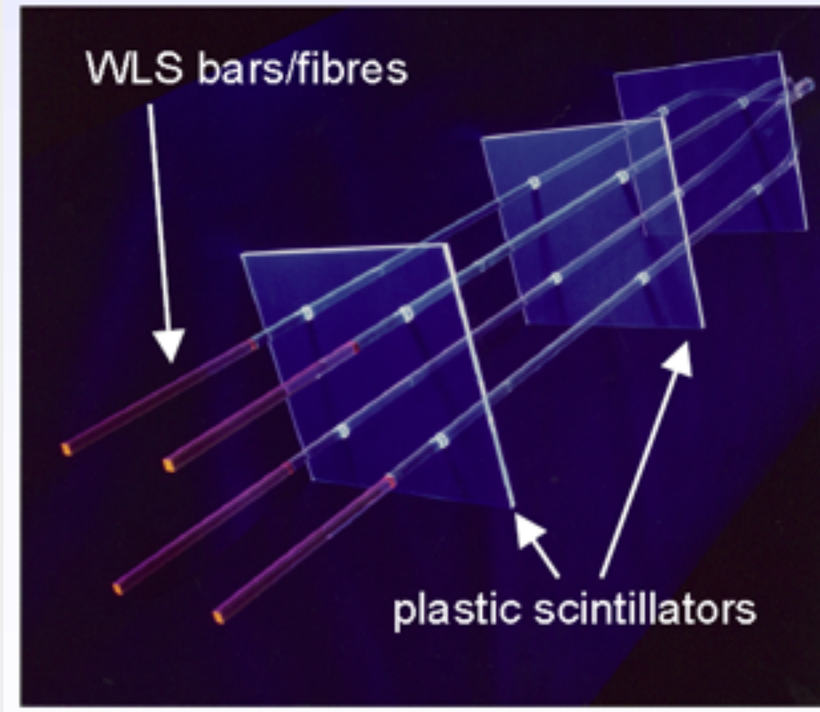


Cloud chamber photograph of e.m. shower developing in lead plates (thickness from top down 1.1, 1.1, 0.13 X_0) exposed to cosmic radiation

Sampling calorimeters : READOUT

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





'Shashlik' readout

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

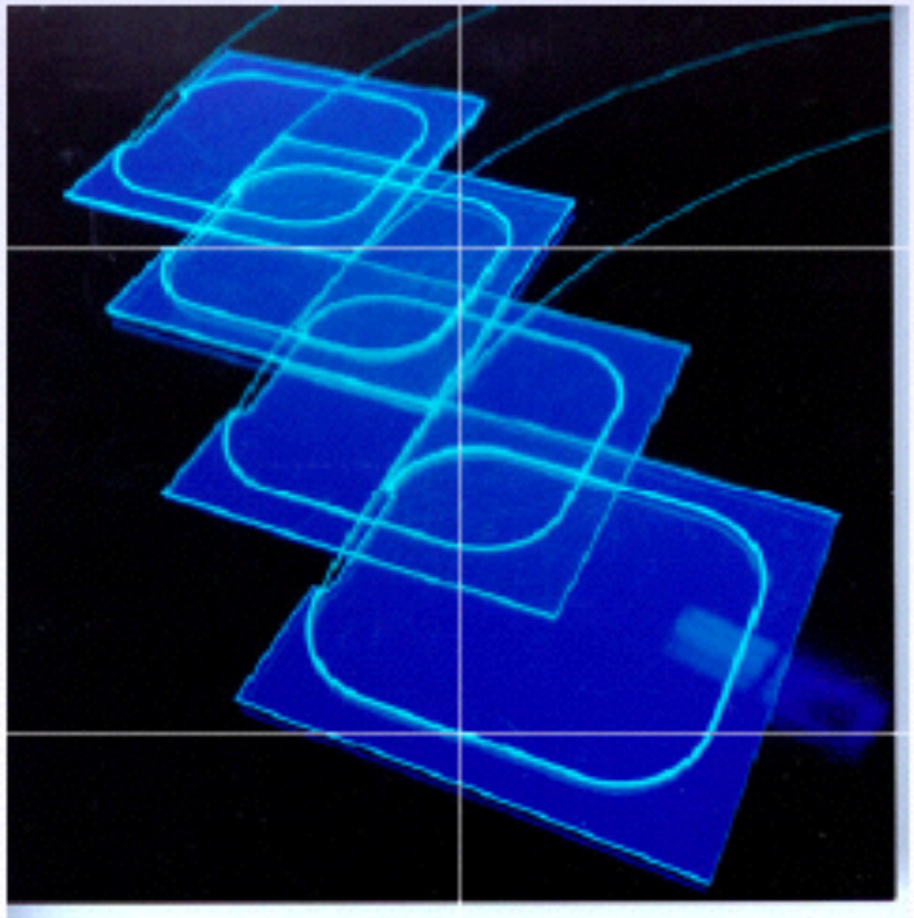
Sampling calorimeters: CMS HCAL

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 showers

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Interaction with matter :

More of EM shower development : (for details clic

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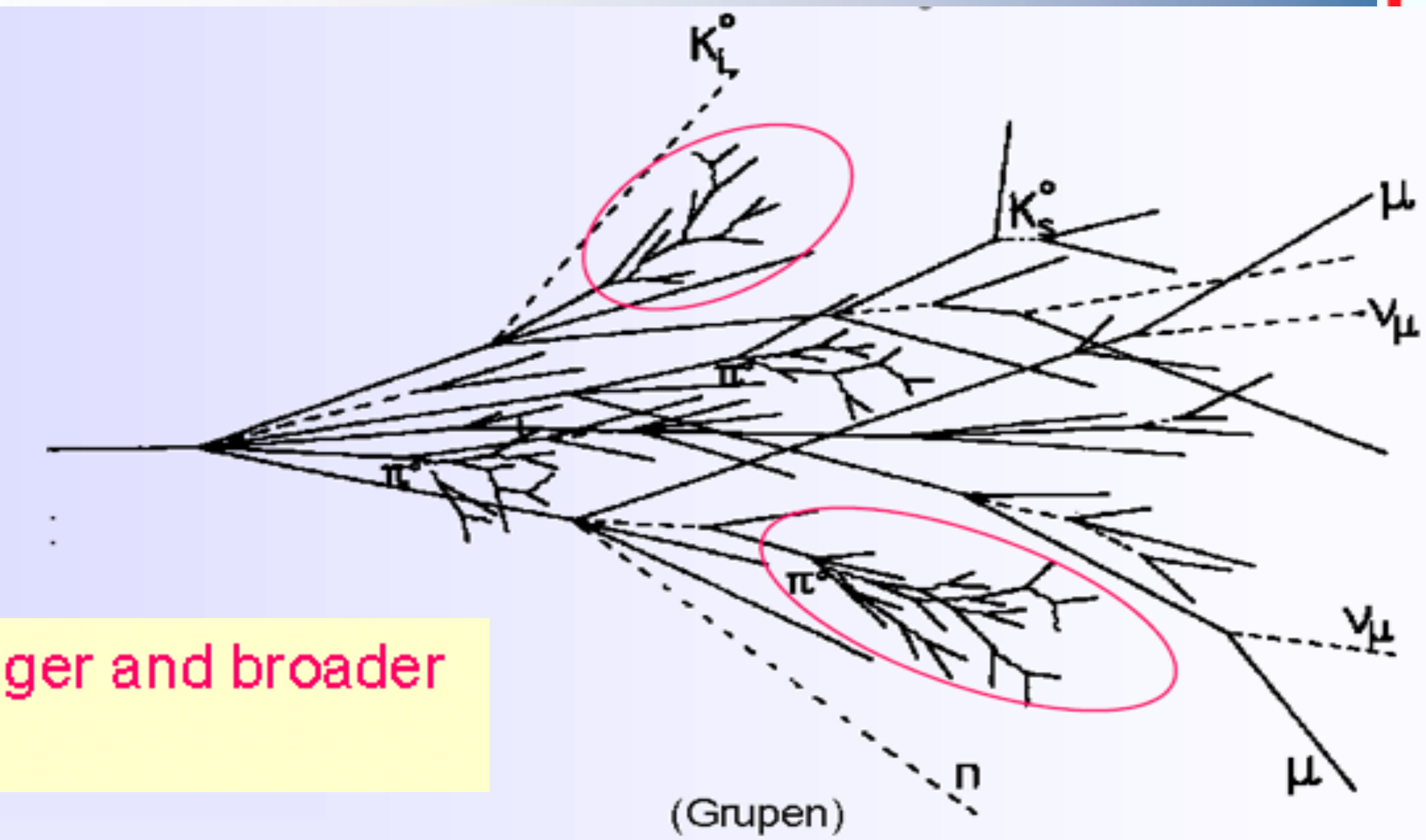
Hadronic cascades

Various processes involved.
Much more complex than electromagnetic cascades.



Hadronic showers are much longer and broader than electromagnetic ones !

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 → large energy fluctuations → limited energy resolution

Hadron Calorimeters

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

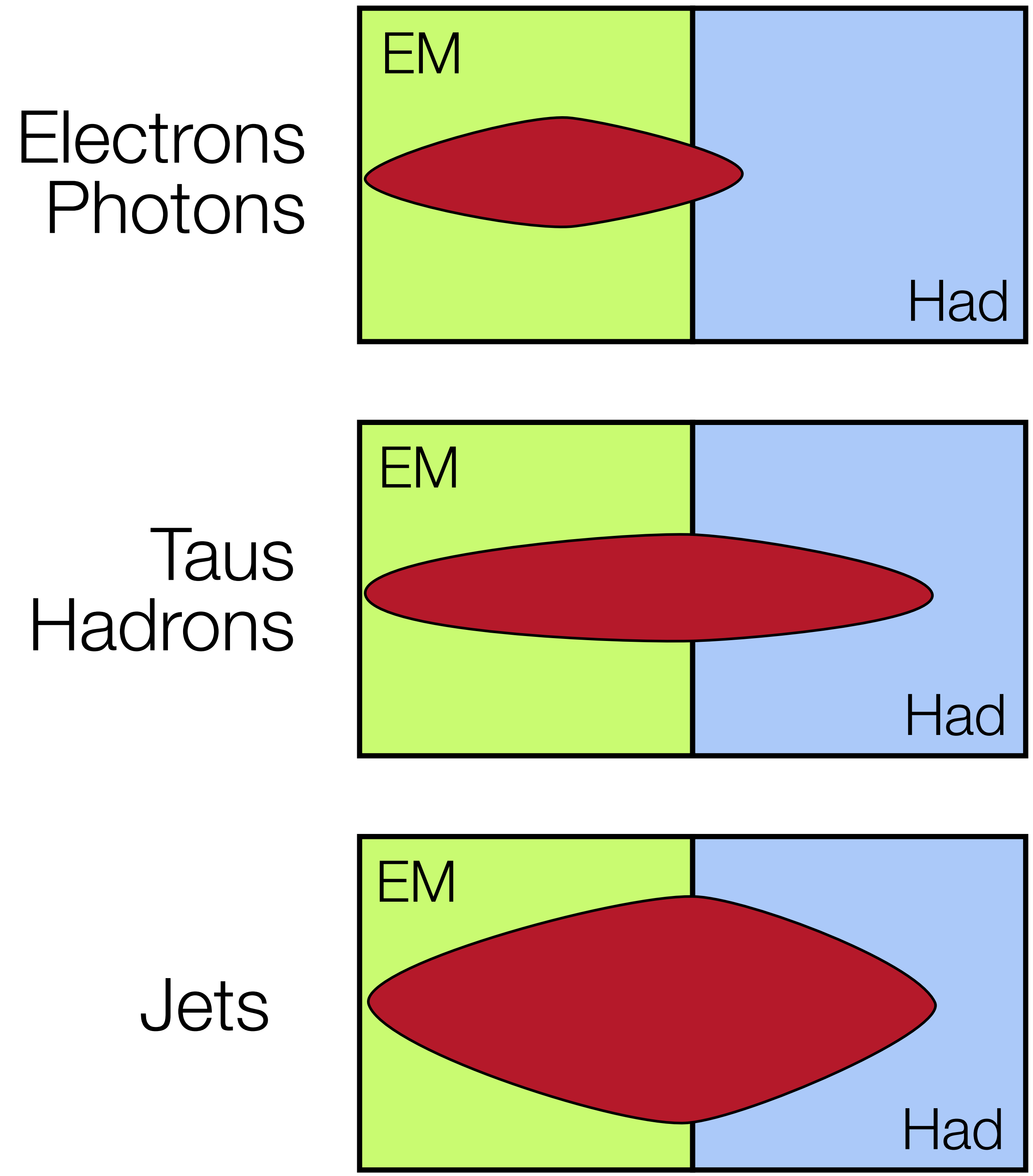
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

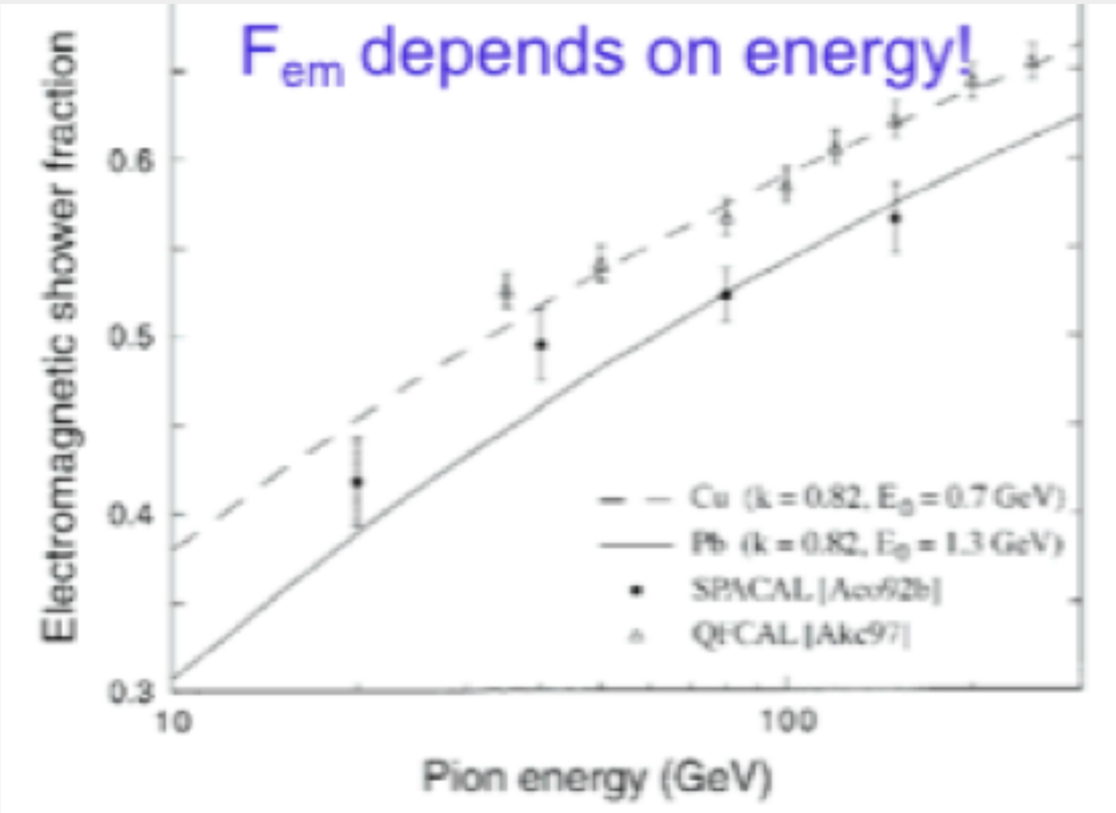
Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



Hadron showers

- A priori e and h give in a calorimeter a different response (e/h>1)
- The fluctuation in 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…+…

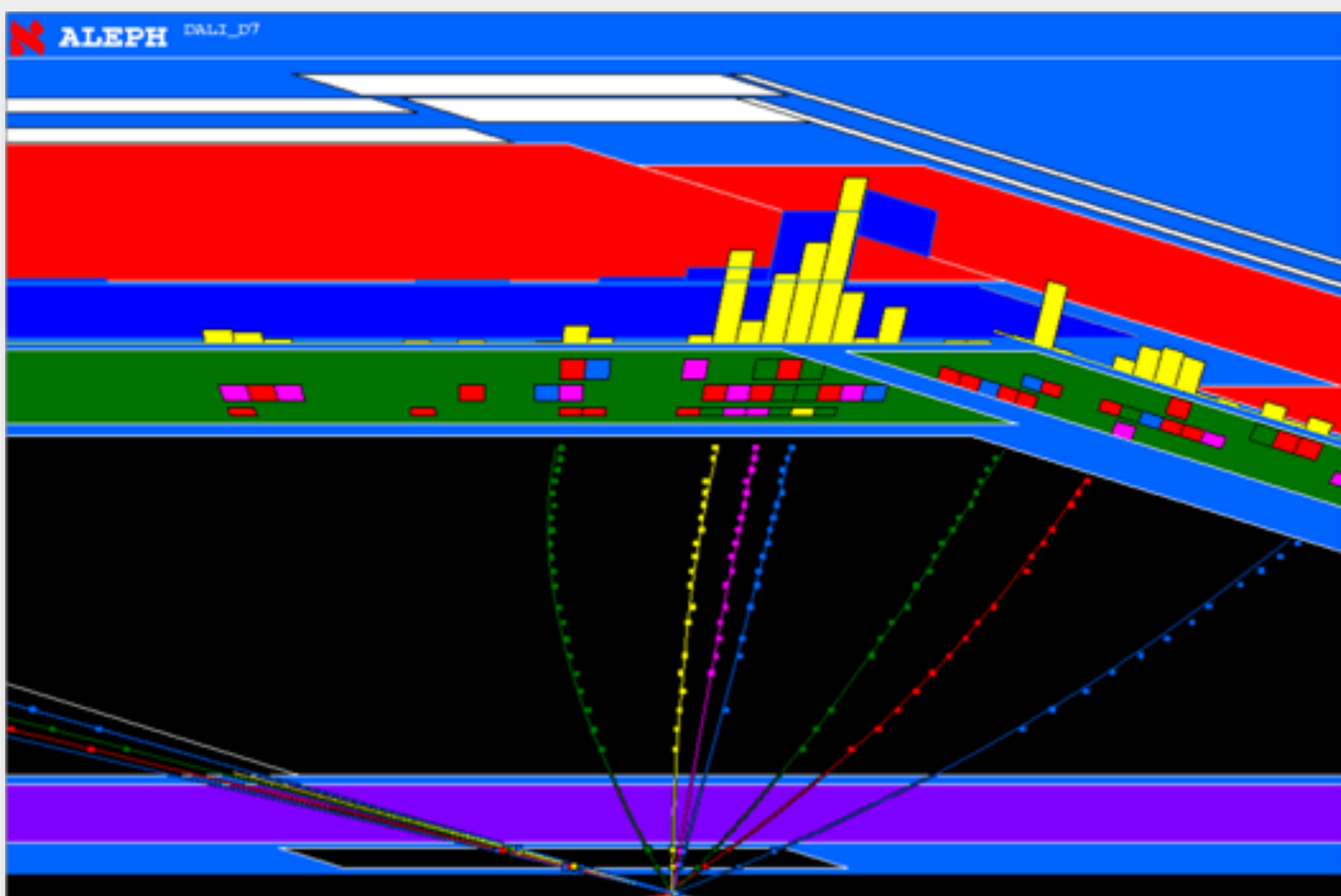
Hadrons interaction with matter :

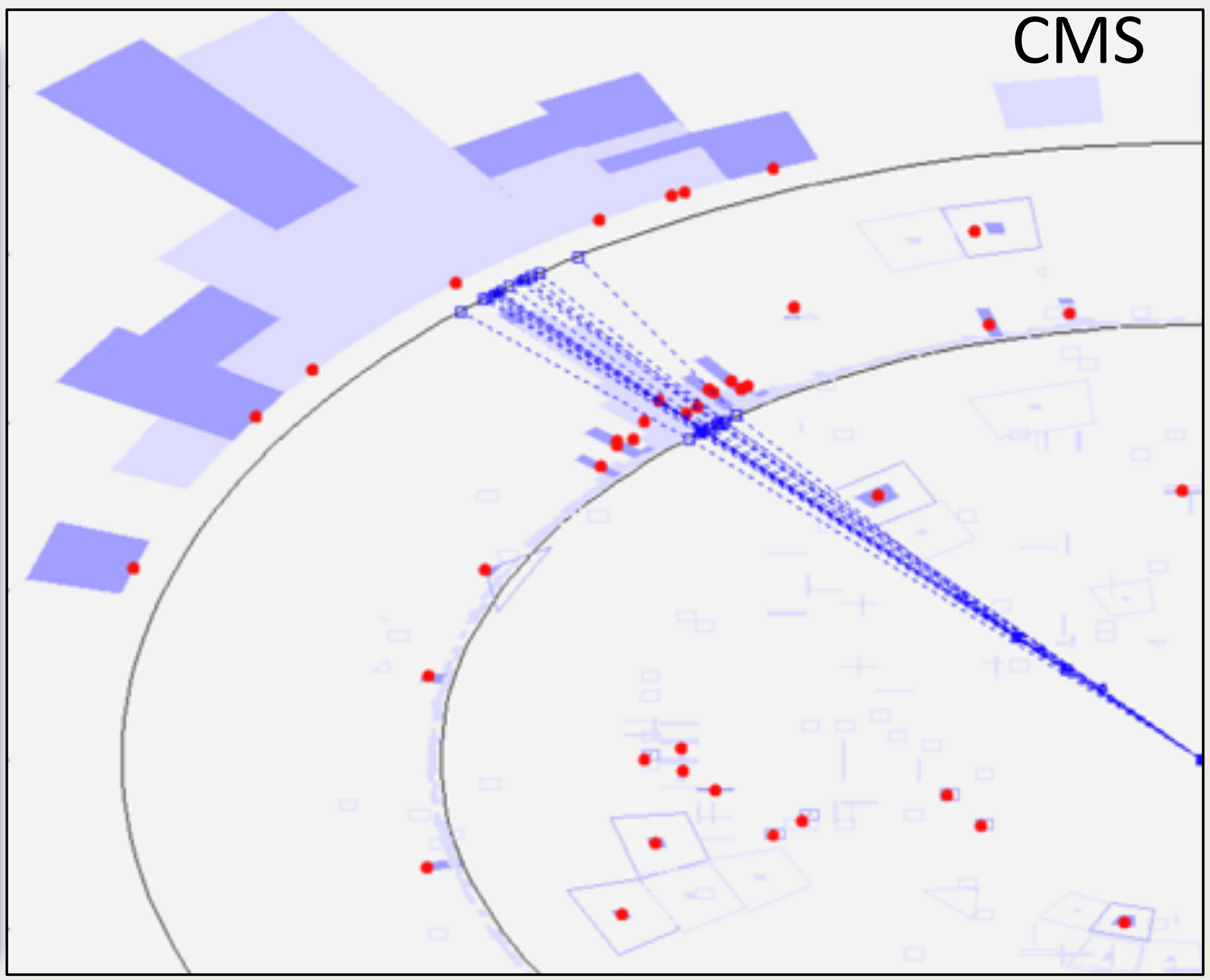
More of Hadron shower development : (for details clic

Energy reconstruction

- Reconstruct energy deposited by charged and neutral particles
- Determine position of deposit, direction of incident particles
- Be insensitive to noise and “un-wanted” (un-correlated) energy (pileup)
- and obtain the best possible resolution!

Obtain energy cluster





Clusters of energy

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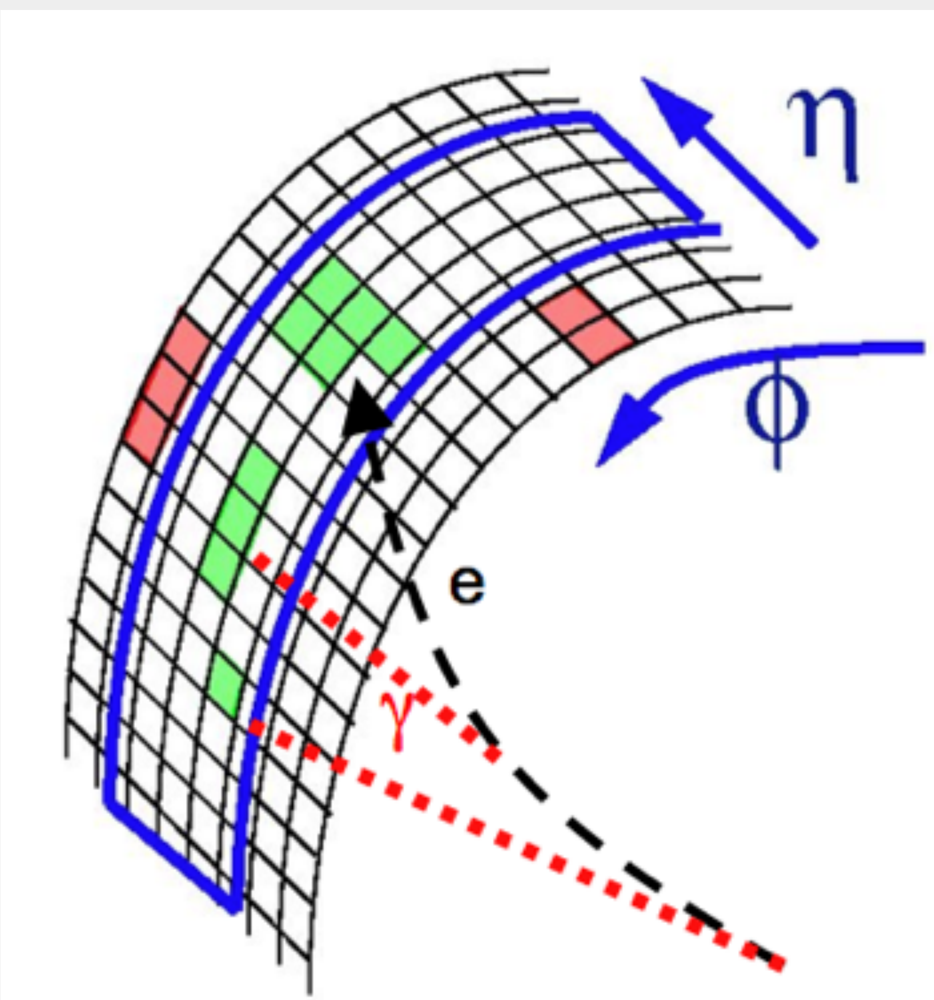
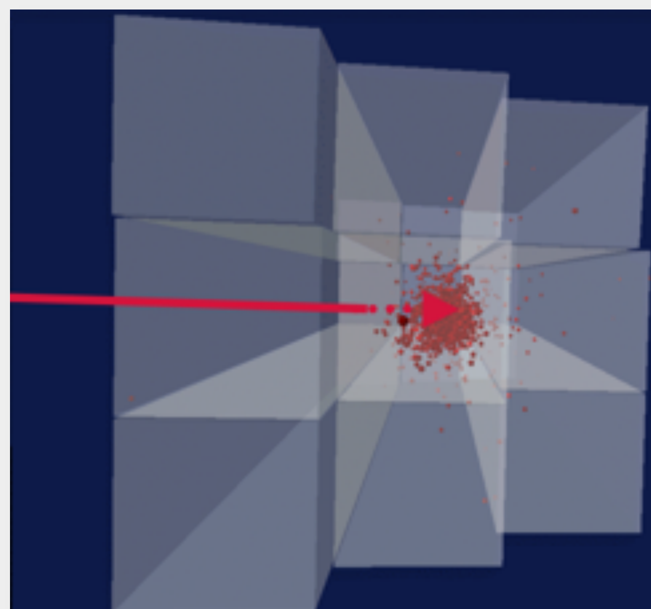
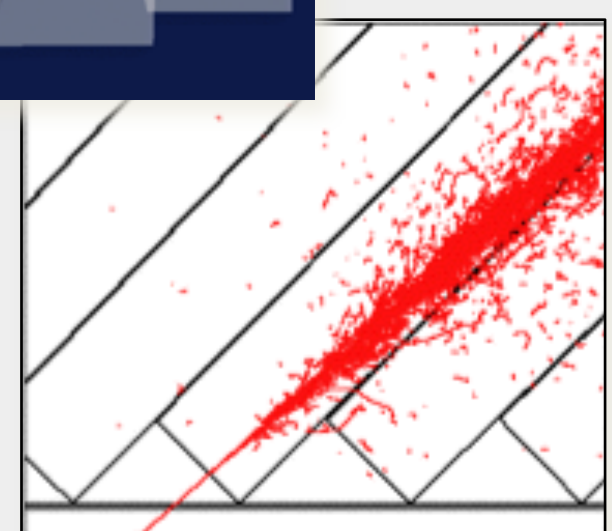
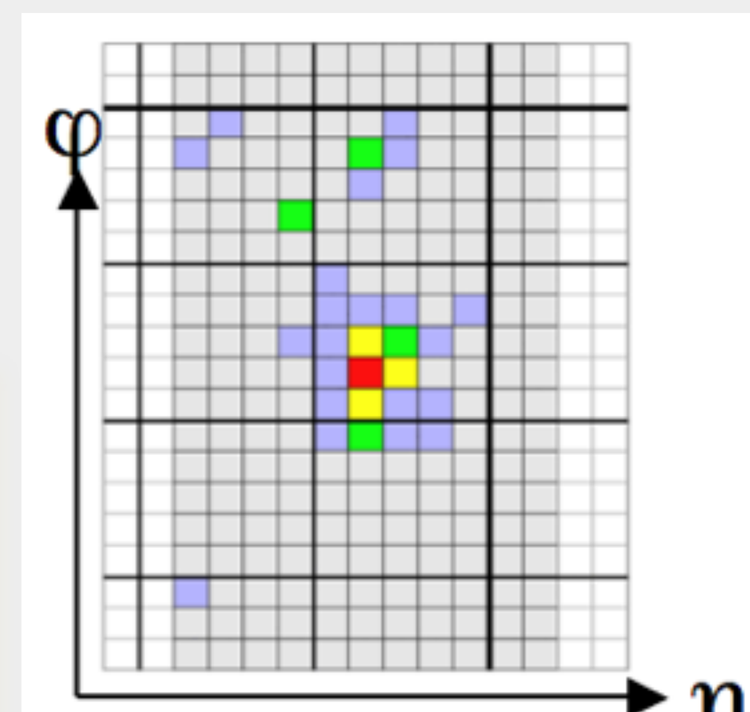




front view



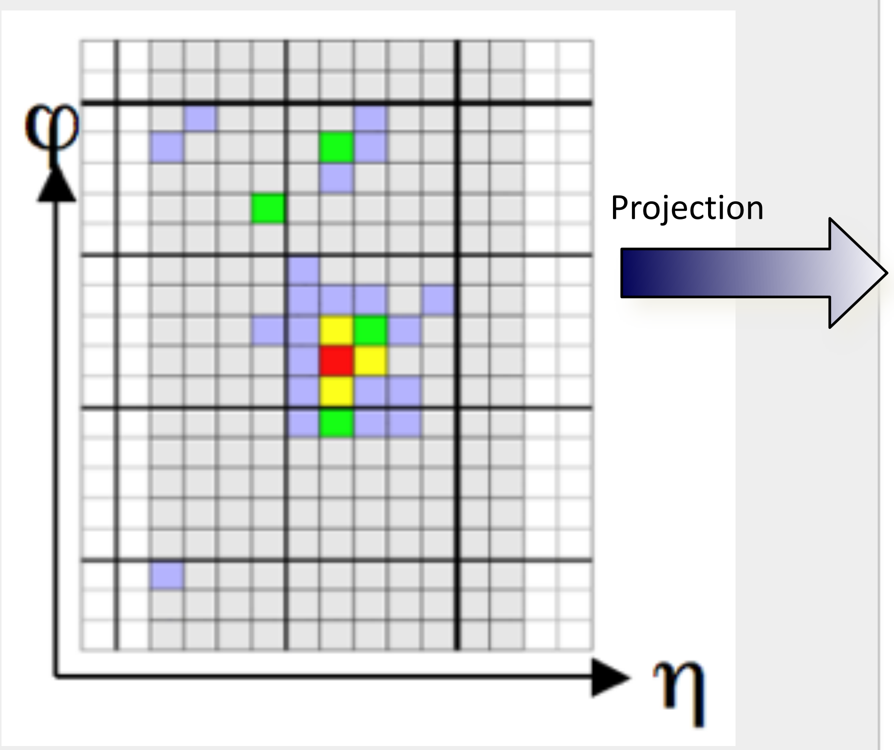
side view

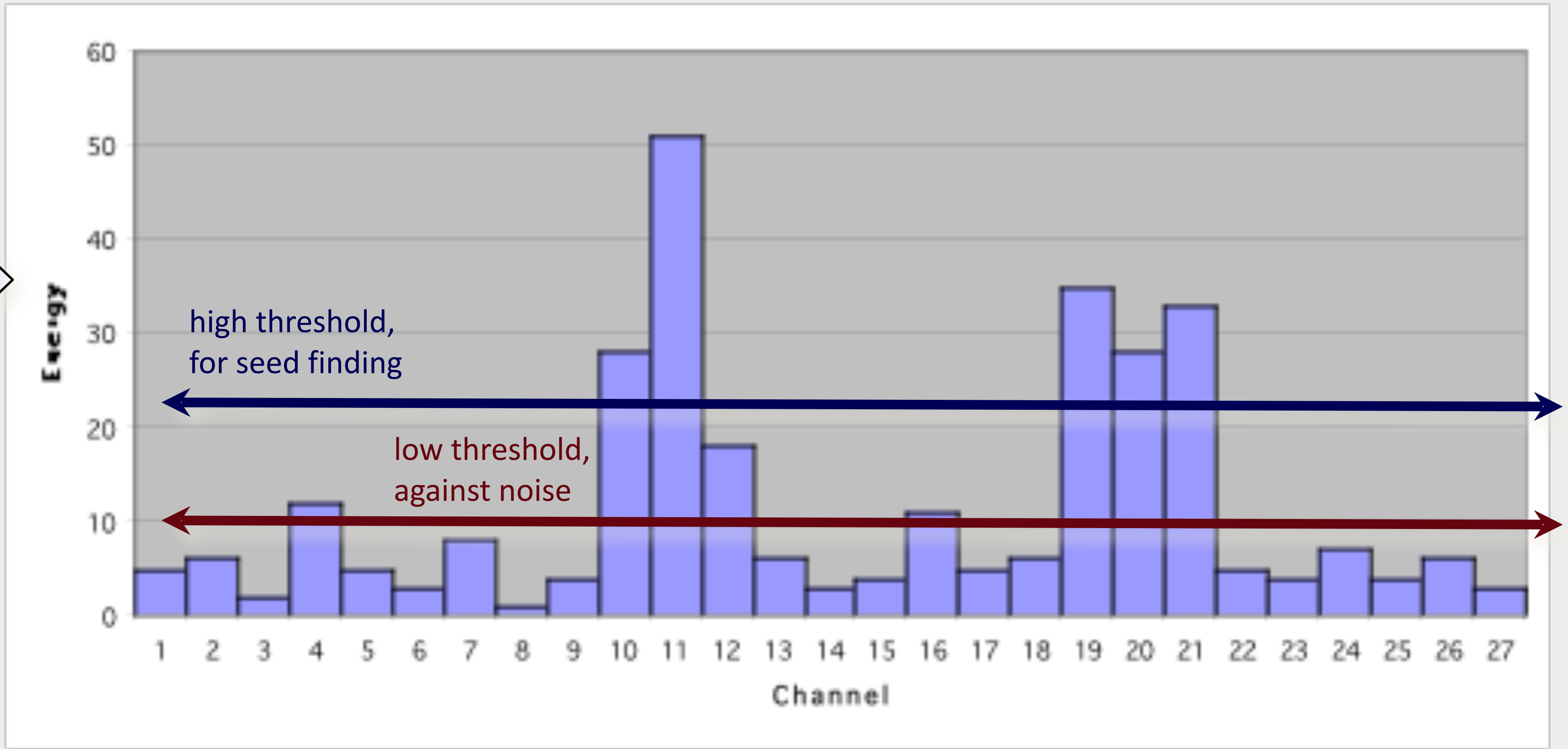


view in (ϕ,η) cells

Cluster Finding

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





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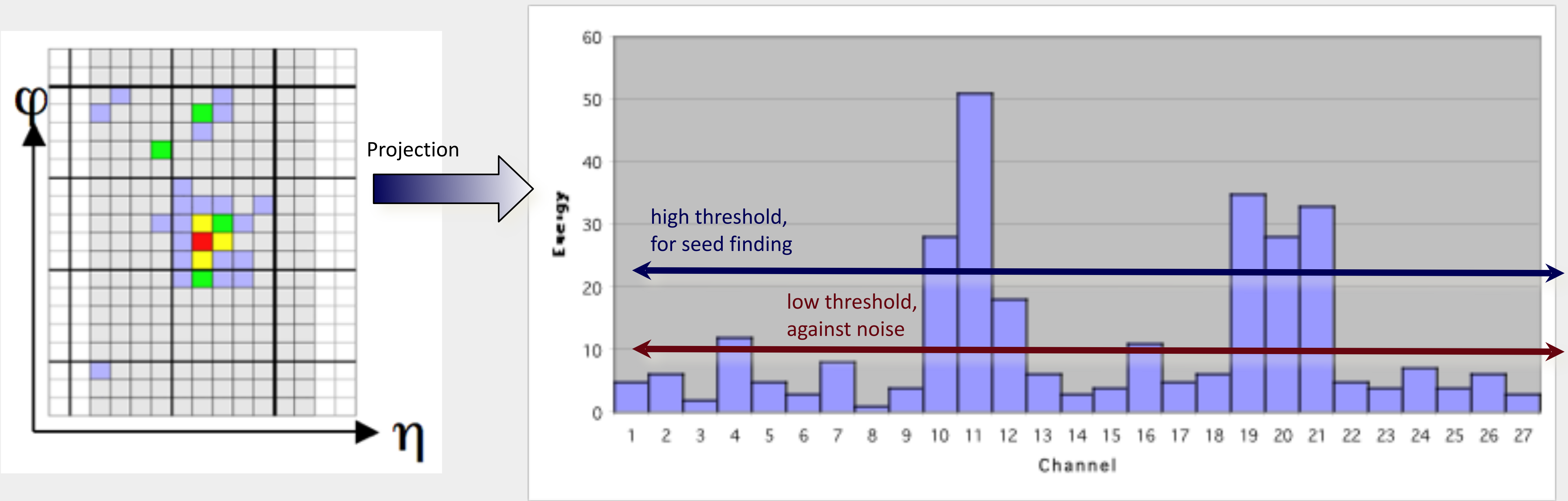

Simple example of an algorithm

- 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

Calibration of calorimeter systems

$$Z, J/\psi \text{ ® } e^+e^-;\ \pi^0, \eta \text{ ® } \gamma\gamma$$

$$W, Z \text{ ® } q\bar{q};\ 'Z, \gamma - jet\ balancing'$$

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

⇨

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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

amplitudes

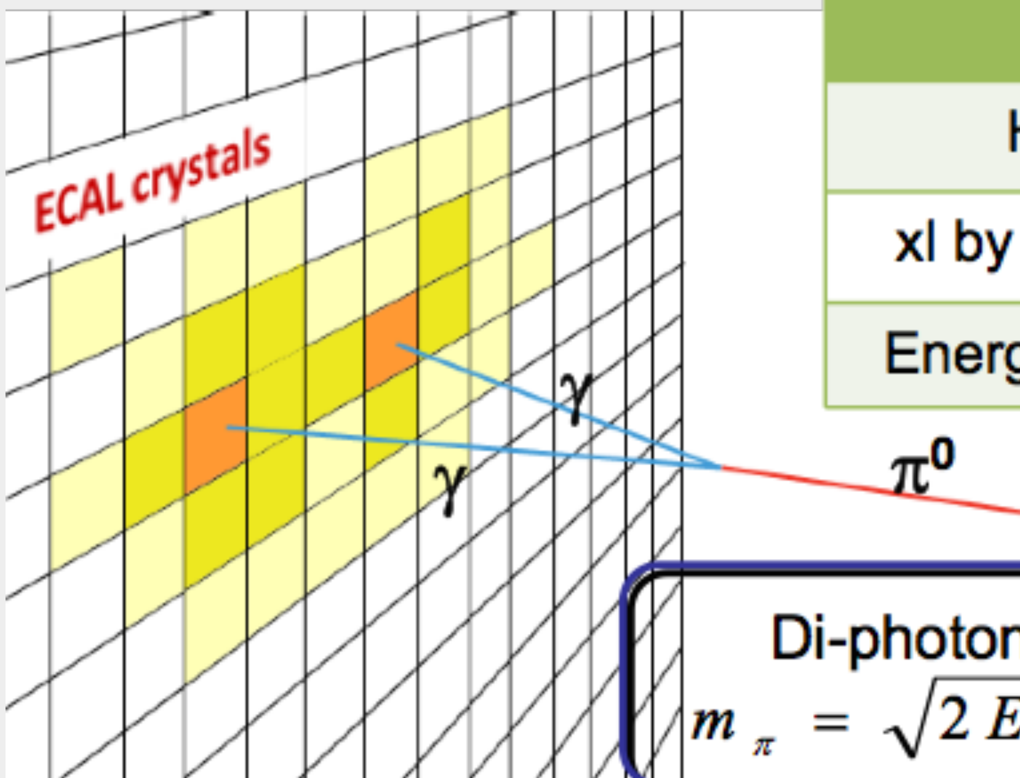
inter-calibration constants

algorithmic corrections

(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

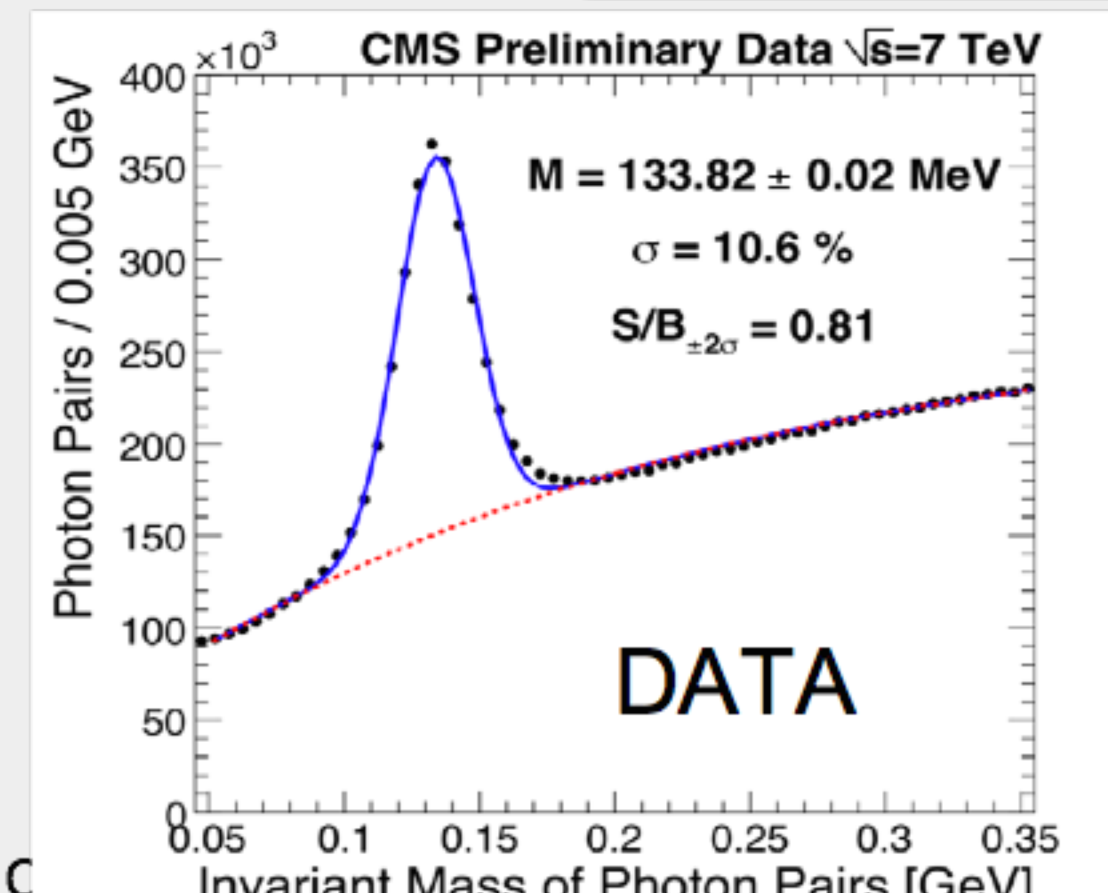
$$m_{\pi} = \sqrt{2 E_1 E_2 (1 - \cos \vartheta)}$$

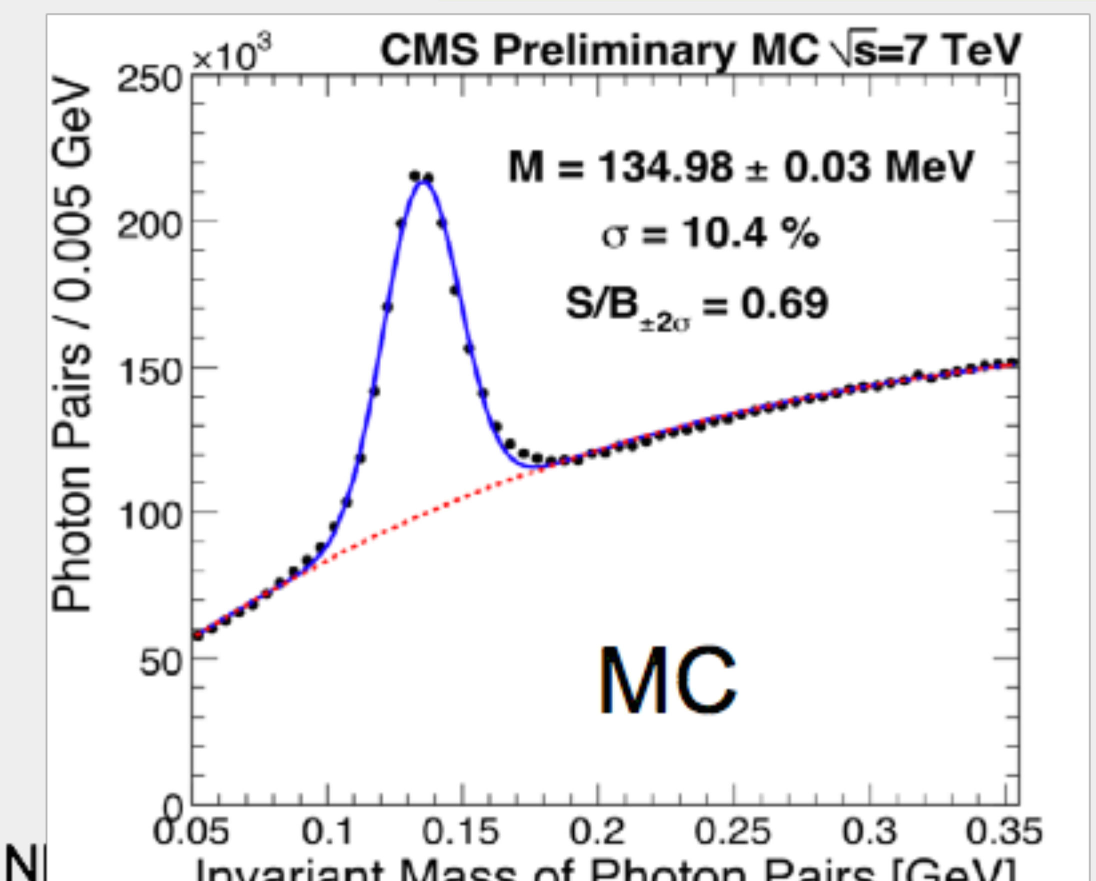
Calibrated photon energy

⬇

π^0 mass peak at right position

Minimum peak spread





Atlas and CMS EM calorimetry

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

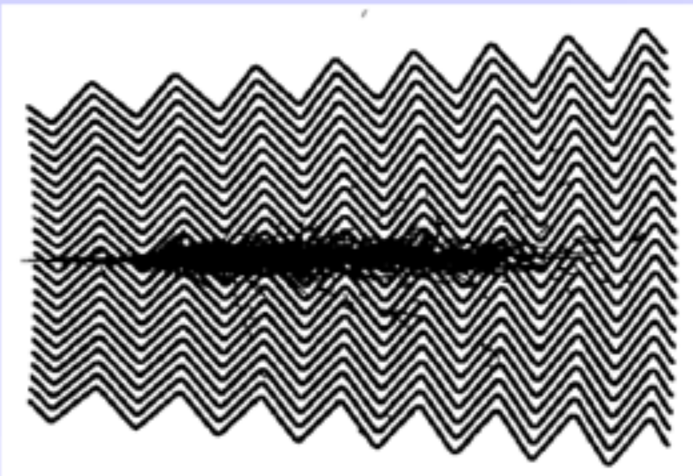
ATLAS and CMS makes different choices:

- sampling calorimeter allow to have redundant mesurement of γ angle
- homogenous calorimeter with very low stochastic term aims to excellent energy resolution, the mesure of γ angle relies on vertex reconstruction from tracking.

Sampling calorimeters: ATLAS ECAL

ATLAS electromagnetic Calorimeter

Accordion geometry absorbers immersed in Liquid Argon



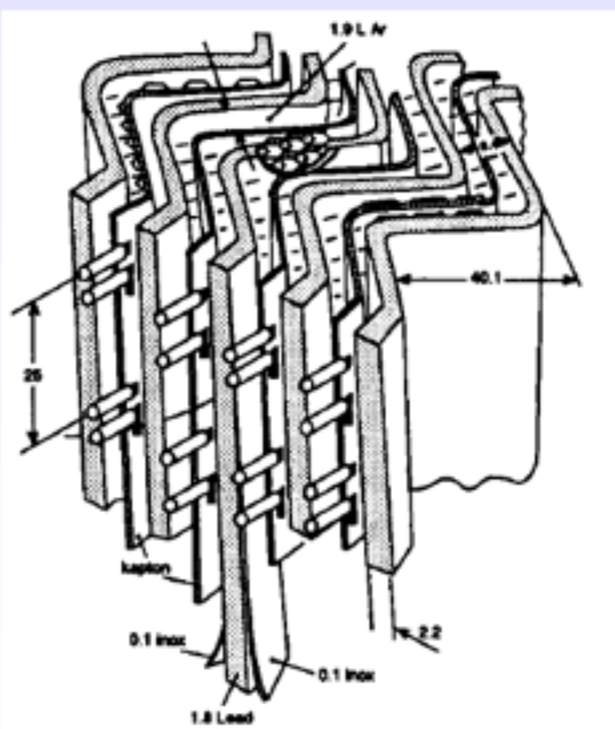
Liquid Argon (90K)

+ lead-steal absorbers (1-2 mm)

+ multilayer copper-polyimide readout boards

$\rightarrow$ Ionization chamber.

