Calorimetry

concept & examples

European School of Instrumentation
in Particle & Astroparticle Physics
ESIPAP 2014

Lecture 3

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Programme

Lesson 1

Why build calorimeters ?

Electromagnetic showers

Detection processes

EM calorimeters

Lesson 2

Hadronic showers & calorimeters

Jets

Missing Transverse Energy

CMS & ATLAS calorimeters

Lesson 3

Other calorimeters

Caolrimeter R&Ds for future colliders

$H \rightarrow \gamma\gamma$ & the EM calorimeter

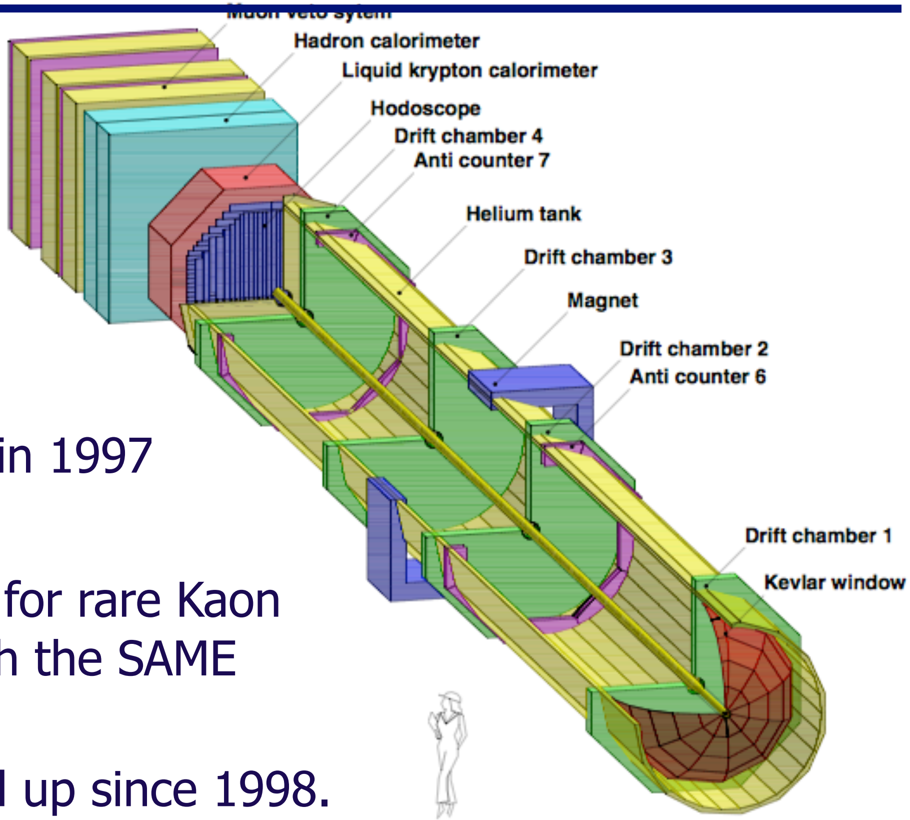
Tutorial

$H \rightarrow \gamma\gamma$ & the EM calorimeter

A few numbers

Existing Calorimeters

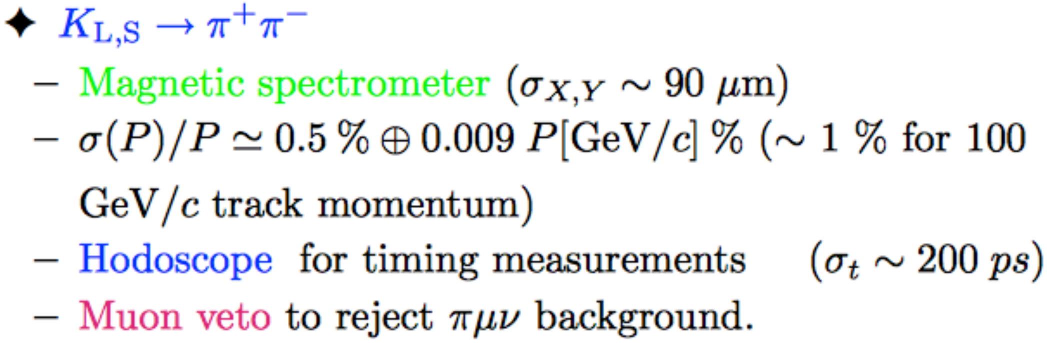
The NA48 experiment



NA48 experiment started data taking in 1997

Now the NA62 experiment, searching for rare Kaon decays is starting data taking with the SAME calorimeter using Liquid Krypton.

The calorimeter has not been warmed up since 1998.