1 GeV E-deposit $\rightarrow$ 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 $\sigma(E)/E = 9.24\%/\sqrt{E} \oplus 0.23\%$

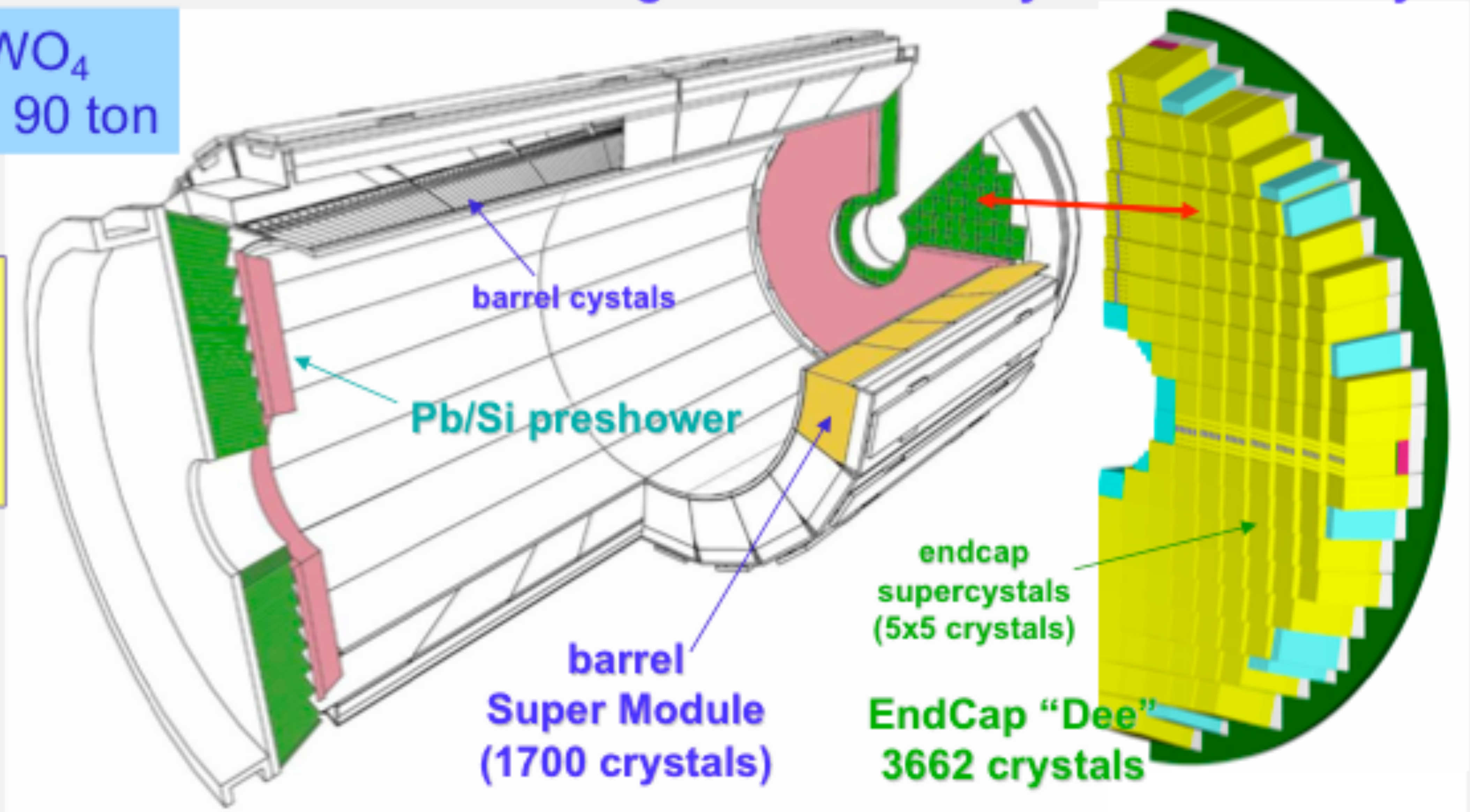
Spatial resolution ≈ 5 mm / √E

CMS ECAL

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m³, 90 ton

Previous Crystal calorimeters: max 1m³



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22cm³)

More about CMS EM calorimeter : for details clic

Electromagnetic calorimeter

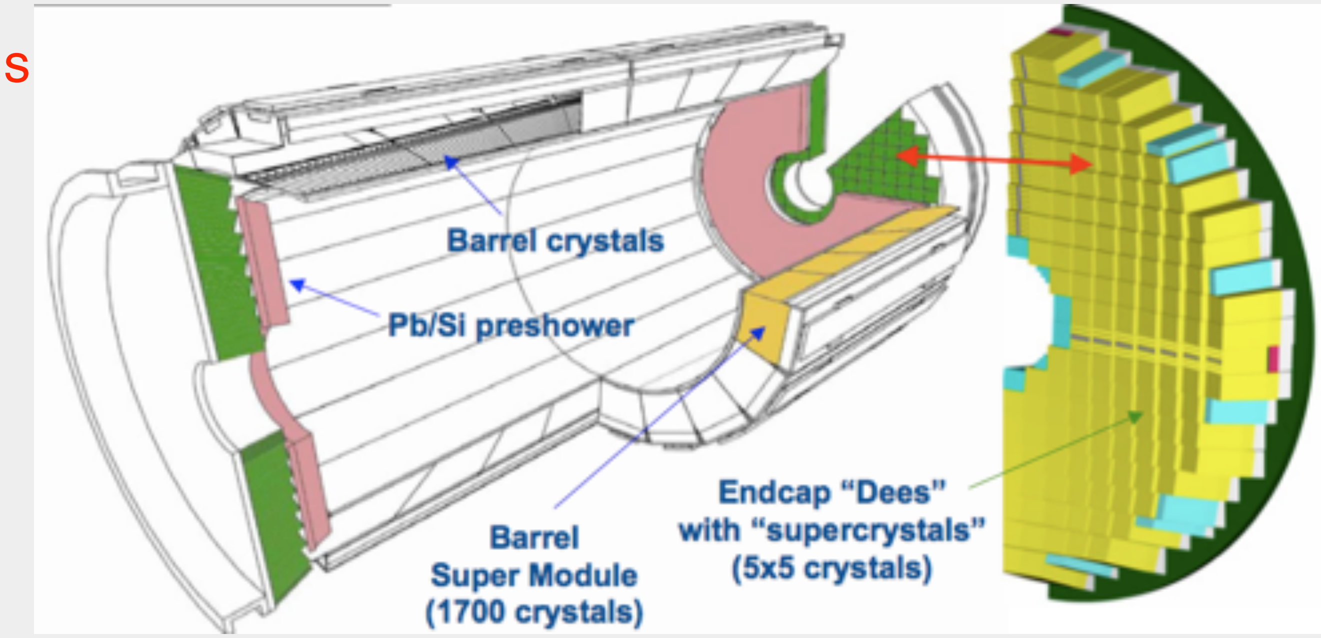
- Homogeneous Lead tungstate $PbWO_4$ crystals
- Fast scintillation response, excellent time resolution
  - about 80% of the light emitted in 25 ns
- Compact & high granularity
  - Molière radius 2.2 cm
  - Radiation length X_0 0.89 cm

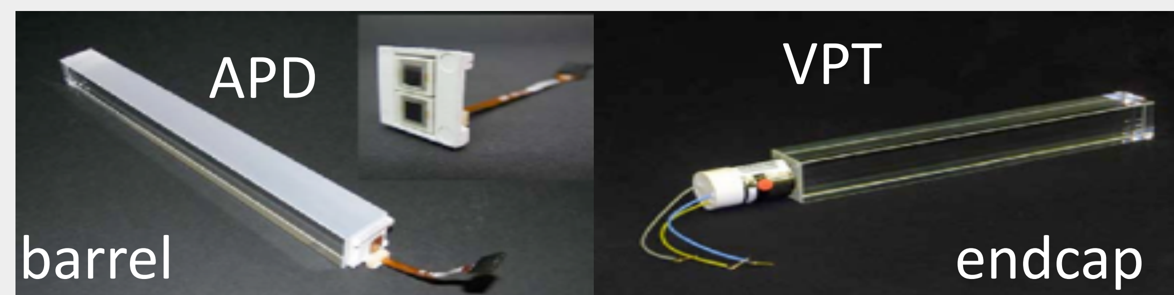
- Barrel $|\eta|<1.48$:
  - ~61K crystals in 36 SuperModules (SM)
  - 2x2x23 cm^3 covering 26 X_0
  - Photodetector: Avalanche Photo Diodes (APD)
- Endcap $1.48 <|\eta|<3.0$
  - ~15k crystals in 4 Dees
  - 3x3x22 cm^3 covering 24 X_0
  - Photodetector: Vacuum Photo Triodes (VPT)
- Preshower $1.65 <|\eta|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

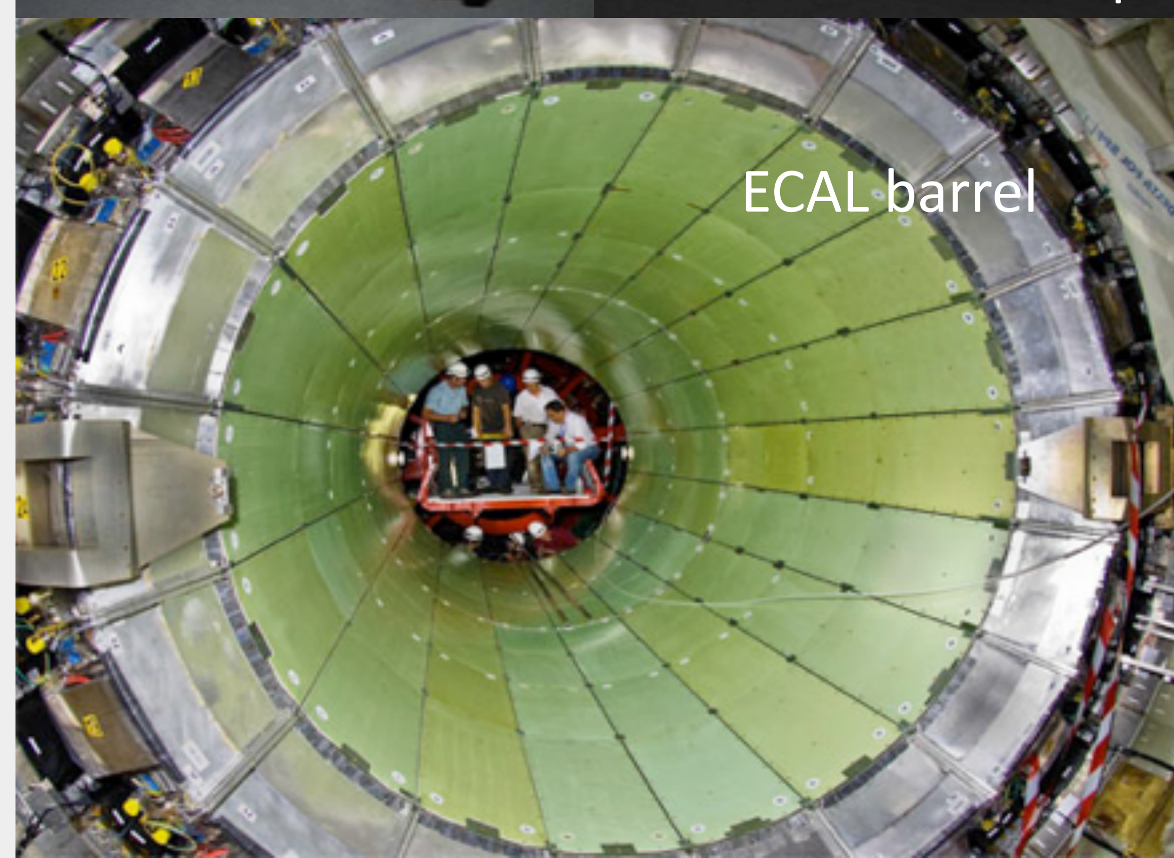
- No longitudinal segmentation

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

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

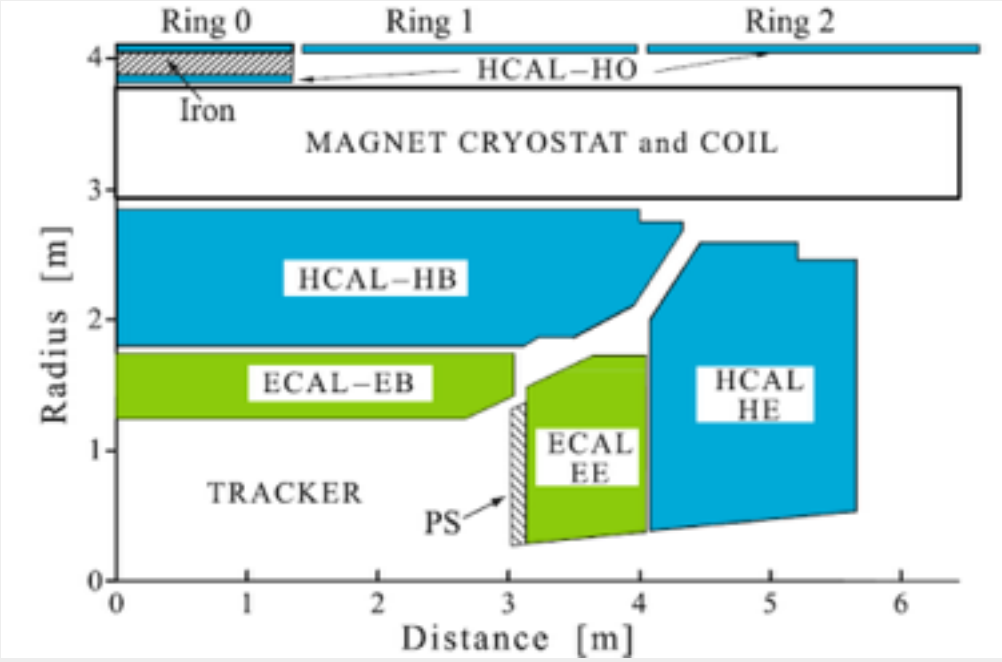


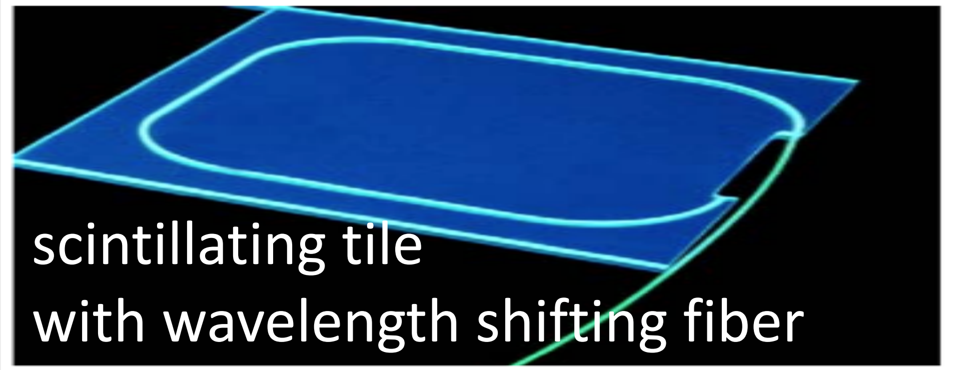


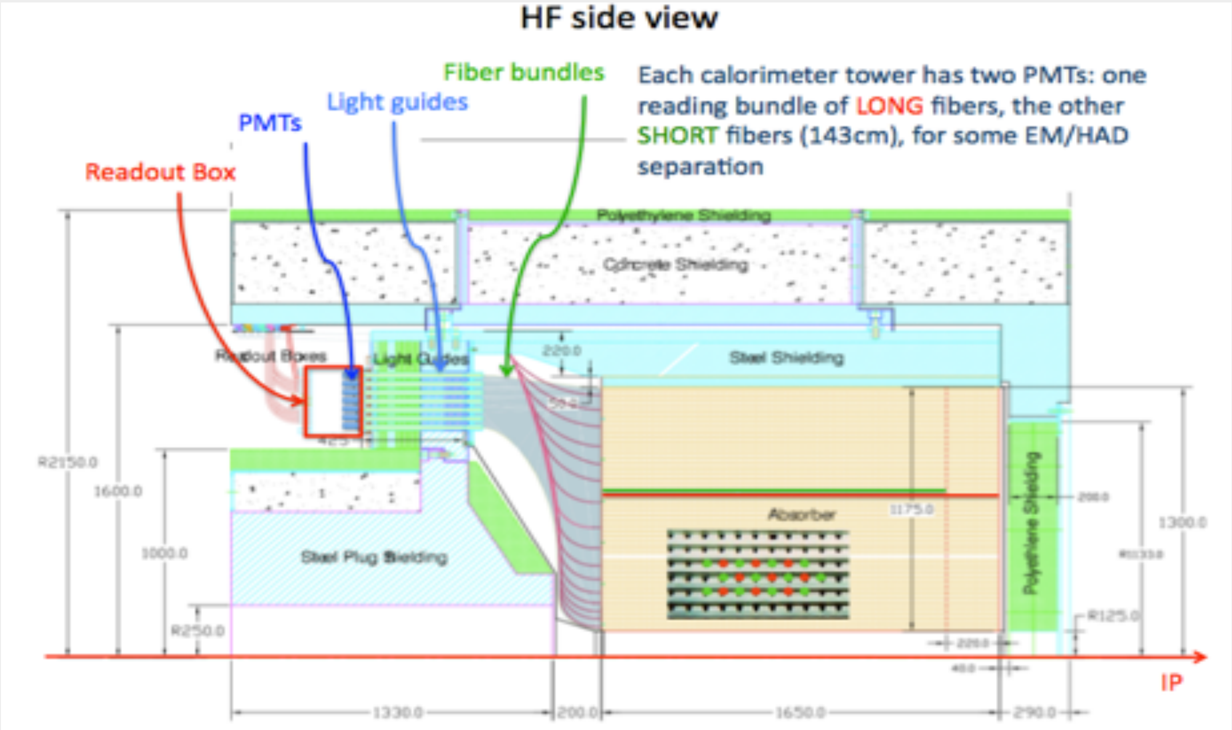


Hadronic calorimeter

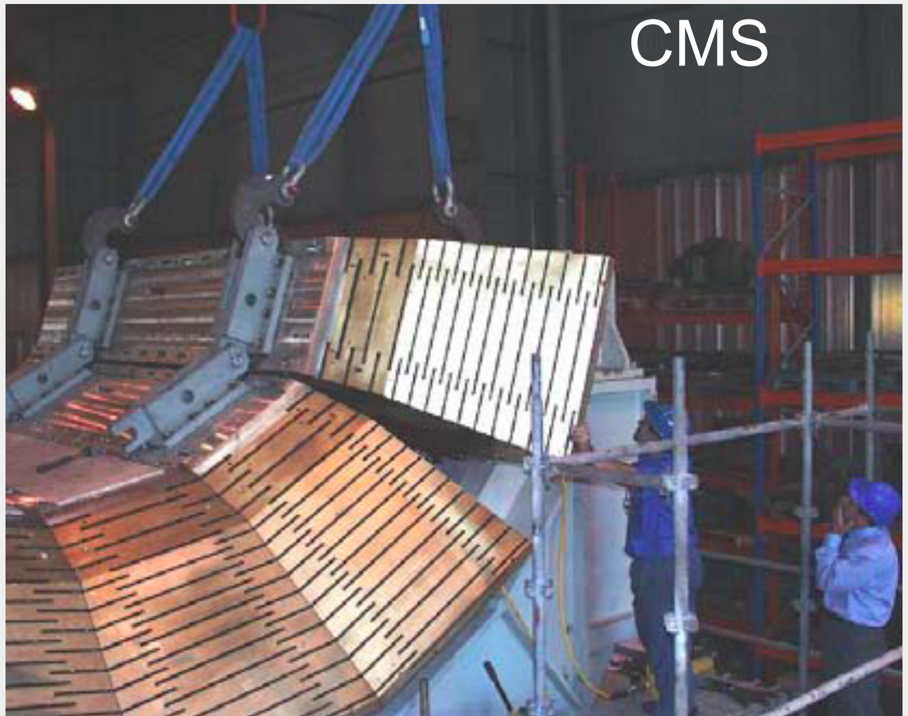
- HCAL Barrel (HB) 0<lηl<1.3 and Endcap (HE) 1.3<lηl<3
  - Sampling calorimeter, alternating layers of brass absorber and plastic scintillator tiles.
  - Hybrid photo-detector (HPD) readout
- Outer (HO): Outside solenoid
  - Tail catcher with scintillator layers
  - HPD readout
- Forward (HF) at lzl=11 m: 2.9<lηl<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







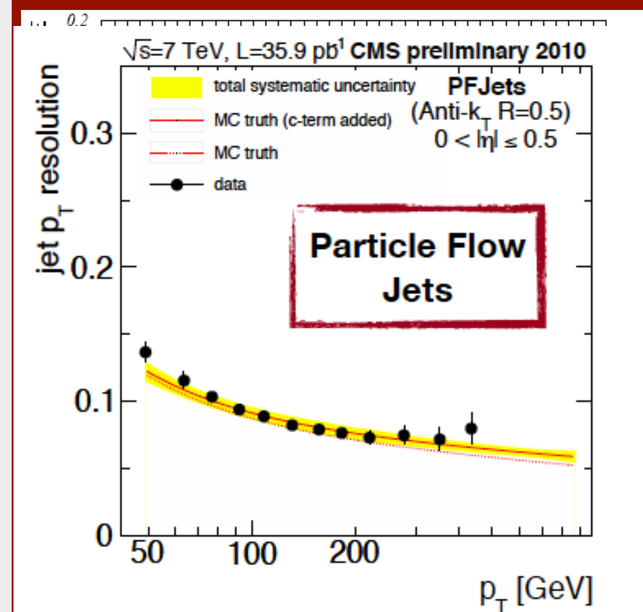
CMS Hadron Calorimeter



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

CMS

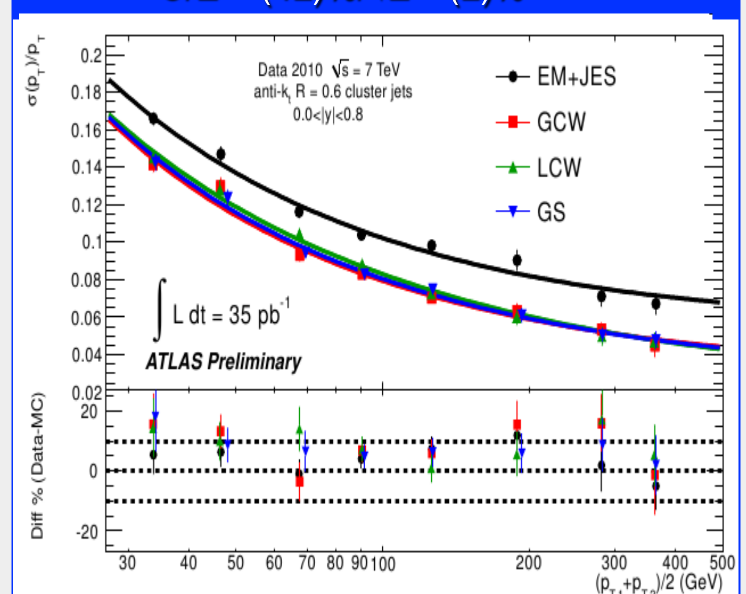
- HCAL only
  σ/E = (93.8)%/√E ⊕ (7.4)%
- ECAL+HCAL
  σ/E = (82.6)%/√E ⊕ (4.5)%



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

ATLAS

- Standalone tile calorimeter
  σ/E = (52.9)%/√E ⊕ (5.7)%
- Improved resolution using full calorimetric system (ECAL+HCAL)
  σ/E = (42)%/√E ⊕ (2)%



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:

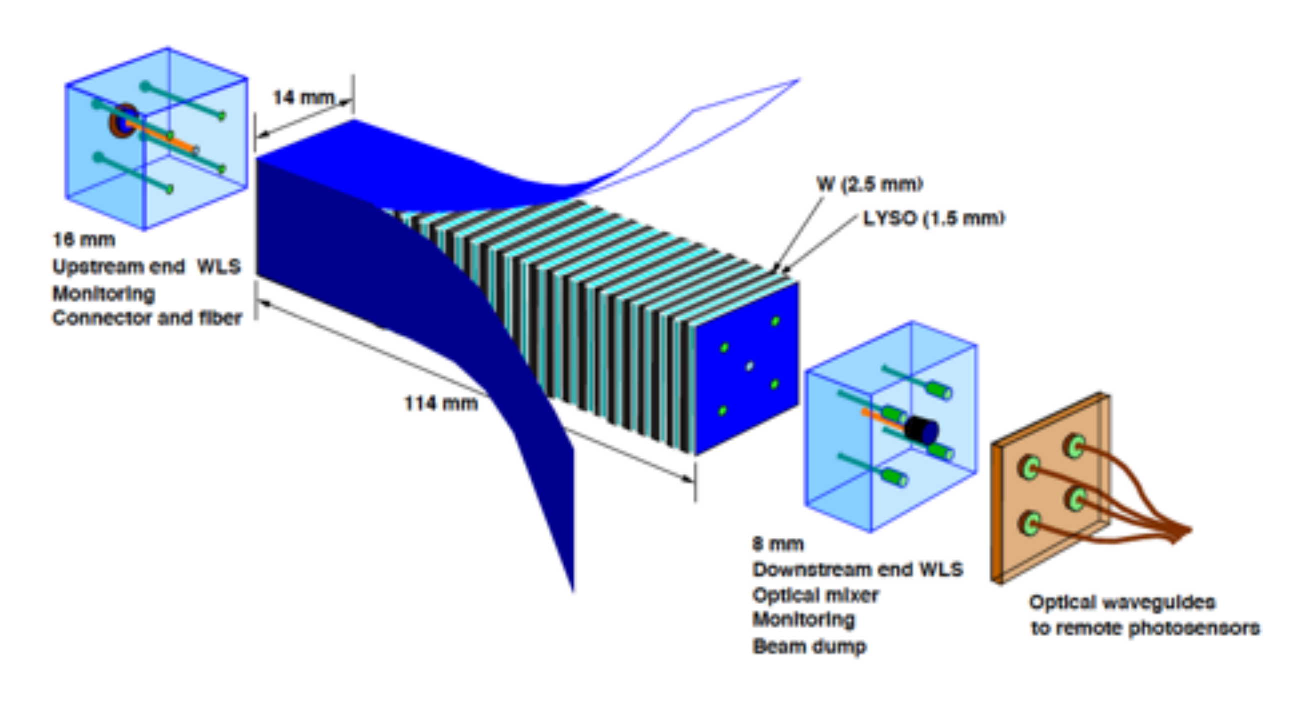
- Replace the forward calorimeter by a radiation hard detector capable of withstanding the very high luminosities expected at HL-LHC

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)



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)

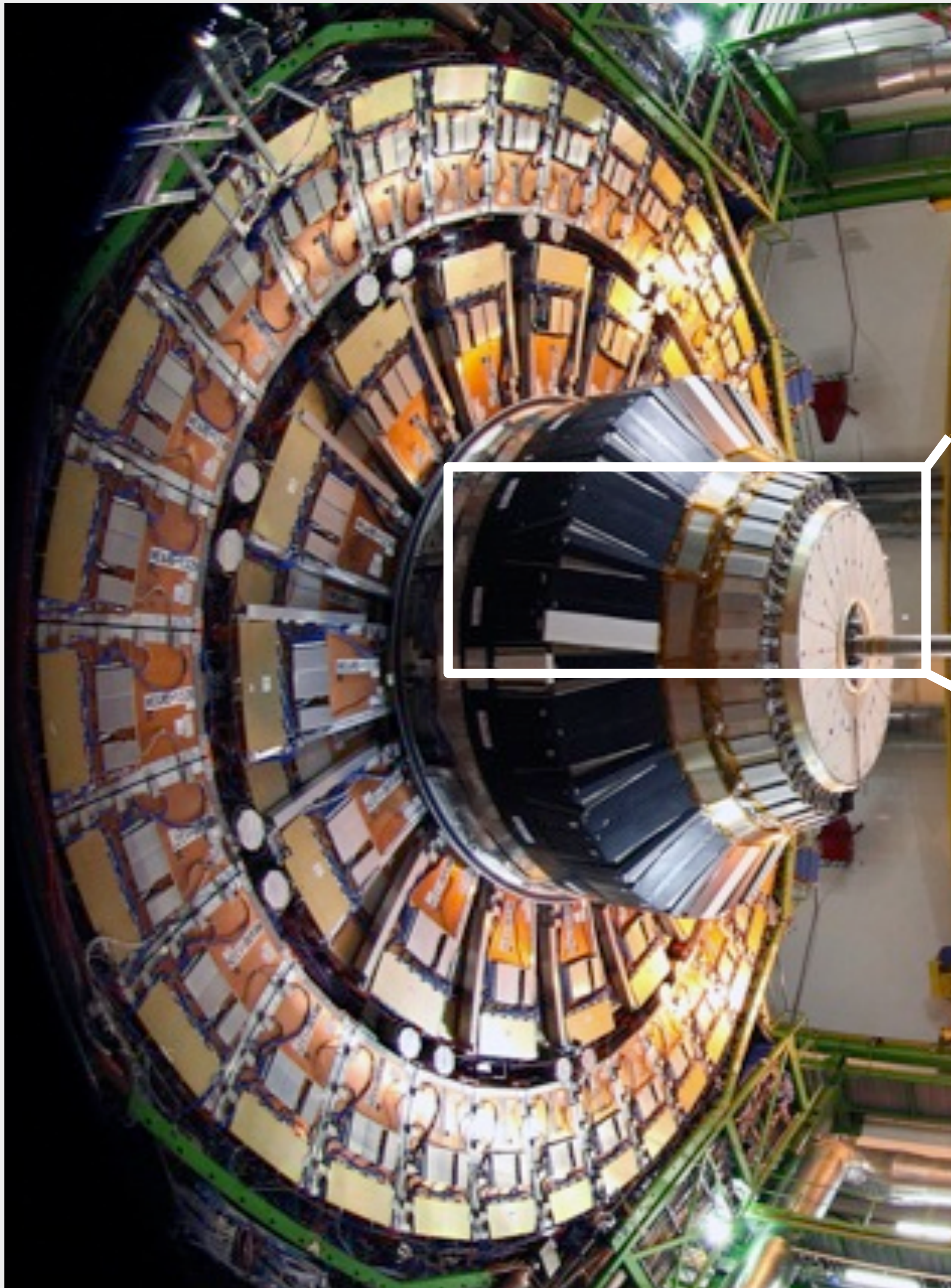
Module Dimensions:
- Transverse Size: Front Face 14 x 14 mm^2
- Length 114 mm

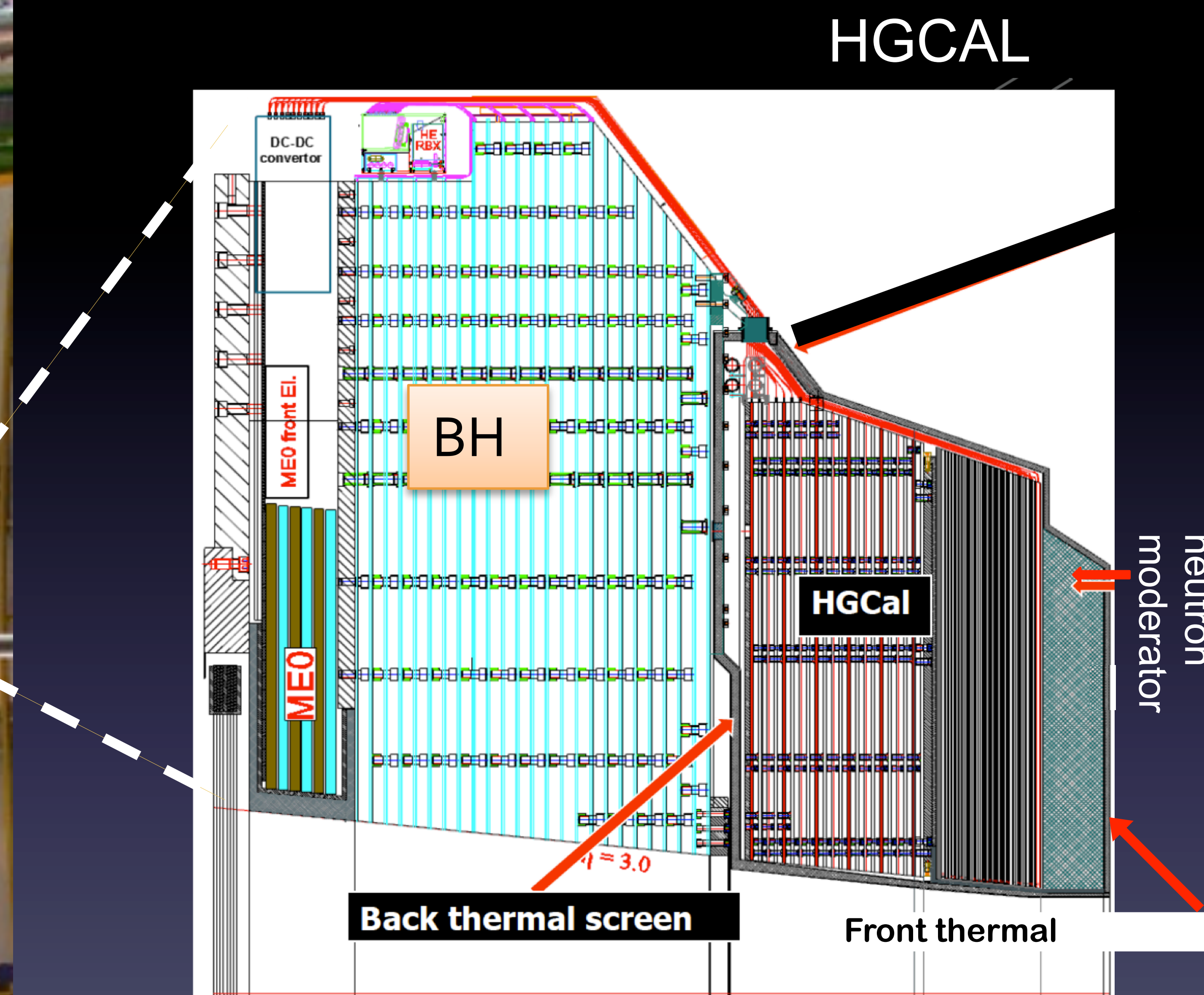
Readout:
- WLS Capillaries (4 per module)
- GaInP/SiPM Photosensors (4 per module)
- One QIE13 channel per module

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

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

Integrated sampling Si ECAL+HCAL and backing Calorimeters

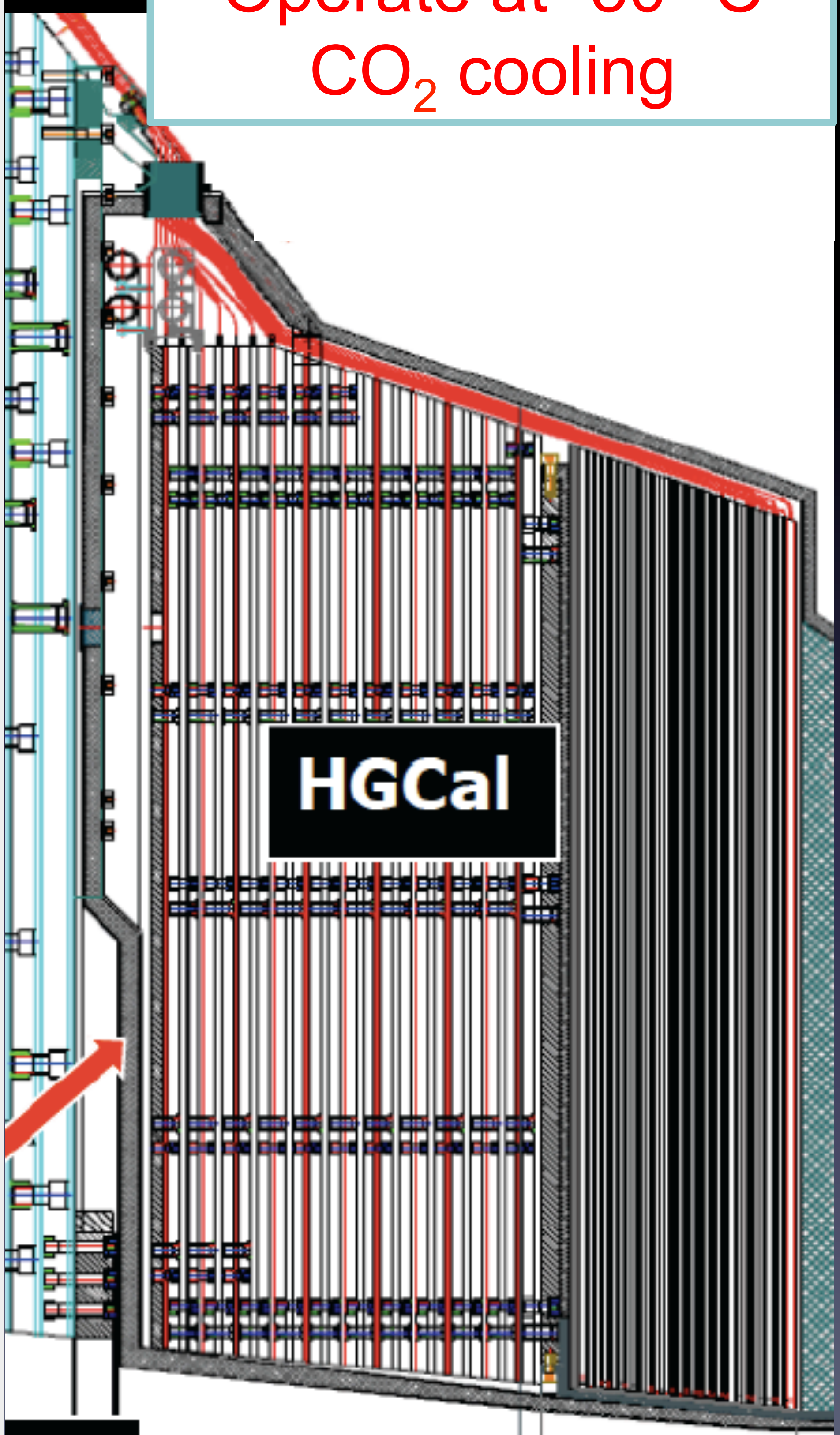




EE	Cu-W / Si	26 X_0 (1.5 λ)
FH	Brass / Si	3.5 λ
BH	Brass / scint. tiles	5 λ

Endcap Calorimeter for HL-LHC : HGCAL

Operate at -30 °C
CO_2 cooling



Si/W-ECAL Section (Σ_{depth}>25X_0, 1.5λ)
10 × 0.65X_0
10 × 0.88X_0
8 × 1.26X_0

Si/Brass Front HCAL (FH) Section (Σ_{depth}> 3.5λ)
12 × 0.3λ

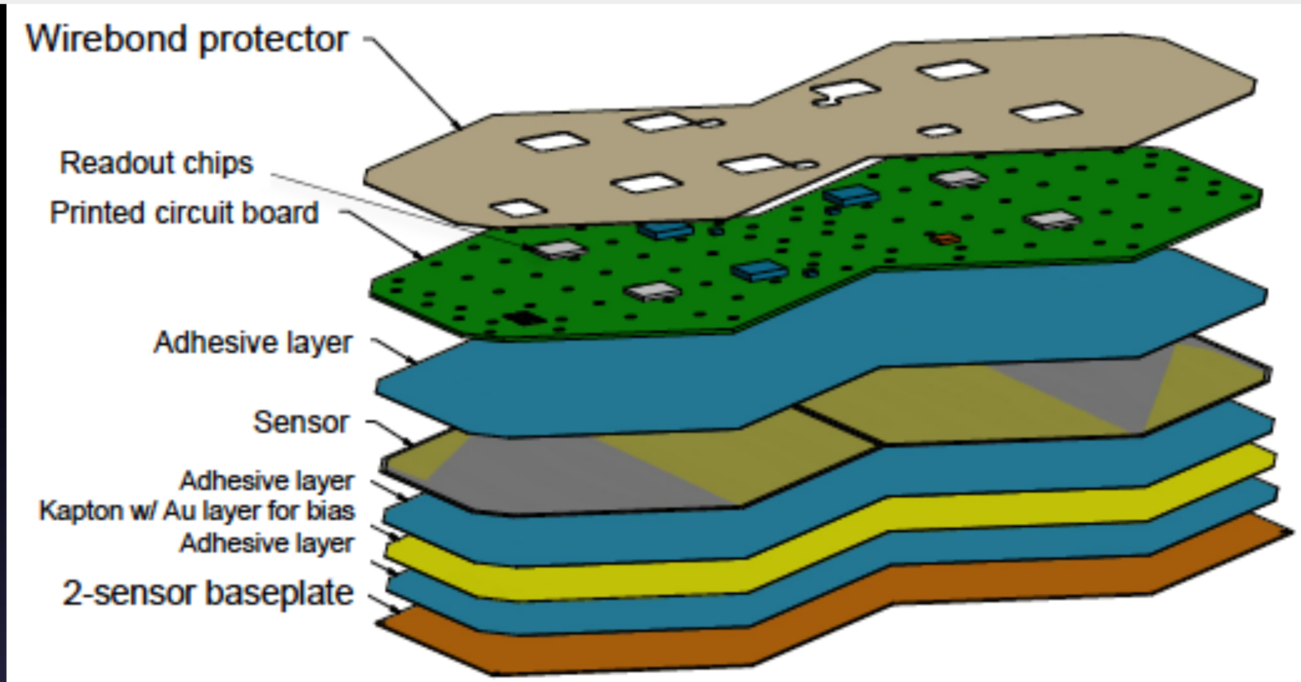
Scint/Brass Backing HCAL(BH)Section(Σ_{depth}> 5λ
12 × 0.45λ

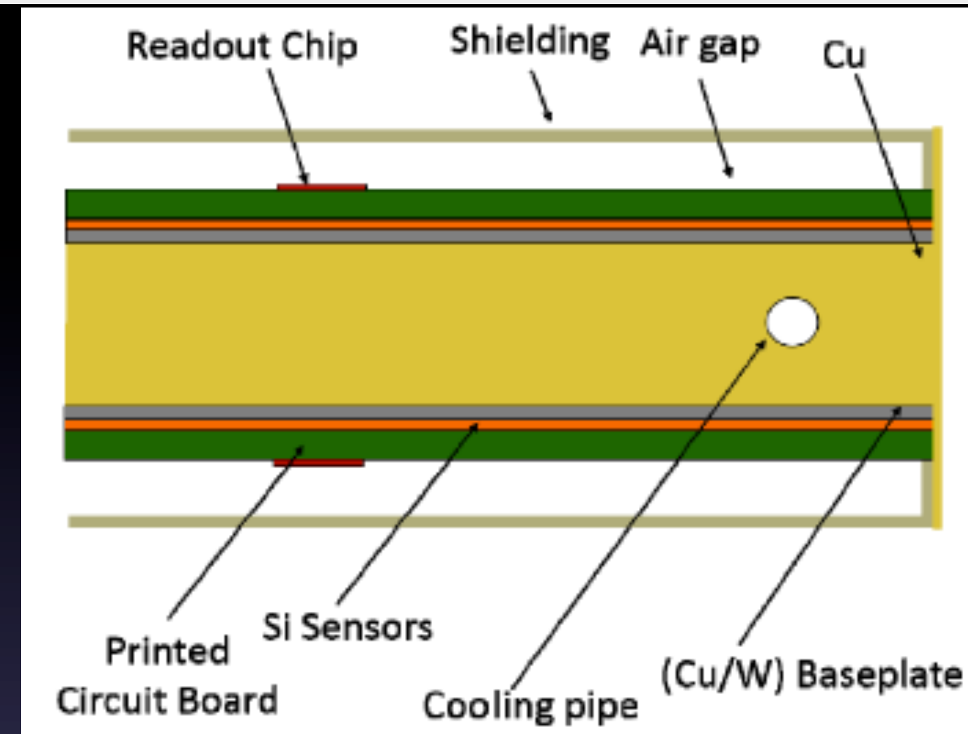
Total Depth >10λ

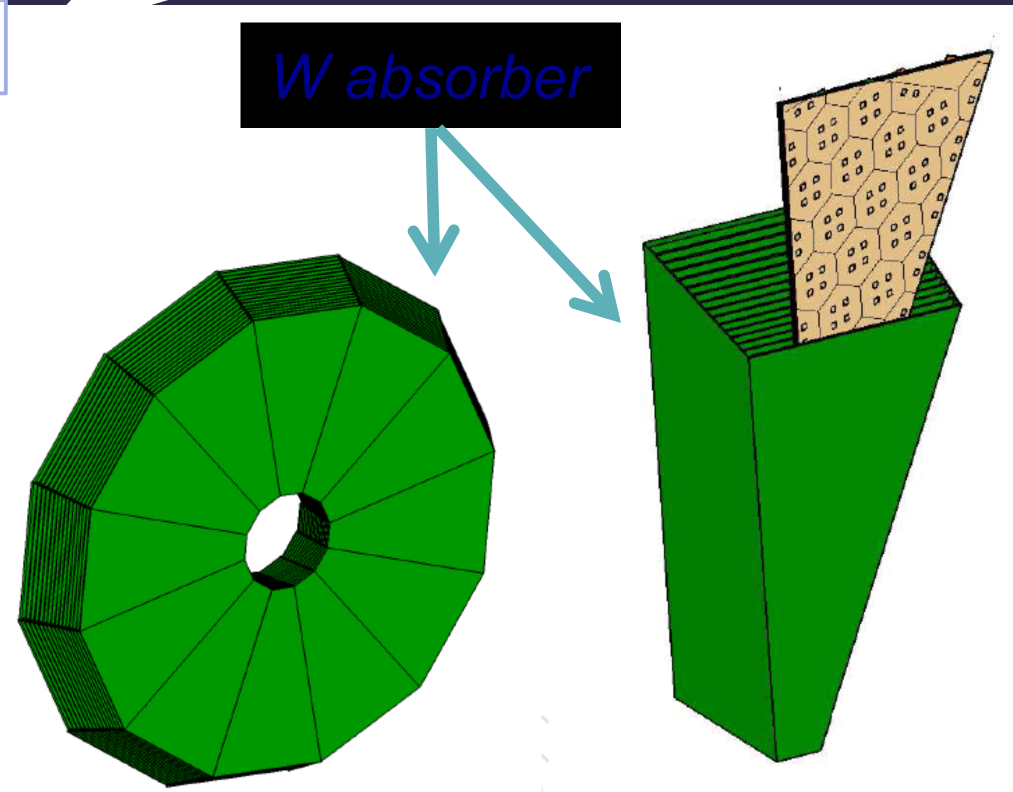
Table 3.2: Parameters of the EE and FH.

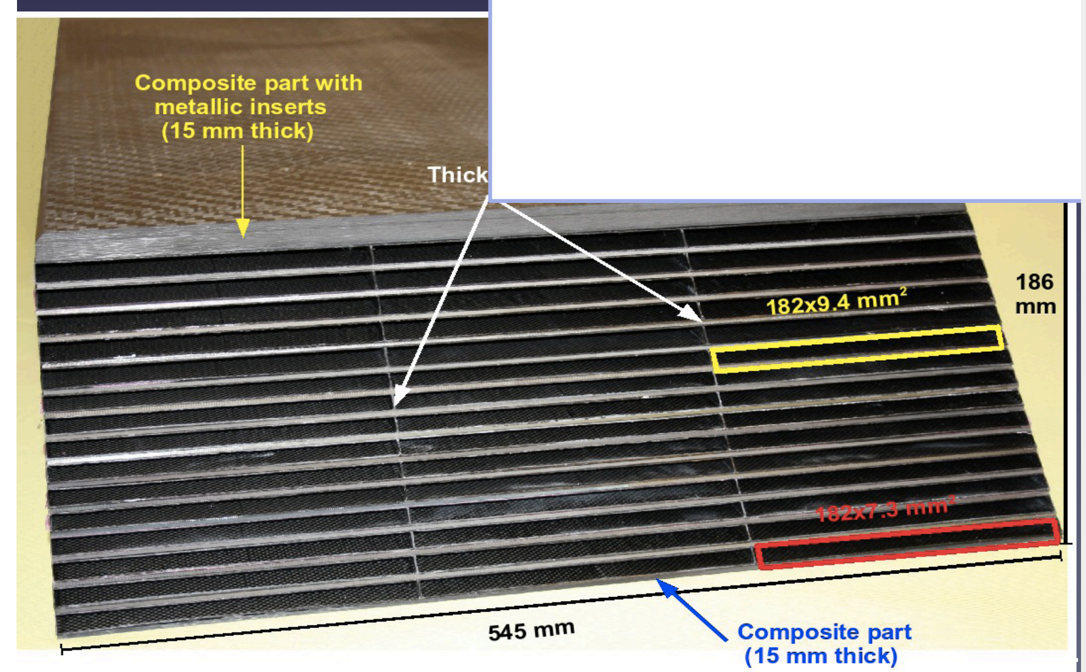
	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

Endcap Calorimeter for HL-LHC : HGCAL

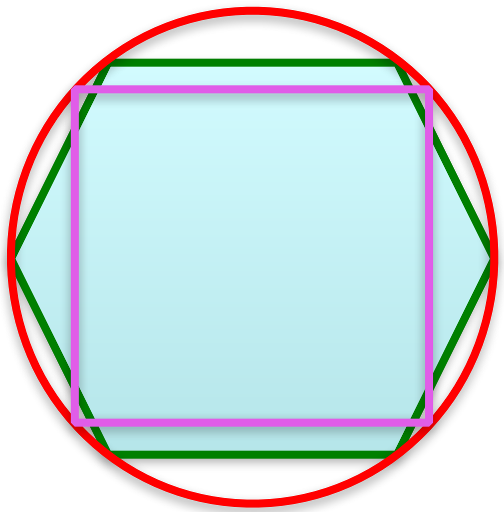








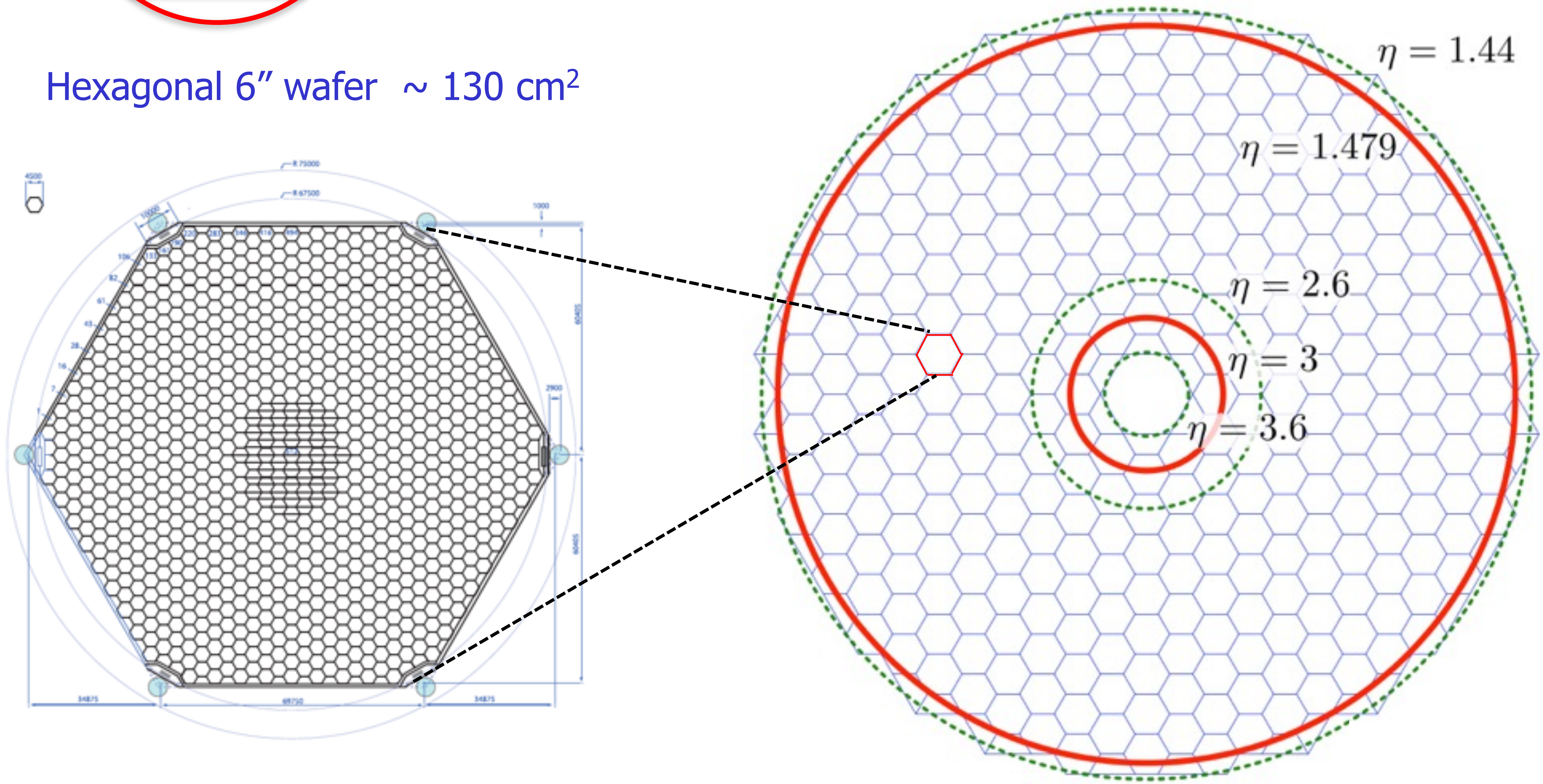
The HGCAL Cells Geometry



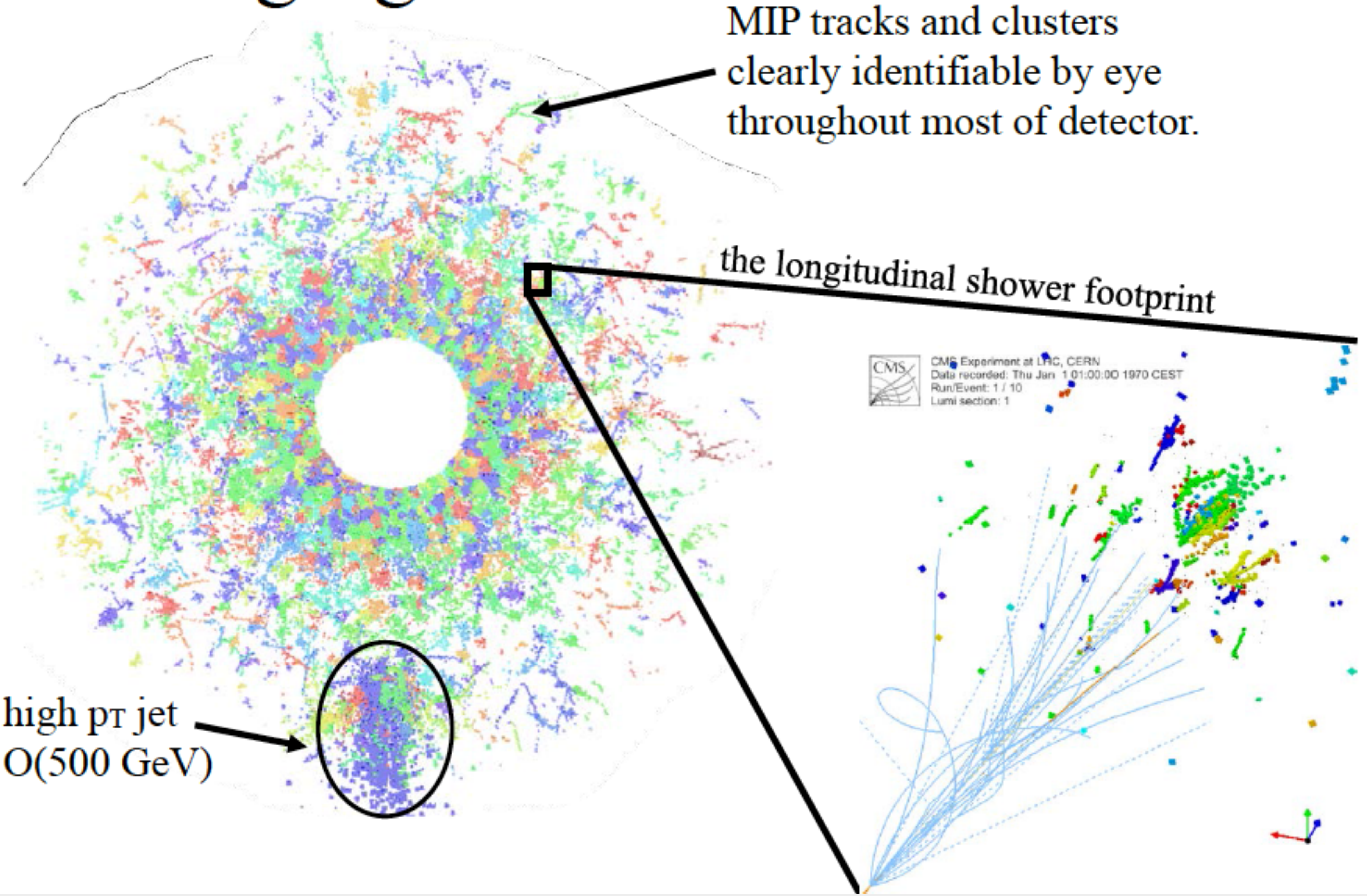
64/128/256 or 512
channels per wafers

~ 25k modules (wafers)
in tiled planes

Hexagonal 6” wafer ~ 130 cm^2

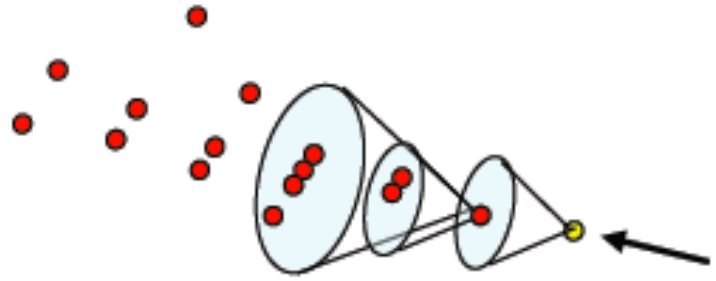


Imaging Showers with the HGC



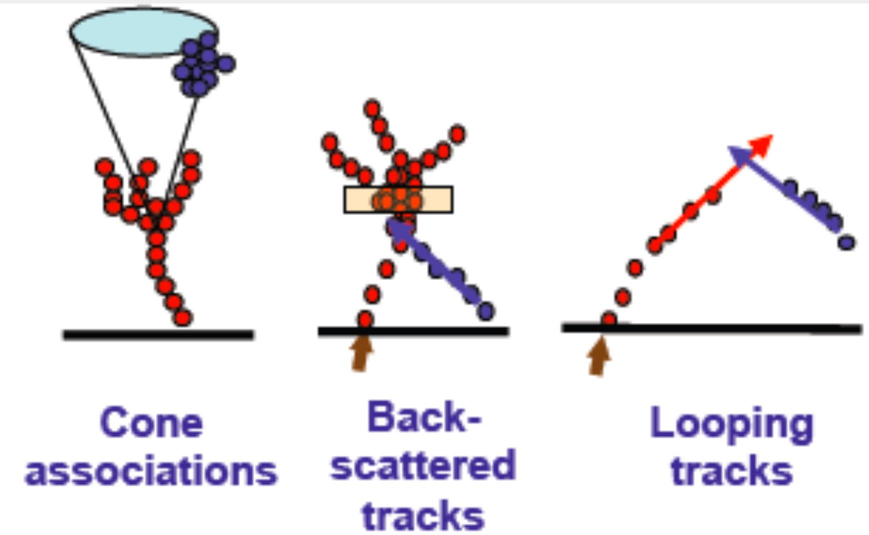
Particle Flow

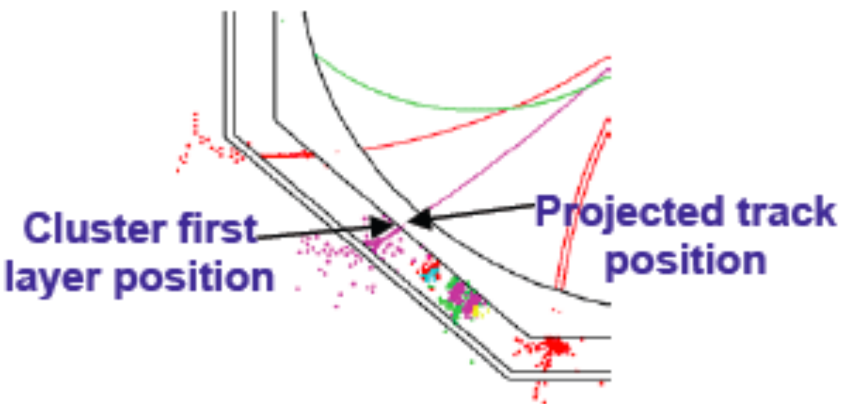
Mark Thomson



ConeClustering Algorithm

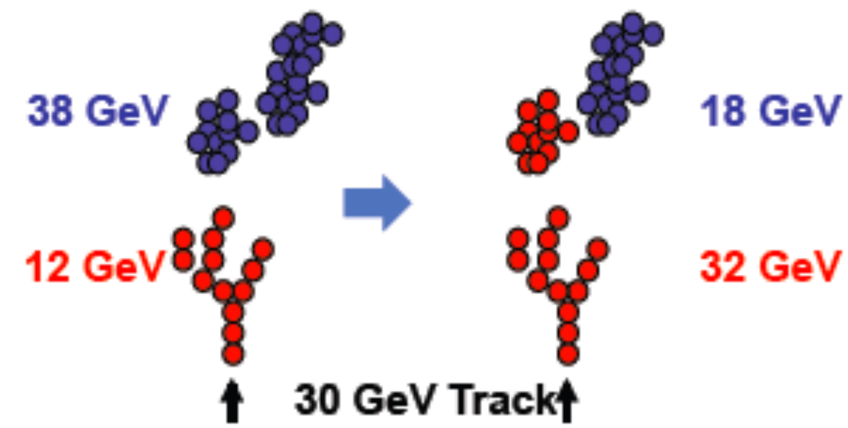
Topological Association Algorithms

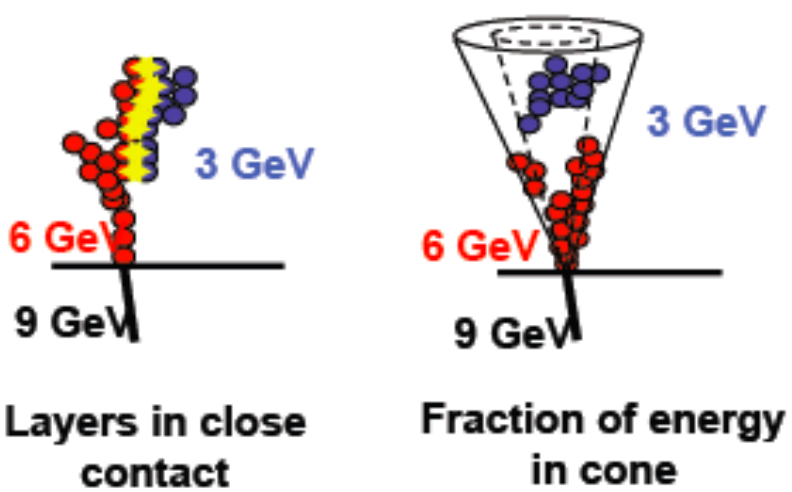




Track-Cluster Association Algorithms

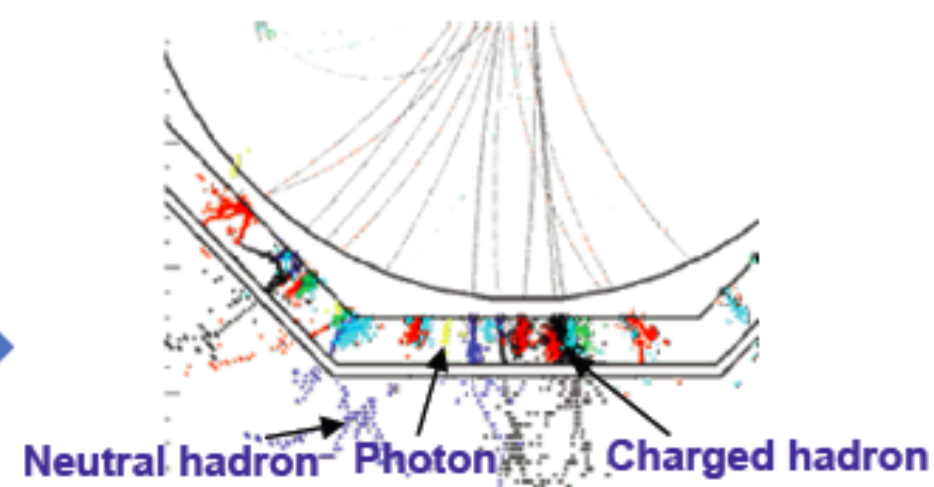
Reclustering Algorithms



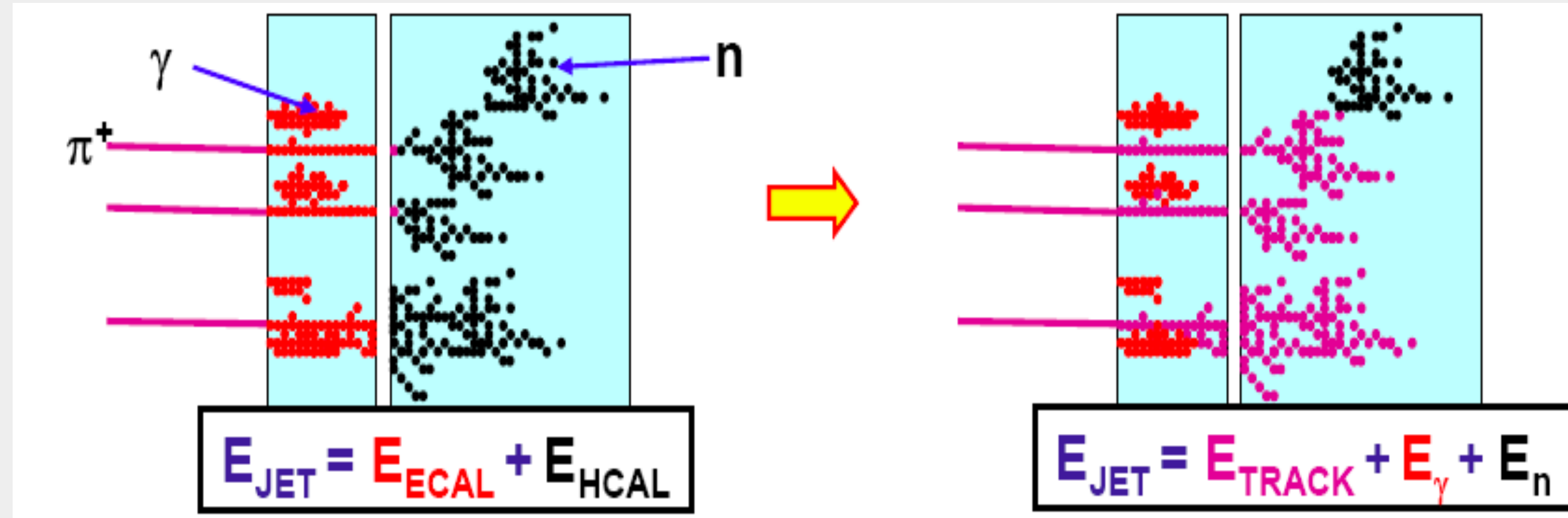


Fragment Removal Algorithms

PFO Construction Algorithms

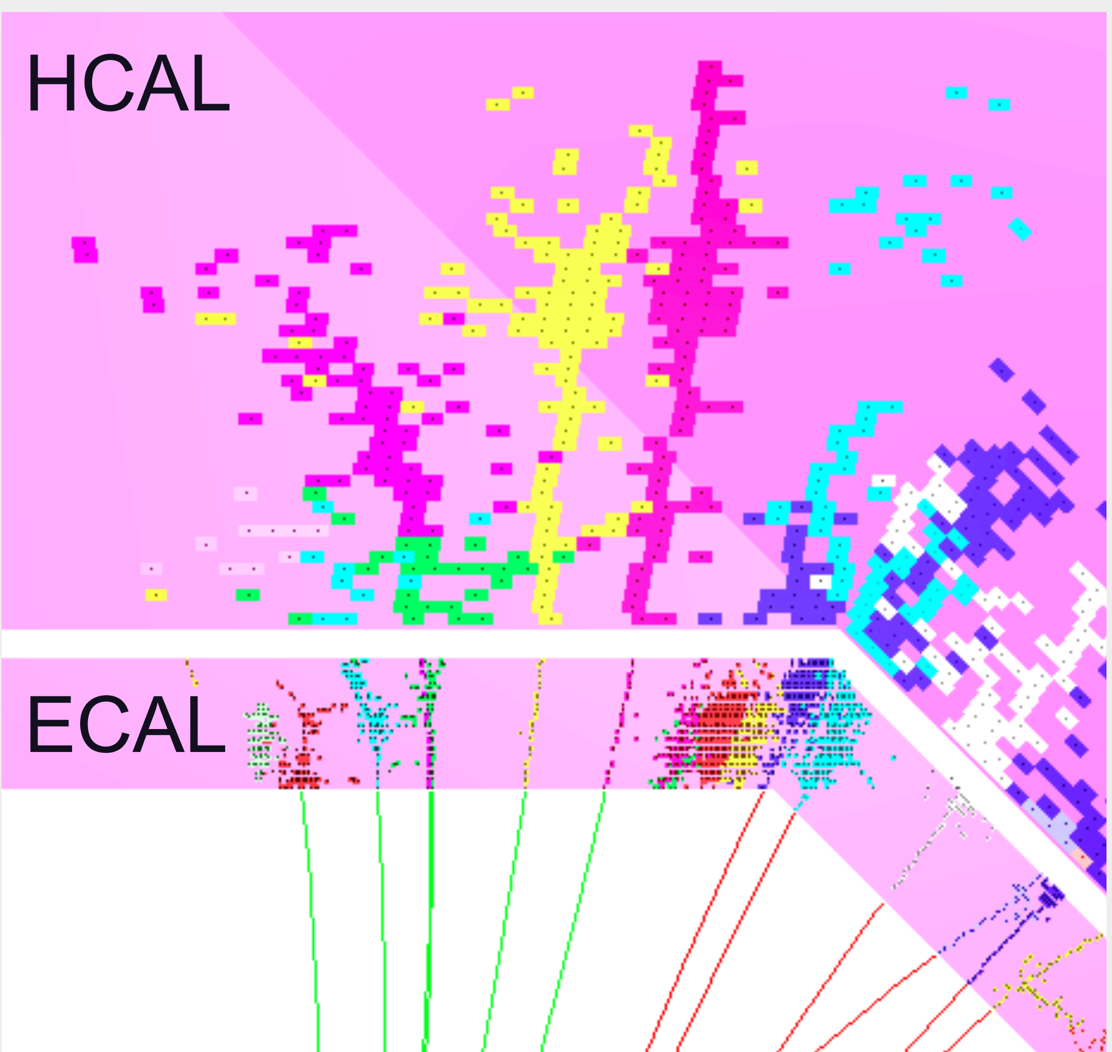


PF calorimetry (CALICE)



Design detectors for Pflow

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



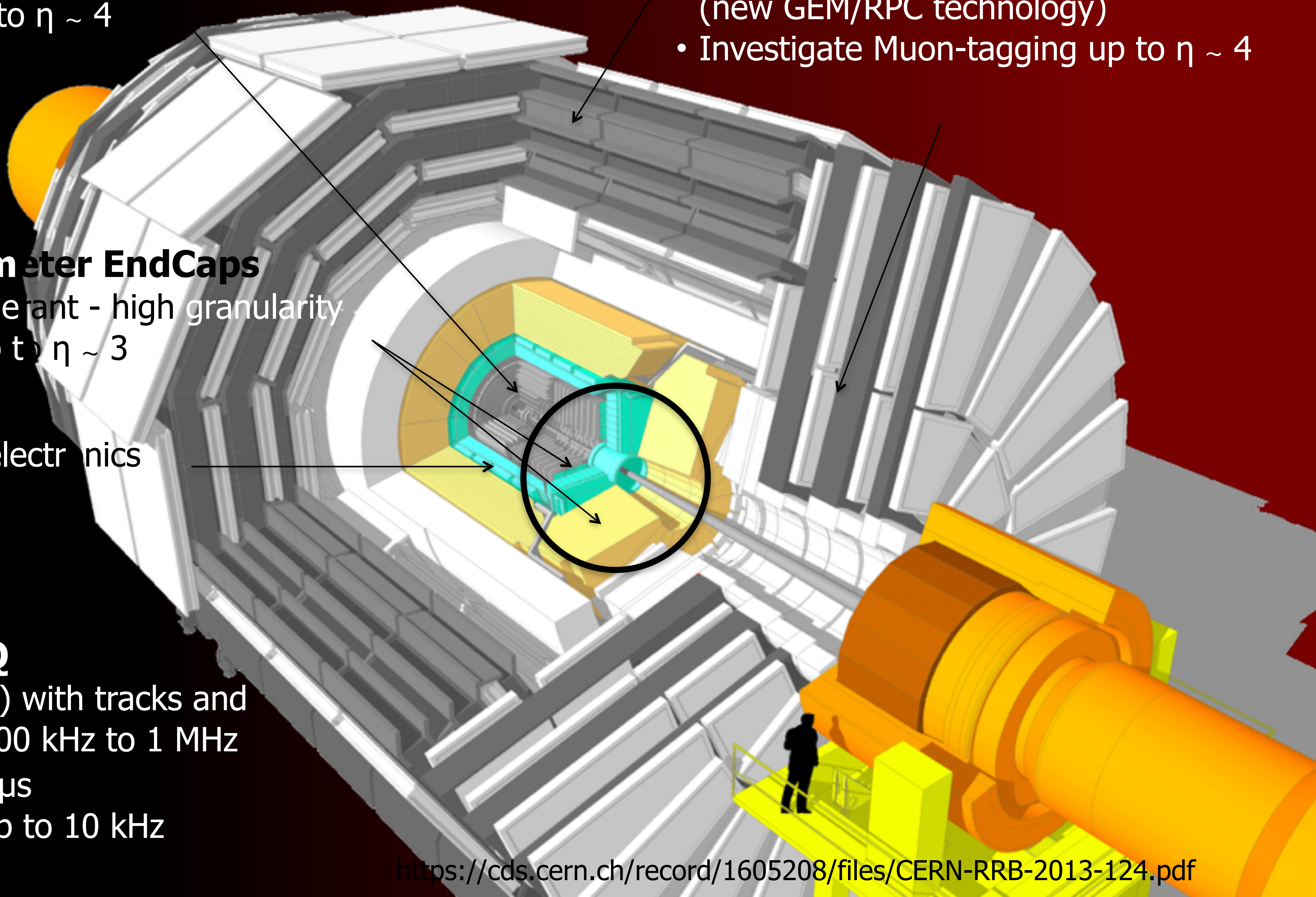
Two proto-collaborations for ILC (ILD and SLD)

- ECAL: Highly segmented S_IW 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



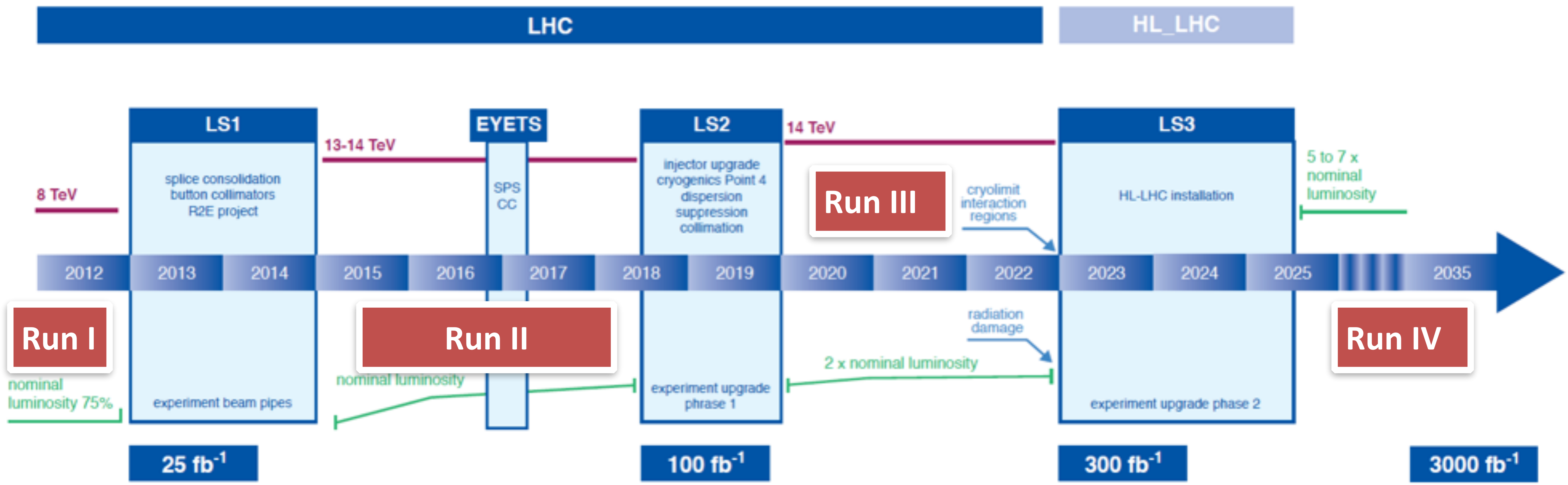
New Calorimeter EndCaps
- Radiation tolerant - high granularity
- Coverage up to η ~ 3

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

LHC / HL-LHC Plan



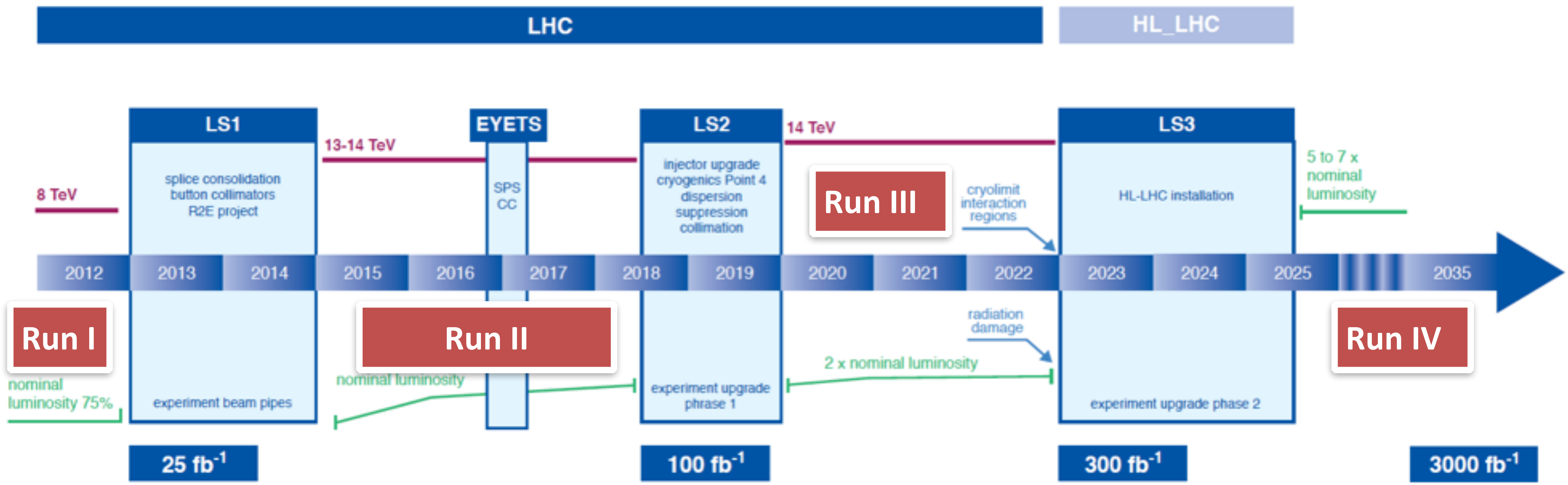
0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

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

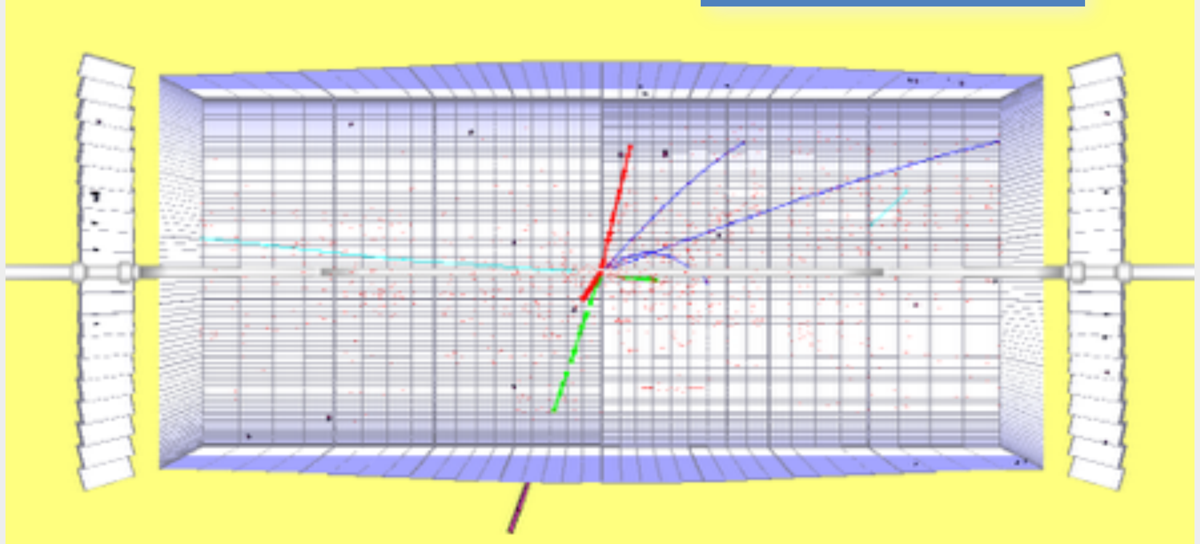
$1.7\text{-}2.2\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

$\sim5(7.5!)\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
pile up ~140 - 200

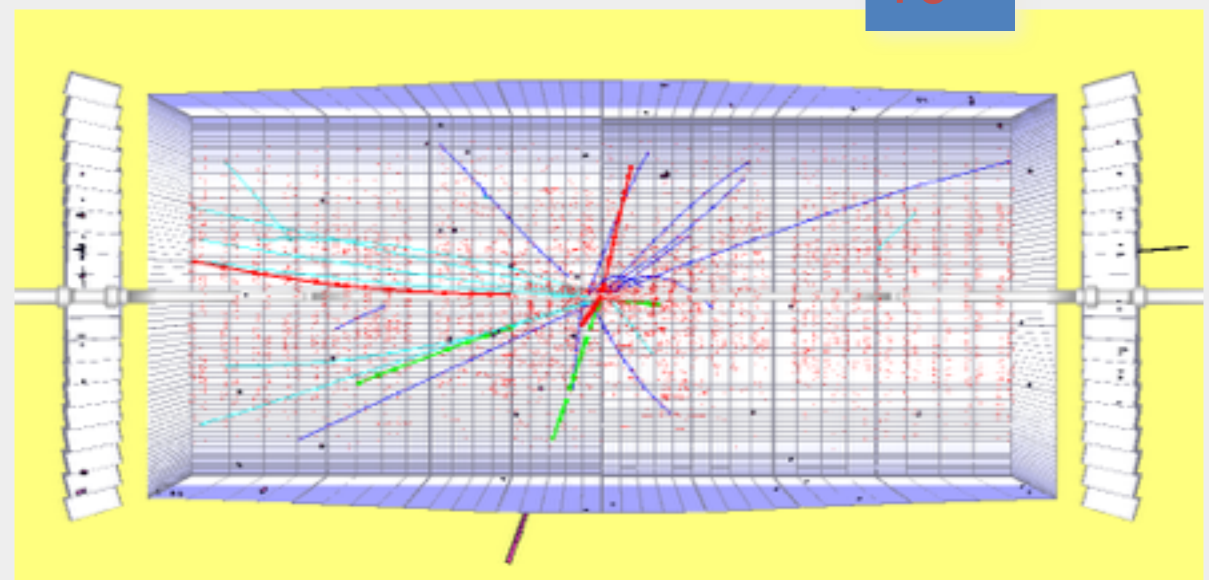
$50 \Rightarrow 25$ ns

Detector occupancy
The challenge from simulation ….

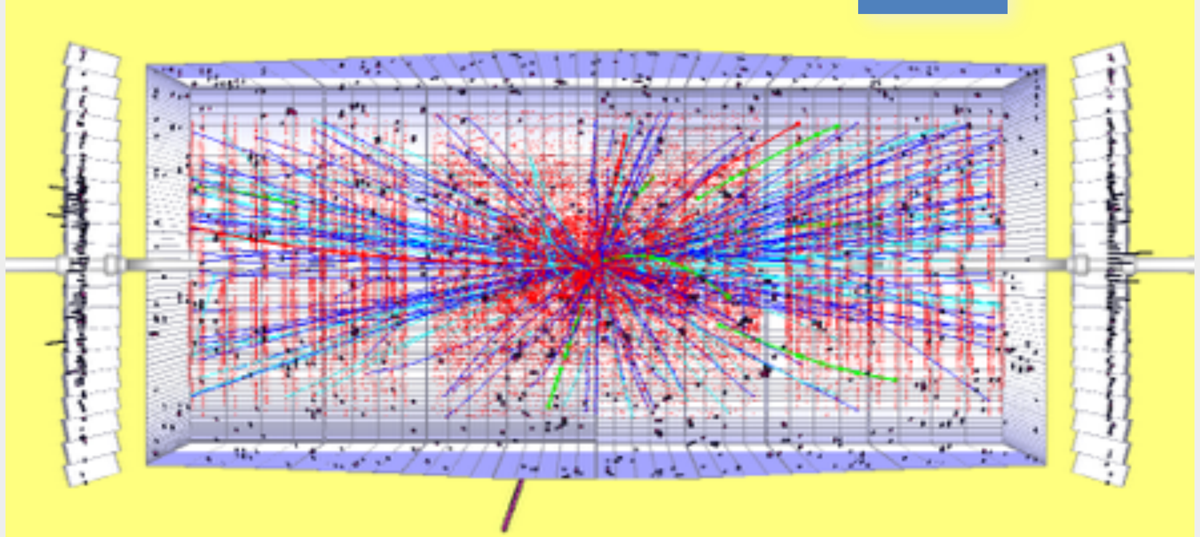
10^{32} cm^{-2} s^{-1}



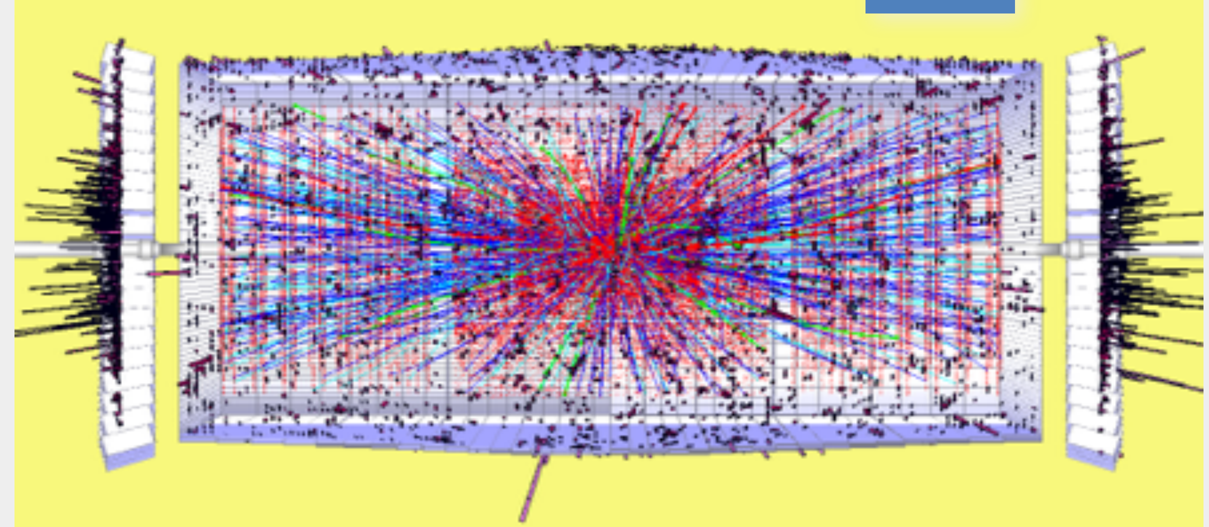
10^{33}



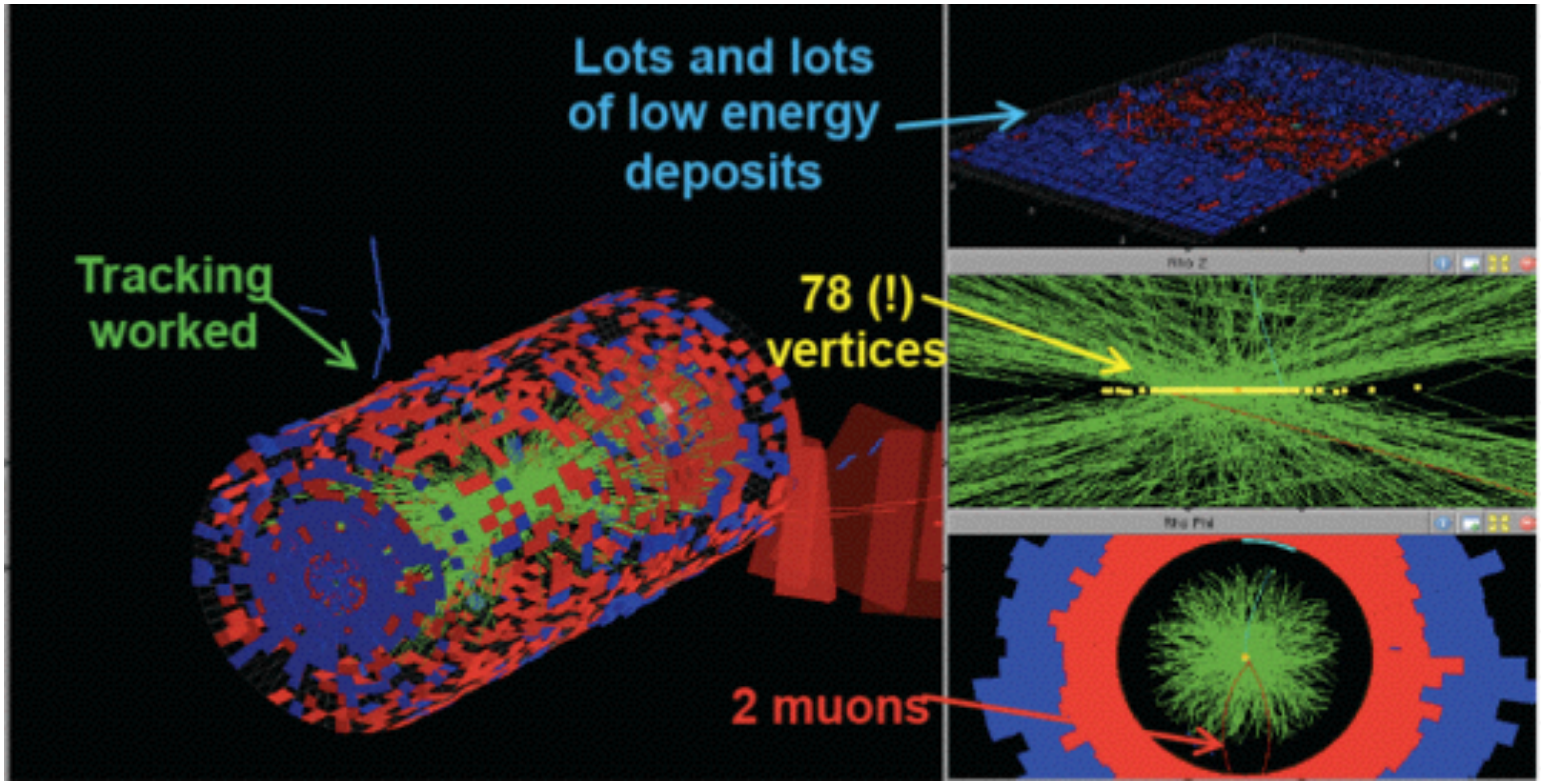
10^{34}



10^{35}



… and reality



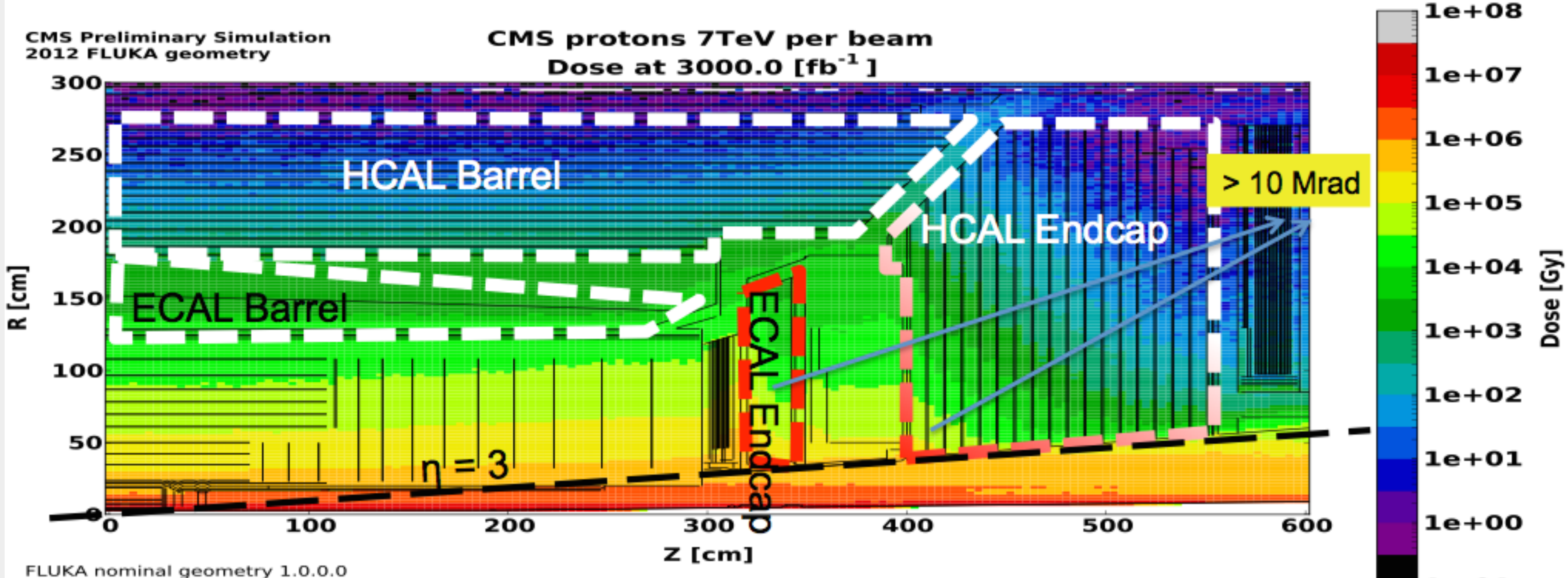
Extreme conditions for:

- radiation
- pileup
- Trigger / DAQ
- Data handling

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

PHASE 2 - Concequence of Radiation and Pile-up environment

– Radiation six times higher than nominal LHC design
– 5(7)E34 Hz/cm^2 → ~ 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**

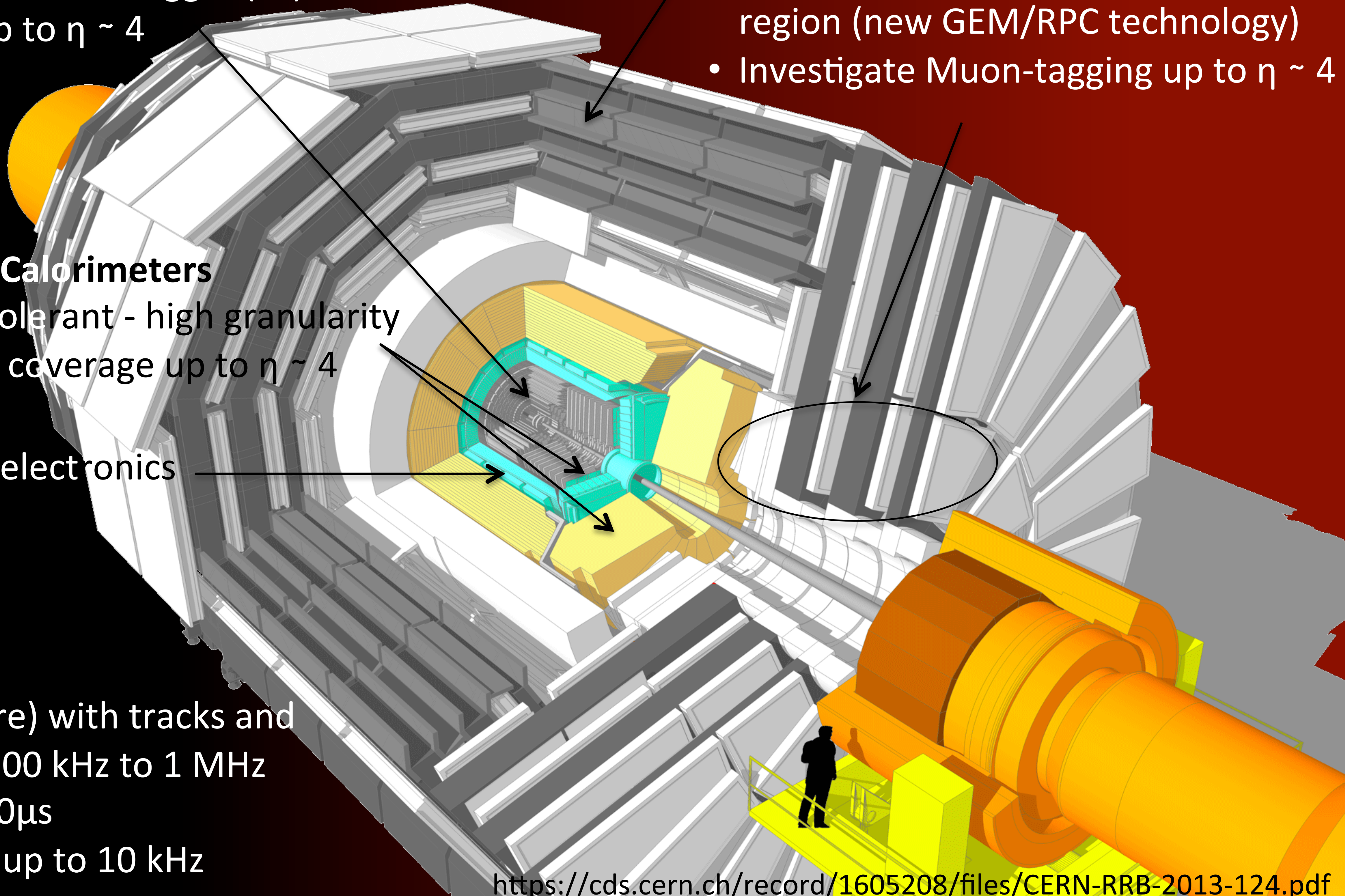
CMS Upgrades for HL-LHC

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

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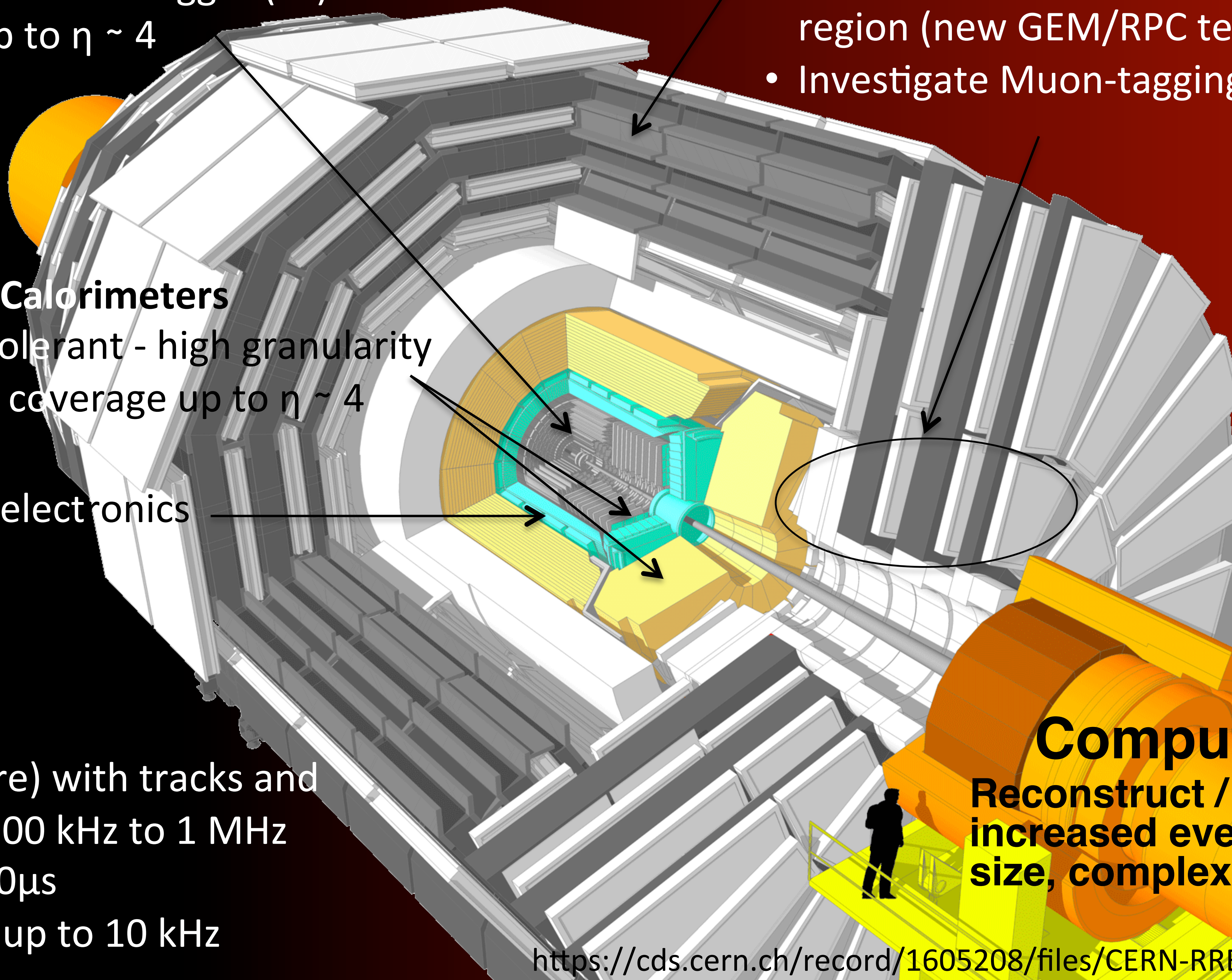

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- Replace FE electronics

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

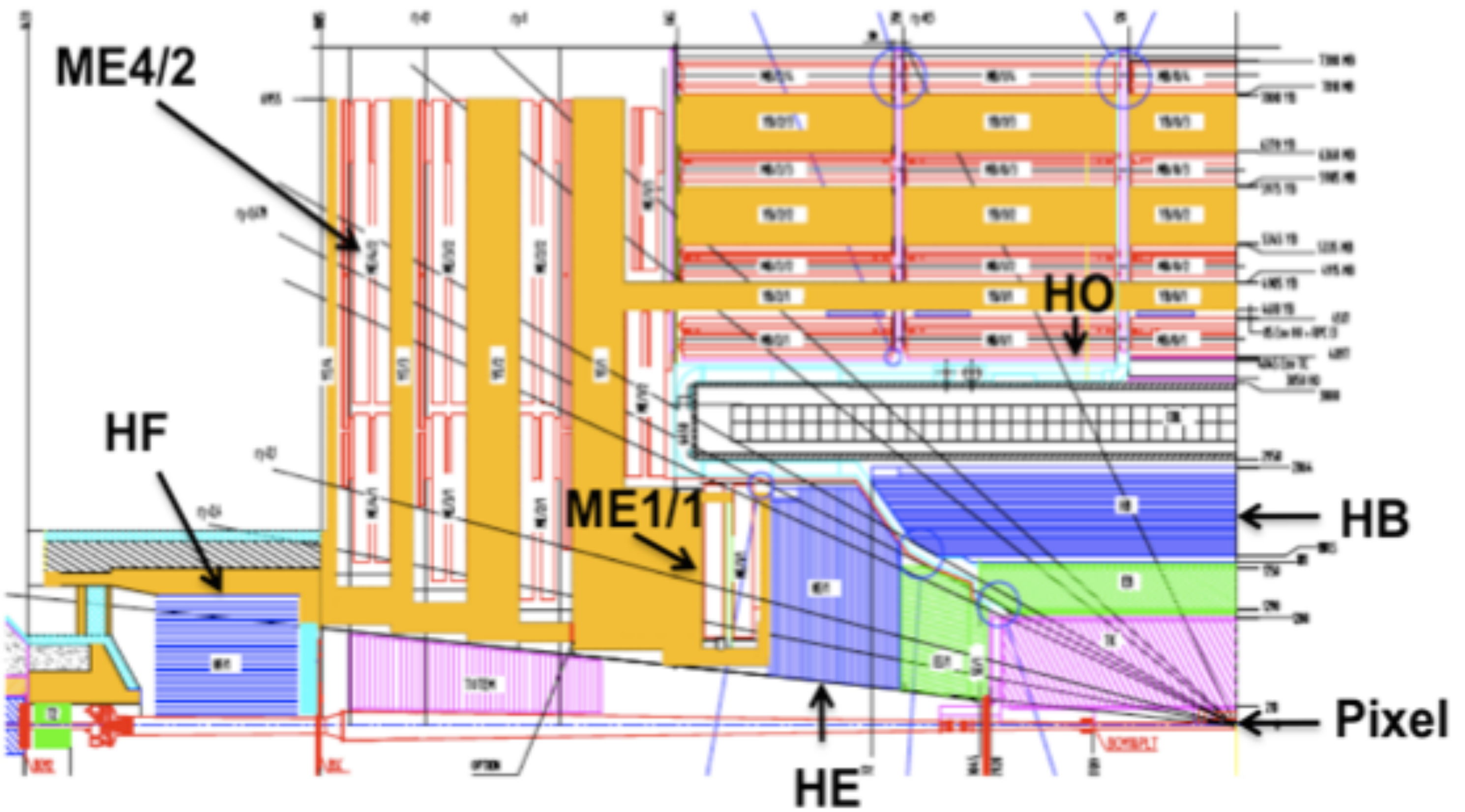
https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

Phases of the CMS upgrade

LS1 Projects: in production

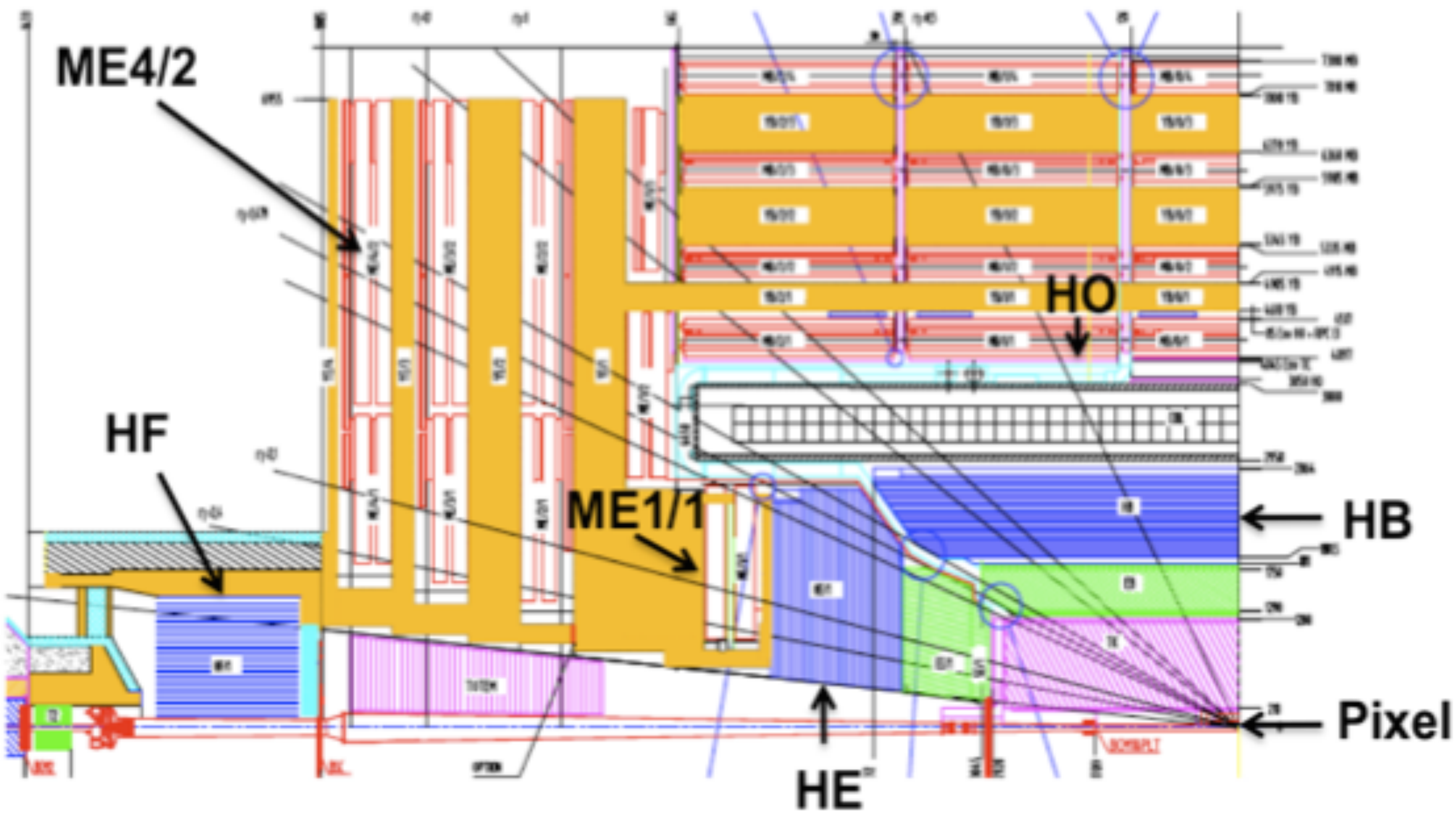
Now

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



LS1 LS2 LS3

Phases of the CMS upgrade



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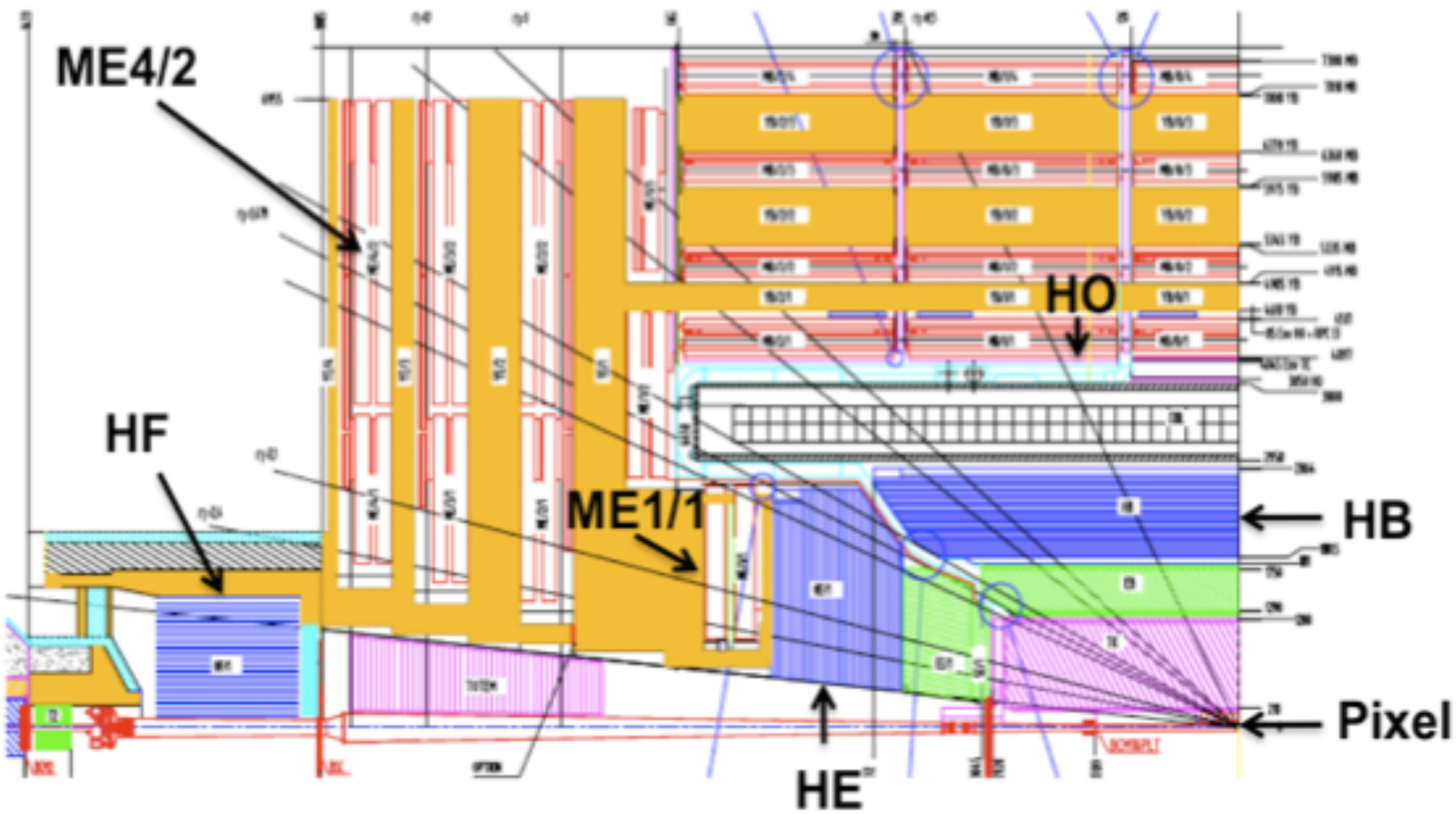
- DAQ1 → DAQ2