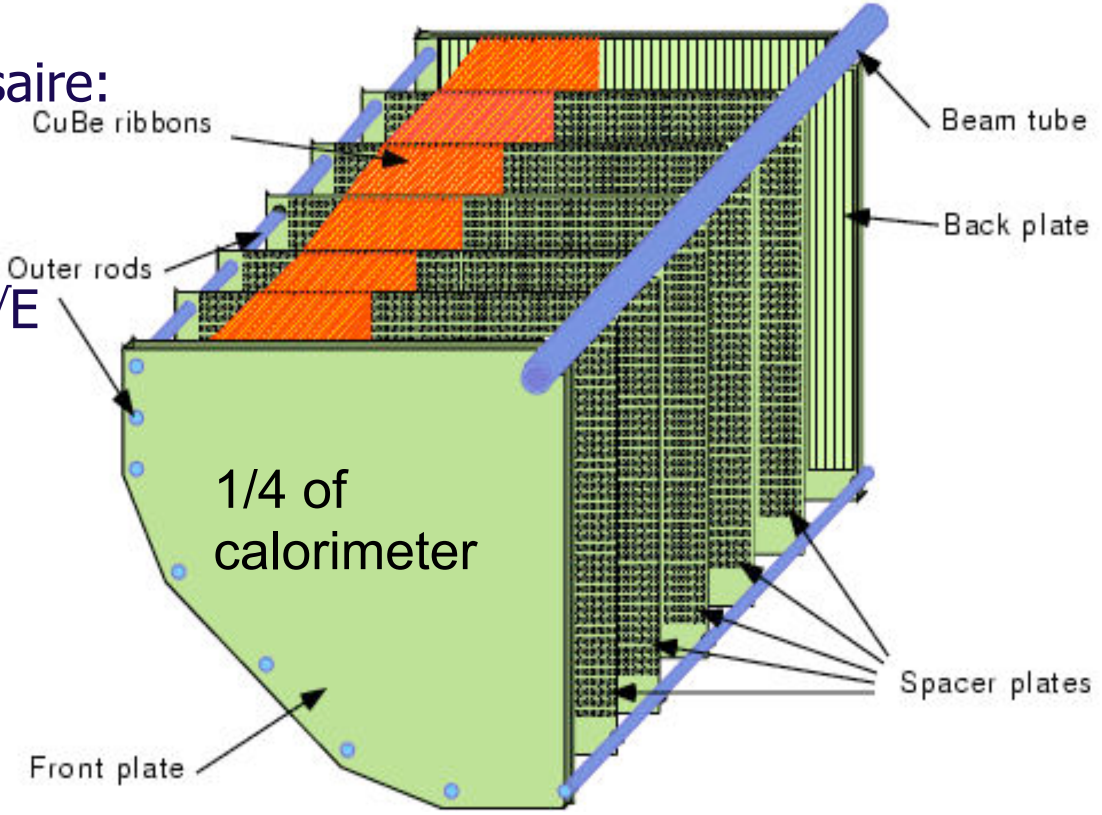


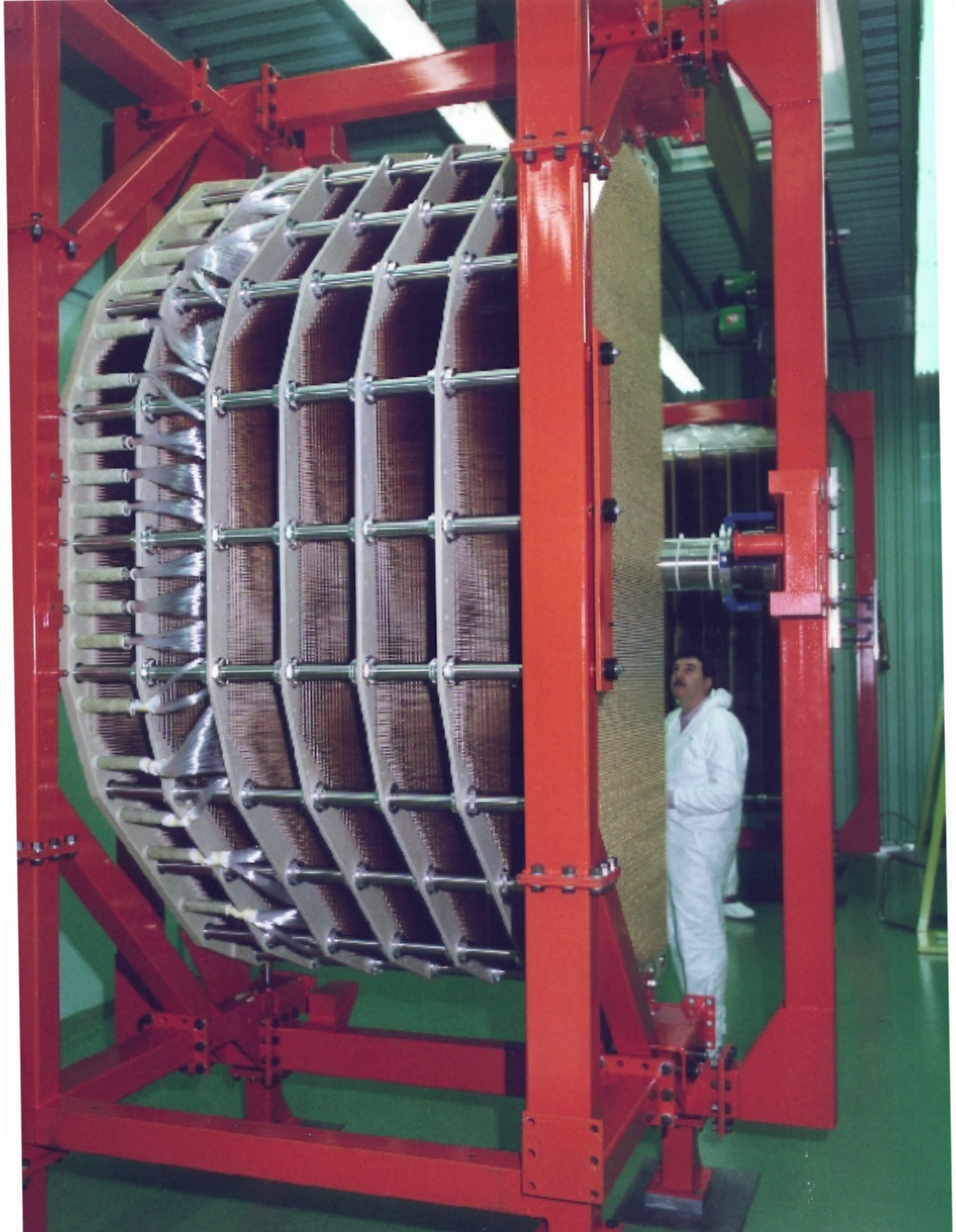
- $K_{L,S} \to \pi^+\pi^-$
  - Magnetic spectrometer ($\sigma_{X,Y} \sim 90\ \mu$m)
  - $\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\,P[\mathrm{GeV}/c]\,\%$ (~ 1 % for 100 GeV/c track momentum)
  - Hodoscope for timing measurements ($\sigma_t \sim 200\ ps$)
  - Muon veto to reject $\pi\mu\nu$ background.