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*

LS1 LS2 LS3

Phases of the CMS upgrade



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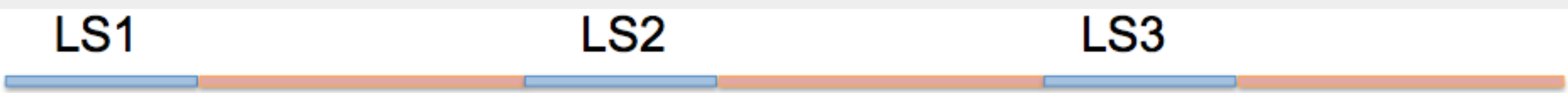
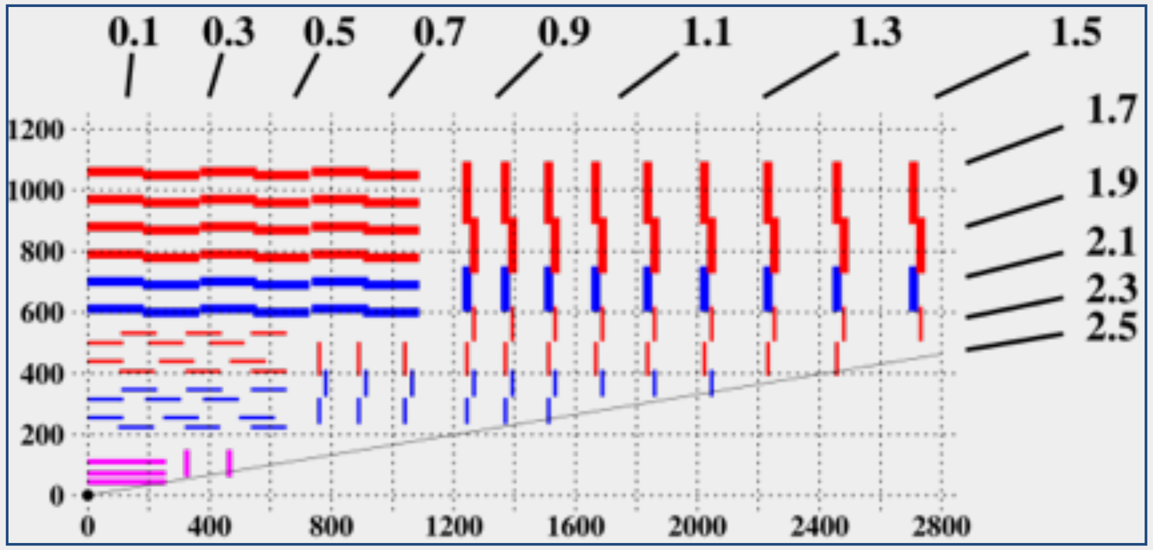
  - New beam pipe
  - Install test slices (*Pixel (cooling), HCAL, L1-trigger)*
  - Install ECAL optical splitters
    - *L1-trigger upgrade, transition to operations*

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

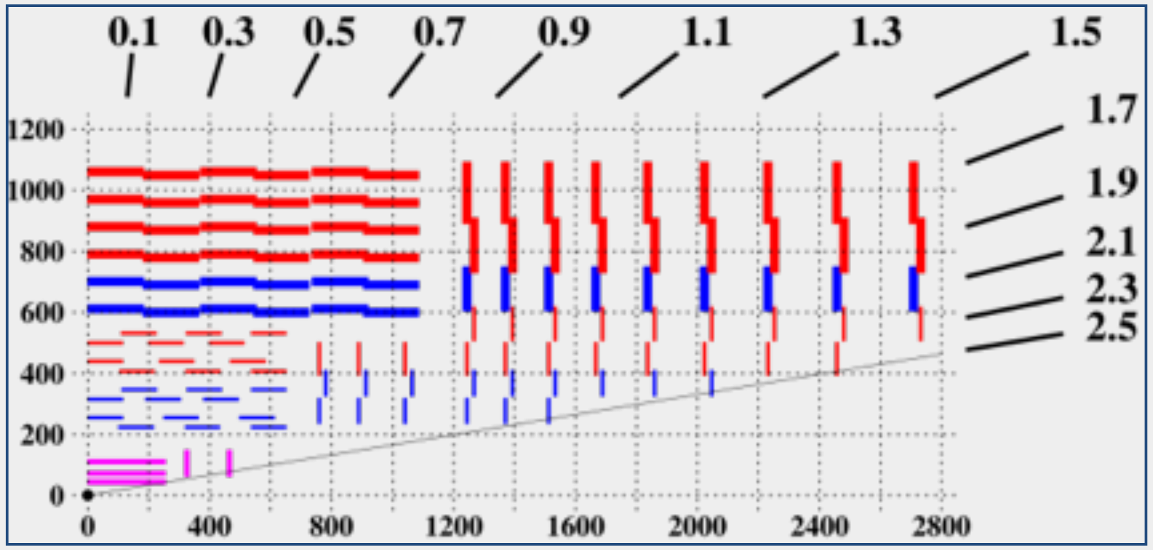


From Current to Phase 2 Tracker



Current CMS Silicon Tracker

From Current to Phase 2 Tracker



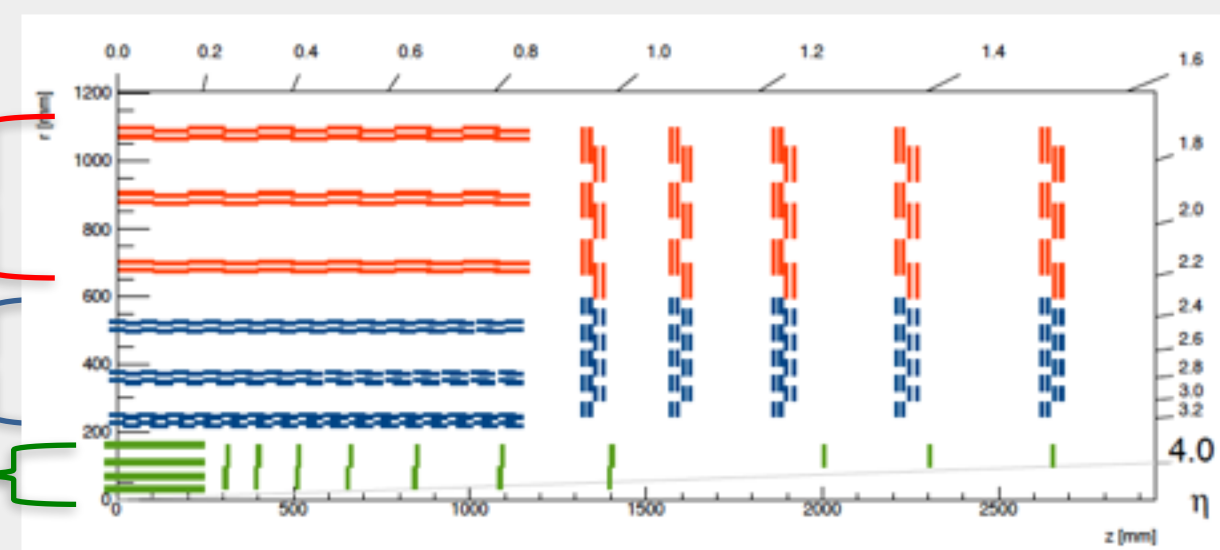
Current CMS Silicon Tracker

Proposed CMS Phase 2 tracker for 2015

Strip/Strip modules SS
(pairs of strip sensors)

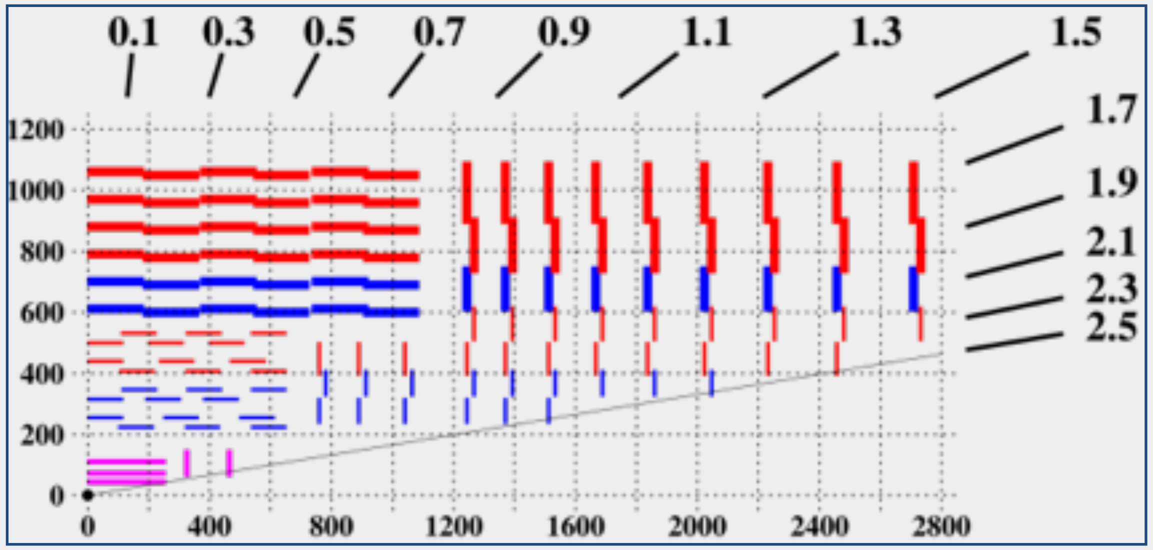
Strip/Pixel modules PS

Pixel modules



Inner Tracker, new
Disks to η=4

From Current to Phase 2 Tracker

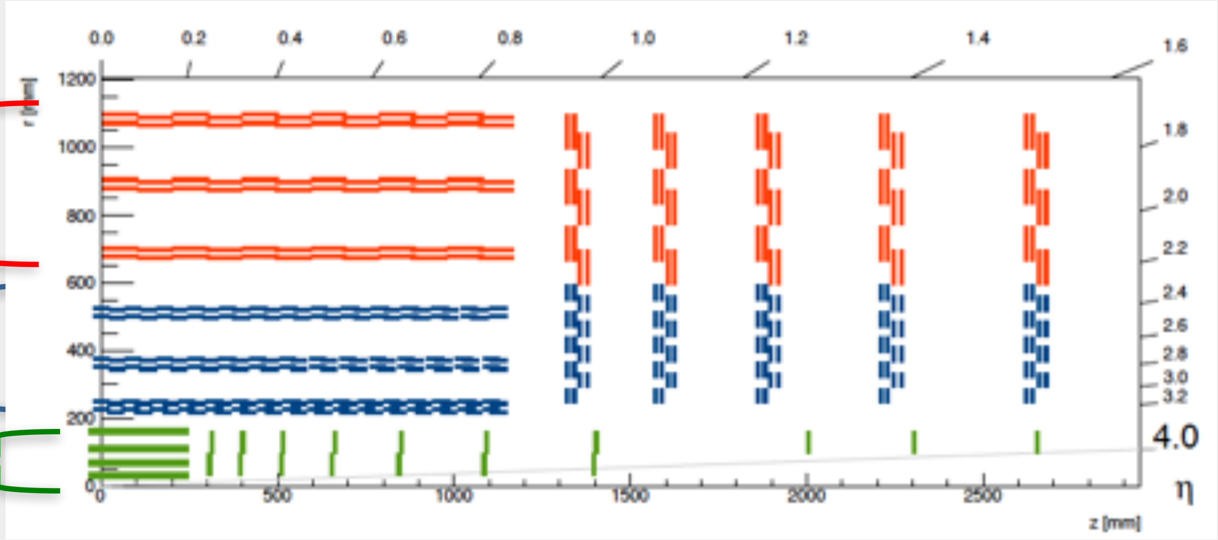


Current CMS Silicon Tracker

Requirements

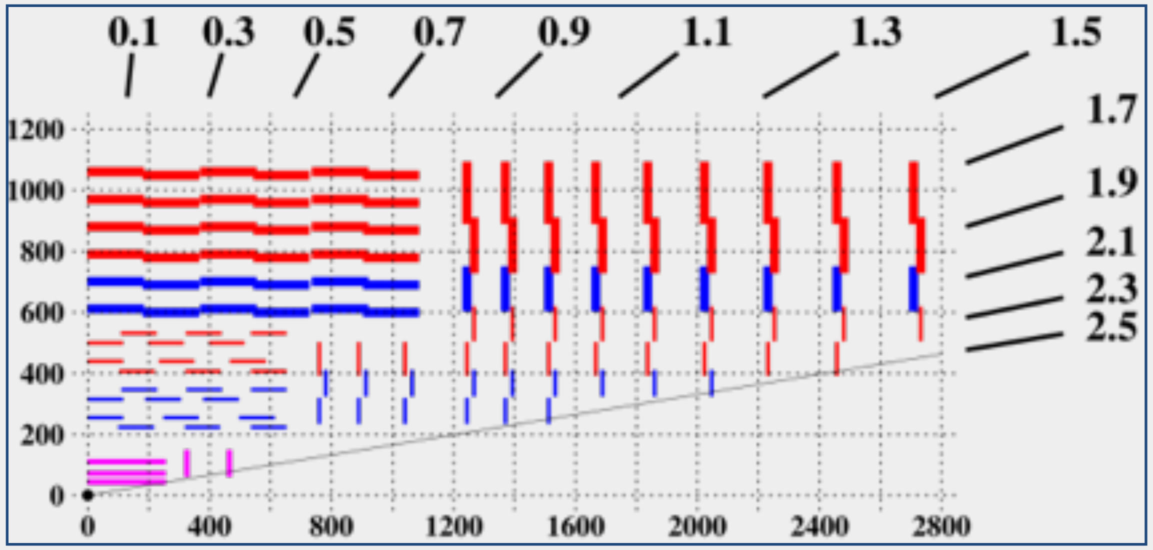
- Radiation tolerance
- Increased granularity
- Improved 2-track separation
- Reduced material
- Robust pattern recognition
- Support for L1 trigger upgrade
- Extended tracking acceptance

Proposed CMS Phase 2 tracker for 2015

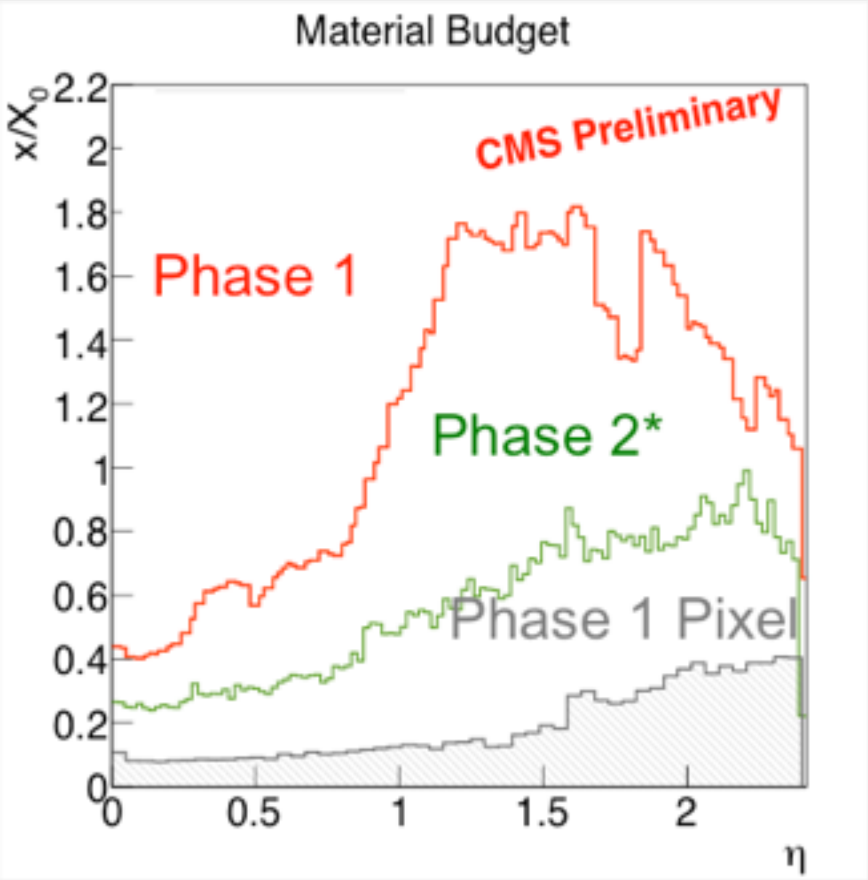


Inner Tracker, new Disks to η=4

From Current to Phase 2 Tracker



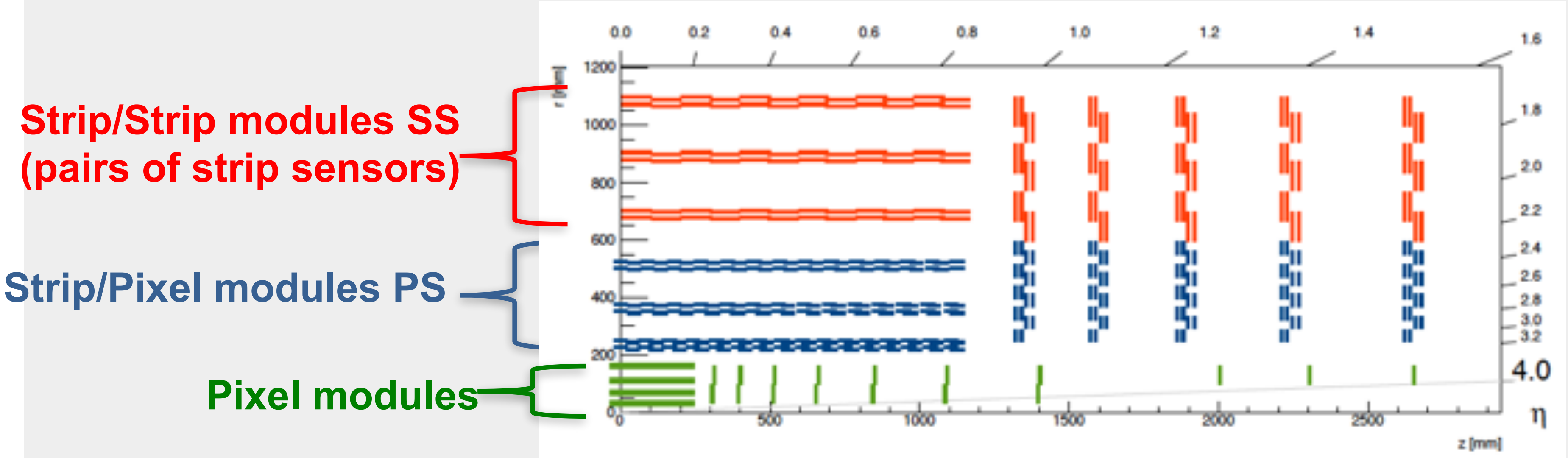
Current CMS Silicon Tracker



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

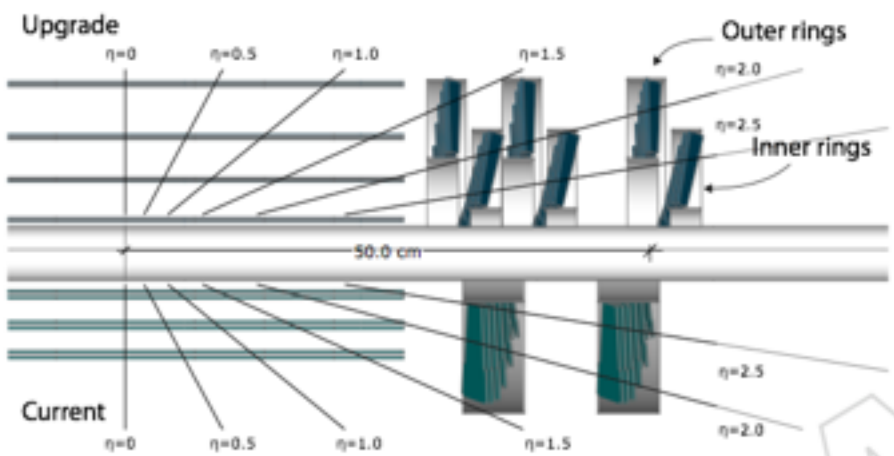


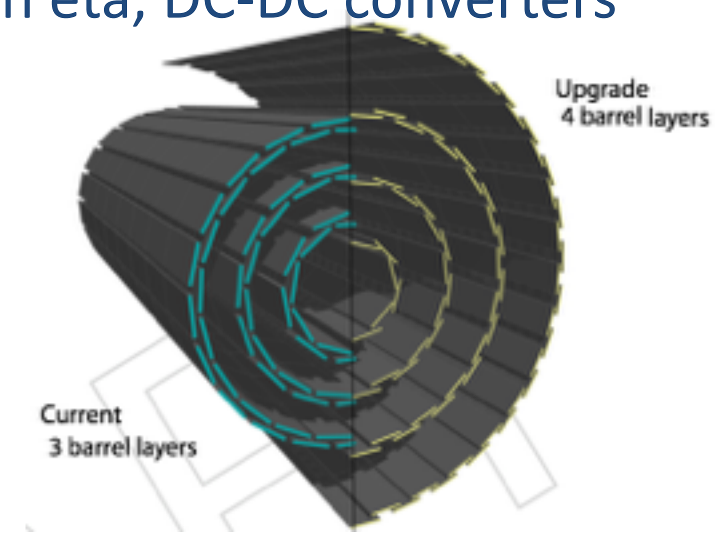
Inner Tracker, new Disks to η=4

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





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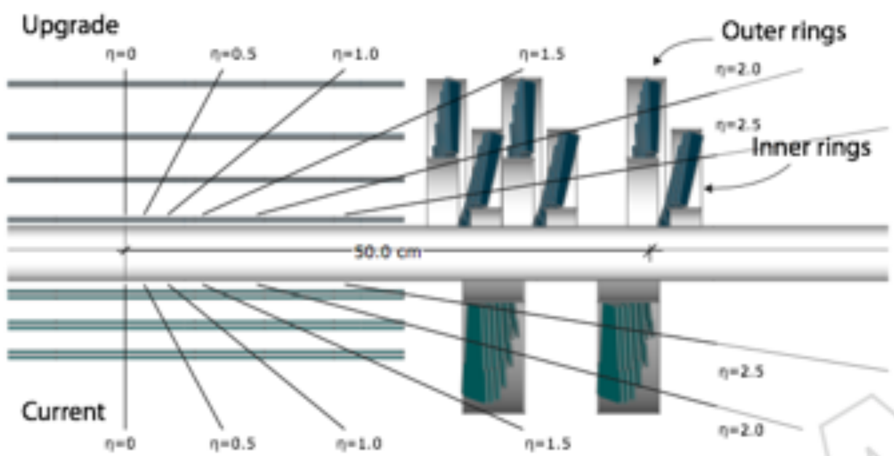
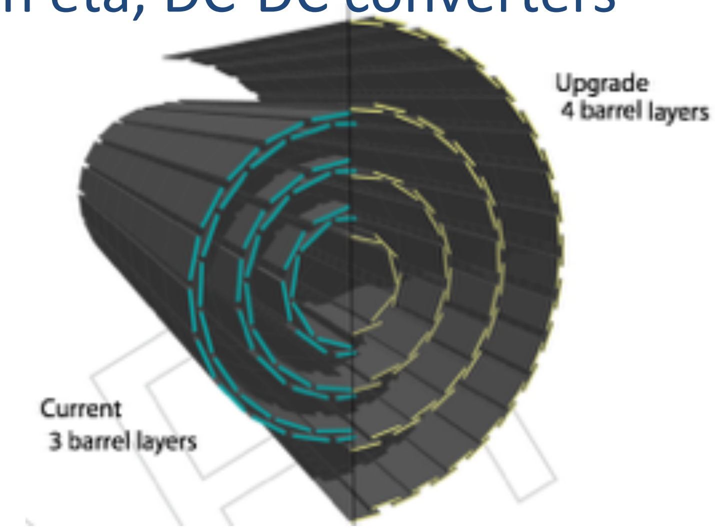


Will be installed (2016-2017)



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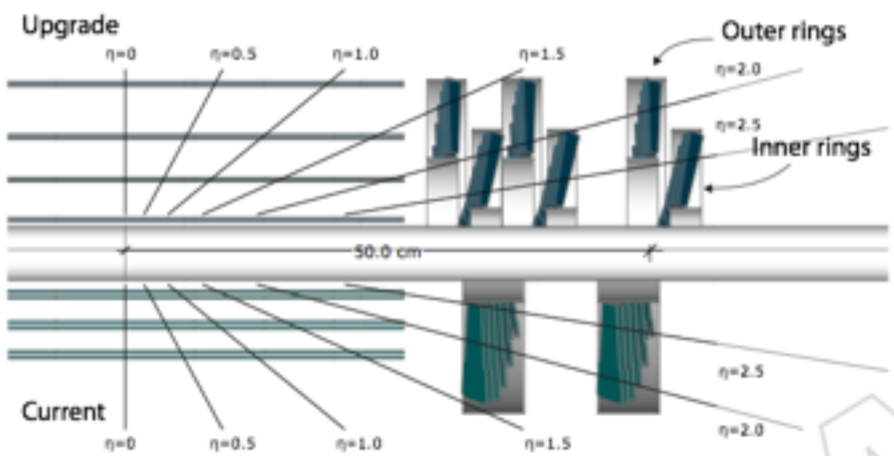

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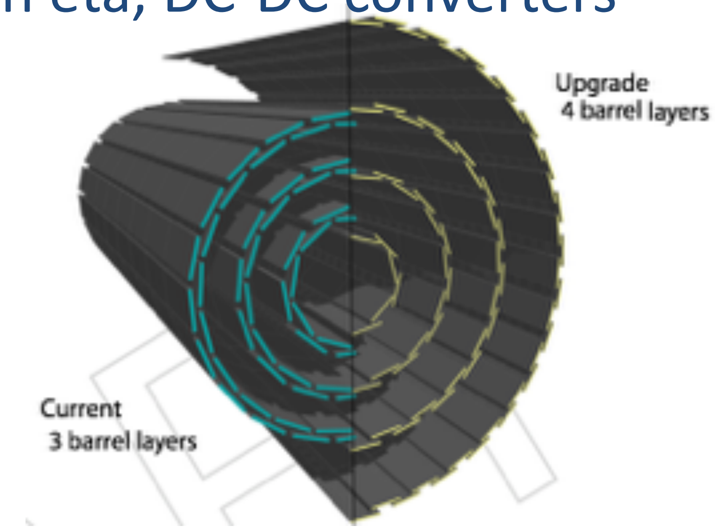
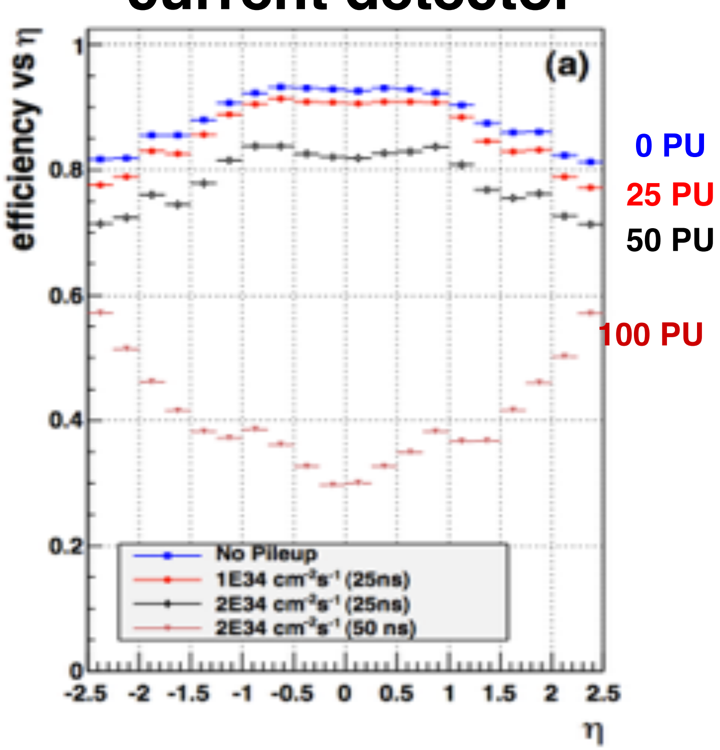
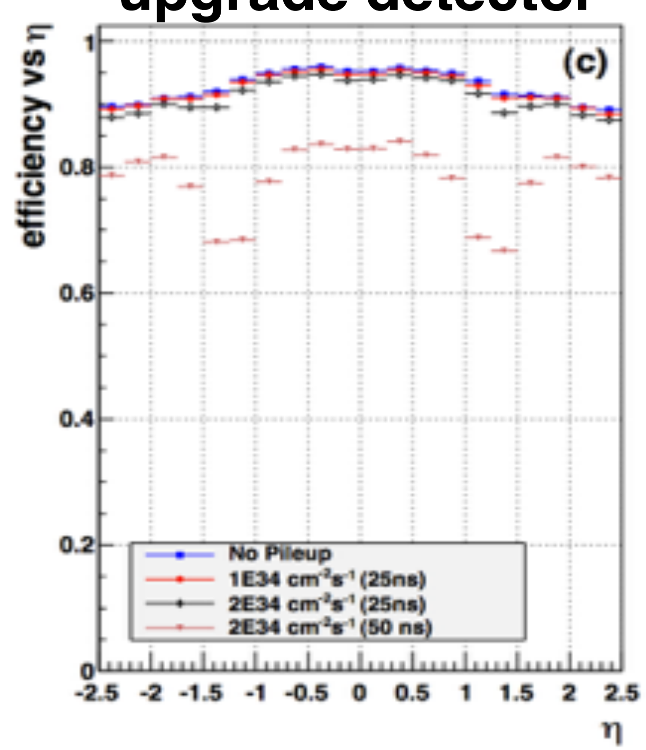


current detector



upgrade detector



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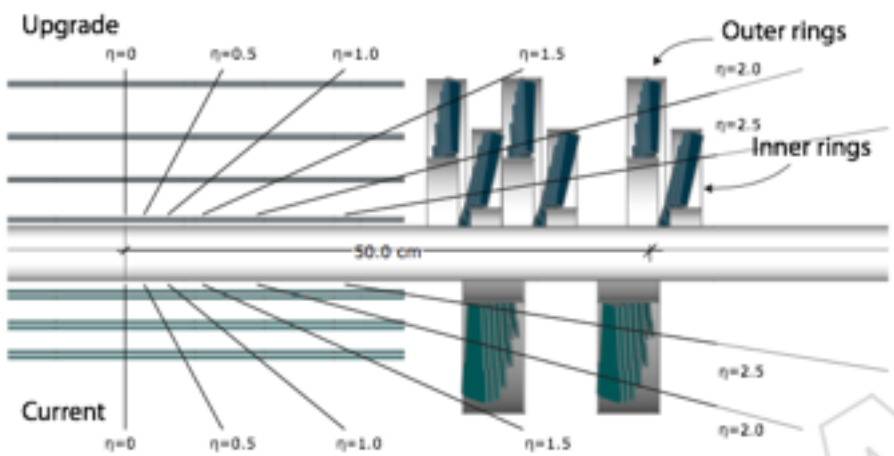

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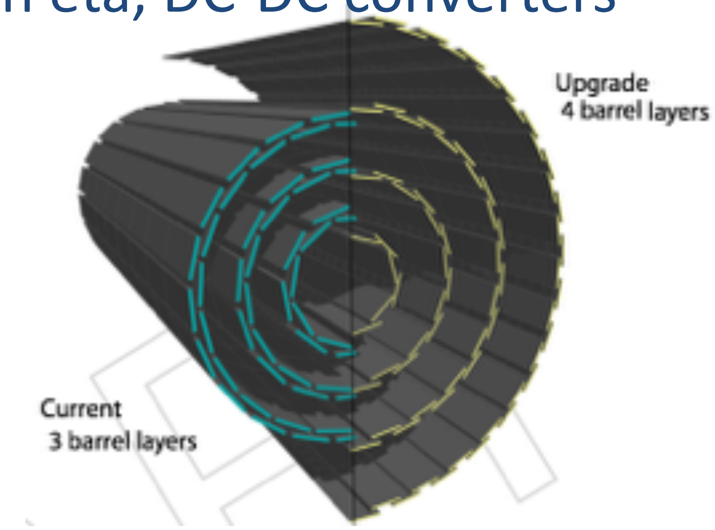

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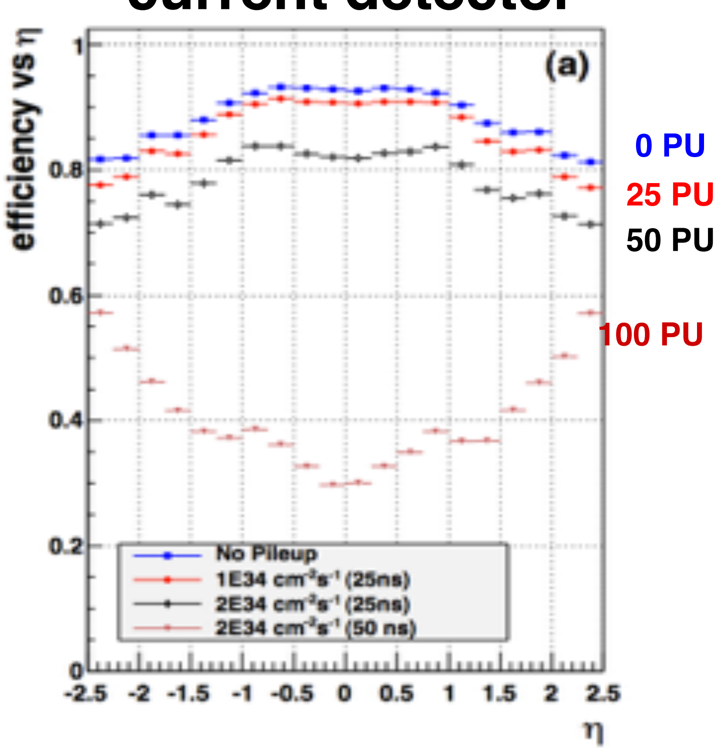

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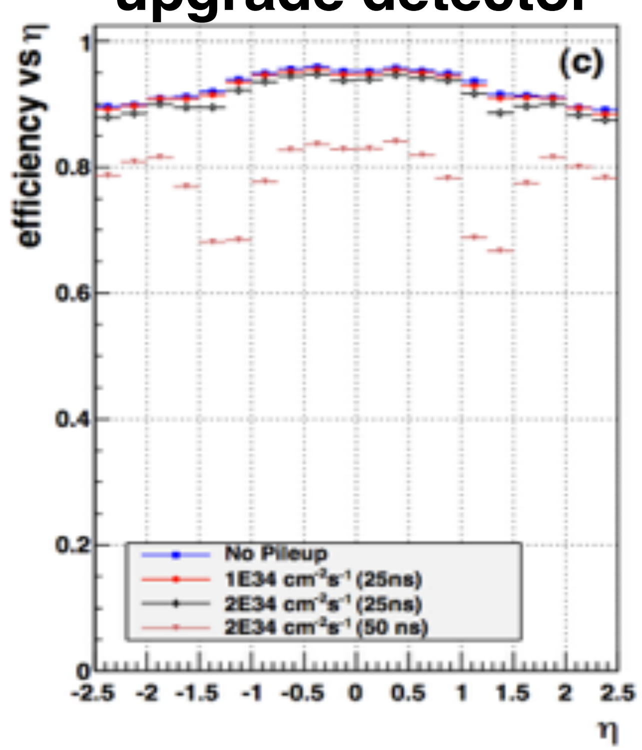


Using same Higgs selections as 2012

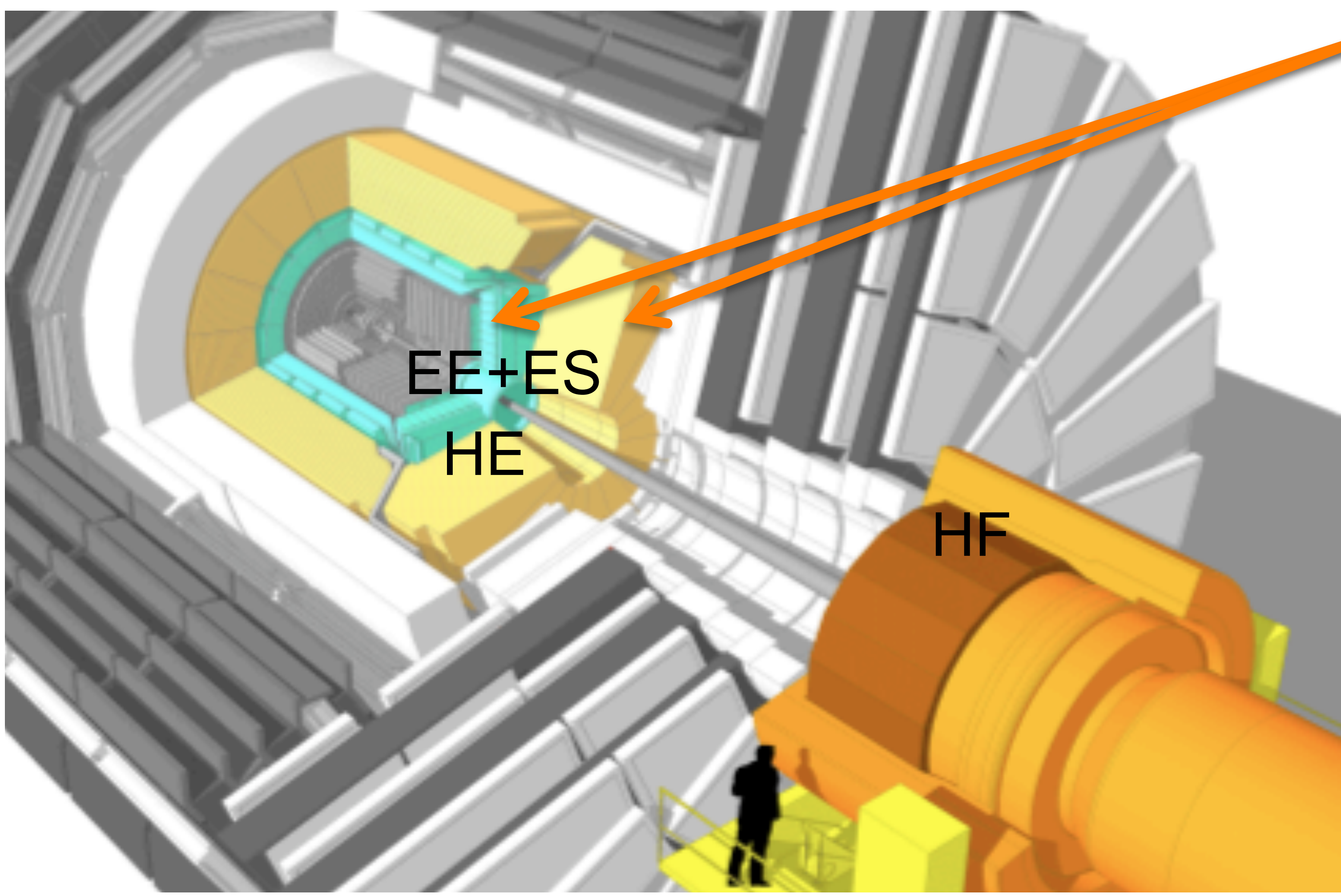
Significant gain in signal reconstruction efficiency:

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)

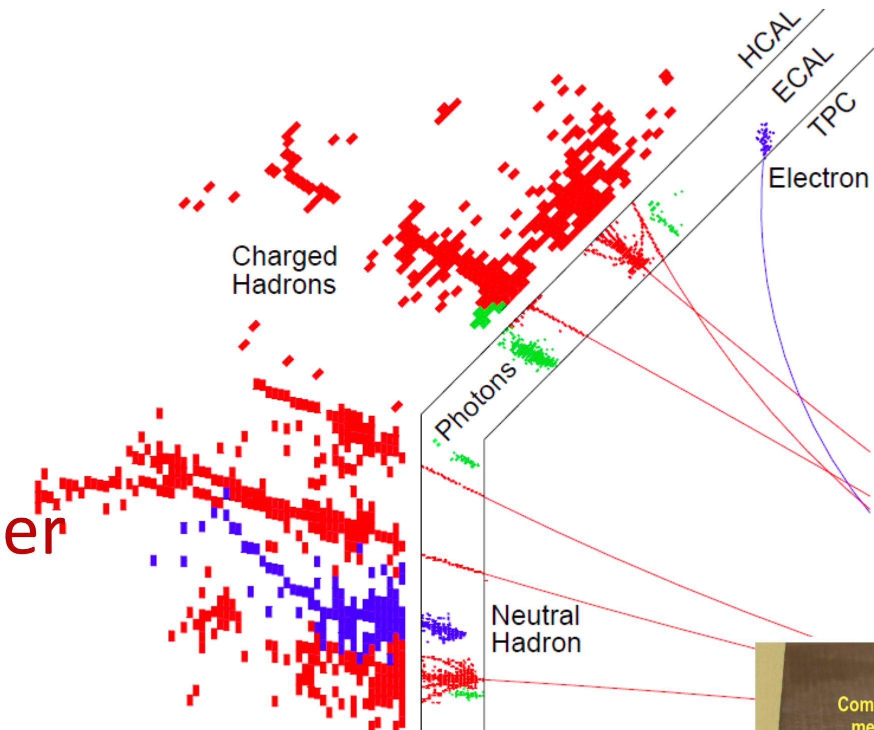
- High Granularity Calorimeter
  - Fine depth segmentation

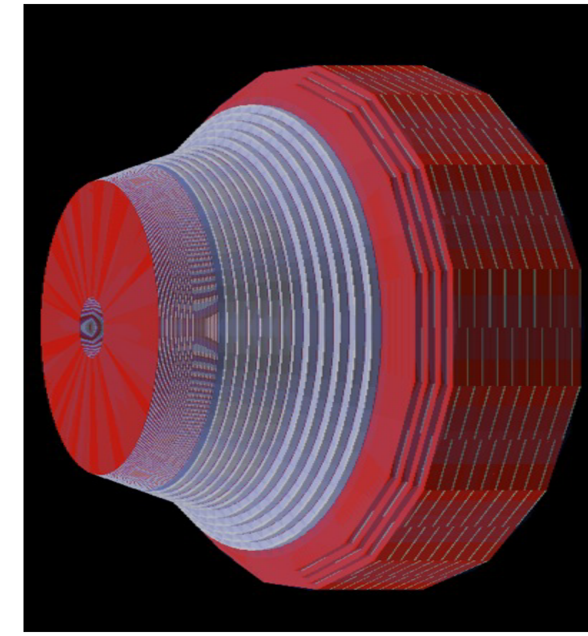
    ECAL: ~33 cm, 25 X_0, 1 λ

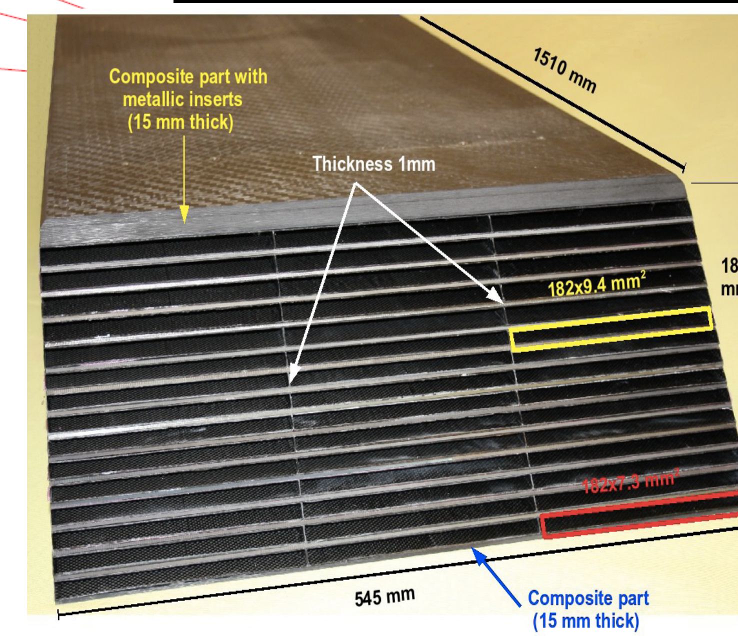
    30 layers Si separated by lead/Cu

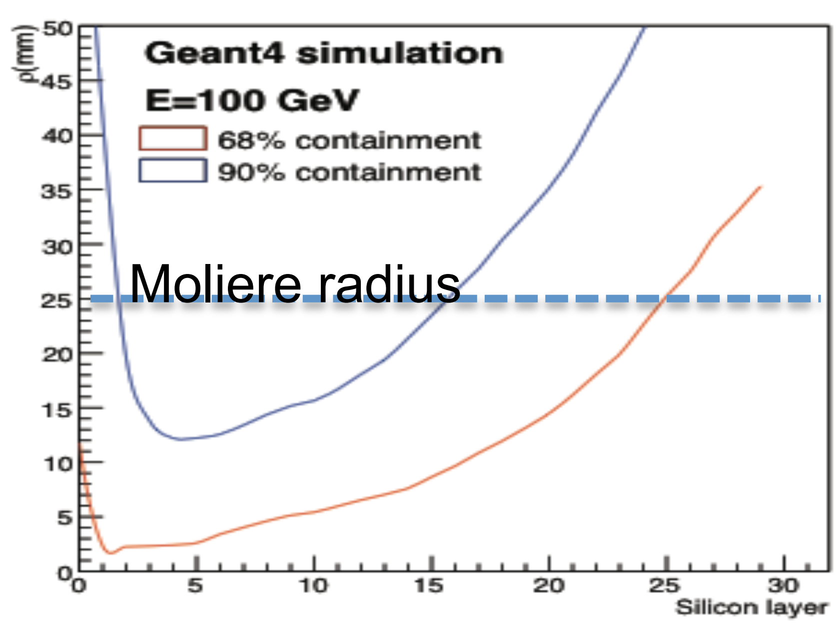
    HCAL: ~66 cm, 3.5 λ

    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



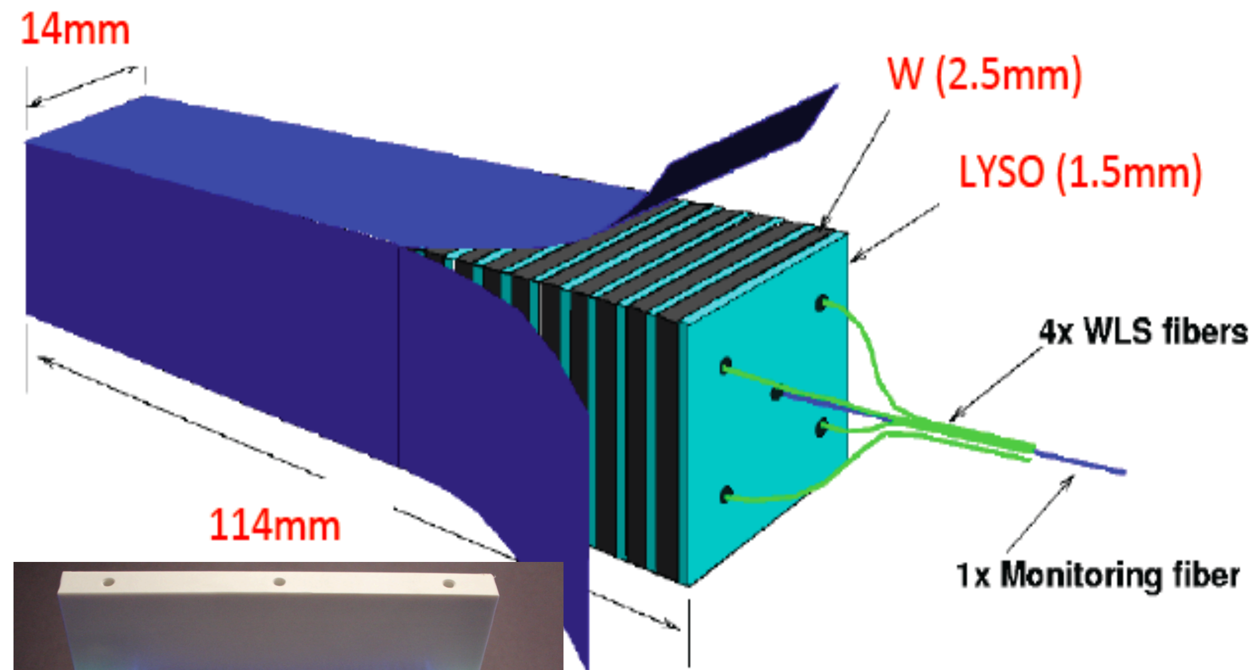


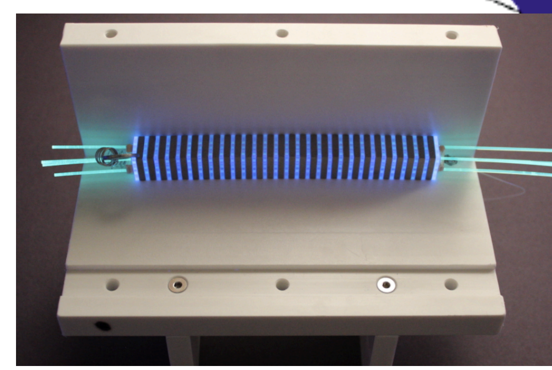


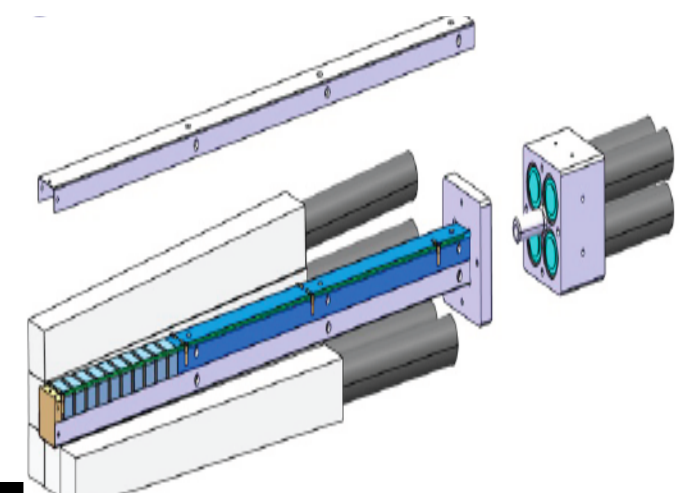


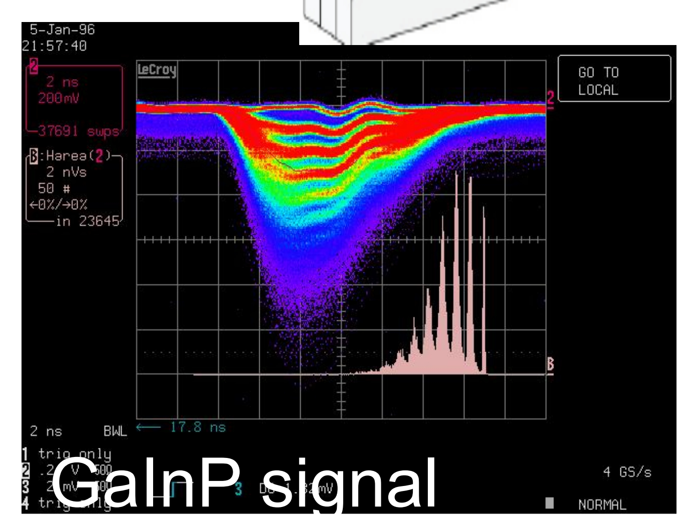
EE Shashlik – Test beam ongoing

- 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









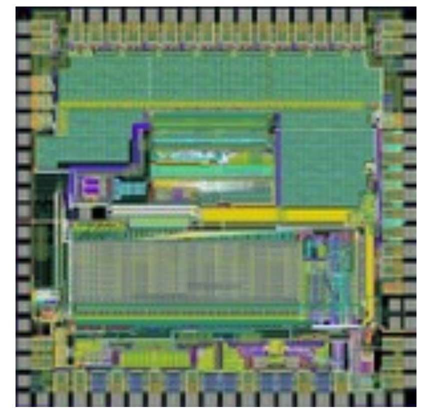
CMS HCAL Read-Out Upgrades

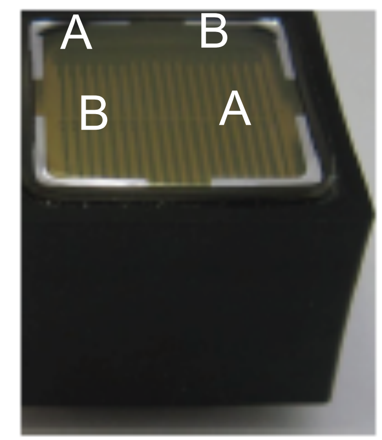
Installation during LS1(HO)/LS2(HB/HE)

Installation during LS1

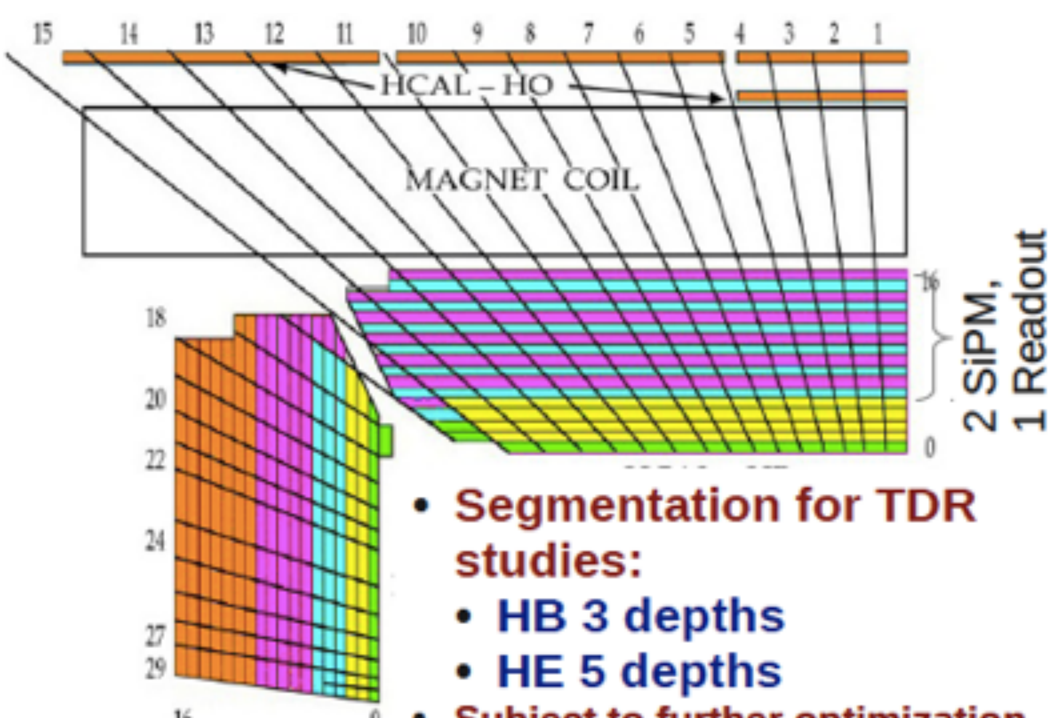
HB/HE/HO
From HPD to SiPM's

HF
From single to multi-anode PMT's

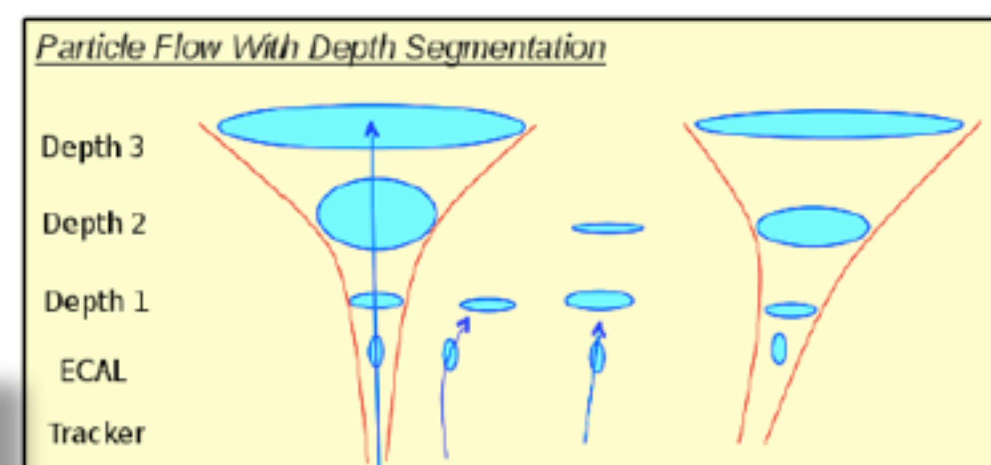




- Use SiPM's to increase HB/HE Depth Segmentation
- Improved PF Hadronic shower localization
- Provides effective tool for pile-up mitigation at high luminosity
- Mitigate radiation damage to scintillator & WLS fibers



- Segmentation for TDR studies:
  - HB 3 depths
  - HE 5 depths
- Subject to further optimization



Depth segmentation: mitigate high pileup

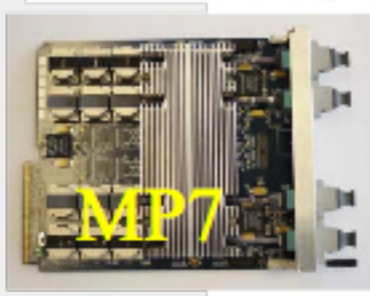
Level - 1 Trigger upgrade

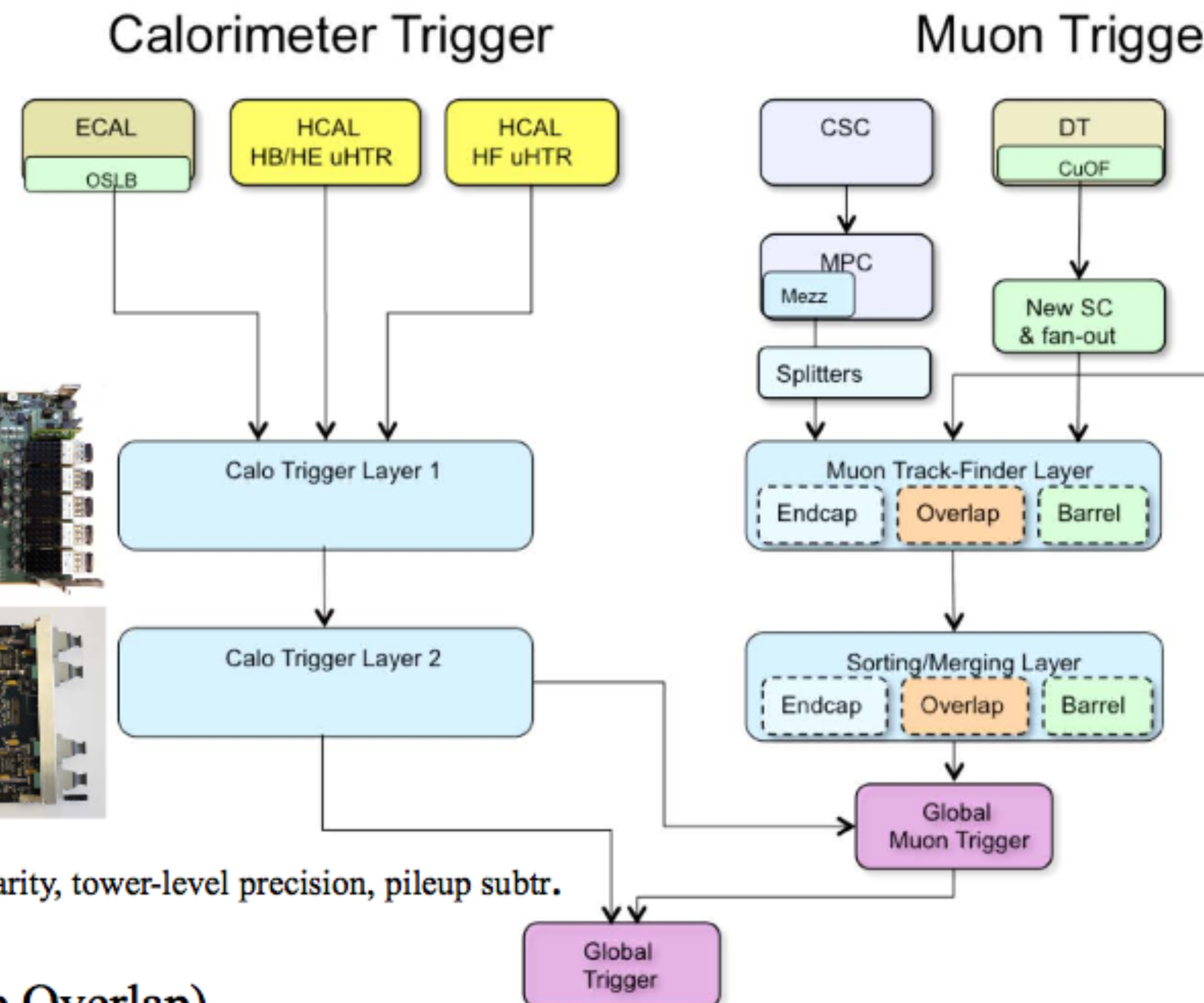
CERN-LHCC-2013-011
(CMS-TDR-012)

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%

Conclusion

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Credit to :
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- ***Missing in my lecture : Photon detectors, scintillators, Cherenkov light detector (see in my Backup slides)***

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Computing behind this all…

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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

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in Instrumentation in High Energy Physics, ed. F.Sauli (1992)

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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

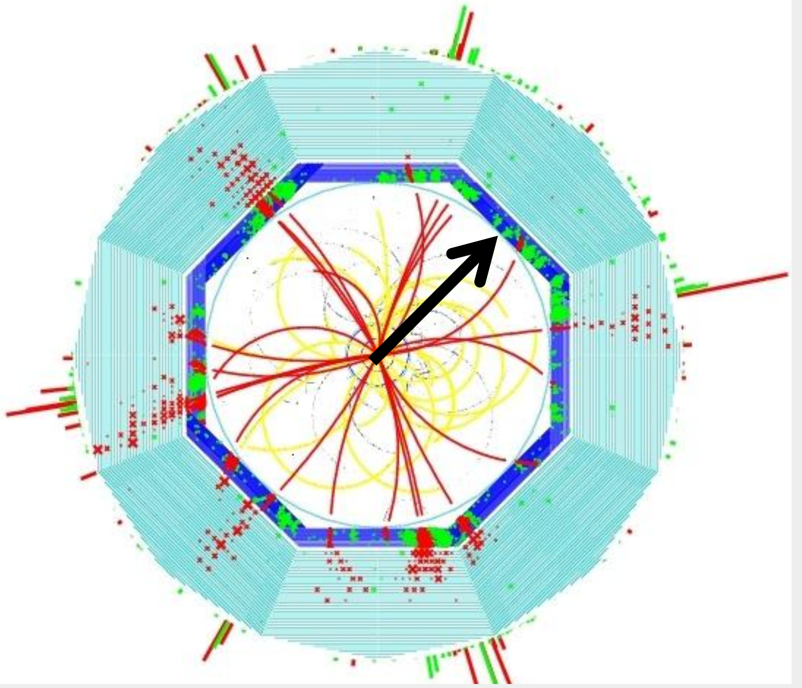
Reminder : EM Calorimeters: MANY (15-30) Xo deep

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

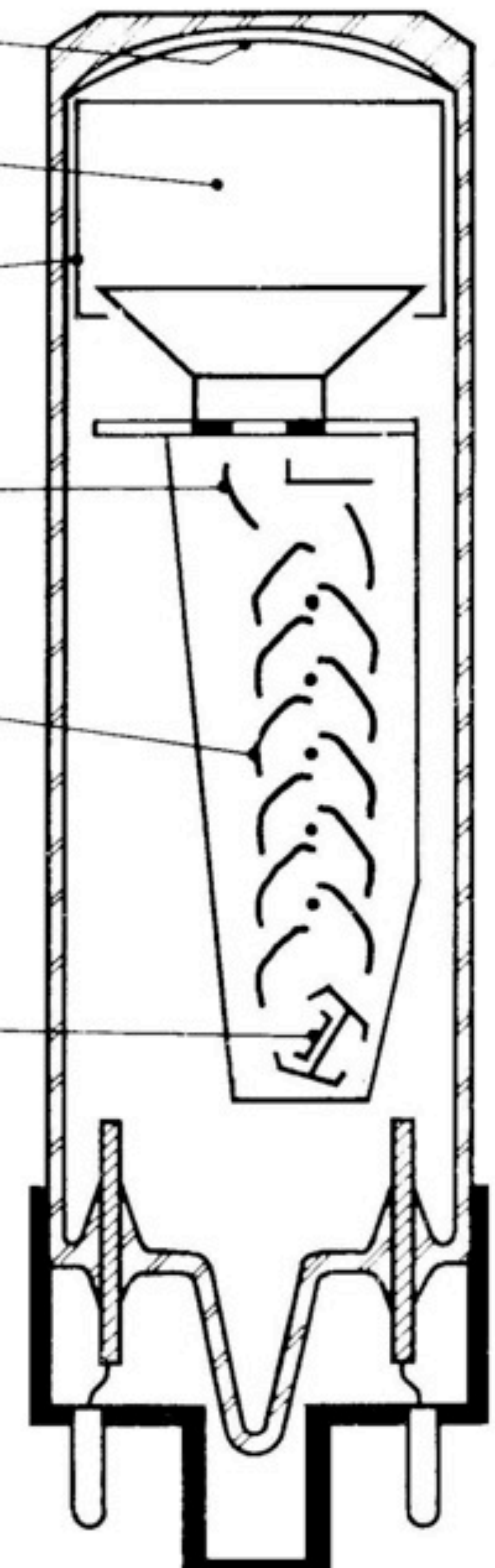
Principle:

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 ...]

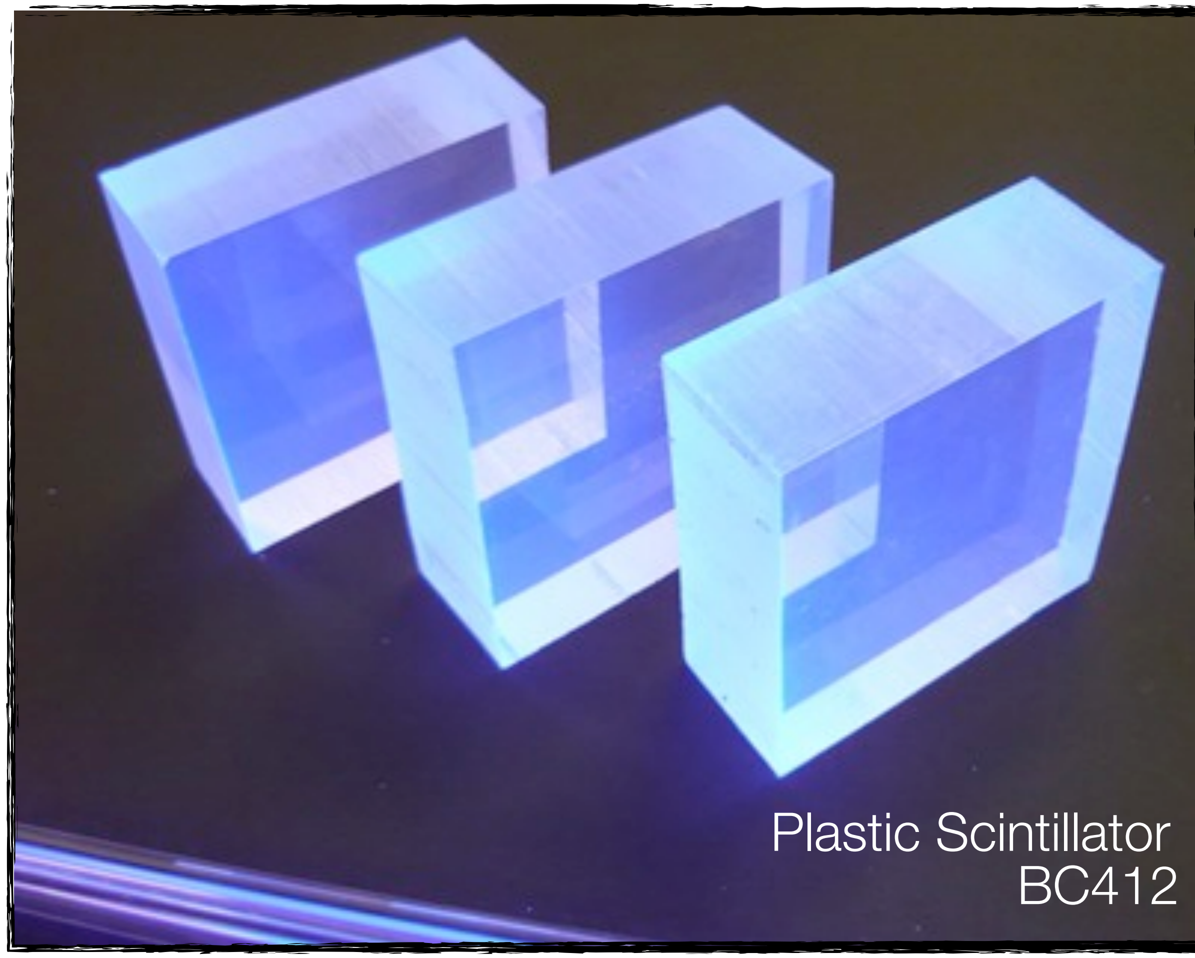
PMT
Collection



Scintillators - General Characteristics

Principle:

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



Plastic Scintillator
BC412

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:

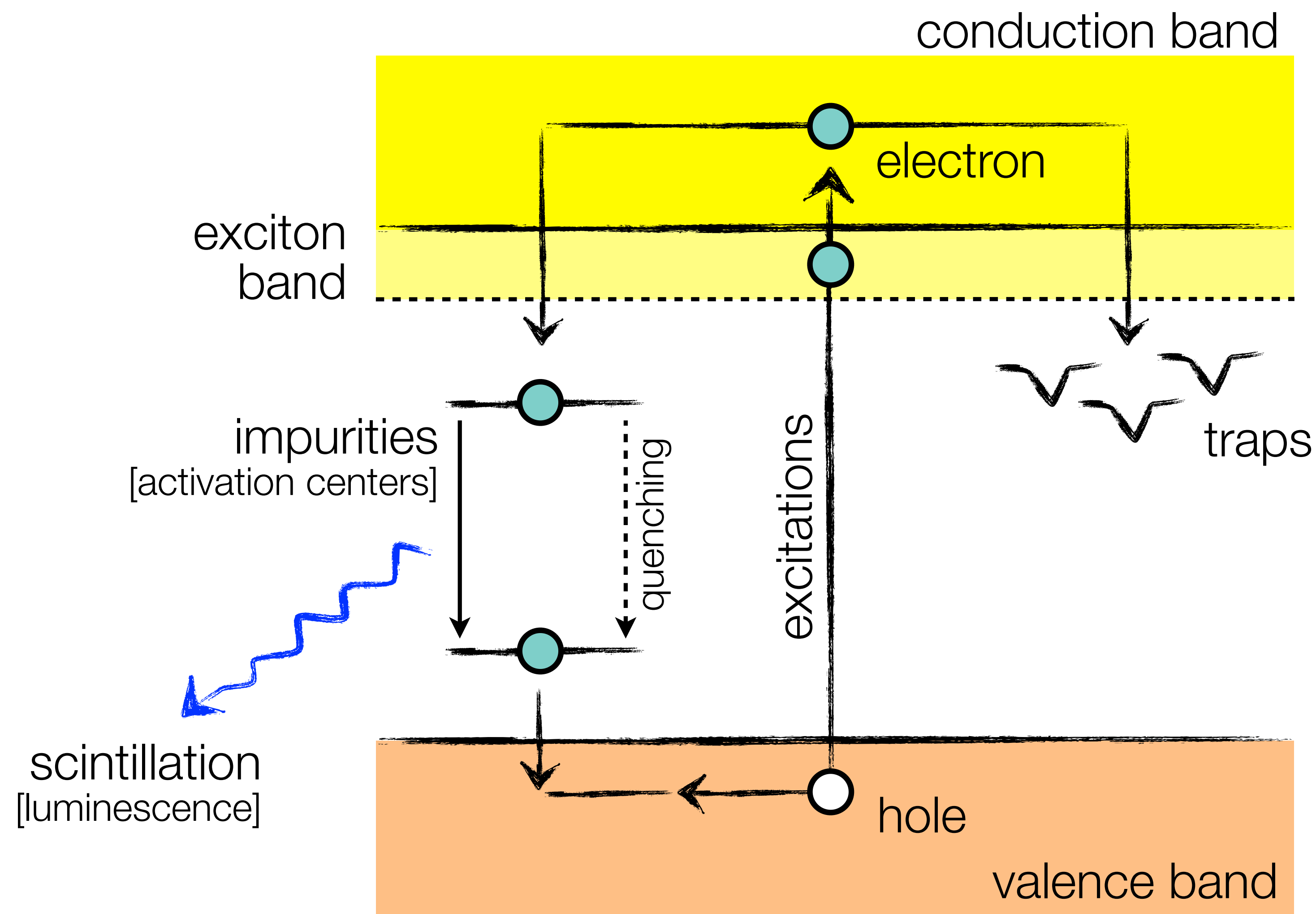
Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)
...

Mechanism:

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

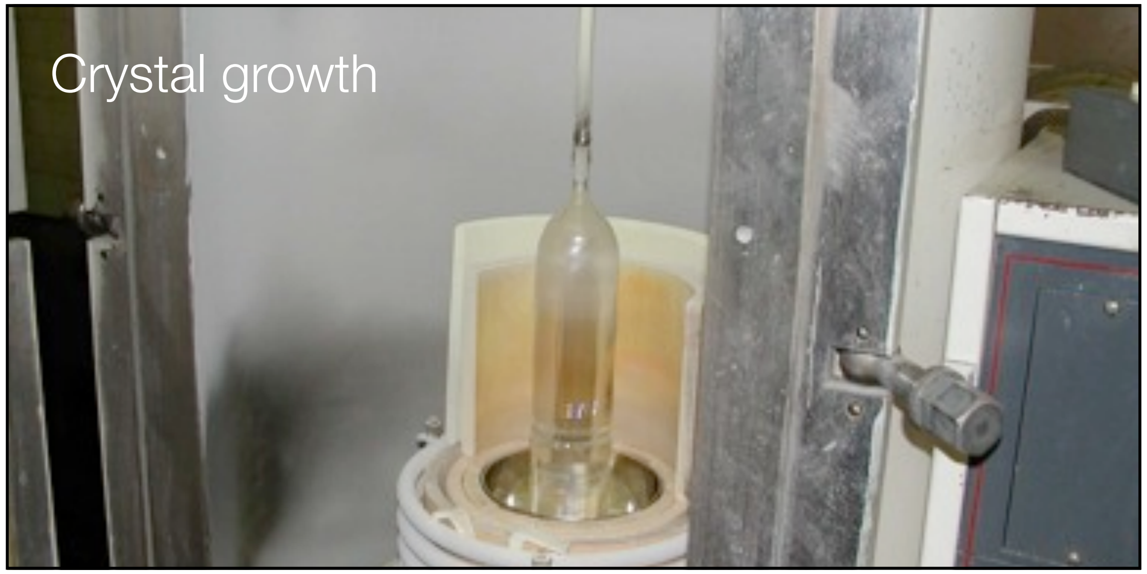
Time constants:

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

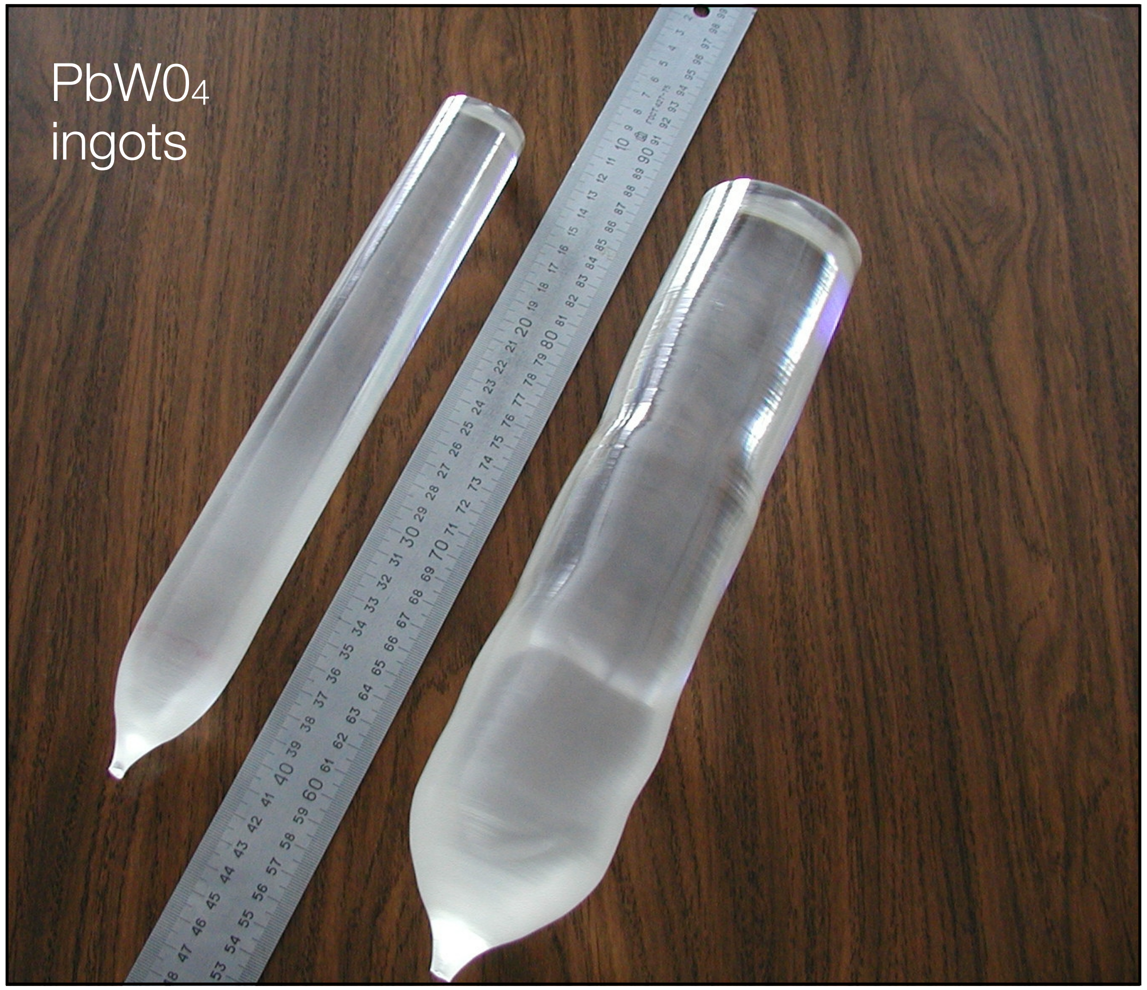


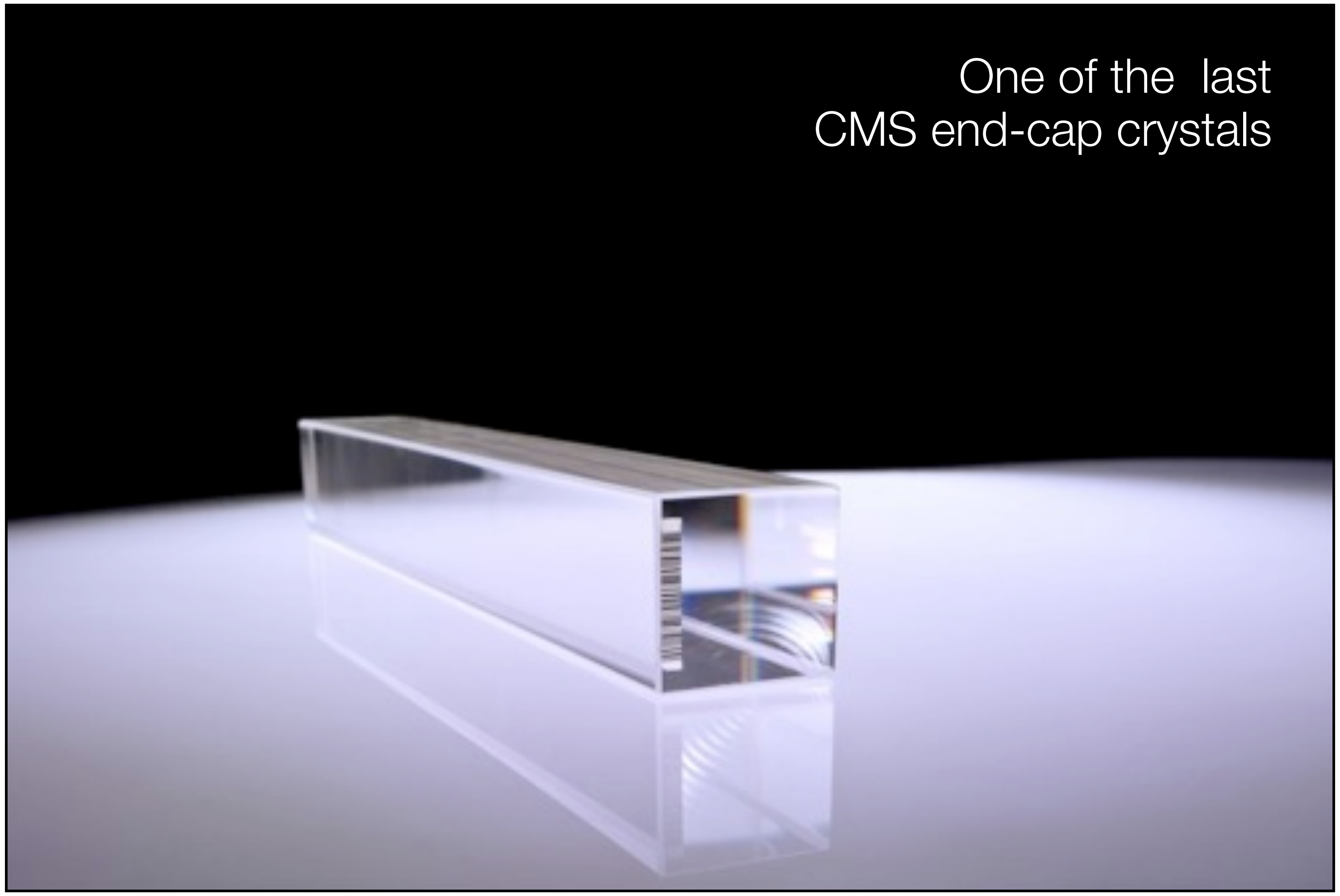
Energy bands in impurity activated crystal
showing excitation, luminescence, quenching and trapping

Inorganic Crystals



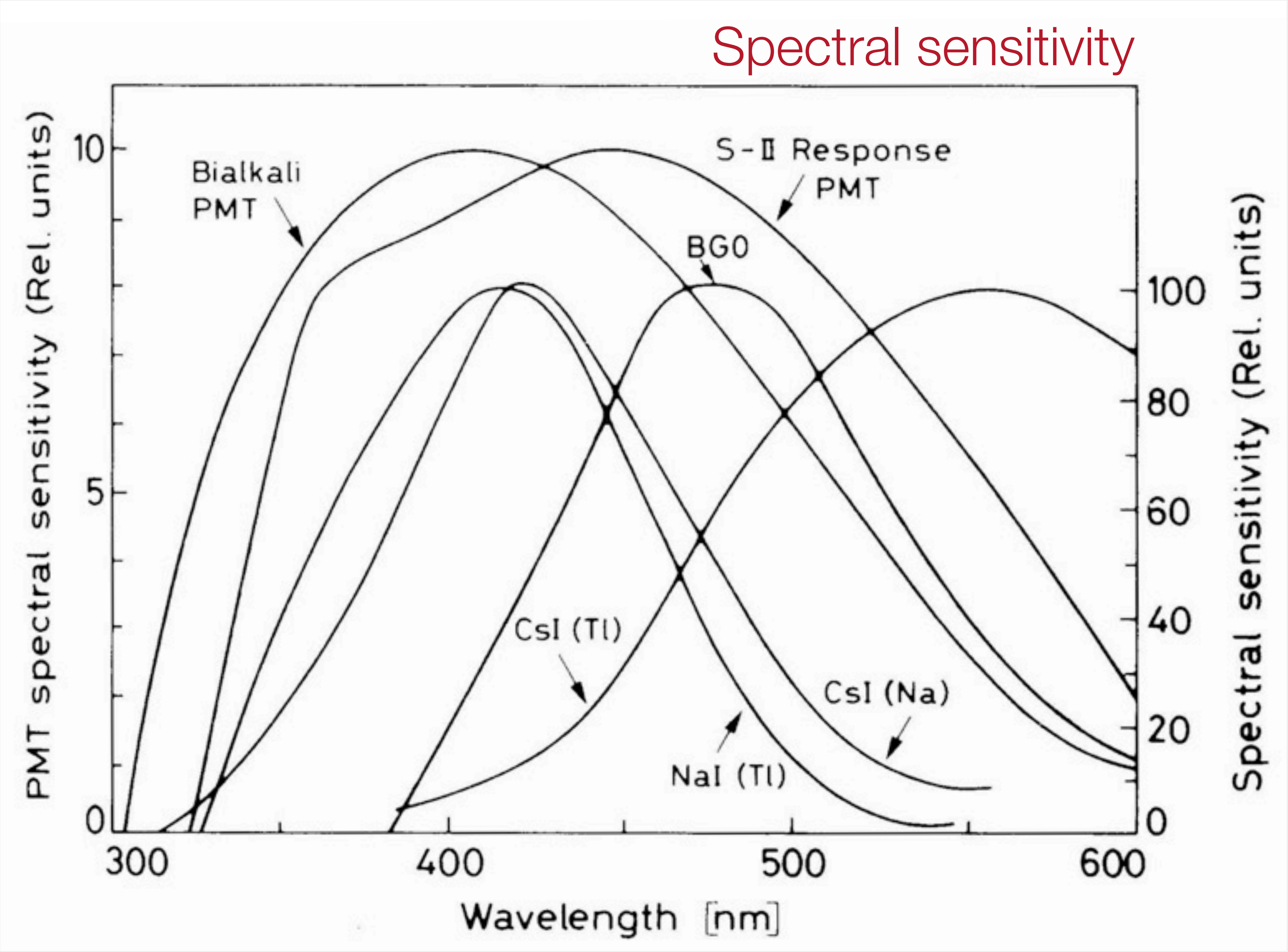
Example CMS
Electromagnetic Calorimeter





Inorganic Crystals

Light Output and PMT Sensitivity



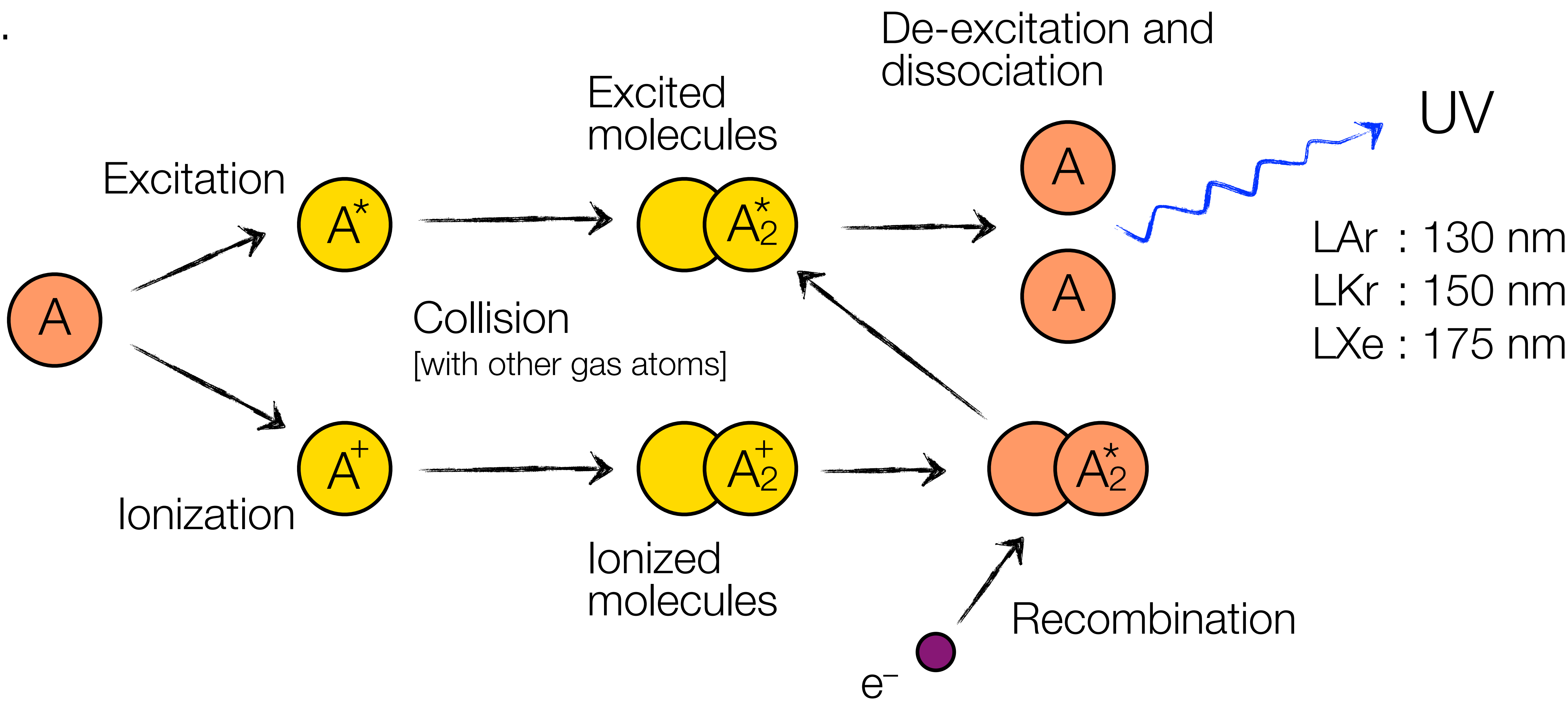
Sintillation in Liquid Nobel Gases

Materials:

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

Decay time constants:

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



Aromatic hydrocarbon compounds:

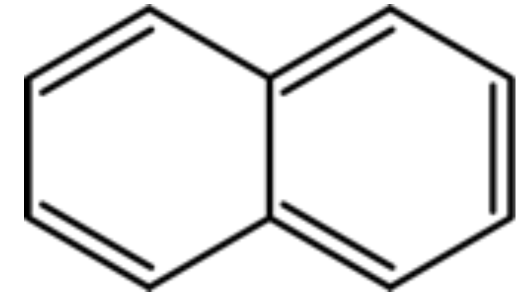
e.g. Naphtalene [$C_{10}H_8$]
Antracene [$C_{14}H_{10}$]
Stilbene [$C_{14}H_{12}$]
...

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

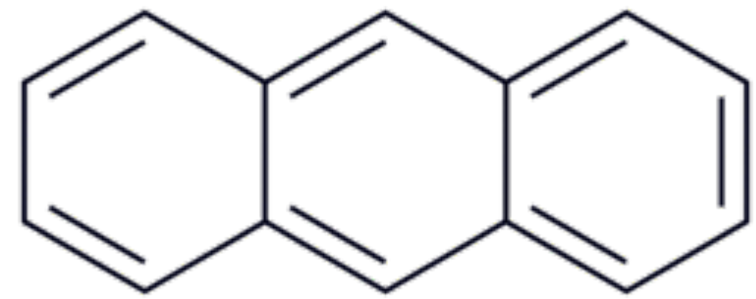
Scintillation light arises from
delocalized electrons in π-orbitals ...

Transitions of 'free' electrons ...

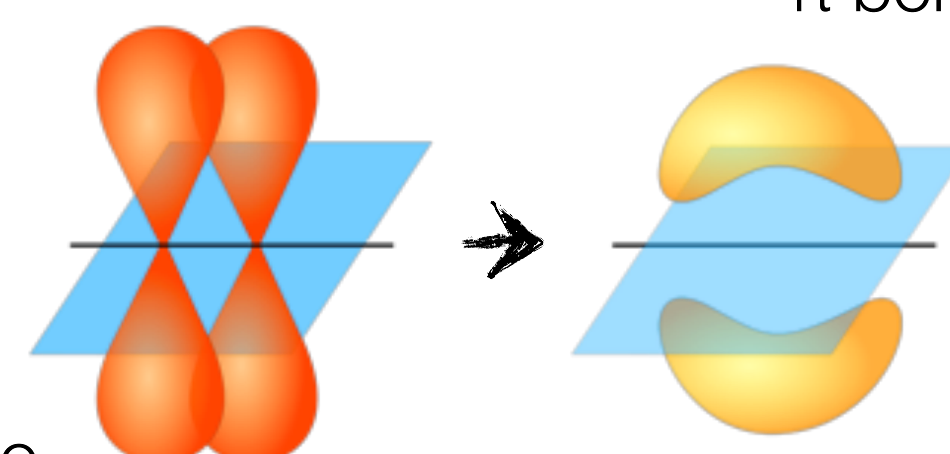
Naphtalene



Antracene



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



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

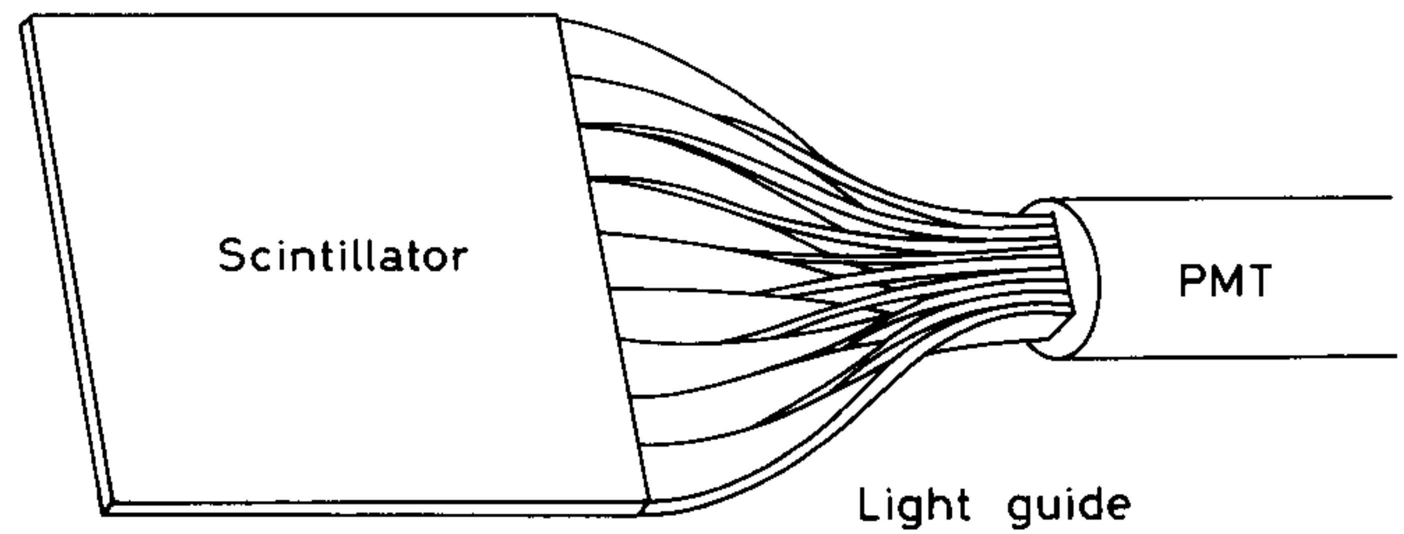
Cheap

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]

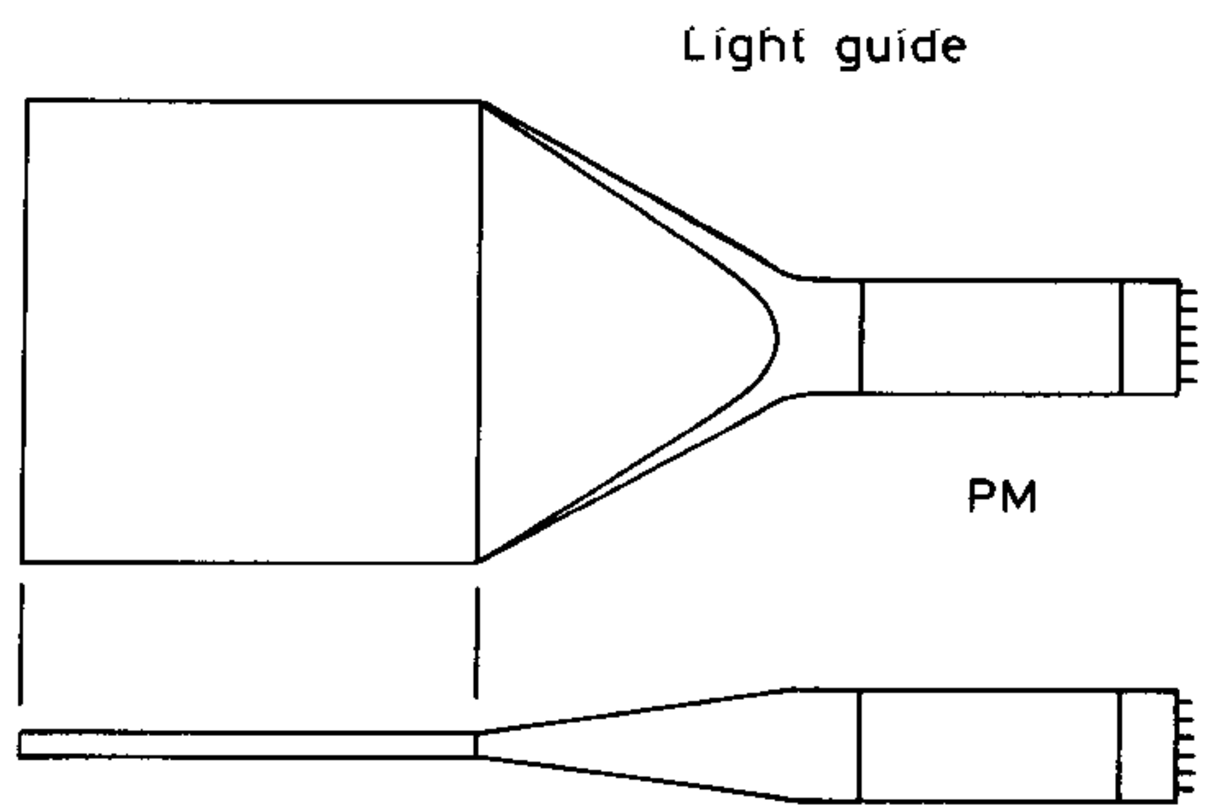


Liouville's Theorem:

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

Use adiabatic light guide like 'fish tail';

➛ appreciable energy loss



'fish tail'

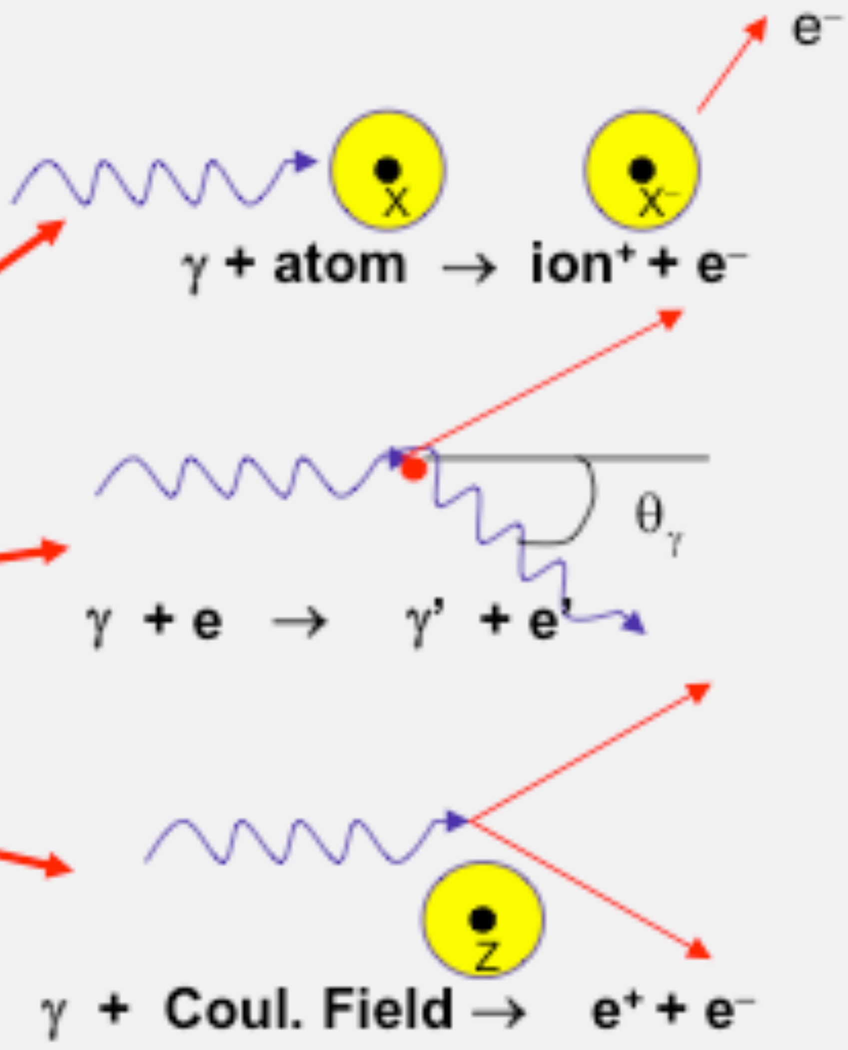
Energy losses by e & γ

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

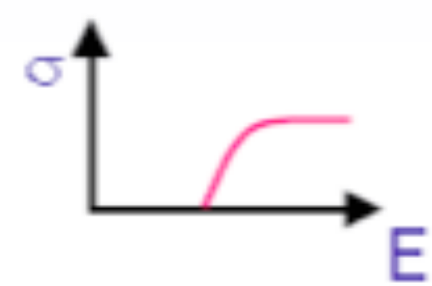
- Bremsstrahlung

γ

- Photoelectric effect

- Compton effect

- Pair production



Electrons

- Ionization

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

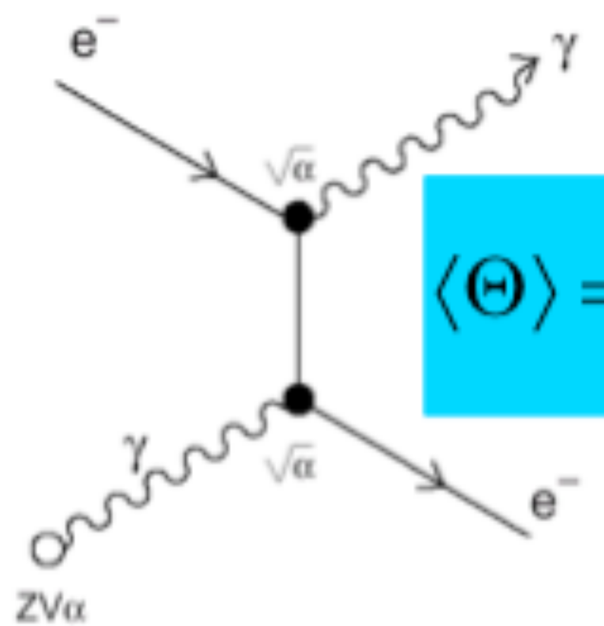
➢ $\sigma \propto Z$; $\sigma \propto \ln E/m_e$

- Bremsstrahlung

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

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

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



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

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

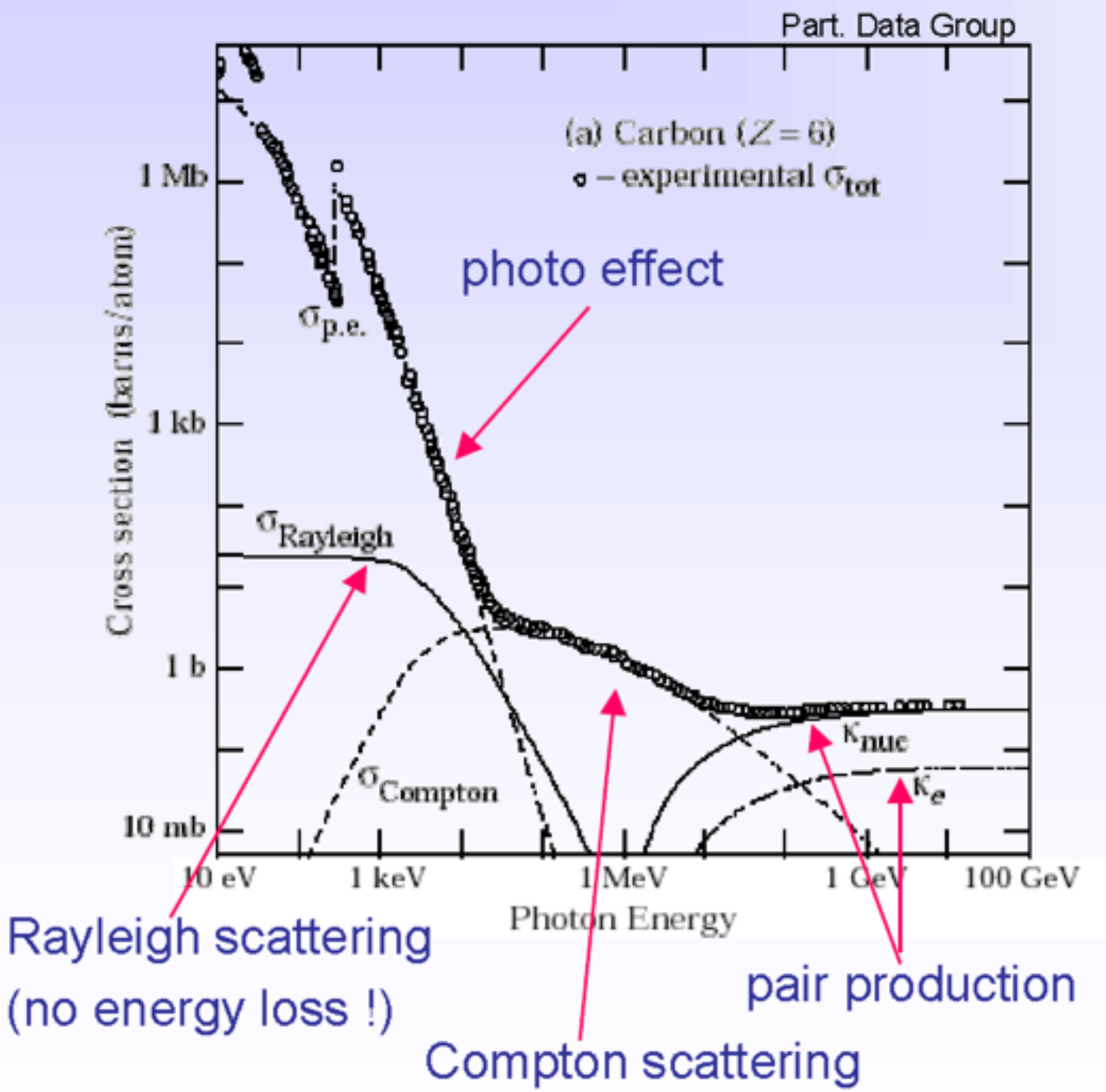
➢ $\sigma \propto Z(Z+1)$; $\sigma \propto A/X_0$ E>1 GeV, $\sigma \propto \ln E/m_e$ E<1 GeV

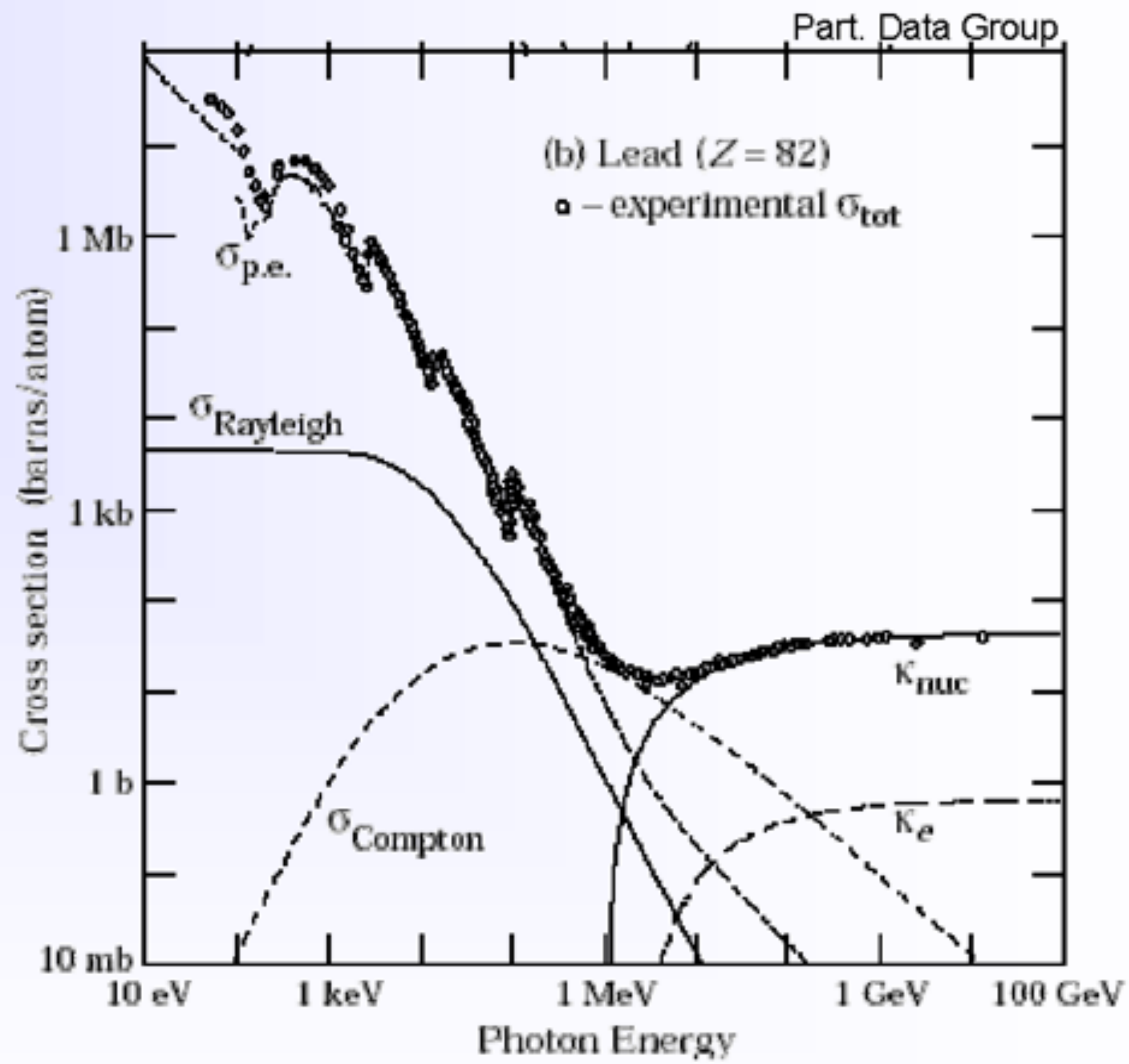
Radiation length: thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e. For dense materials Xo ~ 1 cm.