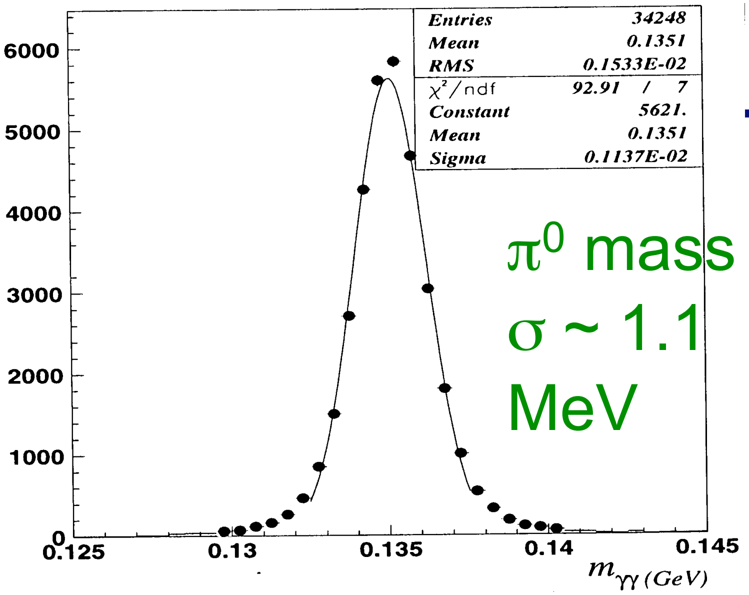
Le calorimètre à Krypton liquide de NA48

- NA48 a mesuré le Re(ε′/ε) ~10^{-4} en identifiant les modes $K_S \rightarrow \pi^0\pi^0$ et $K_L \rightarrow \pi^0\pi^0\pi^0$
- Résolution sur m(π^0) nécessaire: 1MeV (m(π^0) = 135MeV)
- Résolution en énergie 5%/√E
- Bain de LKr instrumenté d'électrodes en zig-zag pour collecter toutes les charges