Interaction of photons: Summary

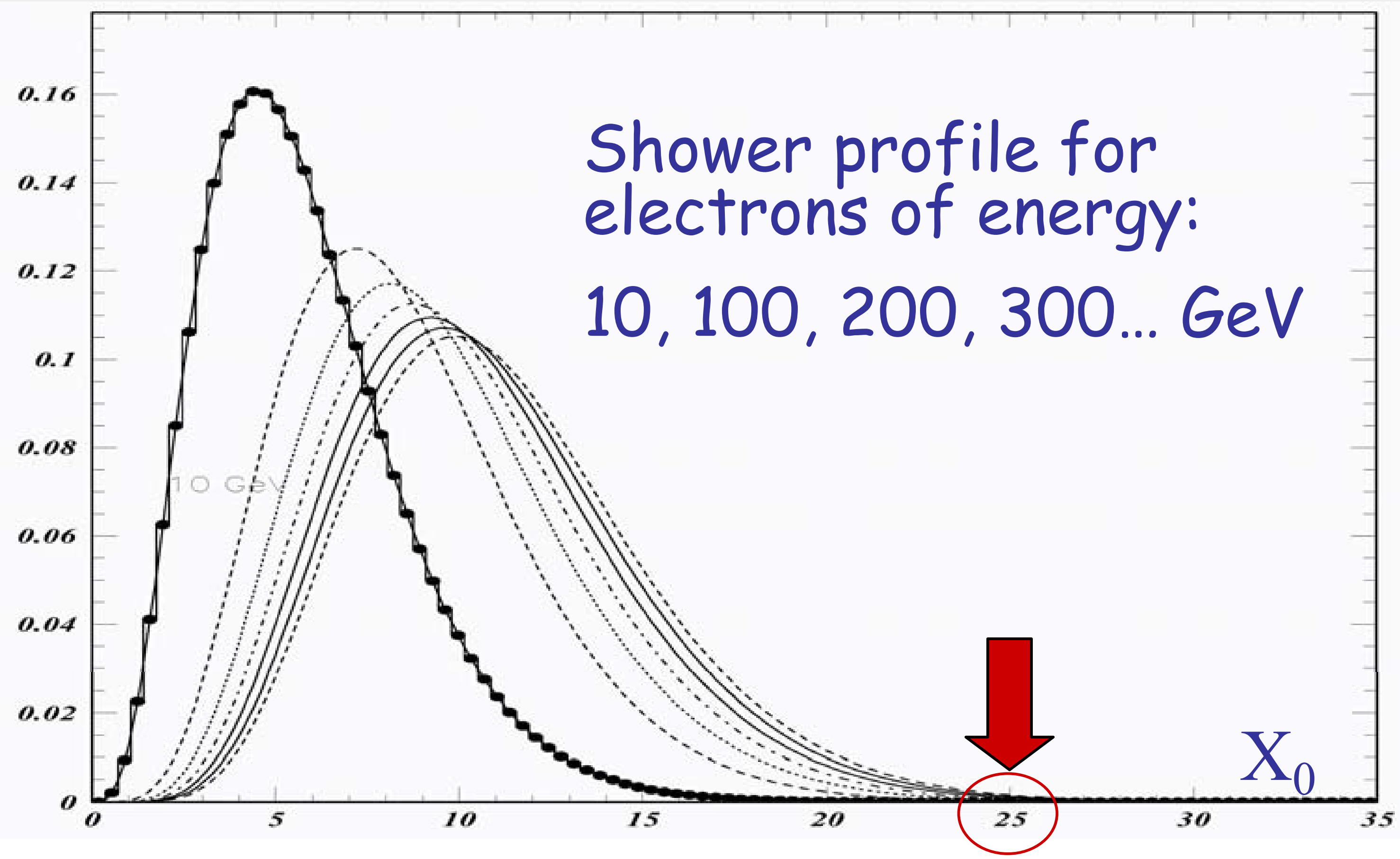
In summary: $I_\gamma = I_0 e^{-\mu x}$

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





EM showers: longitudinal profile



Shower energy dep parametrization:

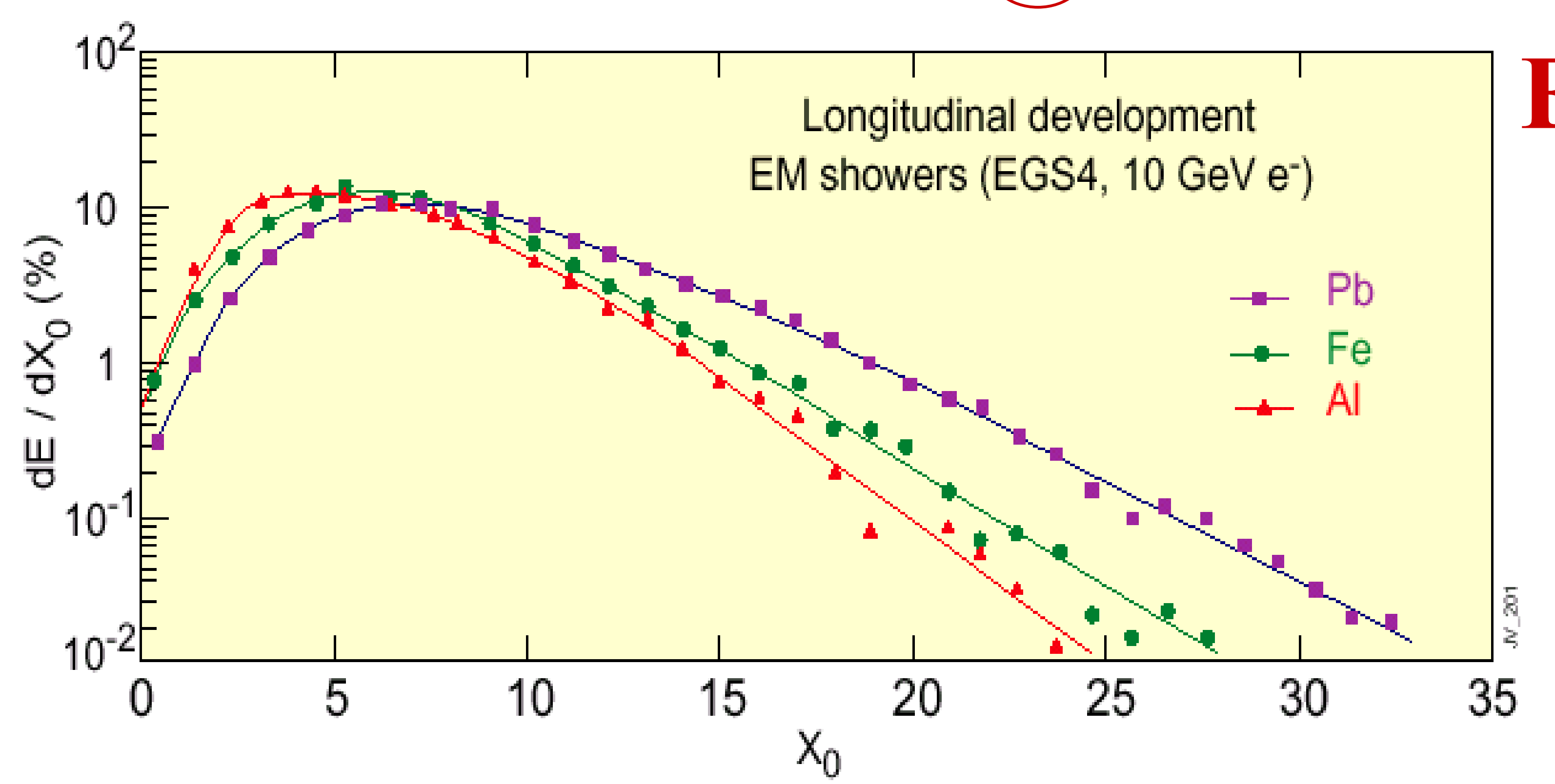
$$\frac{dE}{dt} \propto E_0 t^{\alpha} e^{\beta t}$$

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 α 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 $1X_0$

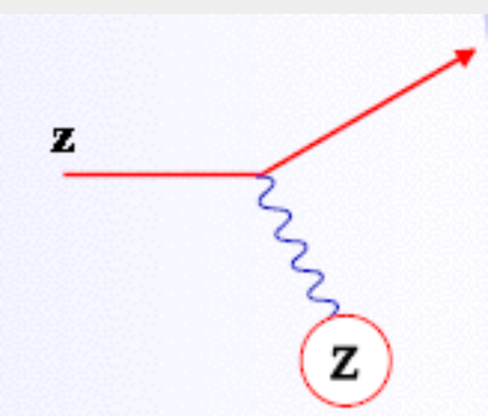
$$R_M = \frac{21\text{MeV}}{E_C} X_0$$

$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} \left(Z >> 1\right)$$

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

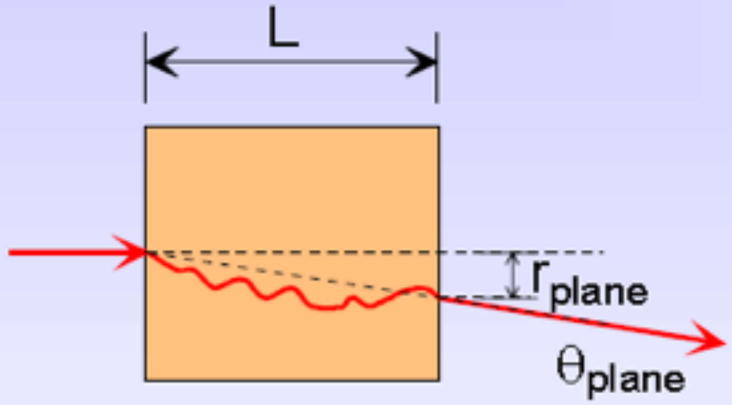
Interaction of charged particles: Multiple Scattering

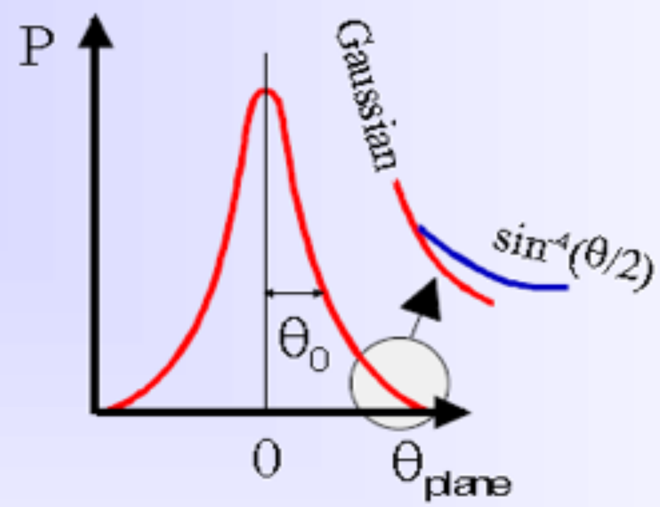
- This process will turn out to be closely related to the transverse profile of electromagnetic showers.
- Coulomb-scattering scales with the squared charges, so scattering in matter is dominated by scattering off nuclei (rather than off electrons), for Z>10. Scattering of spin 0 (Rutherford) and spin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



In a sufficiently thick material layer a particle will undergo ...

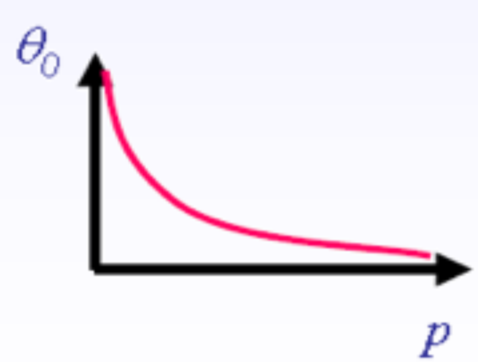
Multiple Scattering





$$\theta_0 = \theta_{plane}^{RMS} = \sqrt{\langle \theta_{plane}{}^2 \rangle} = \frac{1}{\sqrt{2}} \theta_{space}^{RMS}$$

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



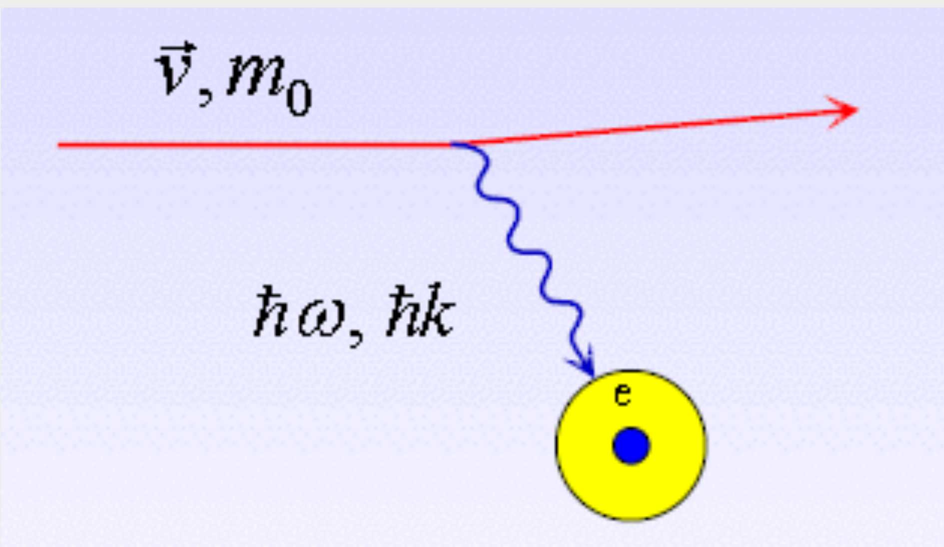
TO BACKUP

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 ($m_e \ll m_N$) for energy loss.

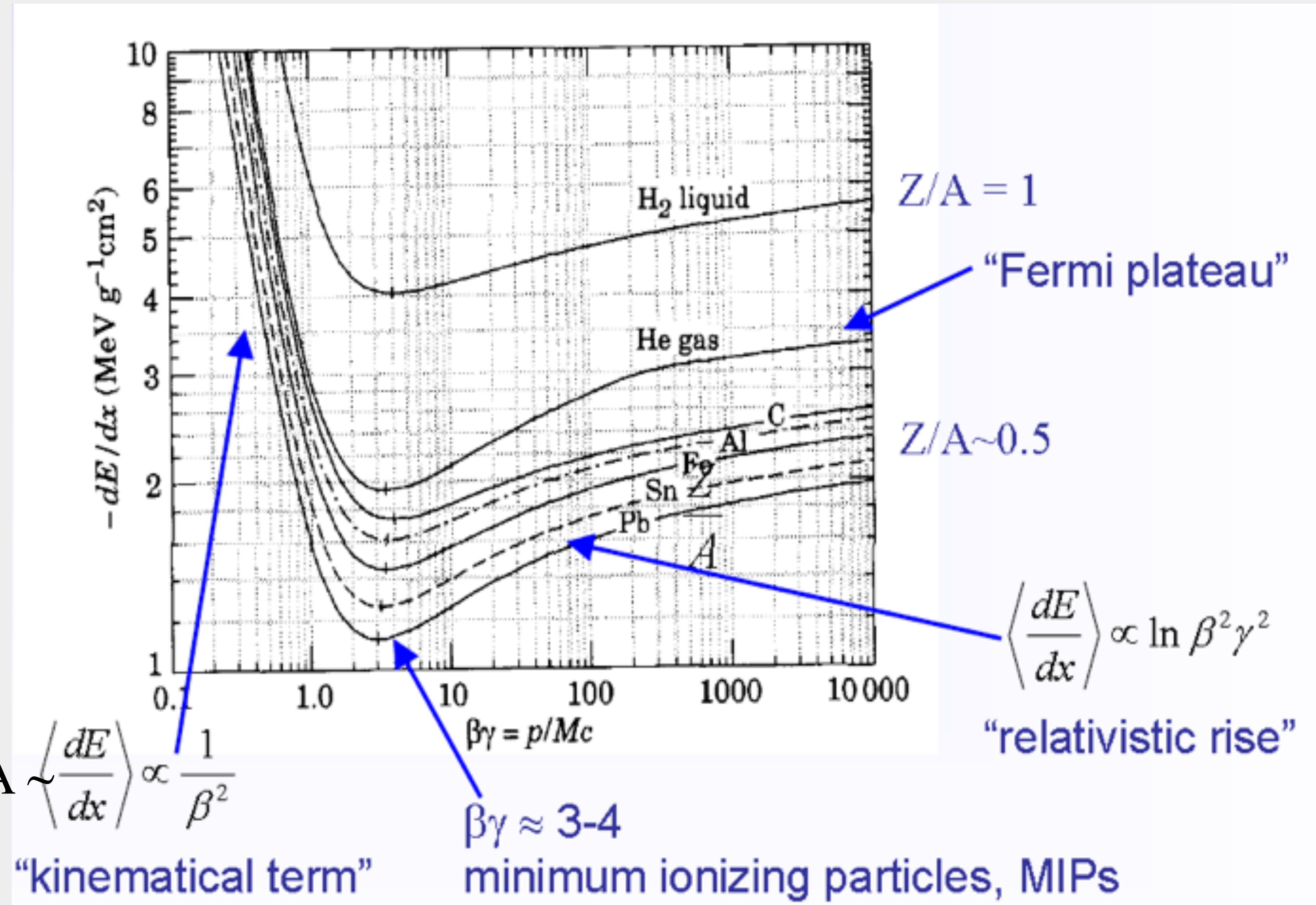
If $\hbar\omega, \hbar k$ are in the right range → **ionization**.

Interaction of charged particles: Bethe-Bloch formula

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

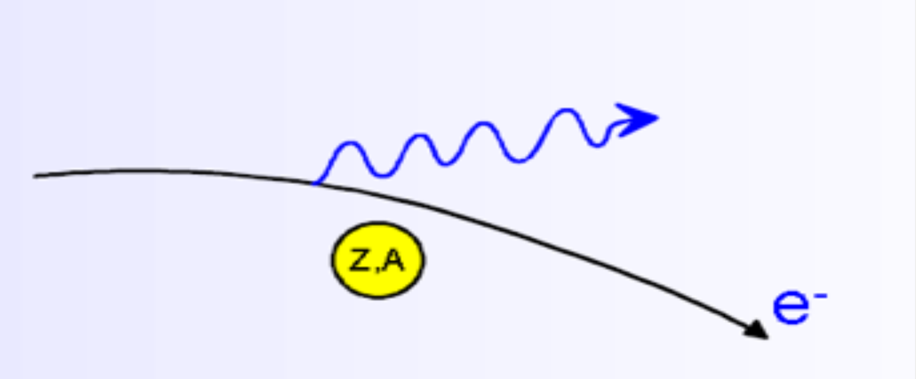
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{max} - \beta^2 - \frac{\delta}{2} \right]$$

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

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

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

radiation length [g/cm²]

(divide by specific density to get X_0 in cm)

- Critical energy E_c

$$\frac{dE}{dx}(E_c)\bigg|_{Brems} = \frac{dE}{dx}(E_c)\bigg|_{ion}$$

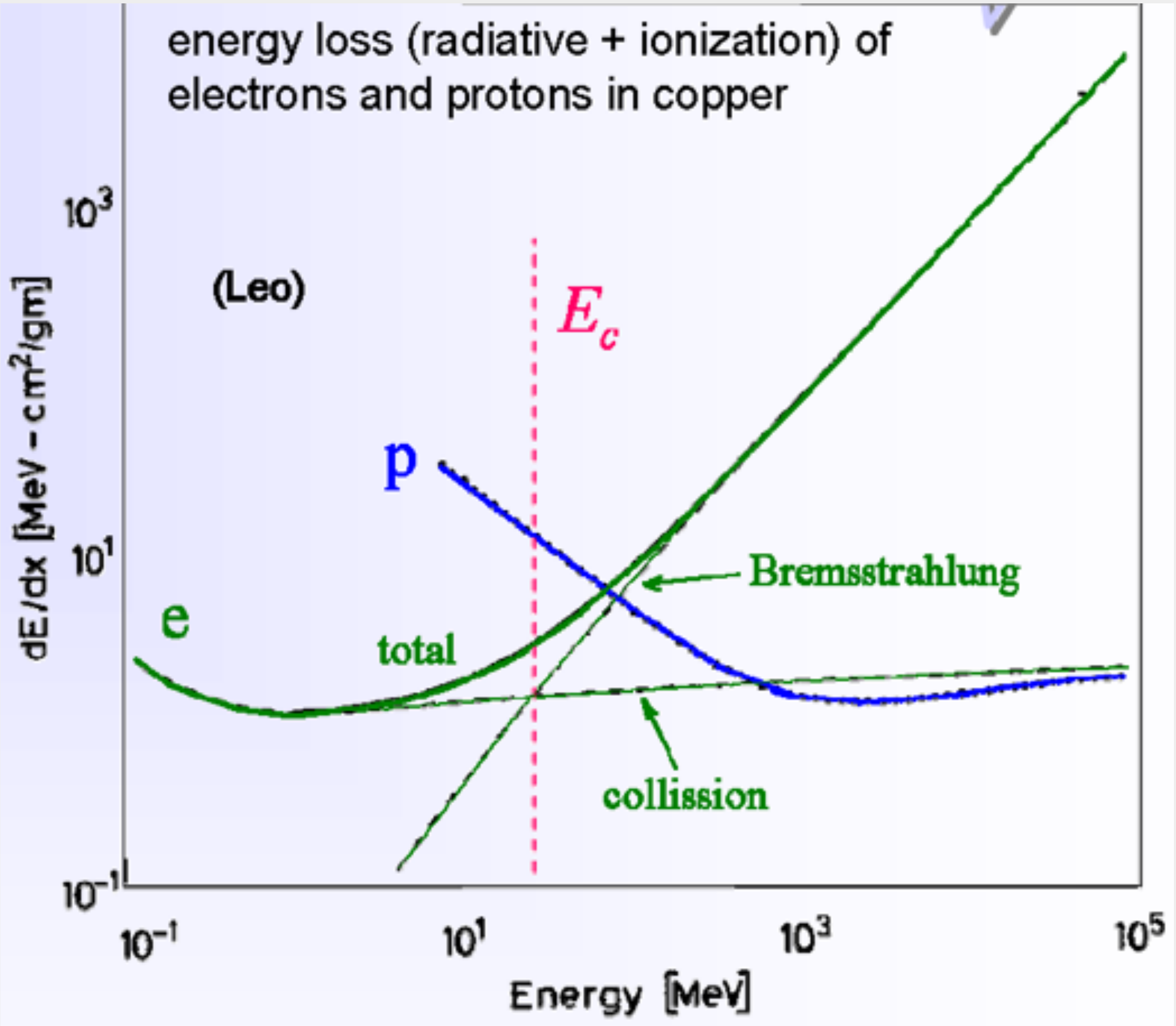
For electrons one finds approximately:

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

$E_c(e^-)$ 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 ≈ 1 TeV

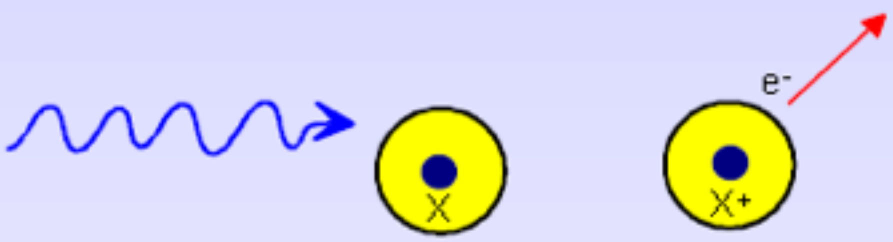


Unlike electrons, muons in multi-GeV range can travers thick layers of dense matter.

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

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 $E_\gamma \approx E_{shell}$

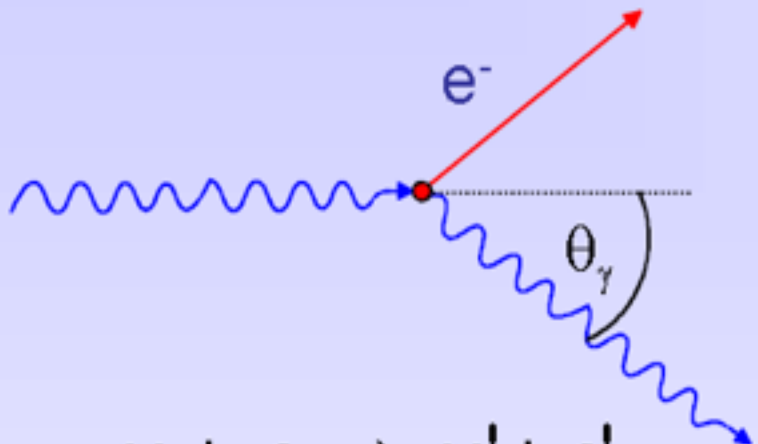
$$\sigma^{K}_{photo} = \left(\frac{32}{\varepsilon^{7}}\right)^{\frac{1}{2}} \alpha^{4} Z^{5} \sigma^{e}_{Th} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2} \qquad \sigma^{e}_{Th} = \frac{8}{3}\pi r_e^2 \quad \text{(Thomson)}$$

At high energies (ε>>1)

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

$$\sigma_{photo} \propto Z^5$$

Interaction of photons: Compton scattering

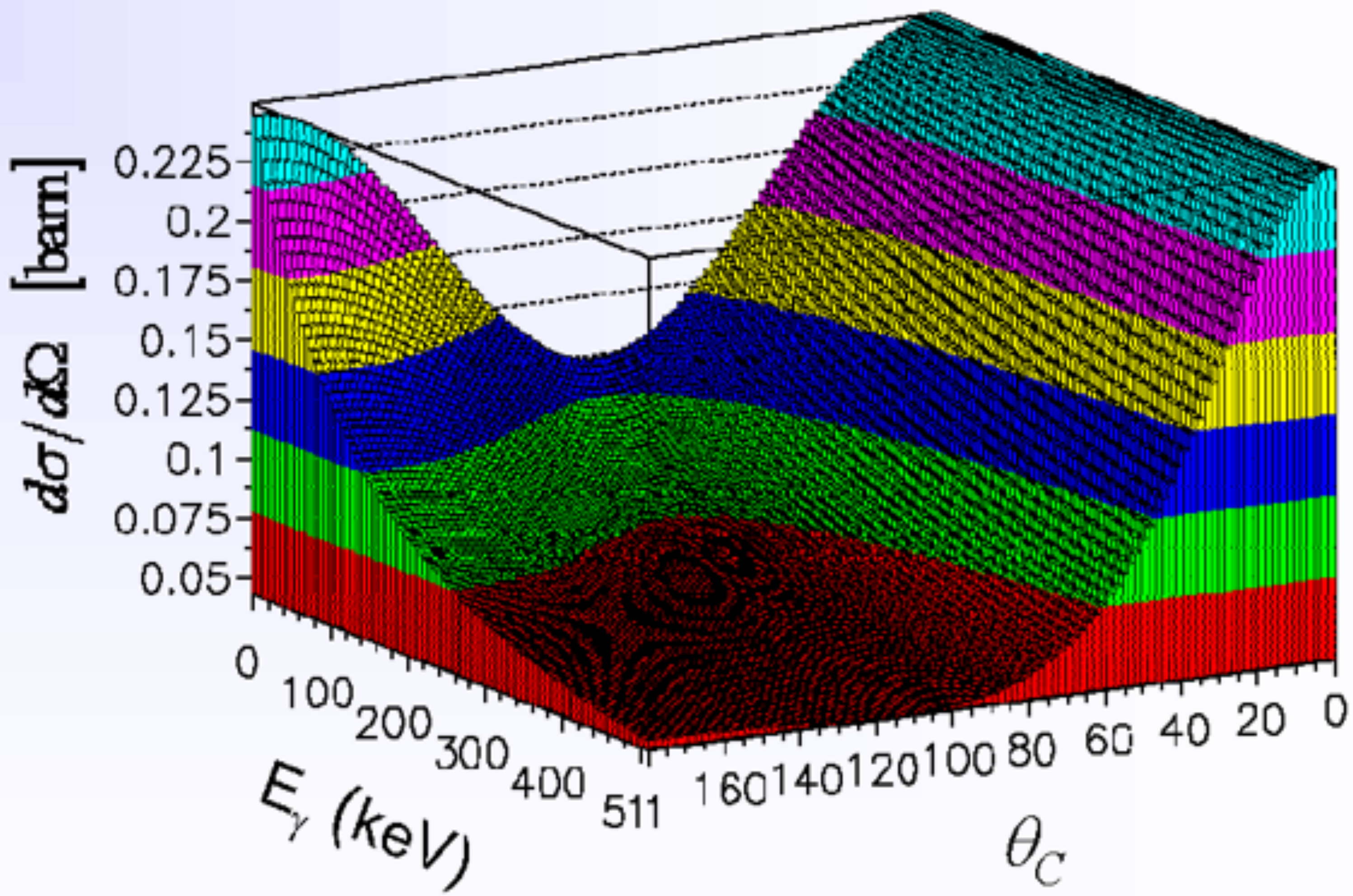


$$\gamma + e \rightarrow \gamma' + e'$$

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

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

Compton cross-section (Klein-Nishina)



Assume electron as quasi-free.

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

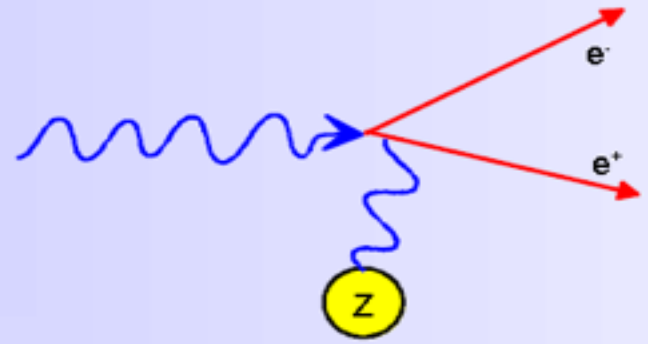
At high energies approximately

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

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 $E_\gamma \geq 2m_ec^2$

Cross-section (high energy approximation)

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

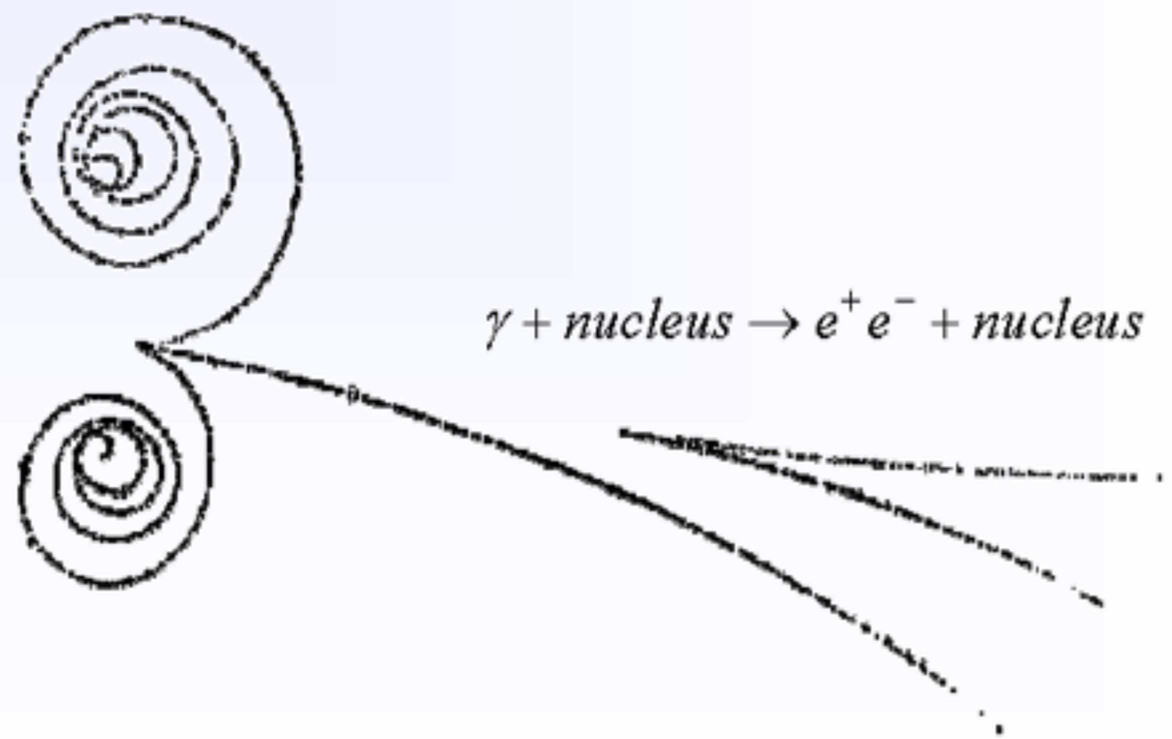
independent of energy !

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

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

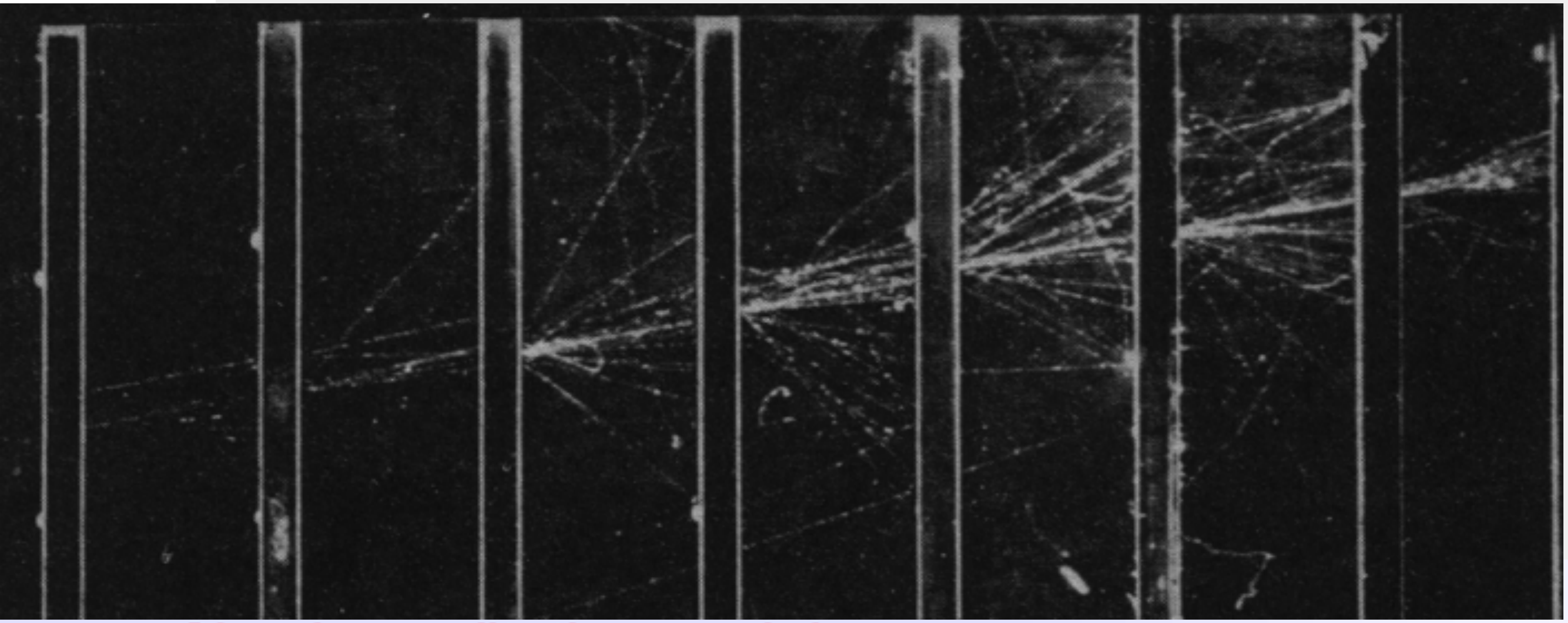
$$\lambda_{pair} = \frac{9}{7} X_0$$

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



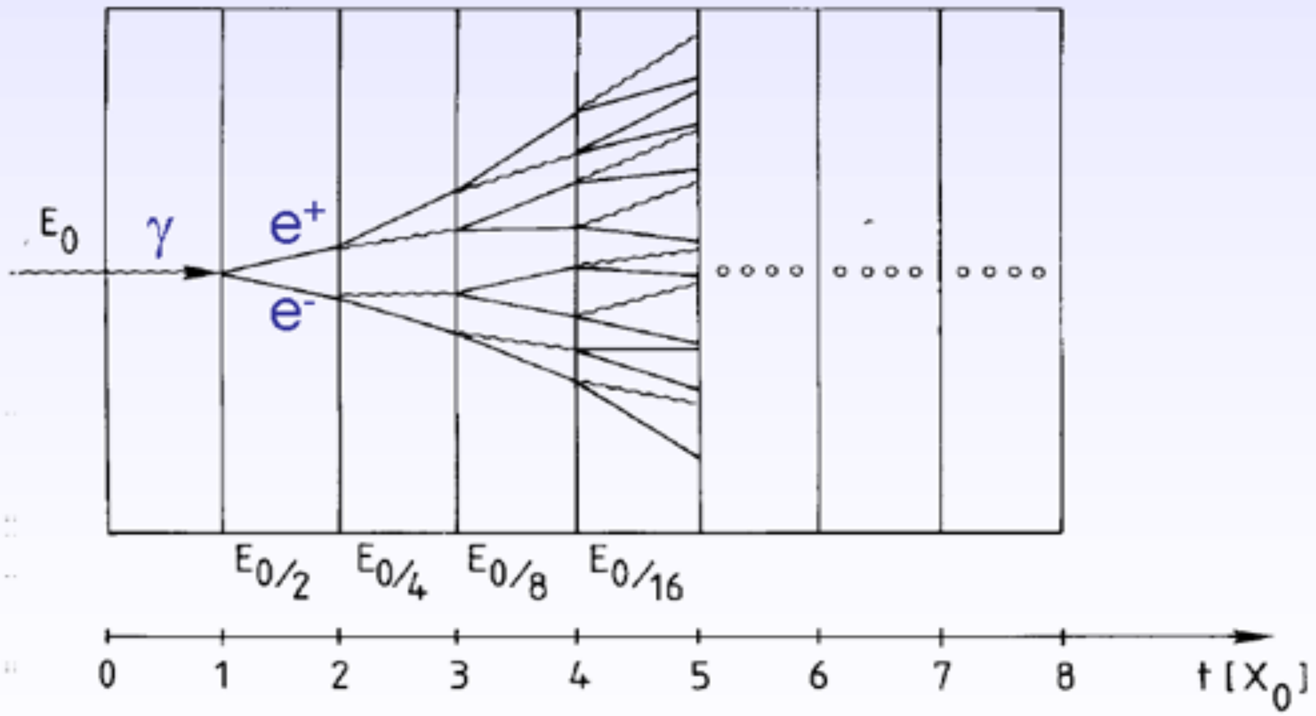
$\gamma + nucleus \rightarrow e^+e^- + nucleus$

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

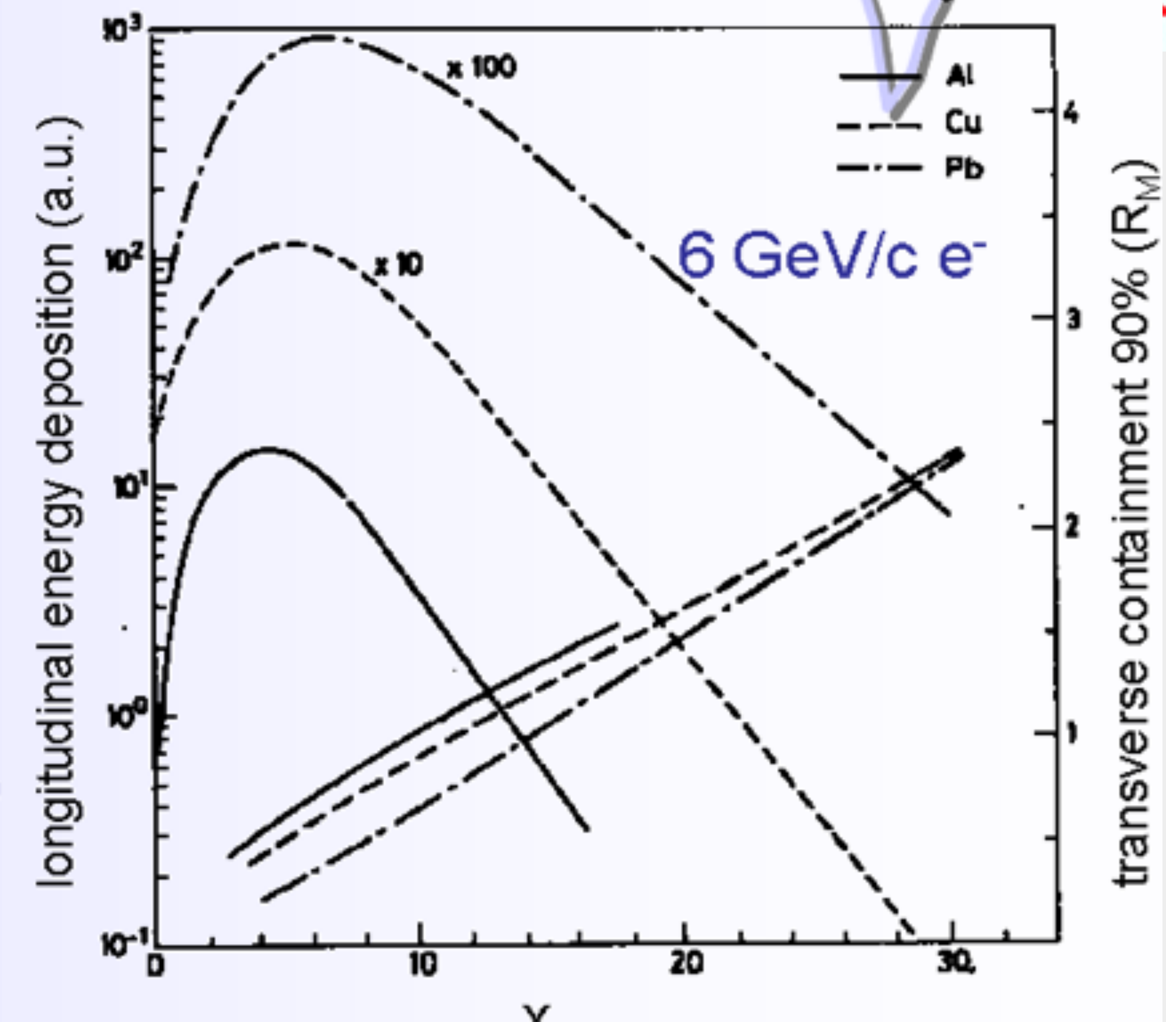
Longitudinal shower development

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

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

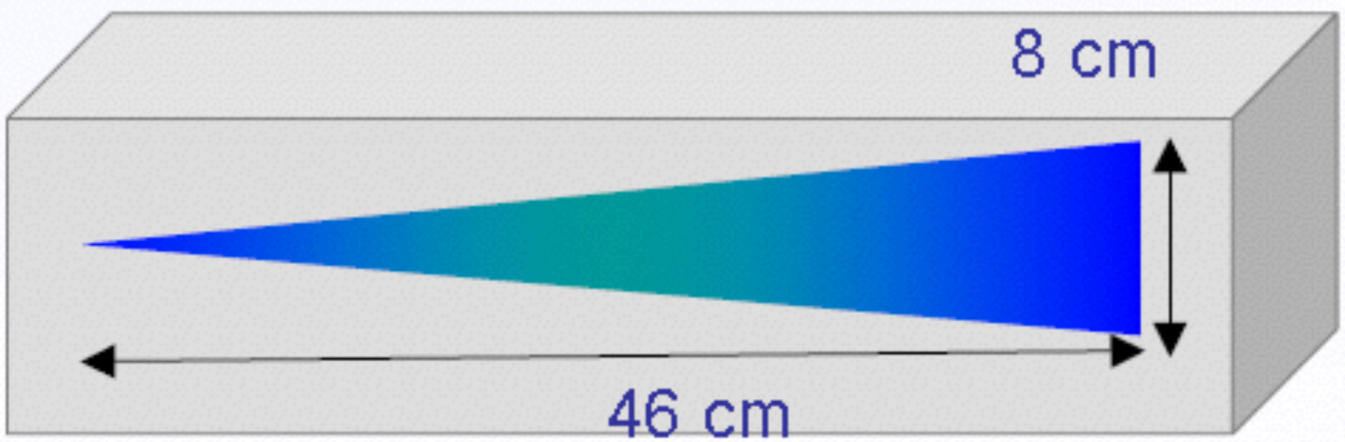
95% of the shower cone is located in a cylinder with radius 2 R_M

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

Example: E_0 = 100 GeV in lead glass

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

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



BACK

Some Useful 'Rules of Thumbs'

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

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:

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

Longitudinal
energy containment:

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

Transverse
Energy containment:

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

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

BACK

Position resolution - EM

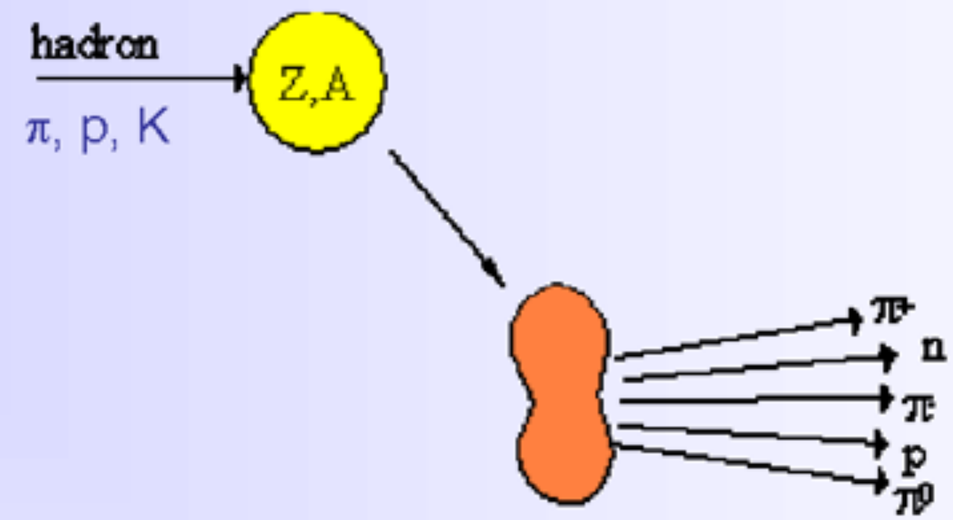
- Reconstruction of invariant masses of particles decaying into photons, electron identification using match with track measured in tracking devices
- Impact position of showers is determined using the transverse (and longitudinal) energy distribution in calorimeter cells
- Method based on center of 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

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.



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…).

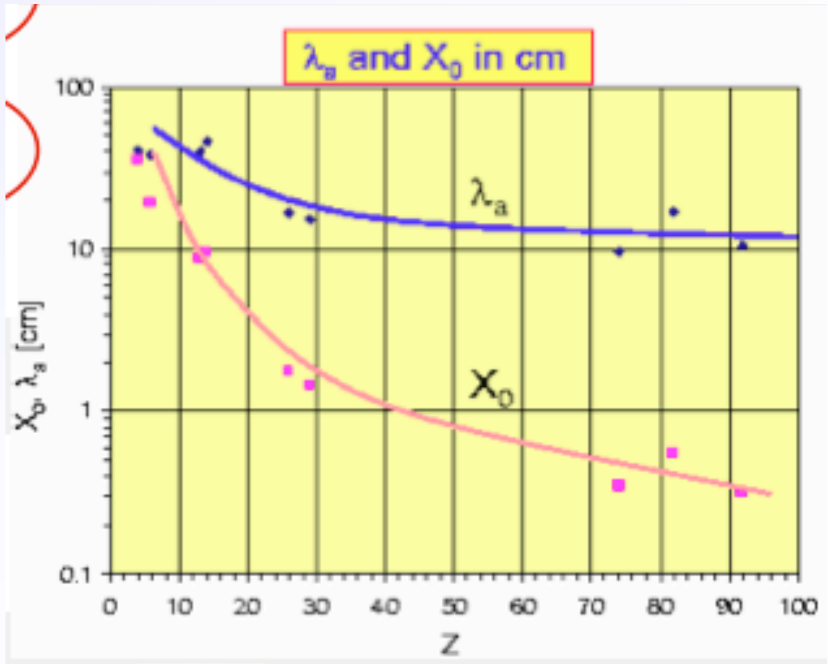
$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \approx 35\, mb$$

In analogy to X_0 a hadronic absorption length can be defined

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

similarly a hadronic interaction length

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



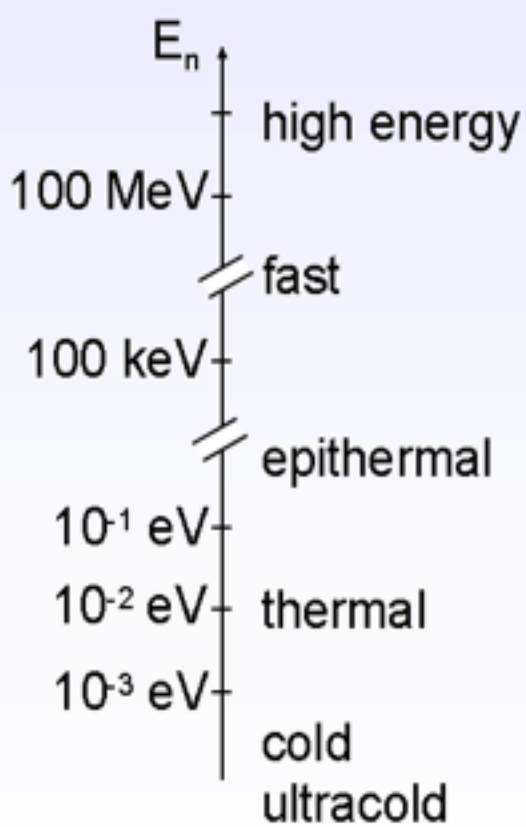
TO BACKUP

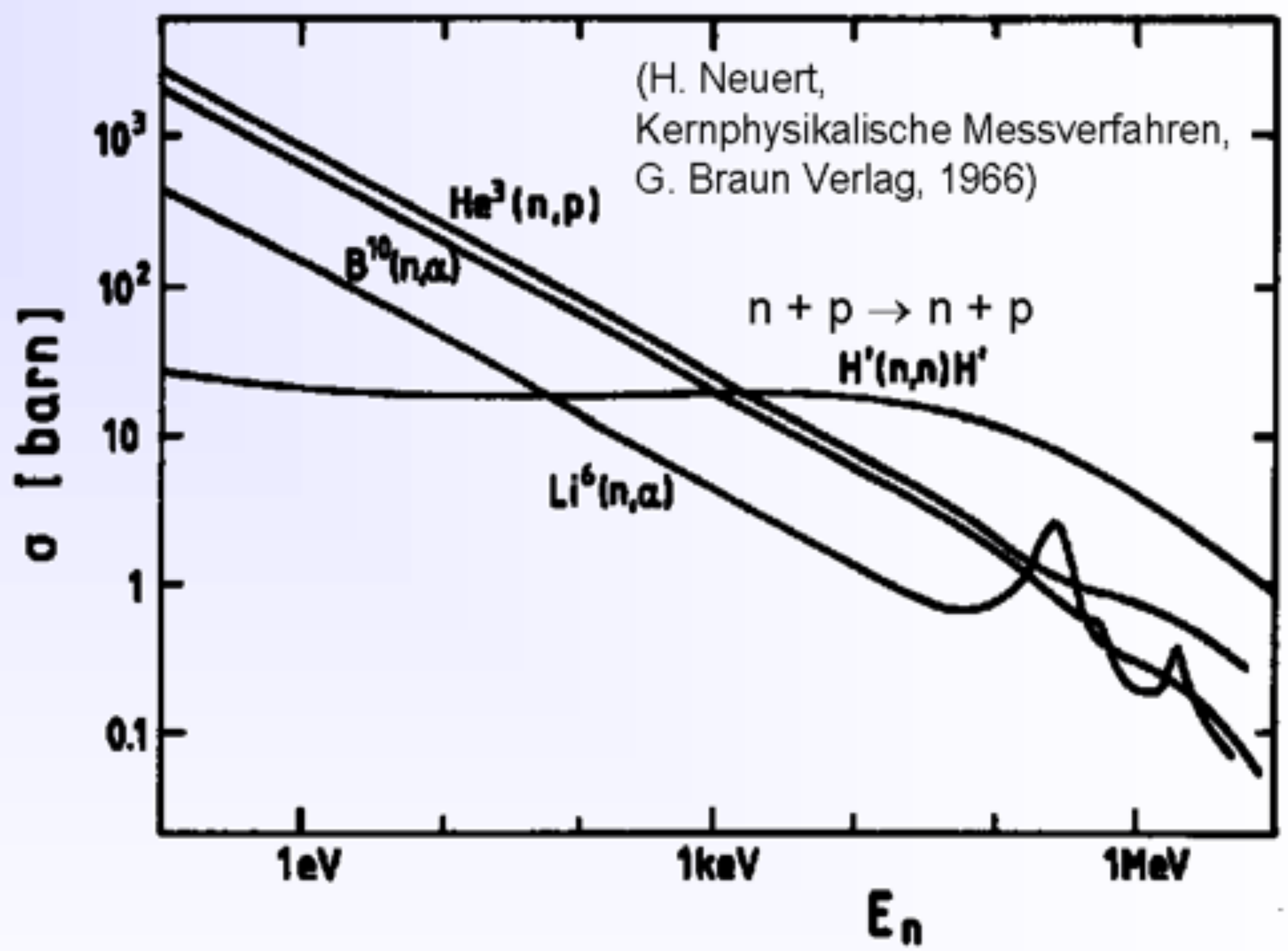
Interaction of neutrons

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 …

$$\left.\begin{array}{l} n + {}^{6}Li \rightarrow \alpha + {}^{3}H \\ n + {}^{10}B \rightarrow \alpha + {}^{7}Li \\ n + {}^{3}He \rightarrow p + {}^{3}H \end{array}\right\} \quad E_n < 20\ MeV$$

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





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

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

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

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

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

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

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

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:

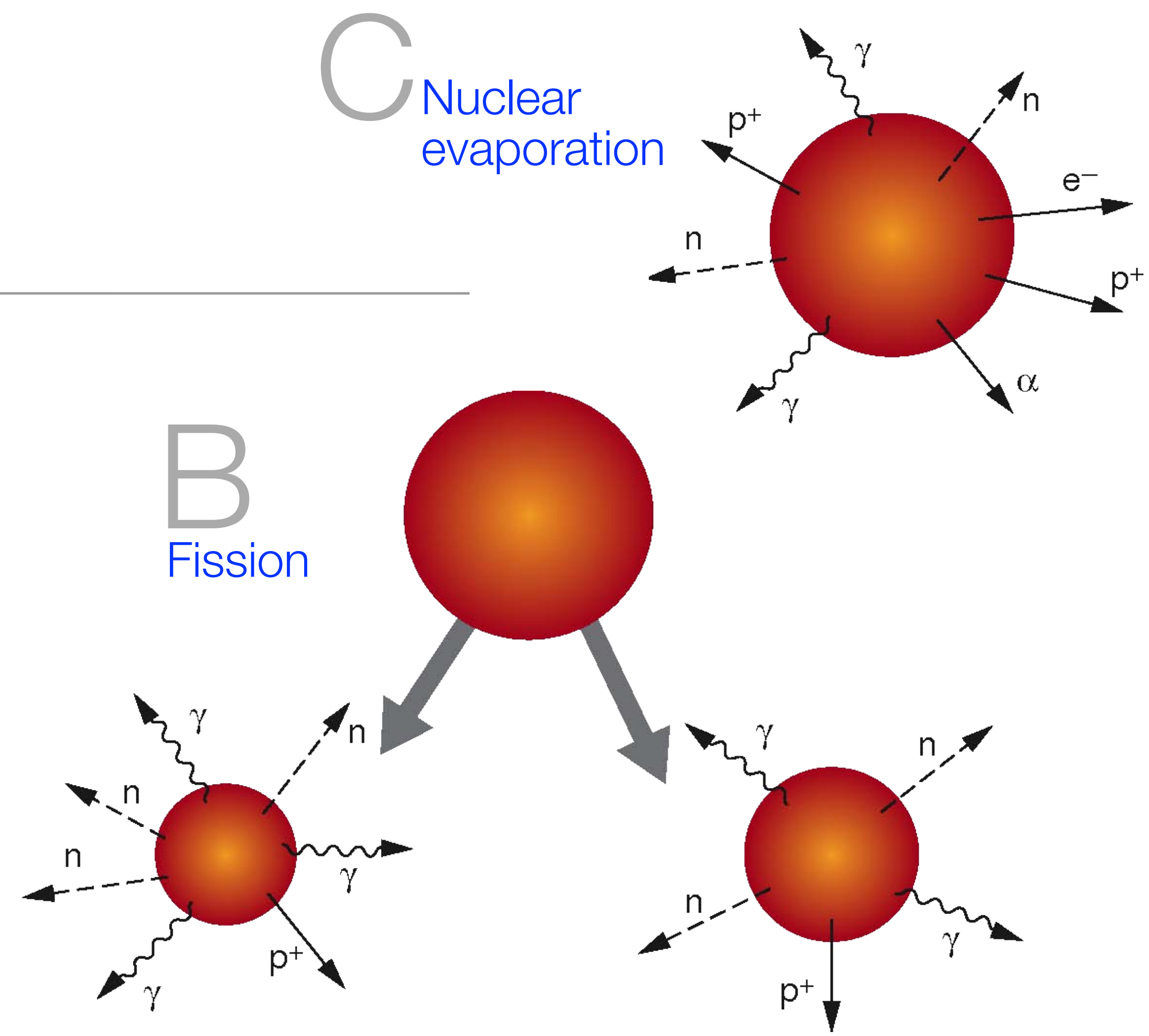
Elastic:

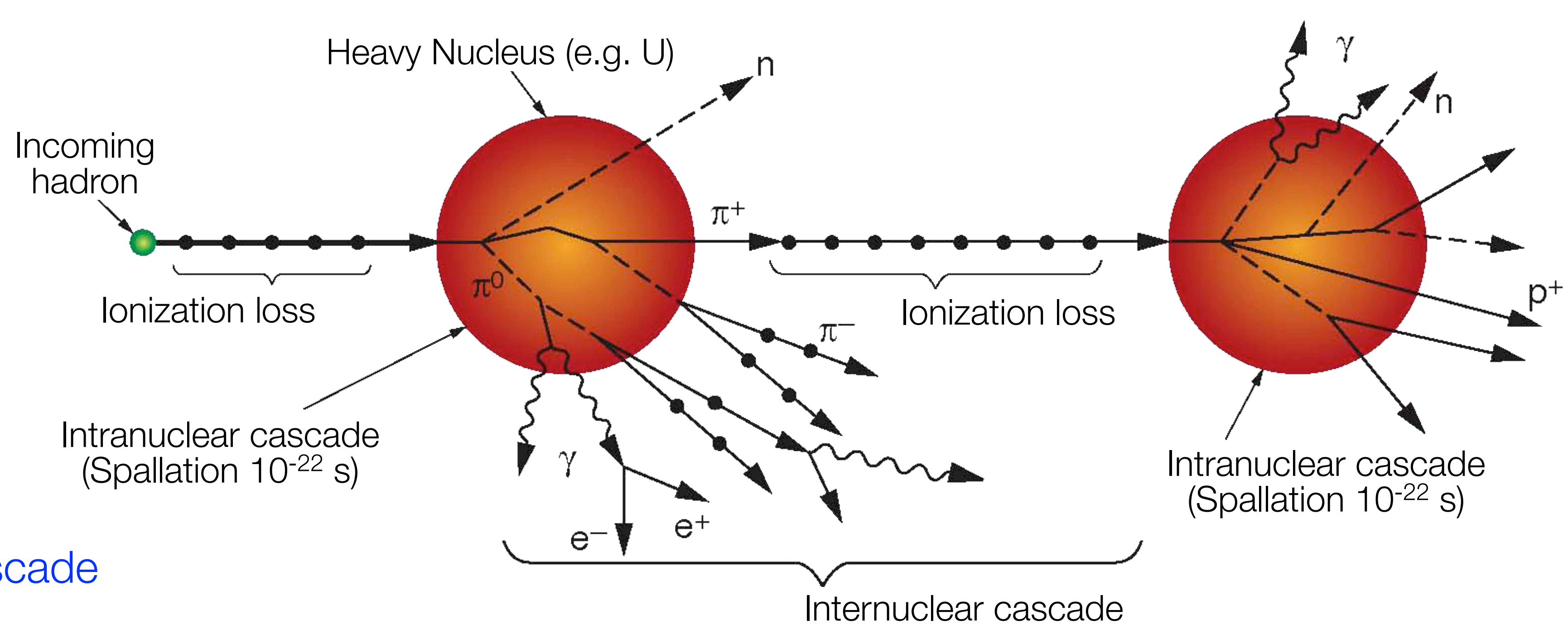
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

Inelastic:

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

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





A
Inter- and intranuclear cascade

TO BACKUP

Hadronic Showers

Hadronic interaction:

Cross Section:

at high energies
also diffractive contribution

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

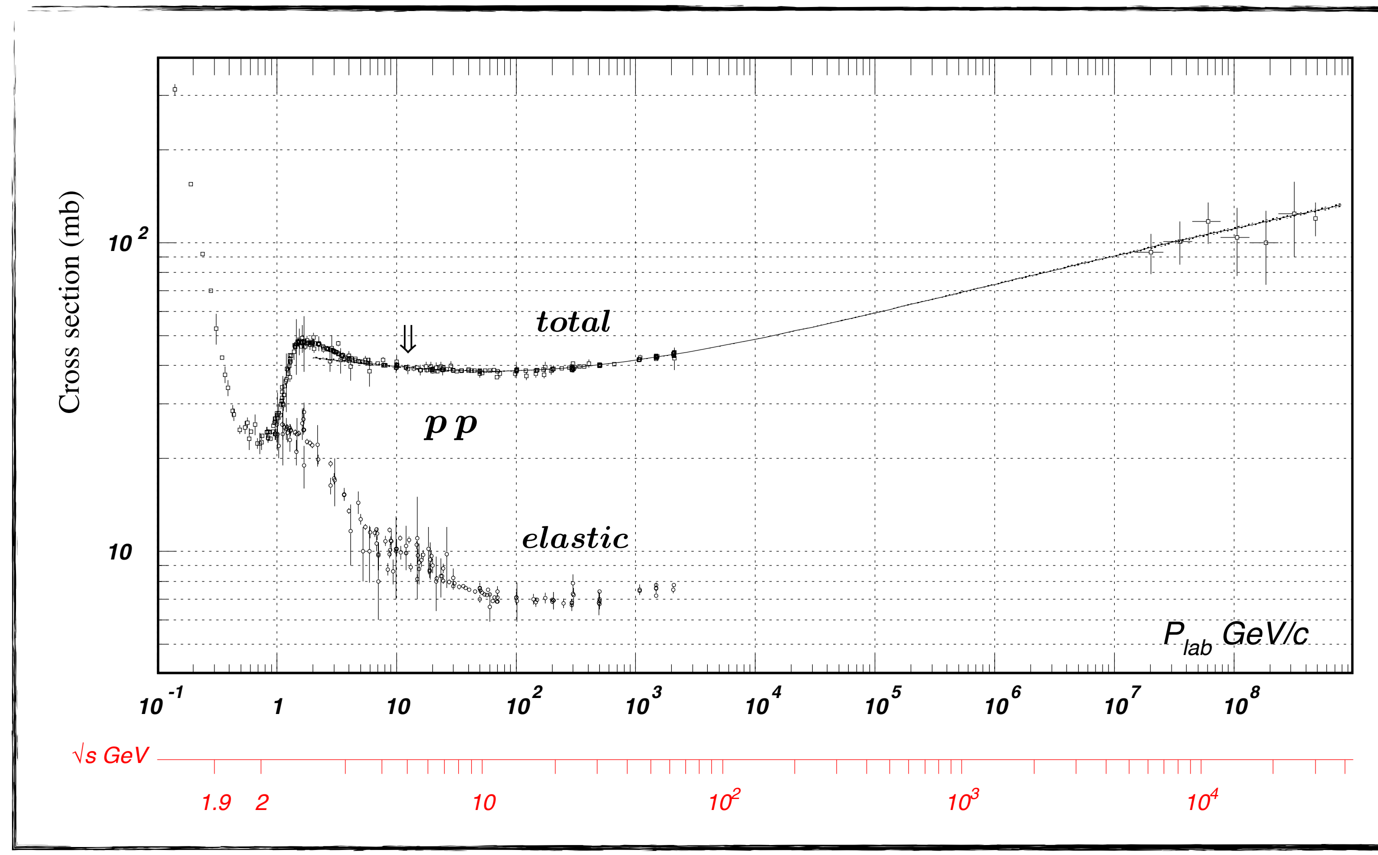
For substantial energies
$\sigma_{\rm inel}$ dominates:

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

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

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

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



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

Hadronic interaction length:

$$\lambda_{\rm int} = \frac{1}{\sigma_{\rm tot} \cdot n} = \frac{A}{\sigma_{pp}\, A^{2/3} \cdot N_A \rho} \sim A^{1/3}$$

[for $\sqrt{s} \approx 1 - 100$ GeV]

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

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

which yields:

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

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

Hadronic Showers

Hadronic vs. electromagnetic interaction length:

$$X_0 \sim \frac{A}{Z^2}$$

$$\lambda_{\text{int}} \sim A^{1/3}$$

$$\rightarrow \quad \frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3}$$

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

[λ_{int}/X_0 > 30 possible; see below]

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

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

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 shower development:

[estimate similar to e.m. case]

Depth (in units of λ_{int}):

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

Energy in depth t:

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

[with E_{thr} ≈ 290 MeV]

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

Shower maximum:

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

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

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

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

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 $\pi^0 \to \gamma\gamma$ increases with energy ...

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

Explanation: charged hadron contribute to electromagnetic fraction via $\pi^- p \to \pi^0 n$; 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

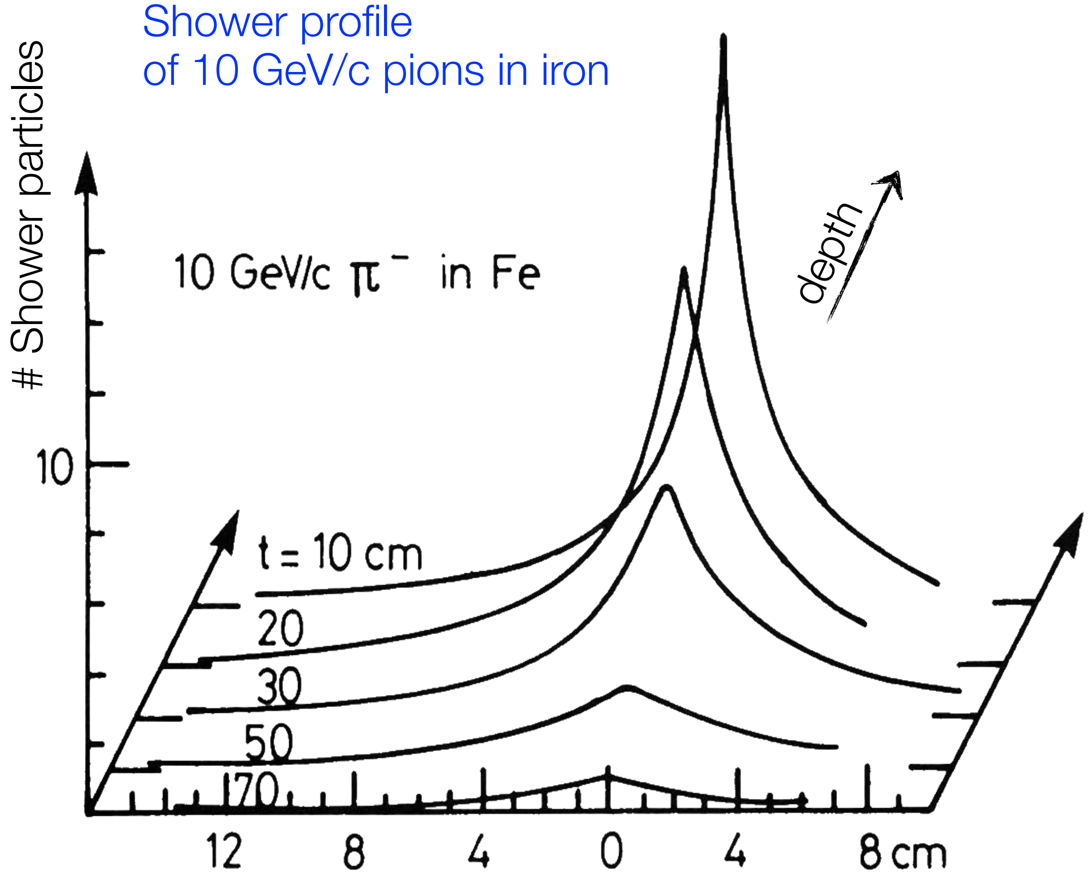
Typical transverse momenta of secondaries: $\langle p_t \rangle \simeq 350 \mathrm{MeV}/c$ ...

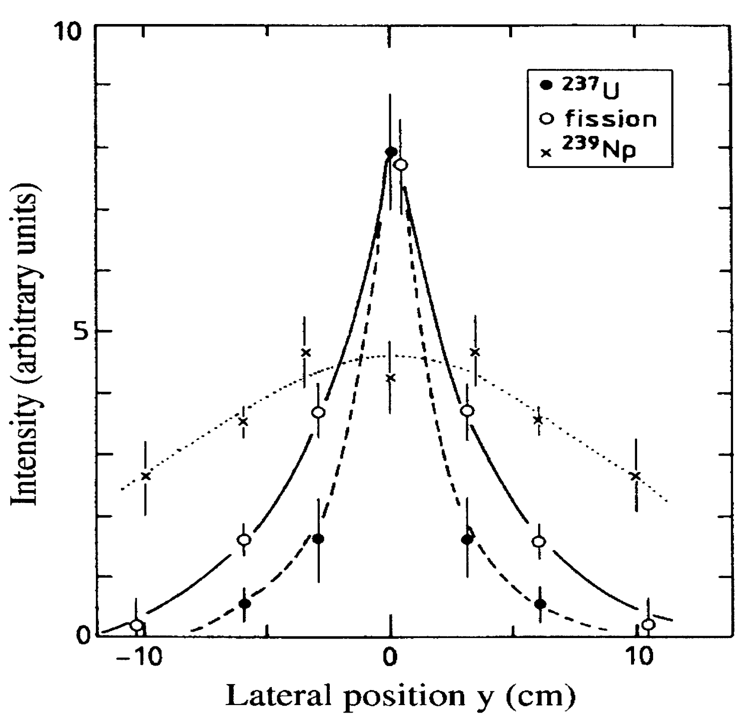
Lateral extend at shower maximum: $R_{95\%} \simeq \lambda_{int}$ ...

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

Exponential decay after shower maximum ...

Shower profile of 10 GeV/c pions in iron





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(γ,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]

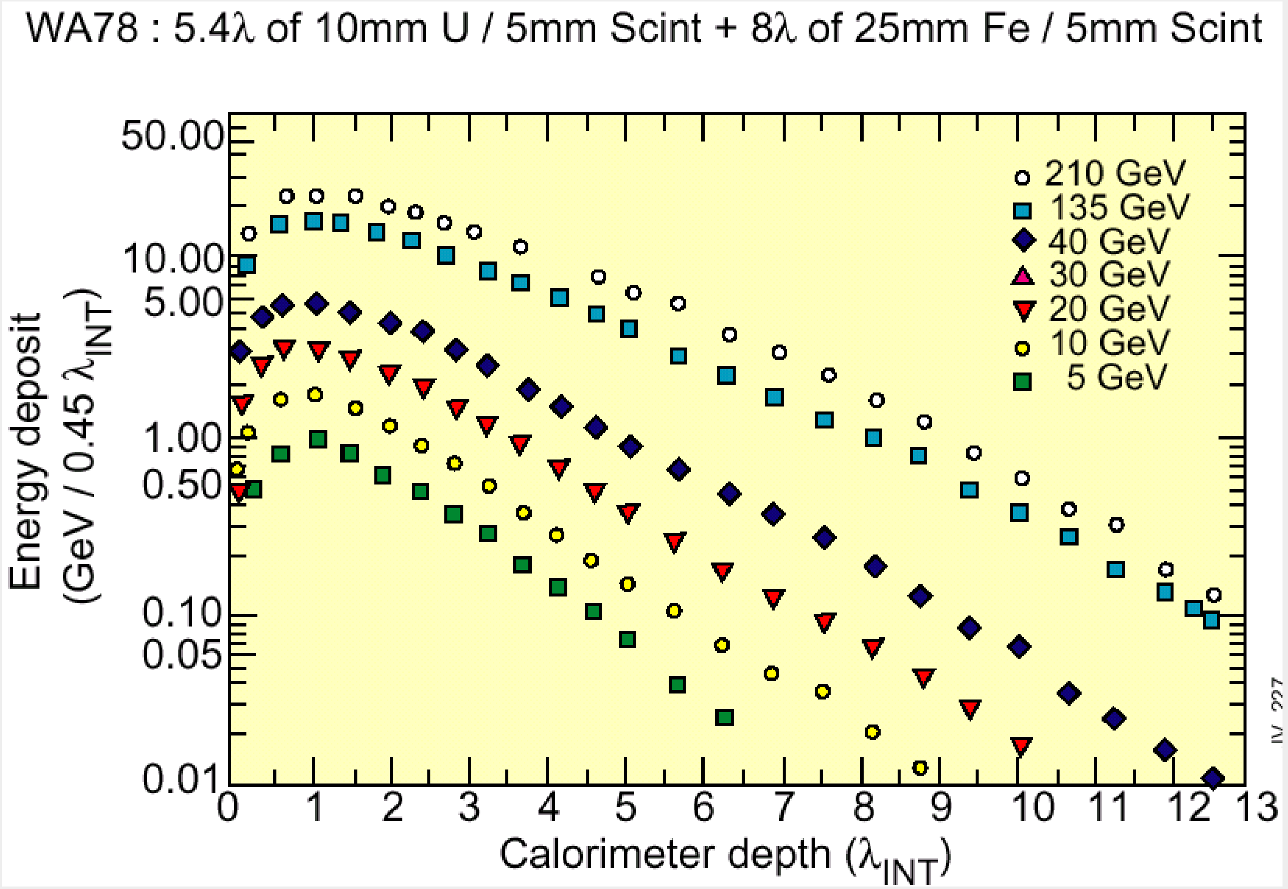
B: 0.03 – 0.05

C: few %

Hadron shower profile

LONGITUDINAL

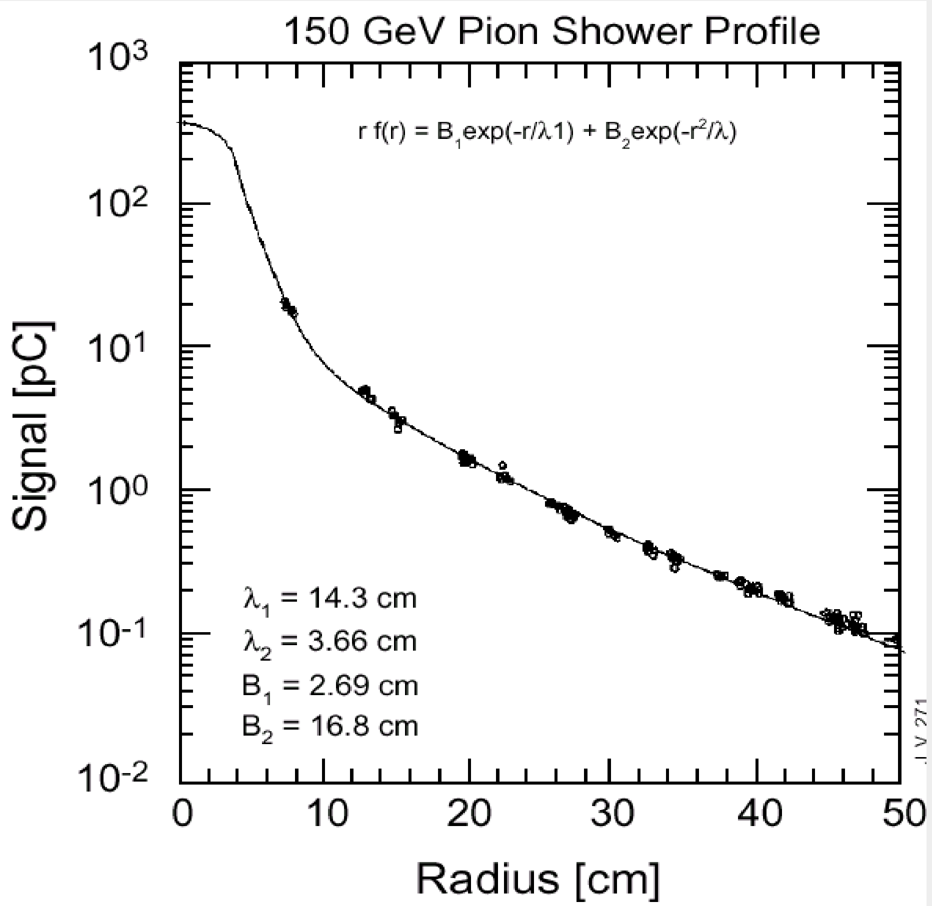
- **Sharp peak from π^o from the 1° interaction**
- **Gradual extinction with typical scale λ_{int}**



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

LATERAL

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



Transverse radius for 95%E containment ~1λ

Need to sample

BACK

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*	$\approx \mathrm{const}$
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

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]

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 ....

Shower leakage:

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

Lateral leakage: limited influence
Longitudinal leakage: strong influence

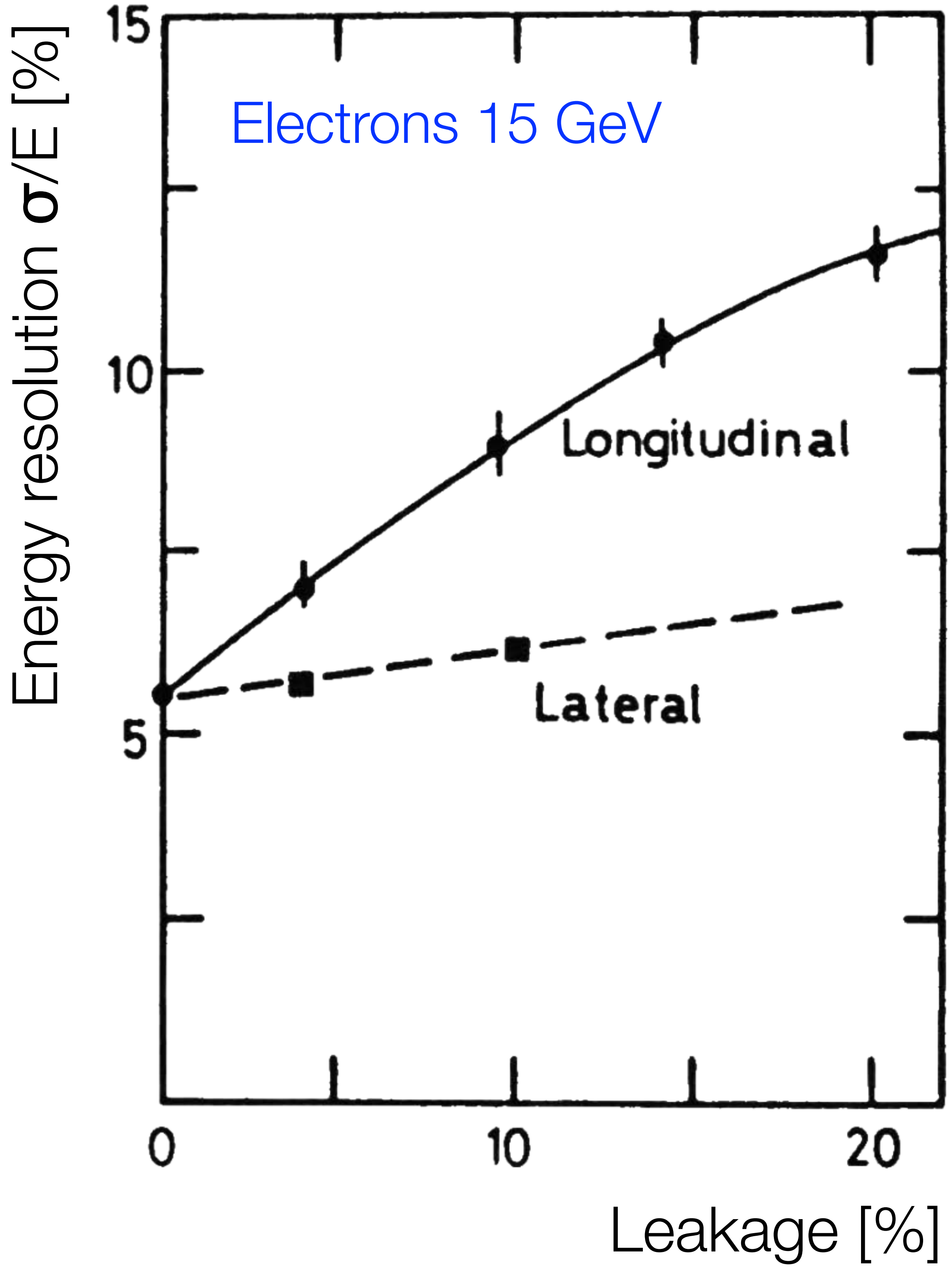
Typical expression when including leakage effects:

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

[f: average fraction of shower leakage]

Remark: other parameterizations exist ...

Marmor Calorimeter
[CHARM Collaboration]



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)

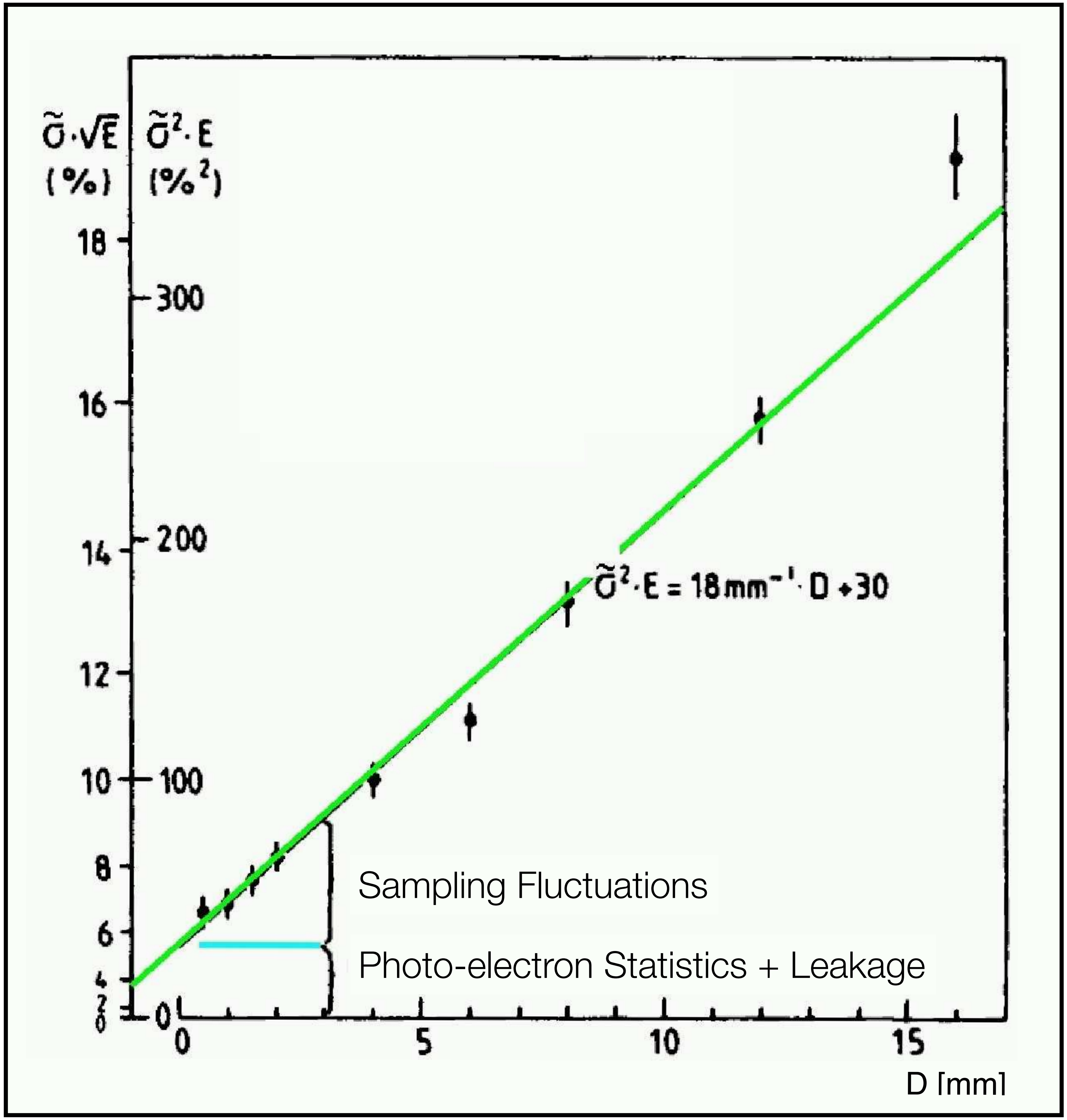
Semi-empirical:

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

where F takes detector threshold effects into account ...

Energy resolution

Measure energy resolution
of a sampling calorimeter for
different absorber thicknesses



Sampling contribution:

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

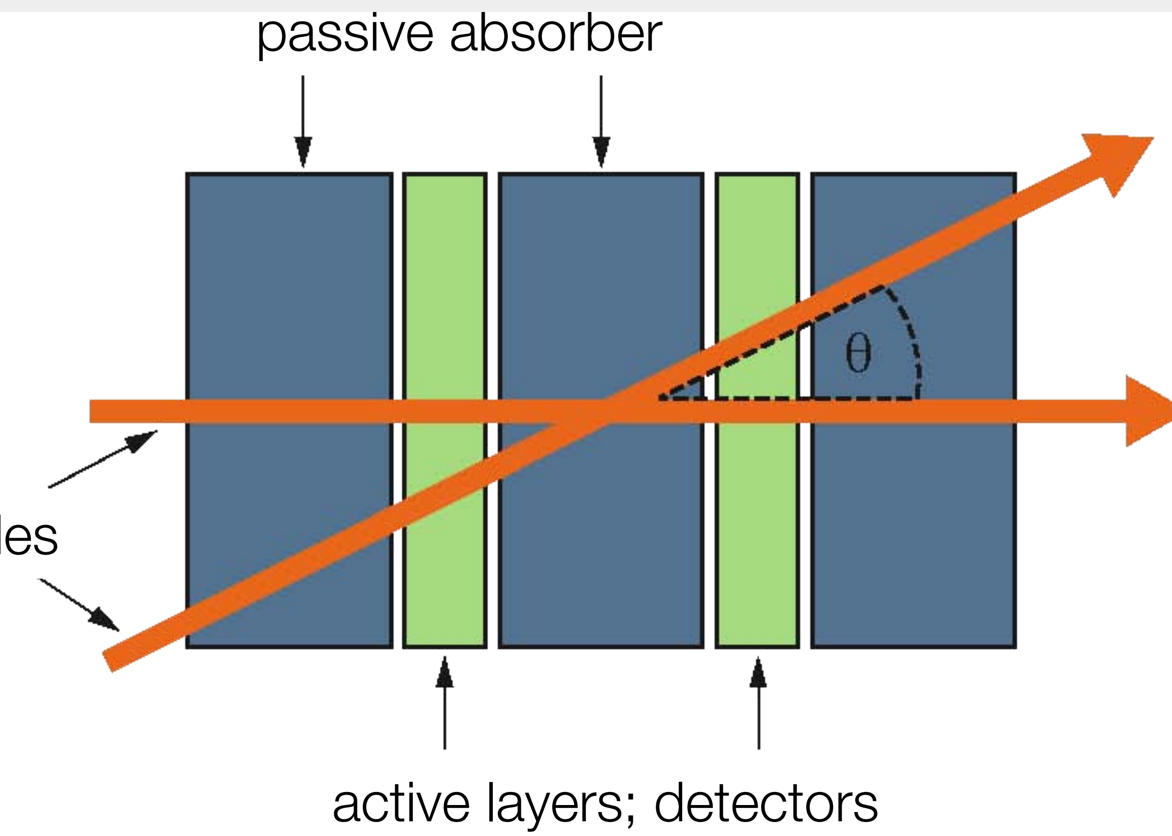
Track length fluctuations:

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

➛ Different effective absorber thickness:

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

[Enters sampling (and Landau) fluctuations]



Landau fluctuations:

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

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

[semi-empirical]

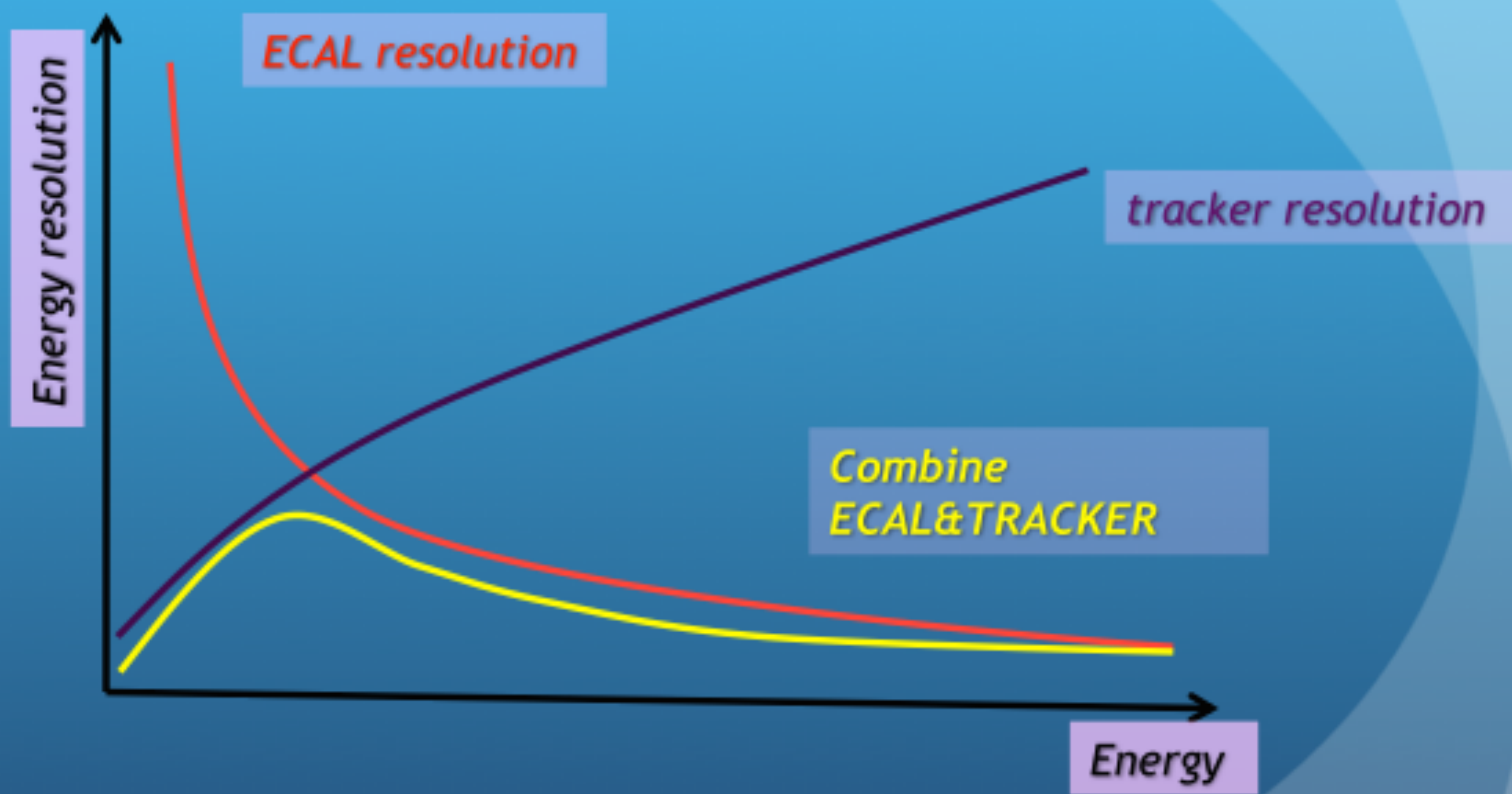
with:

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..



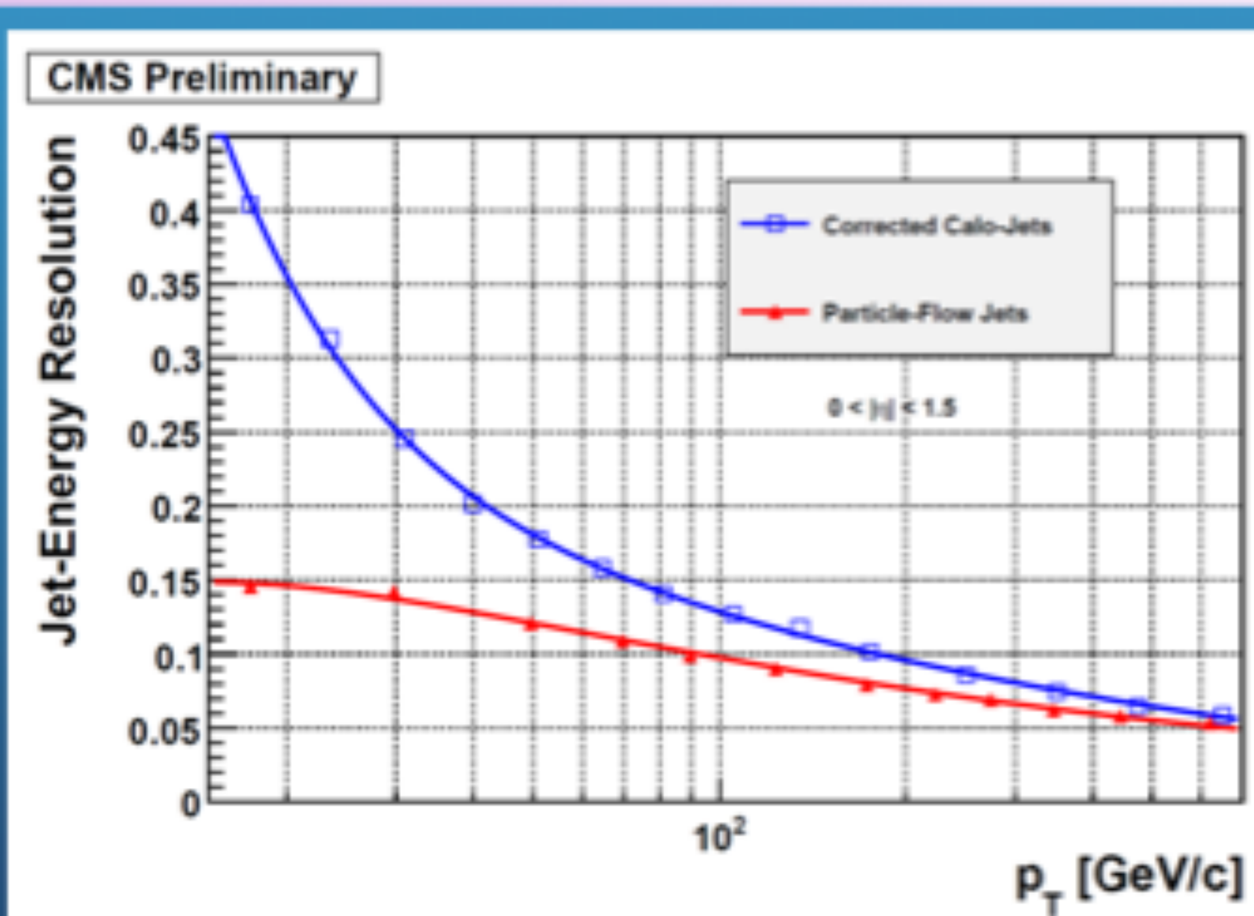
Combining subdetectors info: get a much better resolution on single object

TO BACKUP

Particle Flow Calorimeter

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

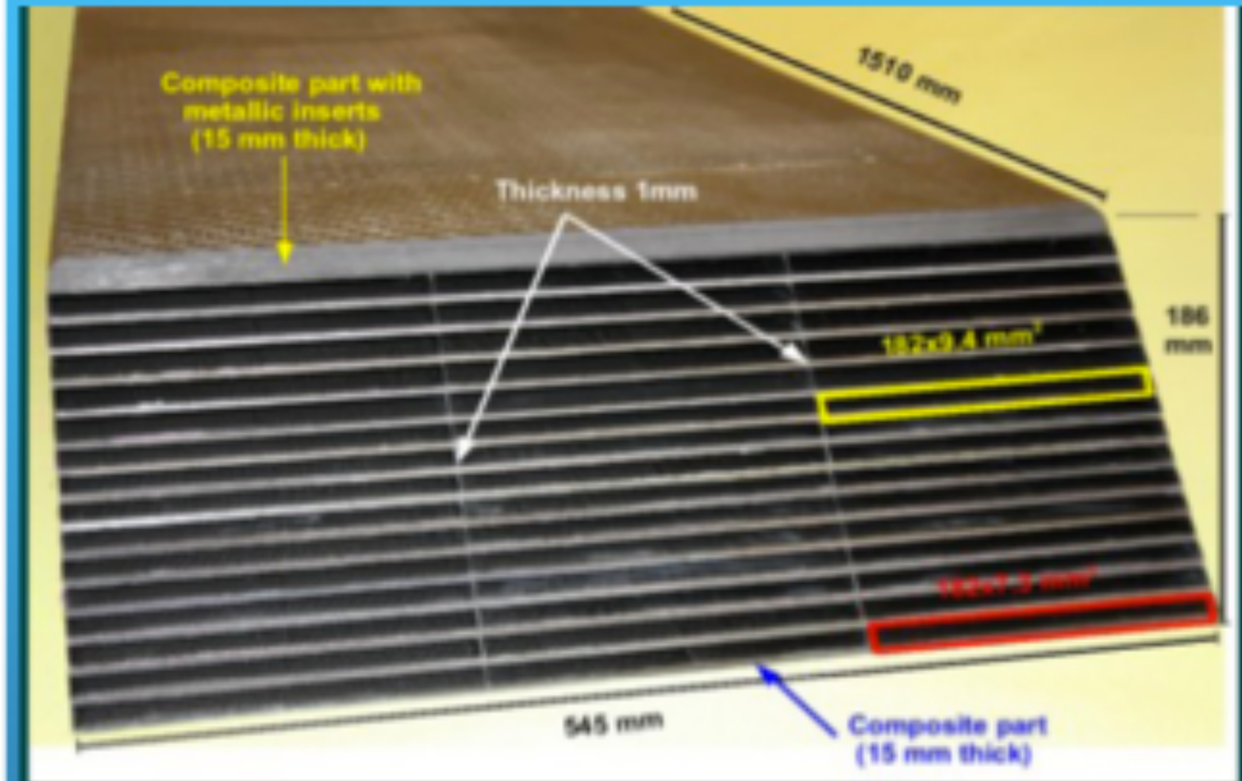
- Use **adapted calibration** for each objects electrons/photons/jets (avoid bias in energy response)
- Get the **best resolution from track** on charged particles (65% of a jet!)
- EM part measured **precisely by the ECAL** (neutral pions = 25% of jet)
- **Deduce neutral energy** from previous info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



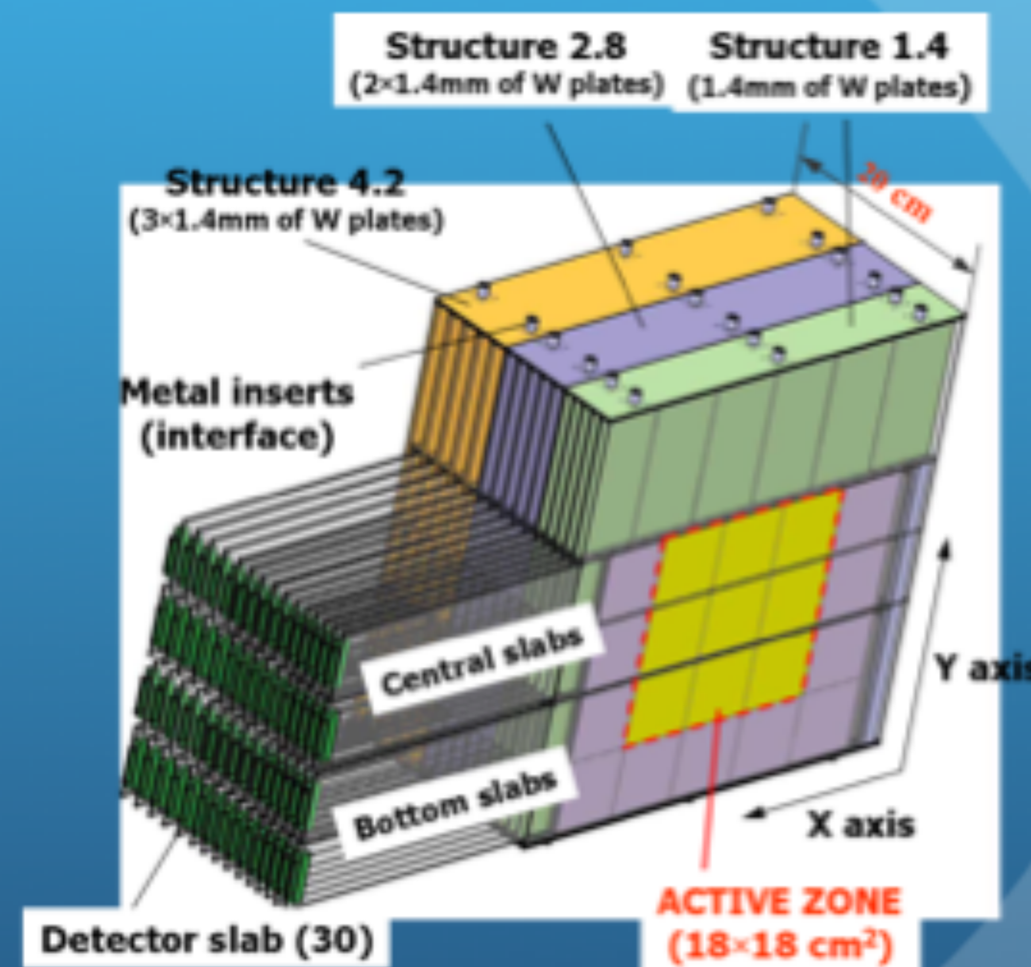
Example of performance on CMS jet energy resolution

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.

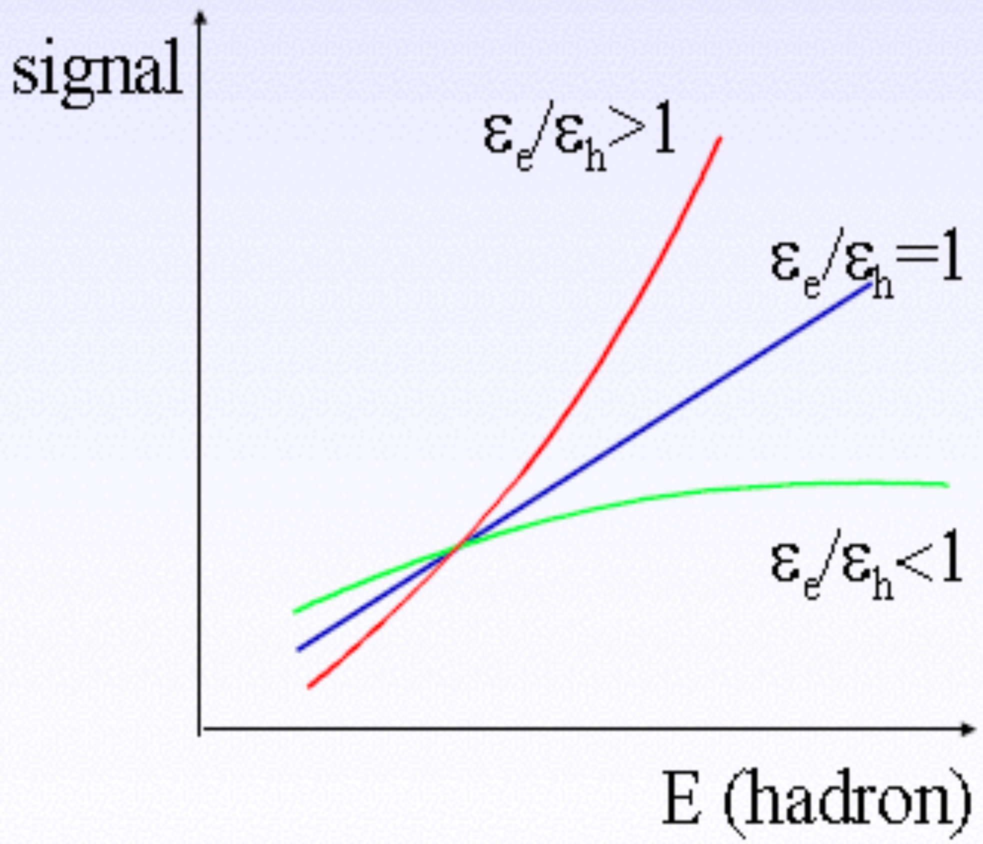
$$R_h = \varepsilon_h E_h + \varepsilon_e E_e$$

ε_h: hadron efficiency
ε_e: electron efficiency

The fraction of the energy deposited hadronically depends on the energy (remember n(π^0))

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

$\rightarrow$ Response of calorimeter to hadron shower becomes non-linear



Energy resolution degraded !