Krypton liquide T = 120 ^{0}K

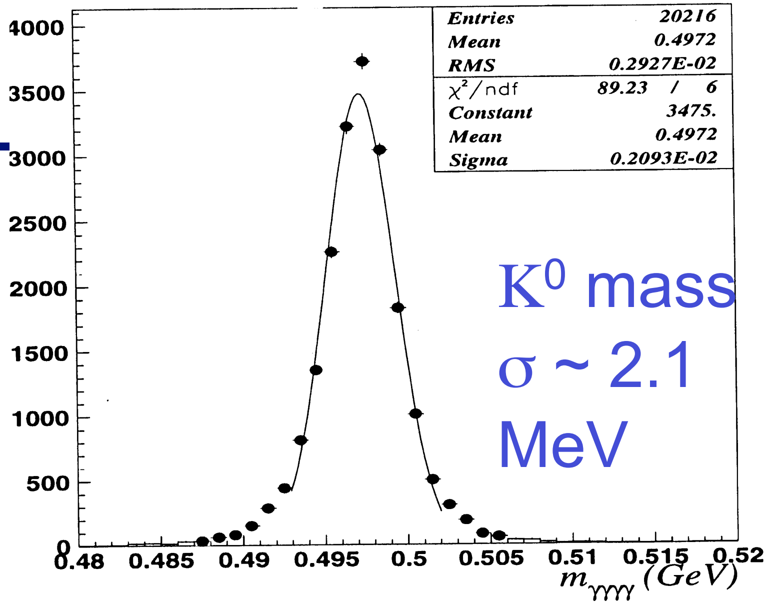






π^0 mass

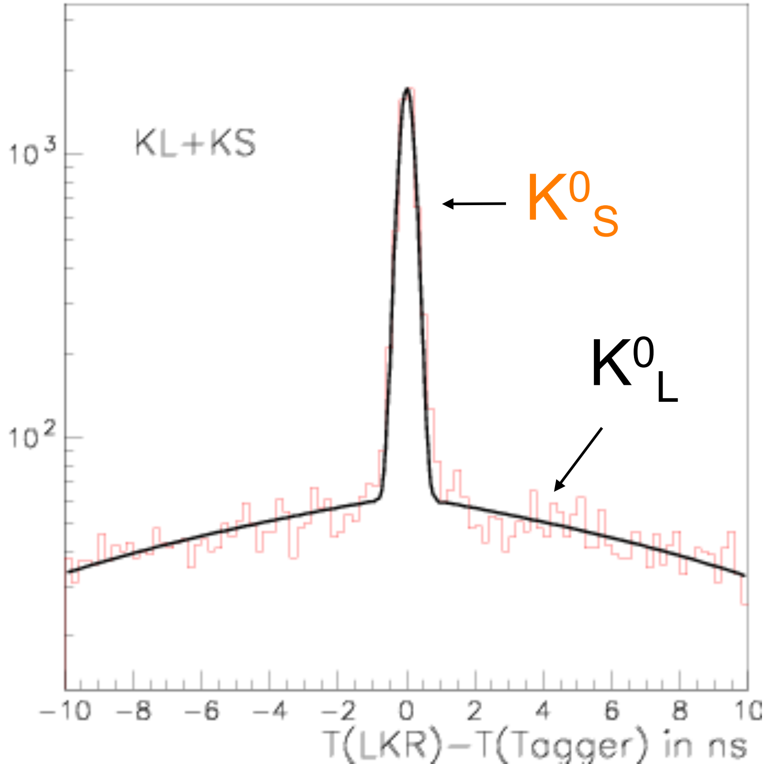
σ ~ 1.1 MeV



K^0 mass

σ ~ 2.1 MeV

NA48



K^0_S

K^0_L

Calorimeter time resolution

σ ~ 220 ps

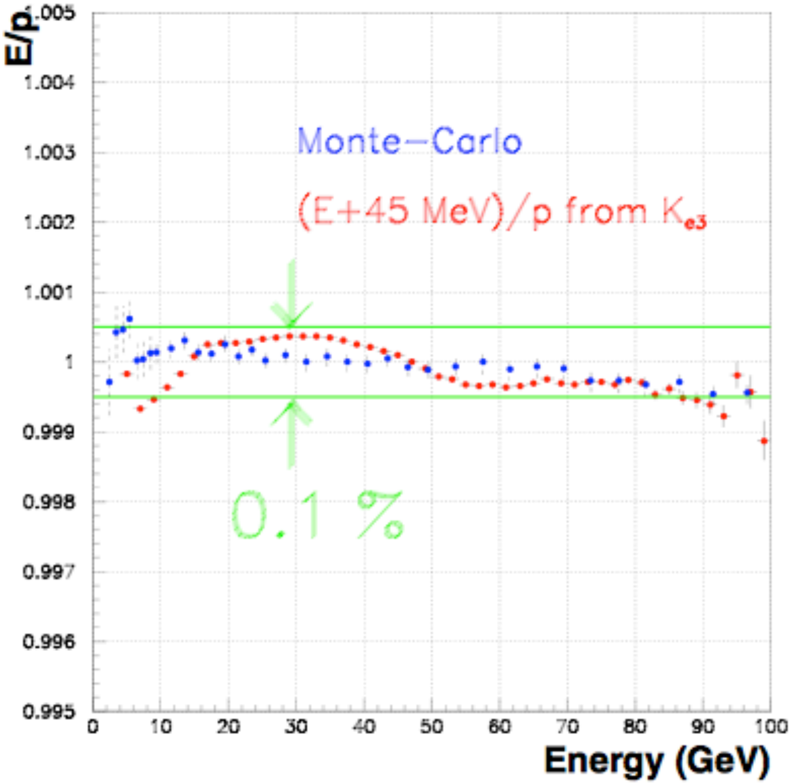
Energy Resolution

Main tool to study in situ the performances of the calorimeter :

$$K_L \to \pi^{\pm} e^{\mp} \nu \text{ decays}$$

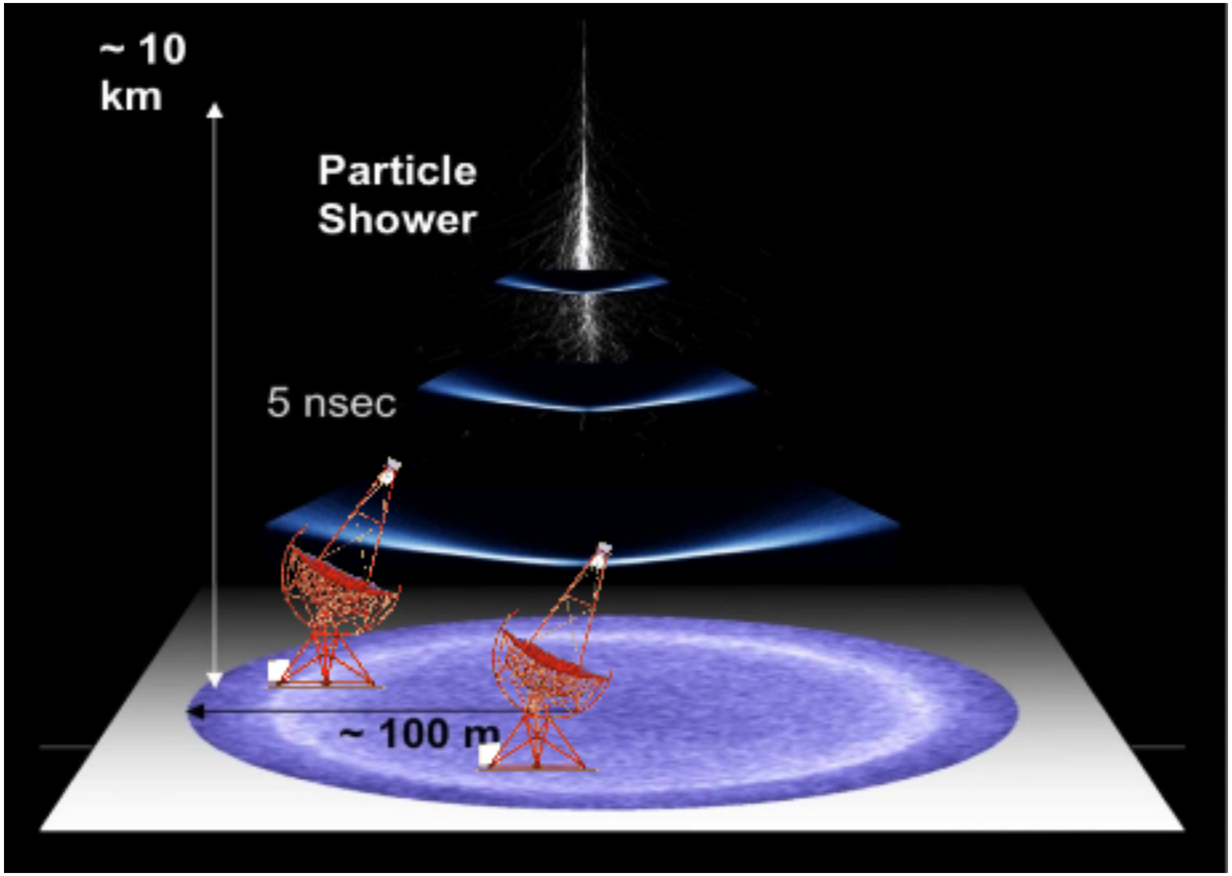
Spectrometer ⇒ Impulsion p (resolution ≈ 0.5% to 1%)
Calorimeter ⇒ Energy E