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

TO BACKUP

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

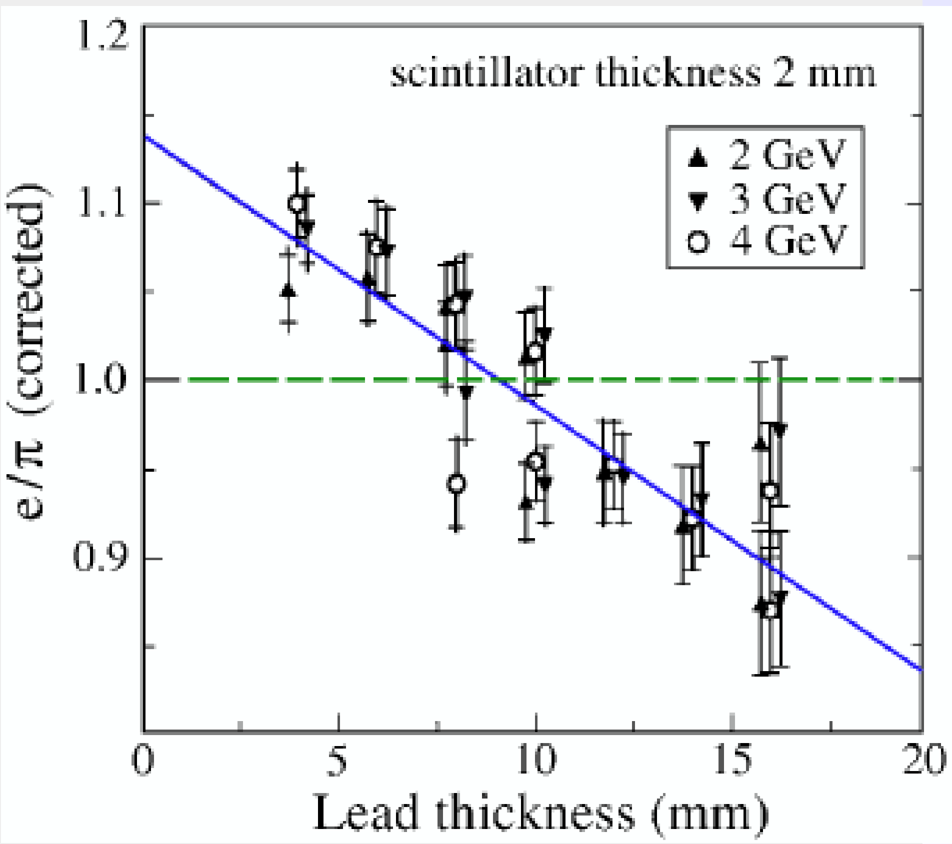
BACK

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

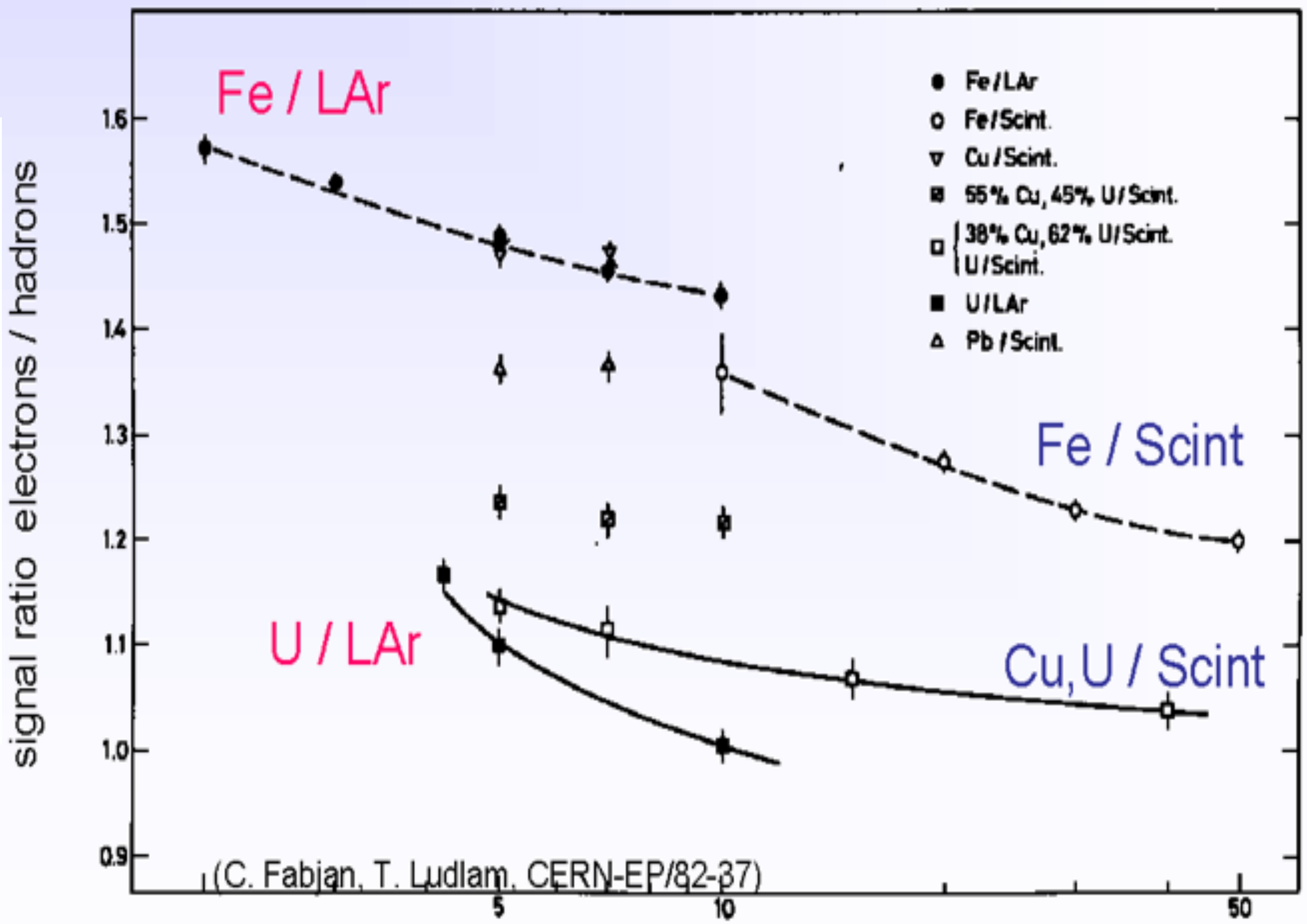
decrease ε_e : combine high Z absorber with low Z detectors. Suppressed low energy γ detection ($\sigma_{photo} \propto Z^5$)

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

Pb/Scintillator



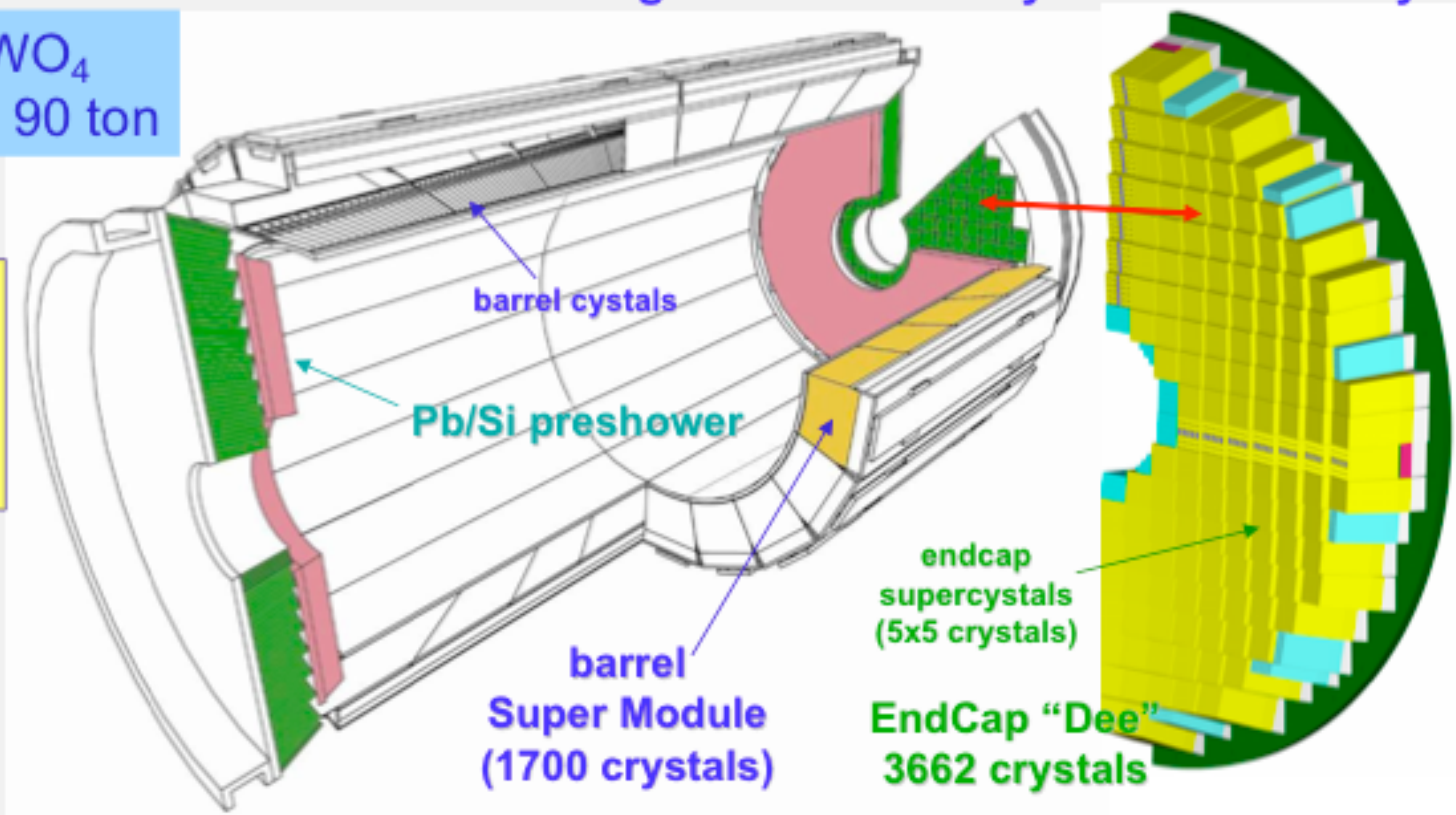
Sampling fraction can be tuned to achieve compensation



Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m³, 90 ton

Previous Crystal calorimeters: max 1m³



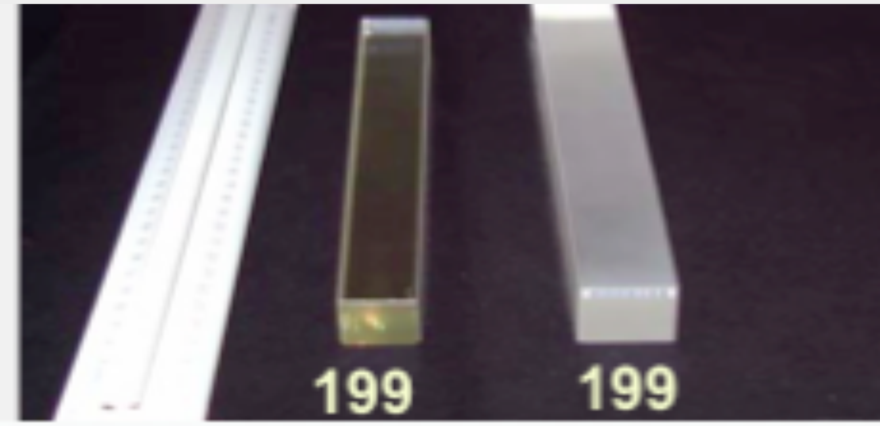
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³)

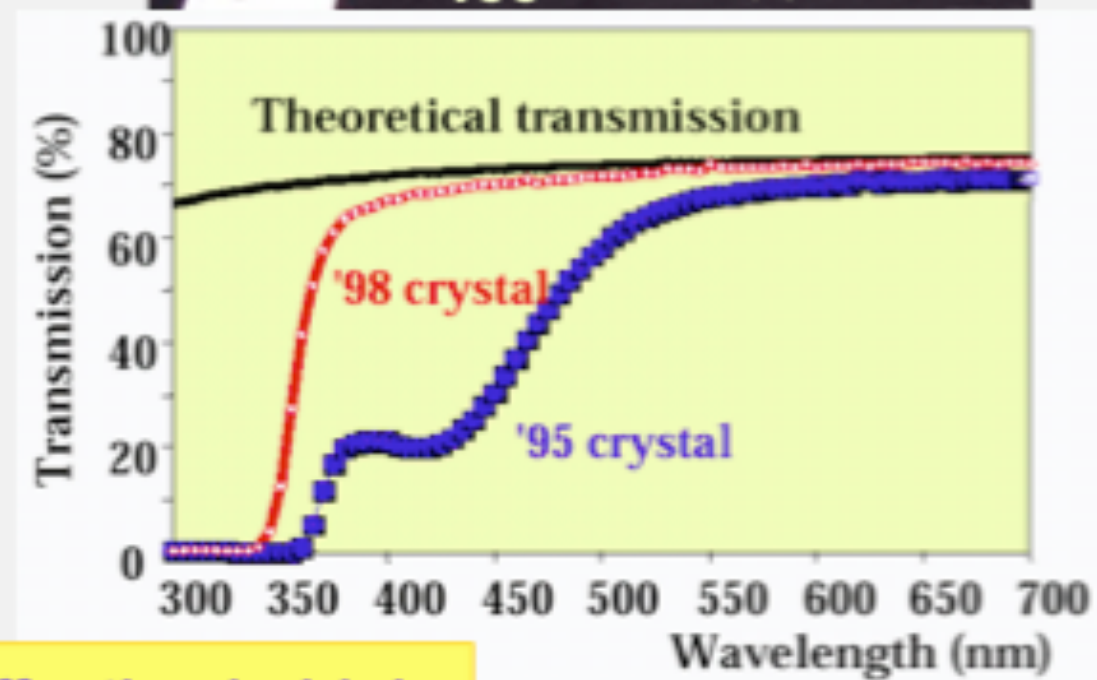
EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22cm³)

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



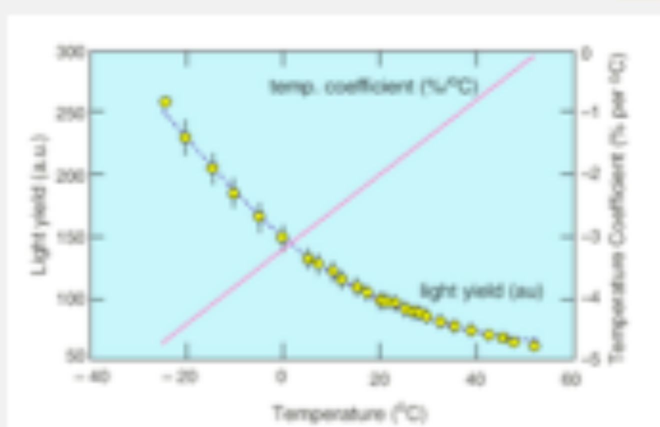


Very low light output

Hard light extraction

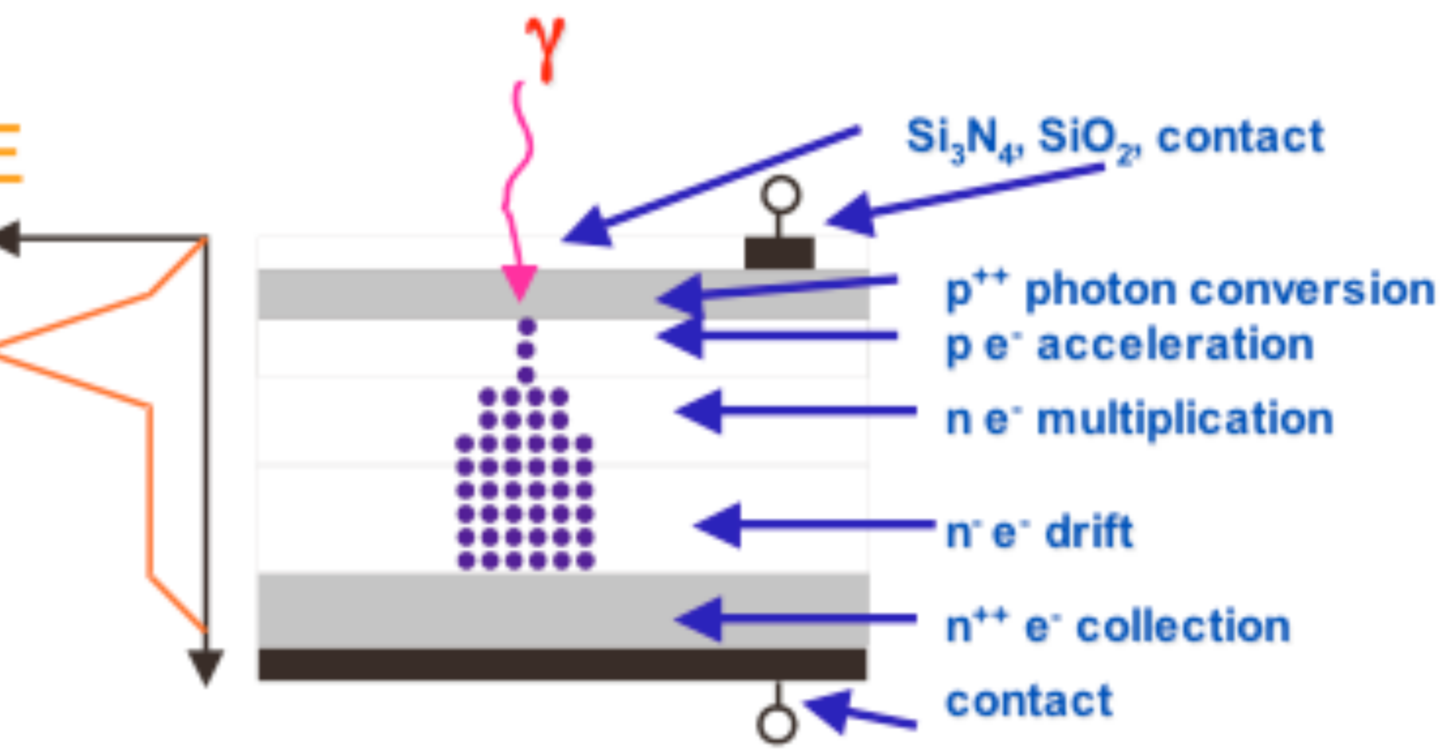
Very effective in high energy γ containment

T dependent: -2%/°C

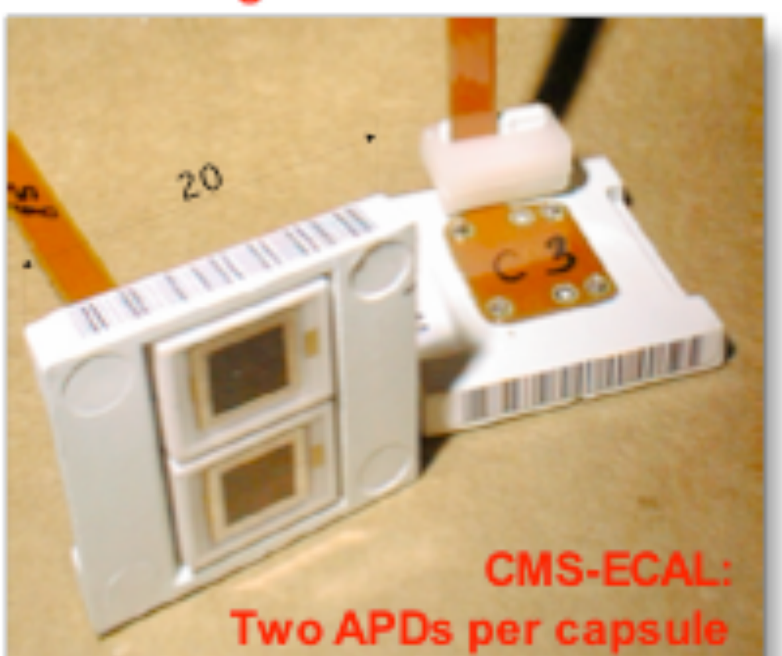


23 cm to contain em showers!

Avalanche Photo Diodes



Internal gain=50 for V=380 V

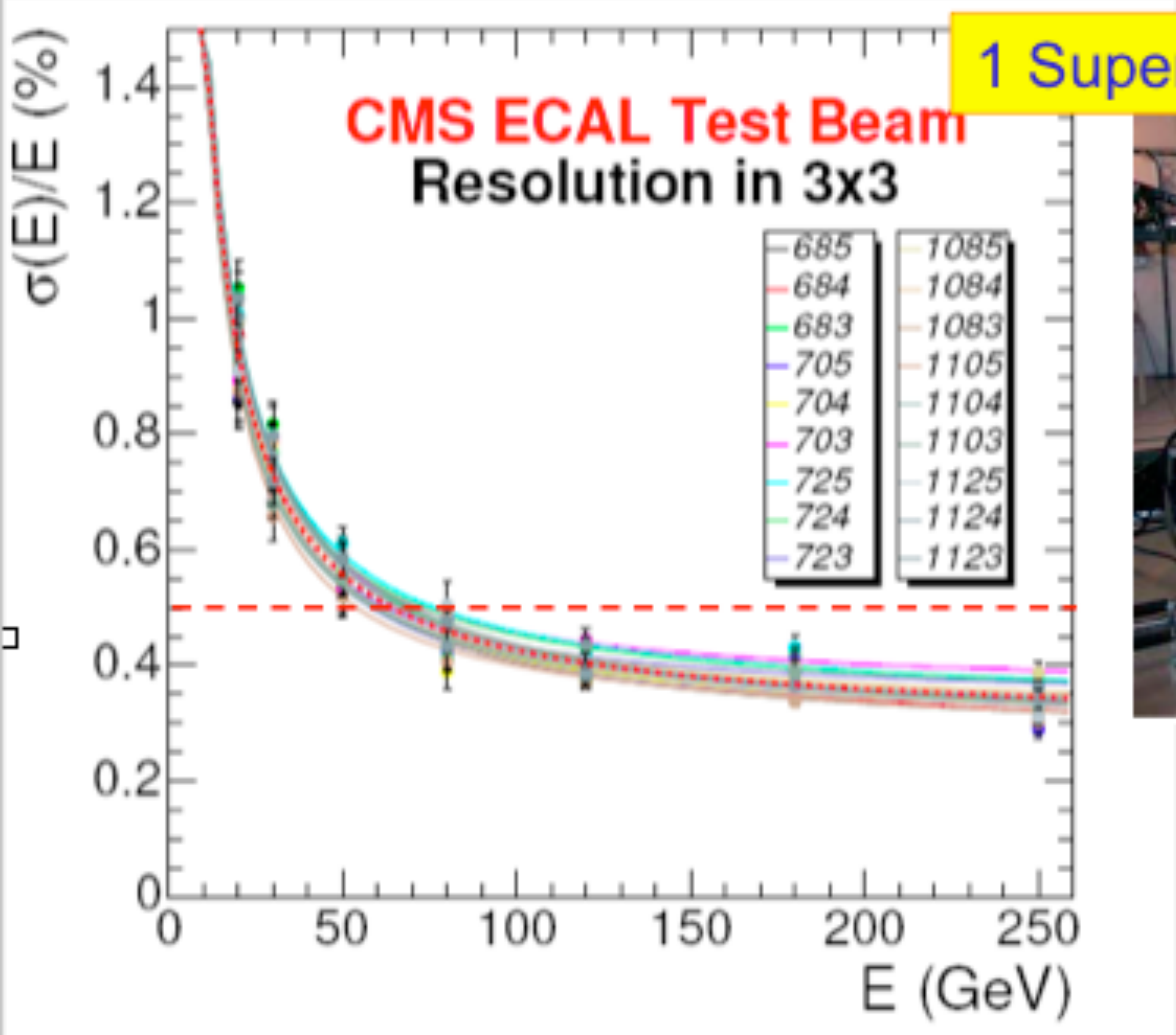


$N_{photons}$/MeV x Light-collection-efficiency (2 APDs) x QE
≈ 5 photo-electrons/MeV (in CMS-ECAL)

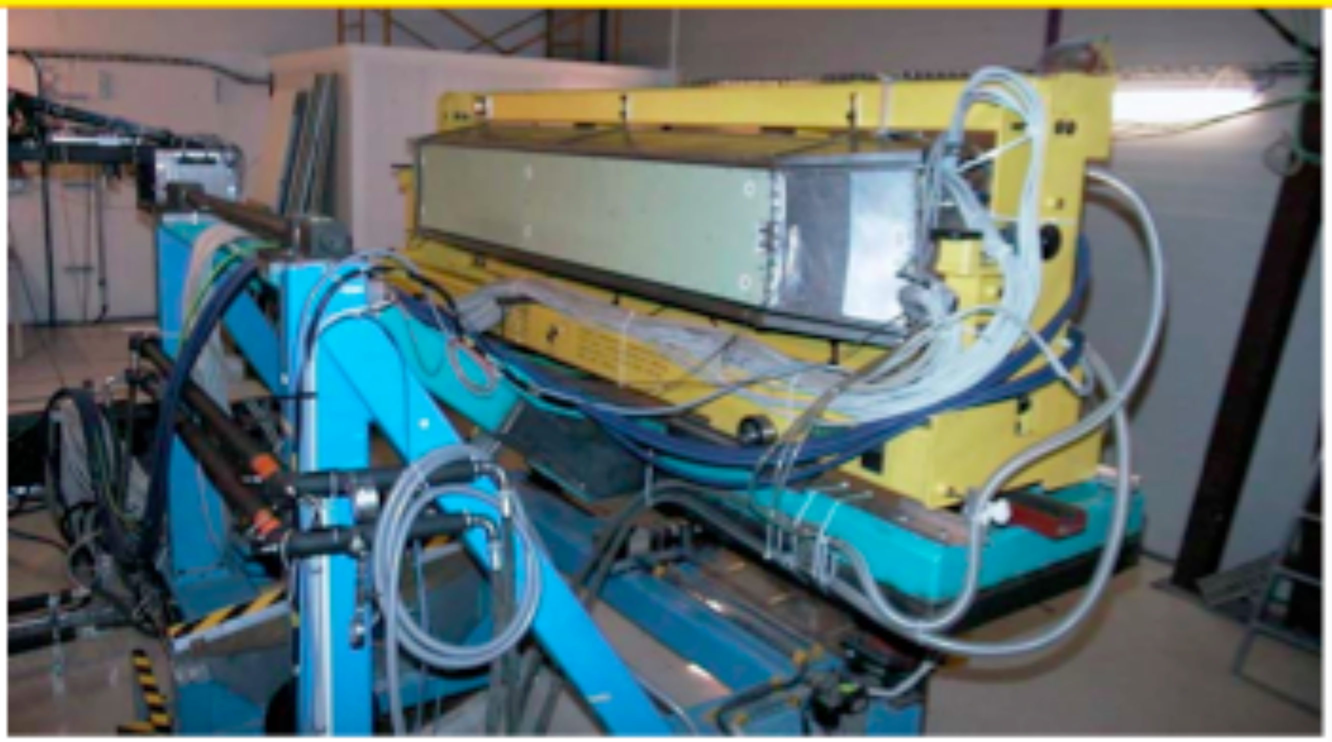
- Drawback of $PbWO_4$:
  Low light yield
  - → Need photodetectors **with intrinsic gain** (+radiation hard, +insensitive to magnetic field)
- Choice for CMS-ECAL Barrel and ALICE PHOS:
  Avalanche Photo Diodes (APD
  - rad. hard, fast (few ns)
  - Quantum efficiency (QE, photon conversion into electrons) : ~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!

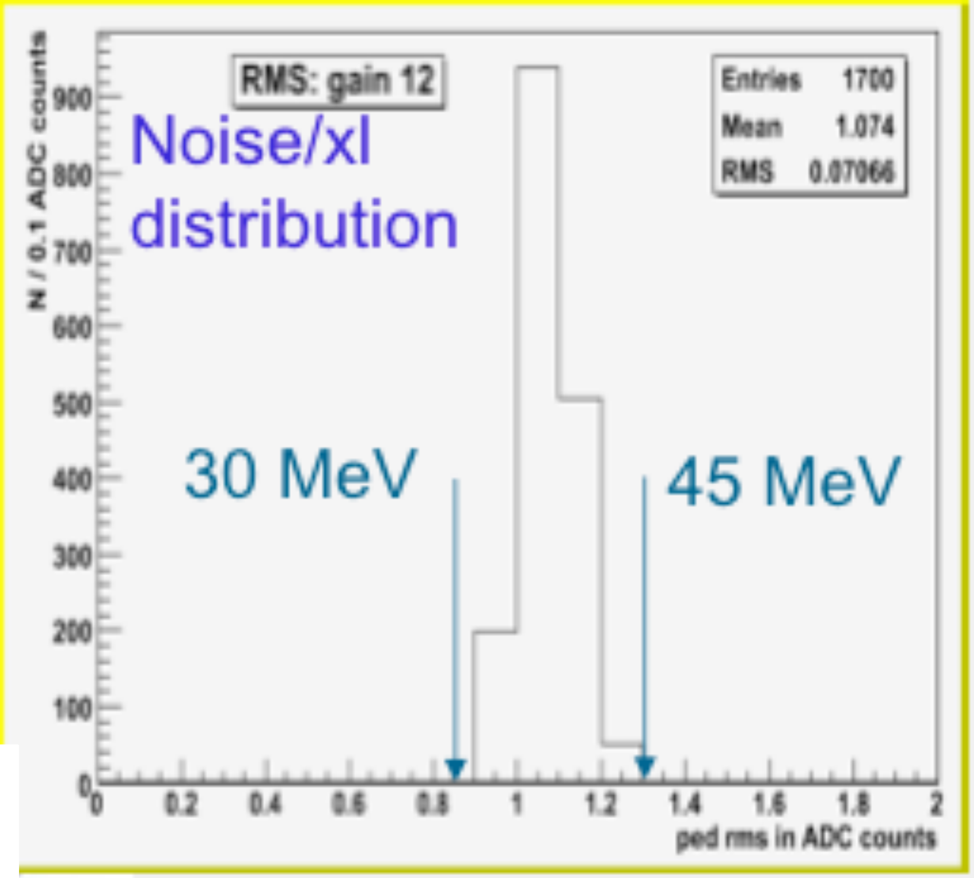
Performance of the CMS ECAL



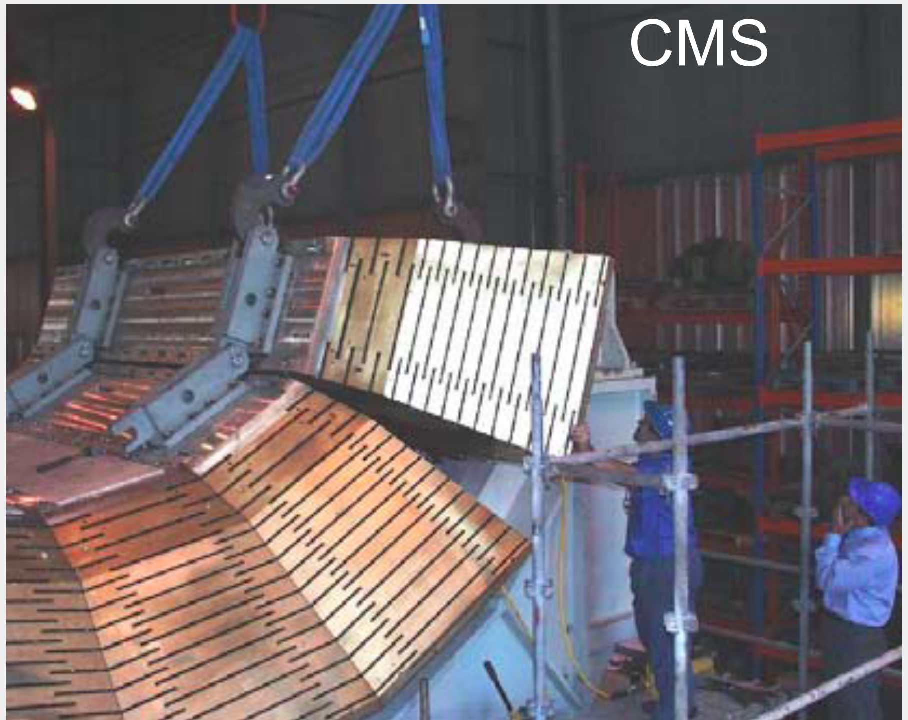
1 Super Module 1700 xl on test beam in 2004



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



CMS Hadron Calorimeter

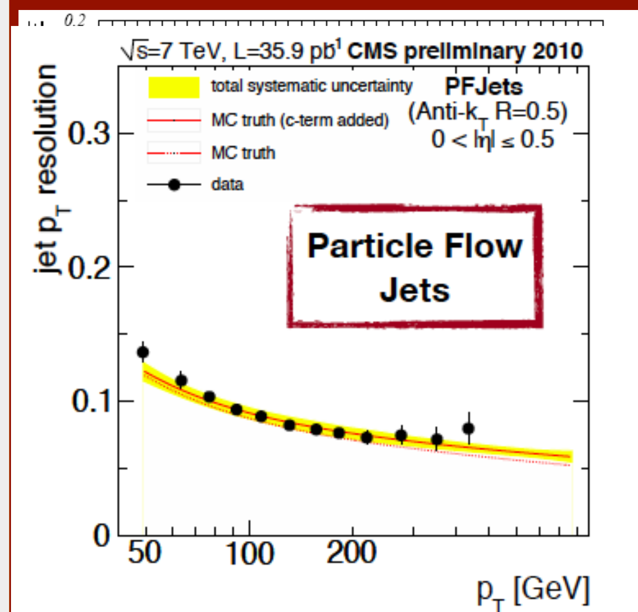


5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

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

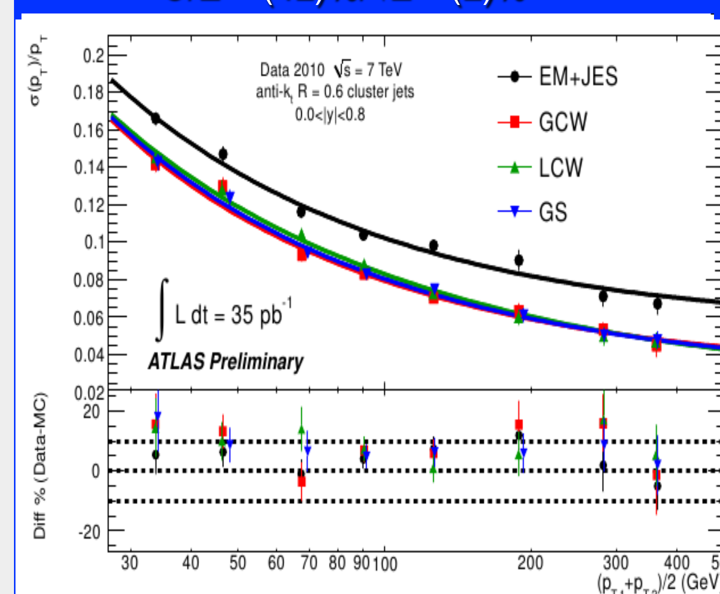
CMS

- 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)
  $\sigma/E = (42)\%/\sqrt{E} \oplus (2)\%$



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.

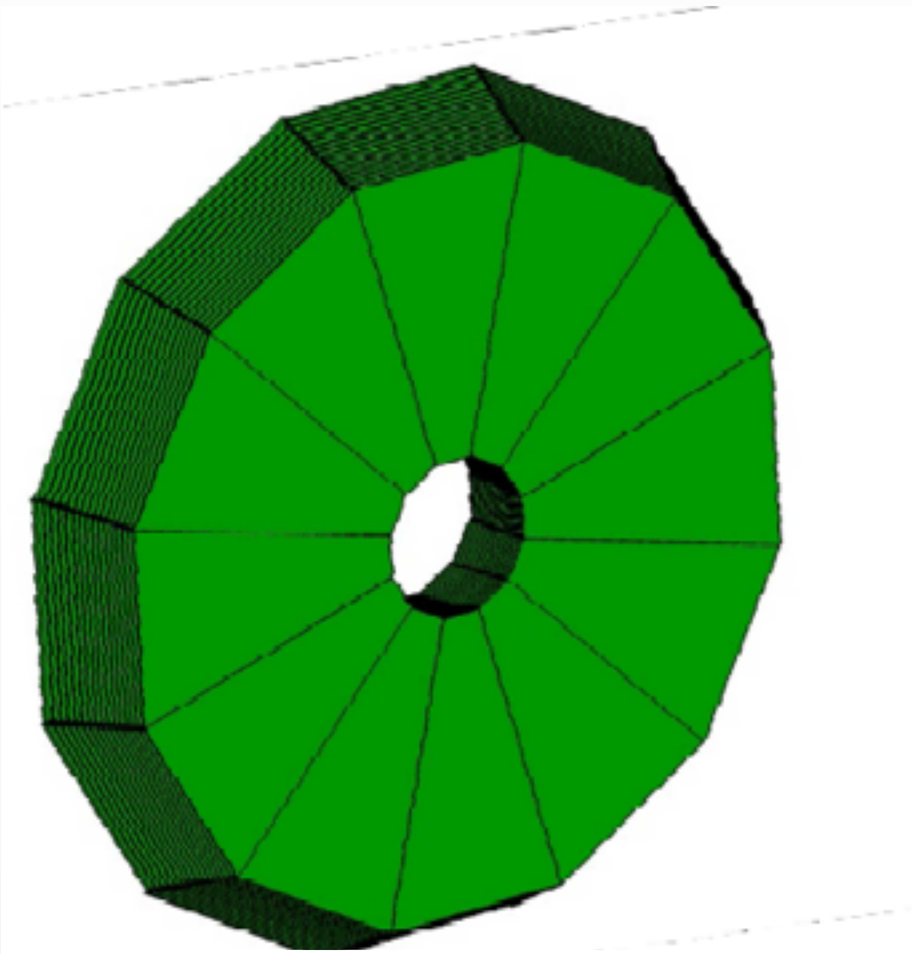
Why HGC?

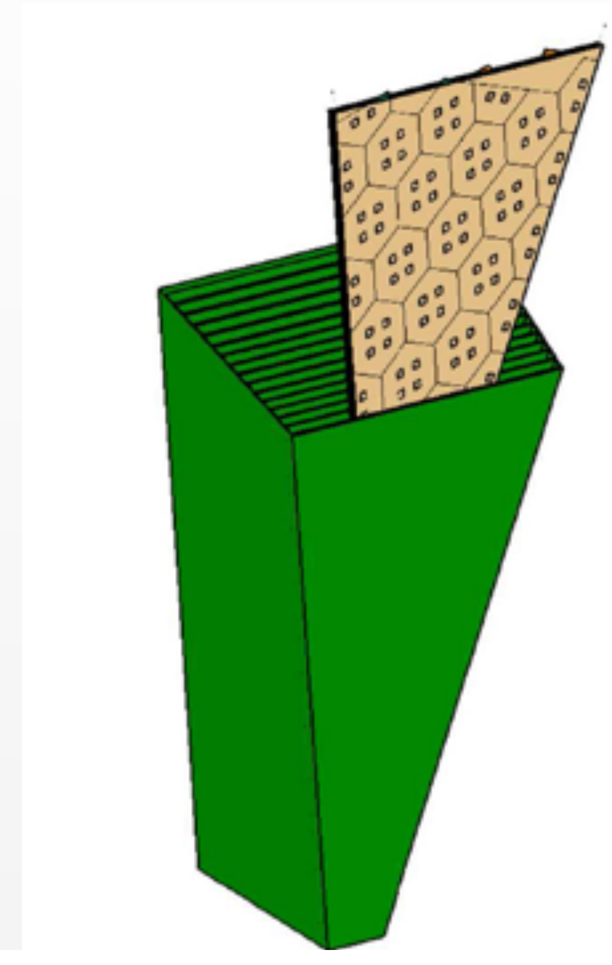
- Tracking Jet shower development as function of depth in order to
  - Unfold the effect of non-projective geometry
  - Apply PU subtraction, identify and measure the energy of (VBF) Jets using narrow cones
    - Layer-by-layer using knowledge of lateral and longitudinal Jet shapes and longitudinal PU 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

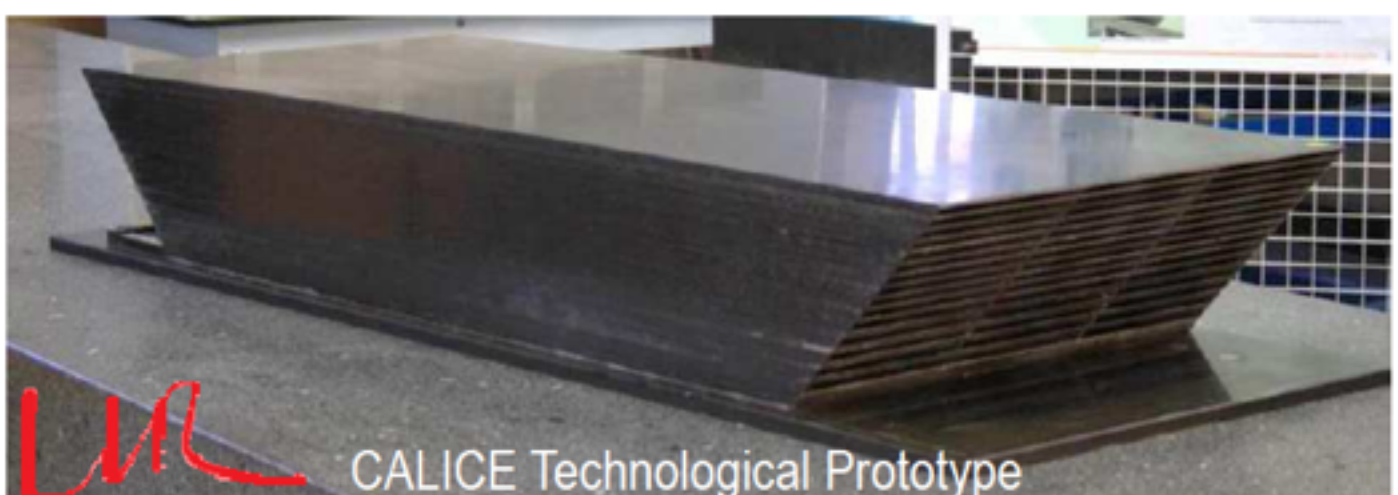
HGCAL Mechanical Design

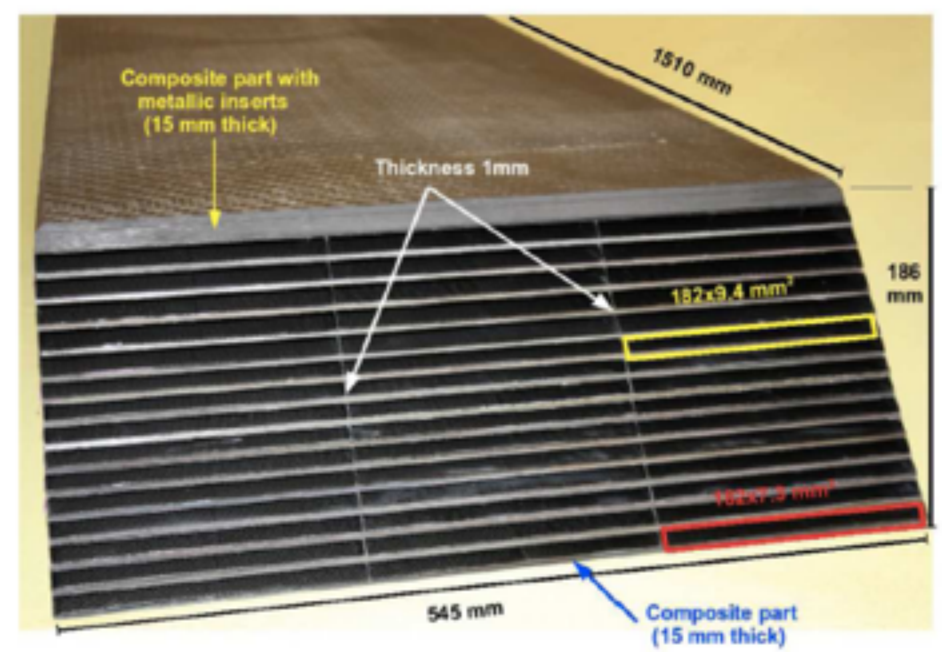
- Developed viable mechanical design, with independent Cassettes inserted into Alveolar support structures
  - Cassettes: Modules mounted on both sides of 6mm thick Cu plate, which integrates CO_2 capillary and cooling pipes
  - EE CF/W composite Alveolar structure based on CALICE design
    - Geometry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

HGC Mechanical Design









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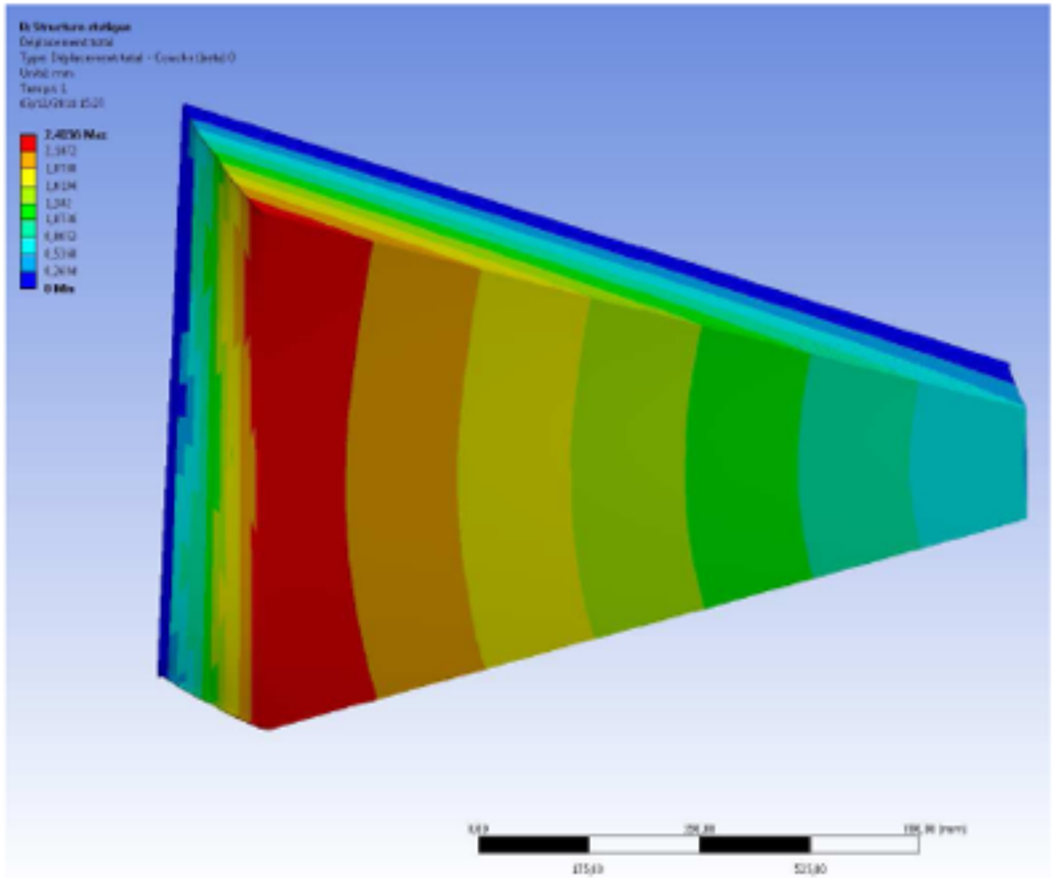
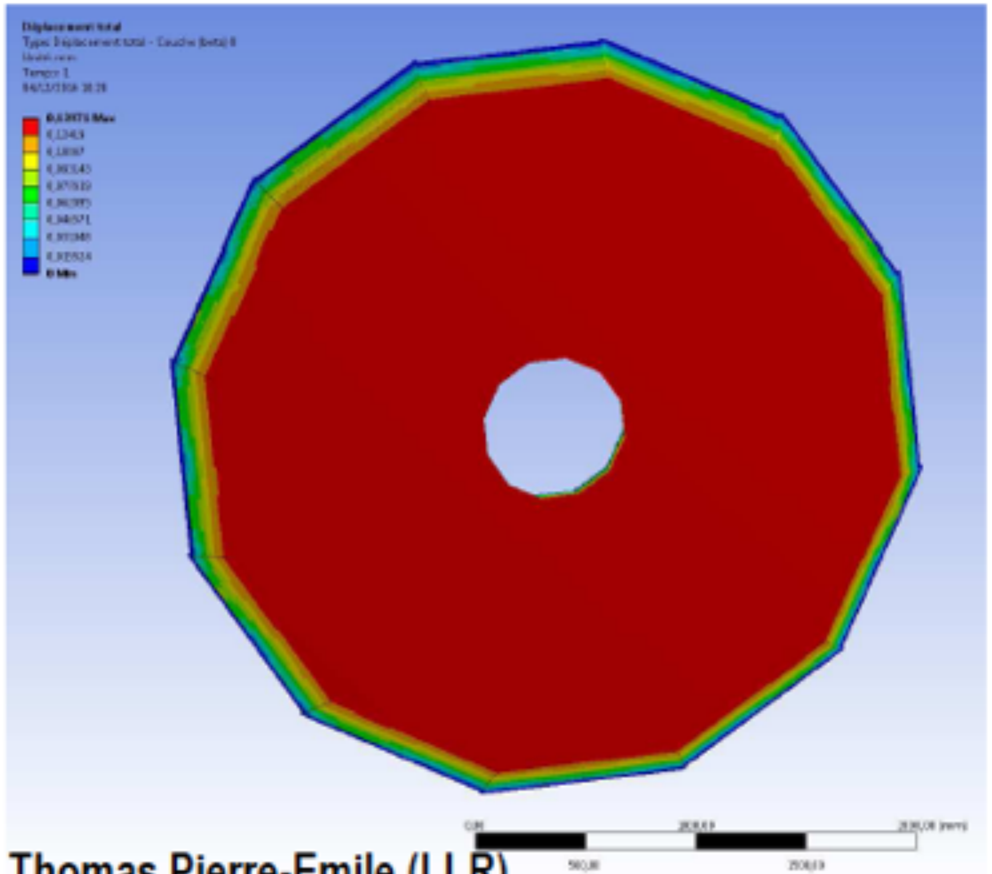
HGC Mechanical Design

Standalone wedge (at 270°)



Full "wheel"



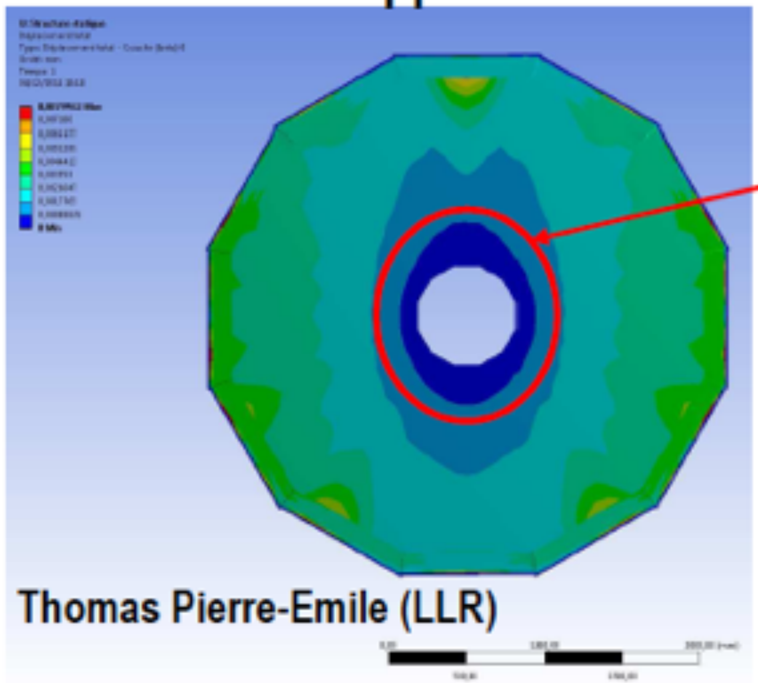
Thomas Pierre-Emile (LLR)

	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 %**

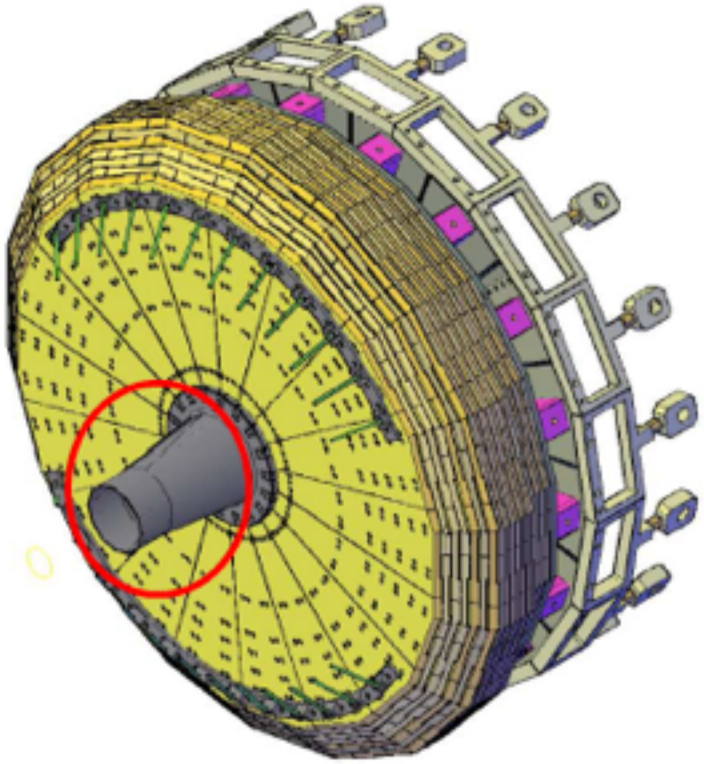
- **Failure occurs when failure criteria F ≥ 1**
- Margin of Safety ∝ $(1/\sqrt{F} - 1)$,
  - **200% is reasonable from engineering point of view**

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**) 9