In ideal world, $\frac{E}{p} = 1$

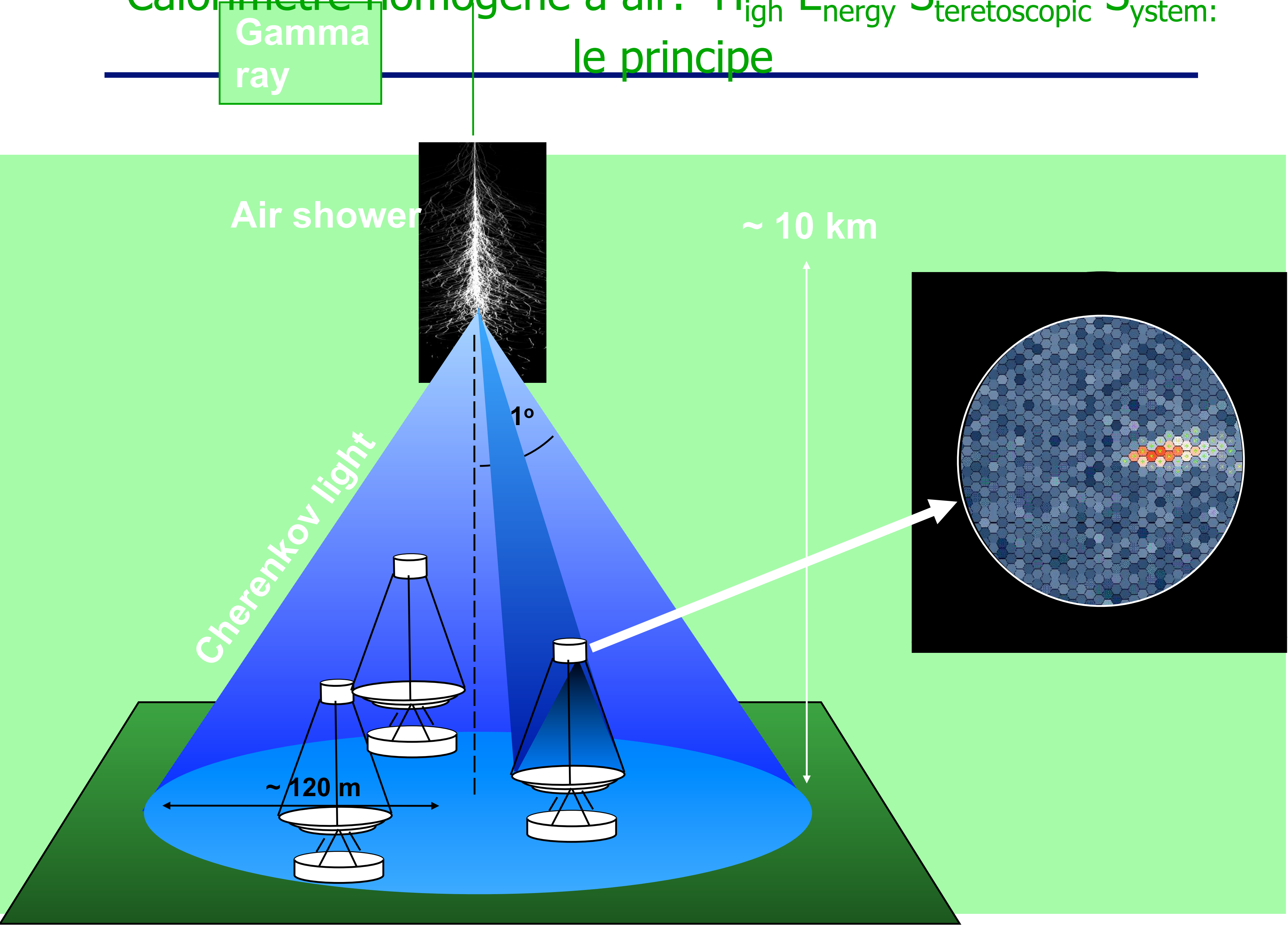


⇒ Non linearity ≈ 0.1%
(from 5 to 100 GeV)

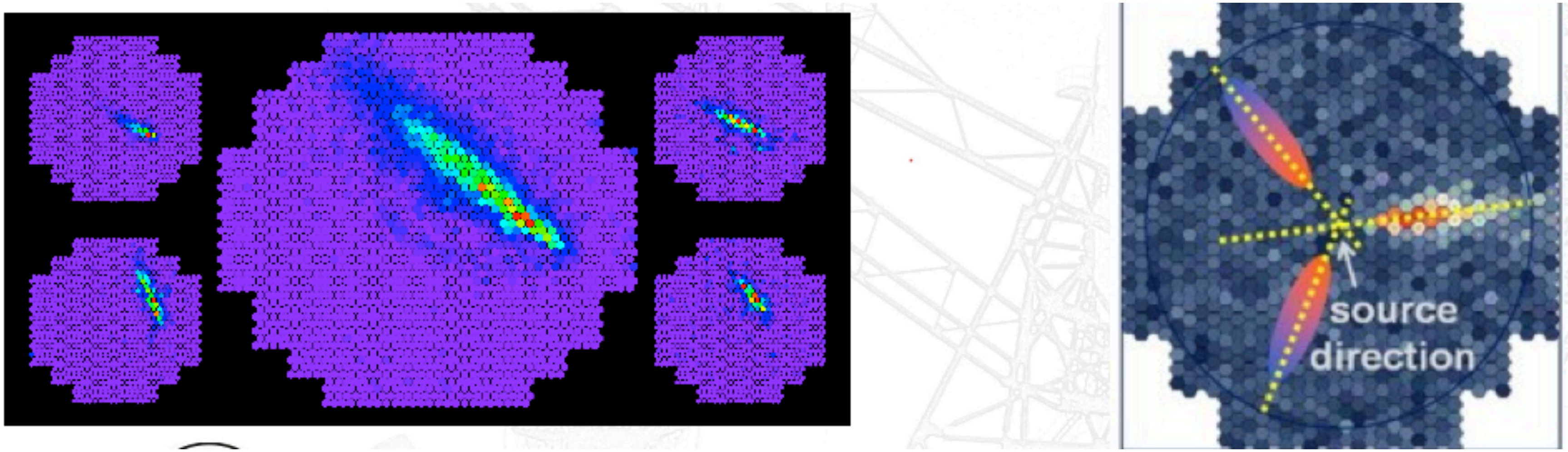
"Natural Calorimeter"



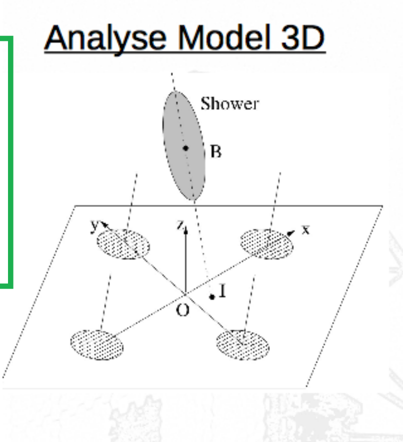
Calorimètre homogène à air: H_{igh} E_{nergy} $S_{teretoscopic}$ S_{ystem}: le principe



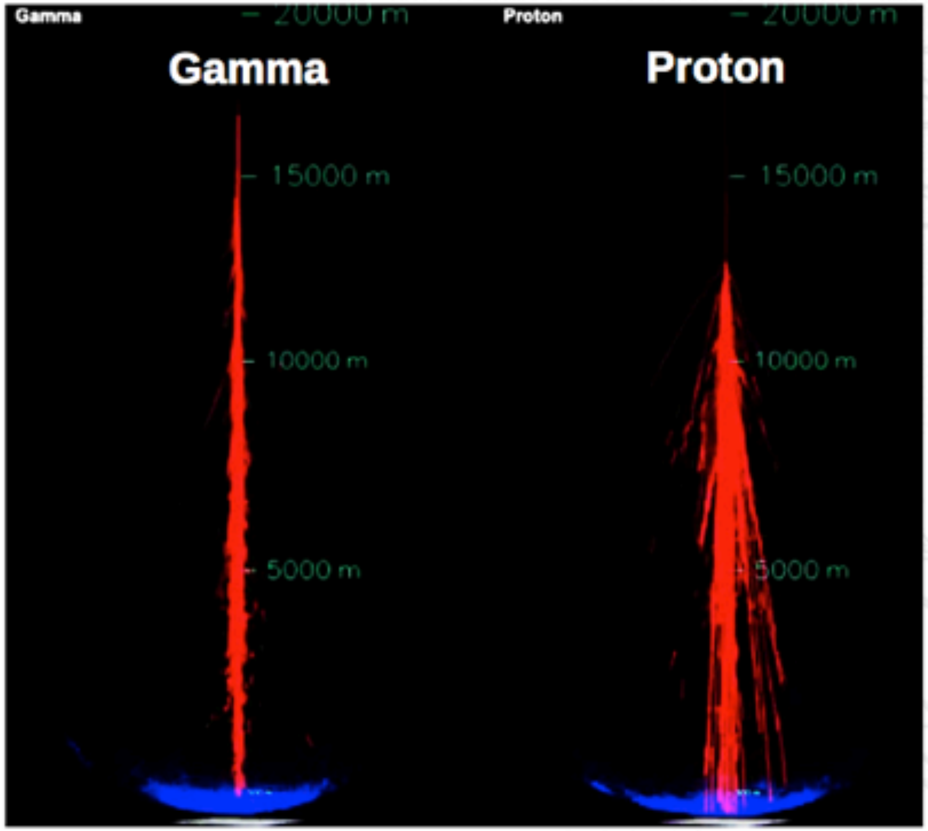
The method



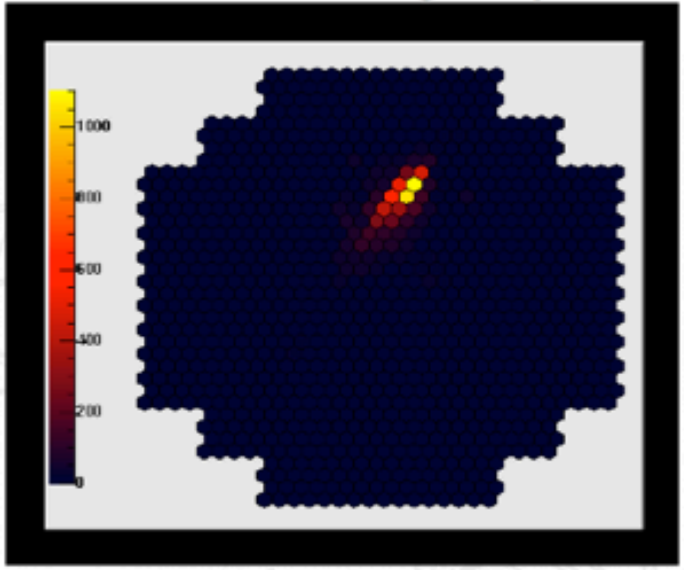
Reconstruct the shower position in atmosphere
Estimate the energy from signal in telepscopes + simulation of air showers



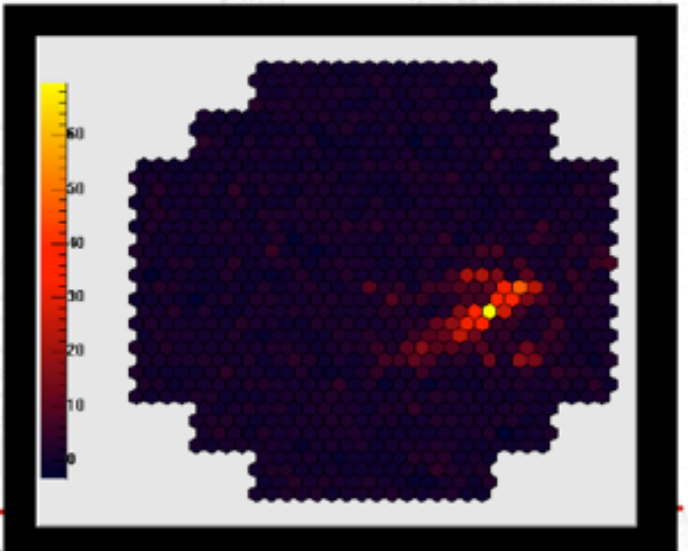
Détection des rayons γ



Gerbe électromagnétique

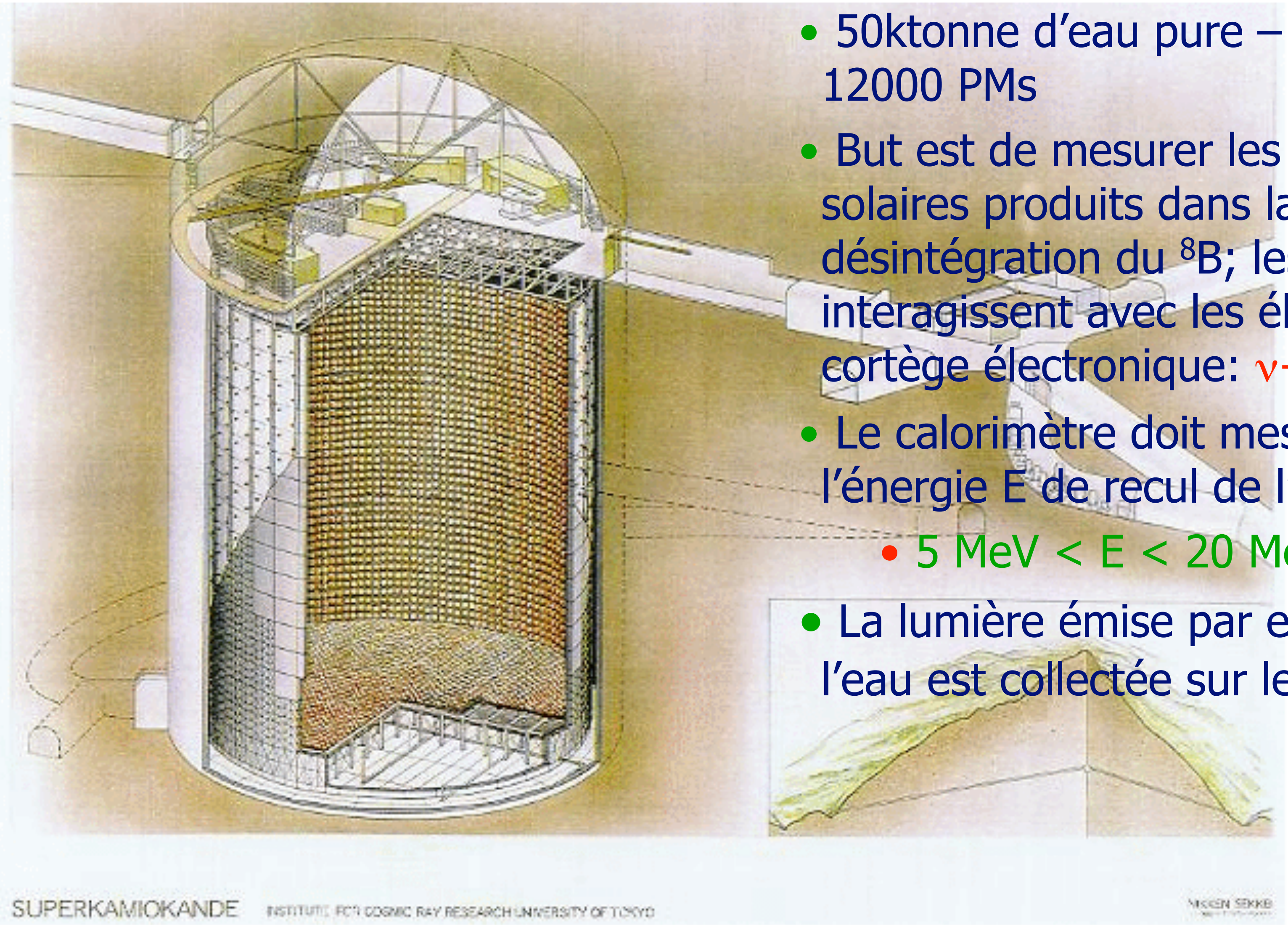


Gerbe hadronique



Calorimètre homogène à air: H_{igh} E_{nergy} S_{teretoscopic} S_{ystem} En Namibie

Super-Kamiokande: Čerenkov dans l’eau

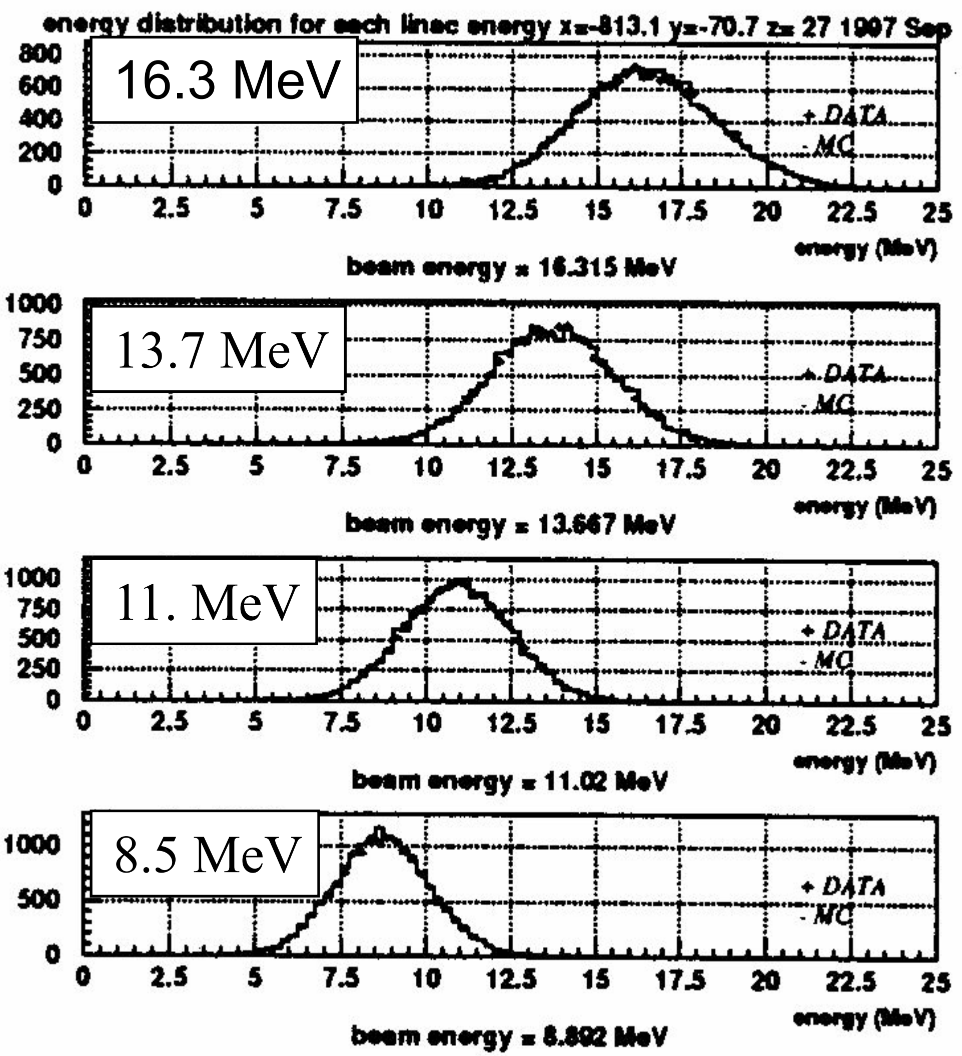


- 50ktonne d’eau pure – lecture par 12000 PMs
- But est de mesurer les neutrinos solaires produits dans la désintégration du ^{8}B; les neutrinos interagissent avec les électrons du cortège électronique: $\nu + e \rightarrow \nu + e$
- Le calorimètre doit mesurer l’énergie E de recul de l’électron:
  - $5 \text{ MeV} < E < 20 \text{ MeV}$
- La lumière émise par effet Č dans l’eau est collectée sur les 12000 PM

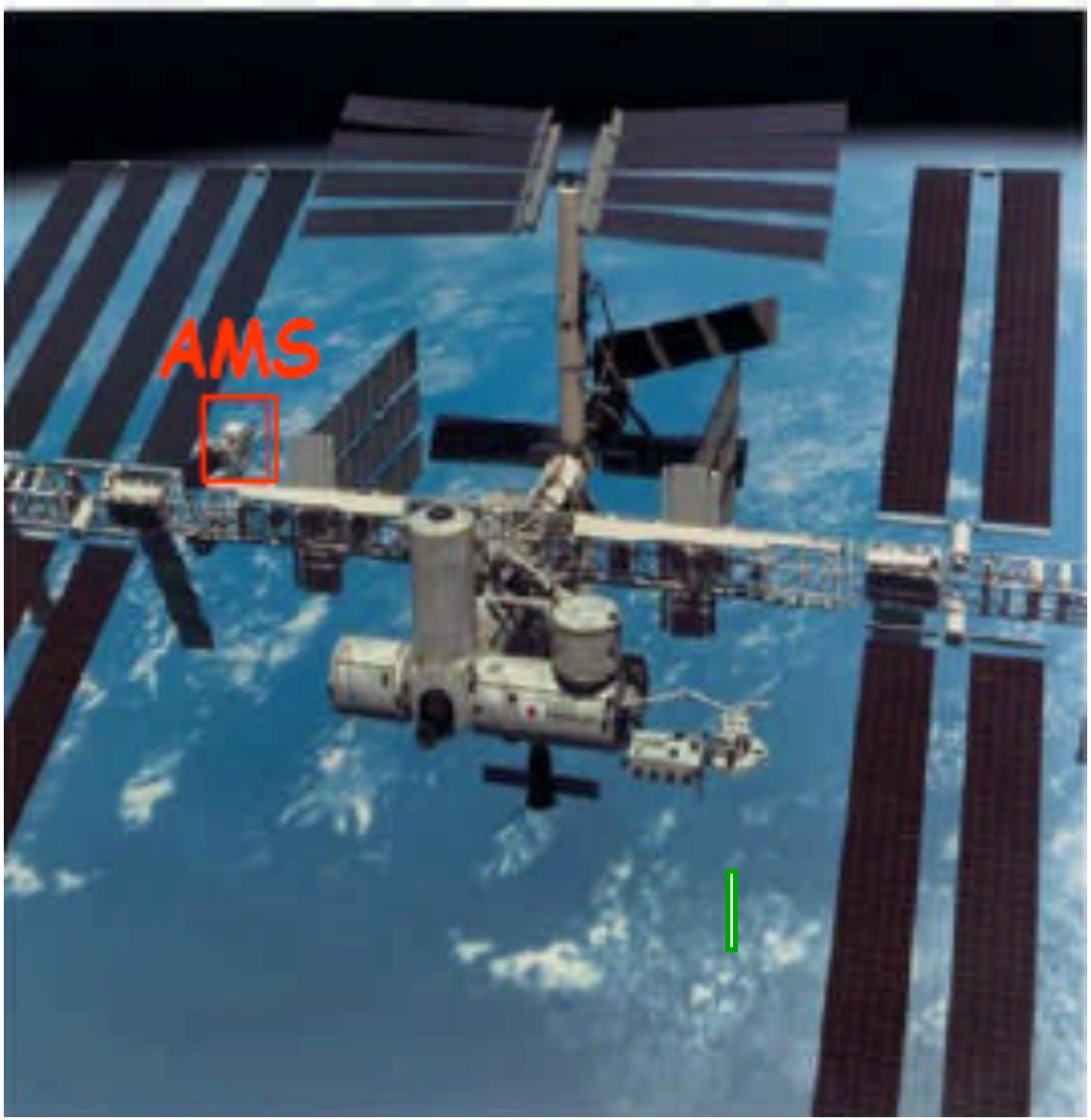
Performances Super-Samiokande

- Mesures faites auprès d'un accélérateur à diverses énergies
- Uniformité de réponse en position et en temps à mieux que 0.5%

•10% à 10MeV

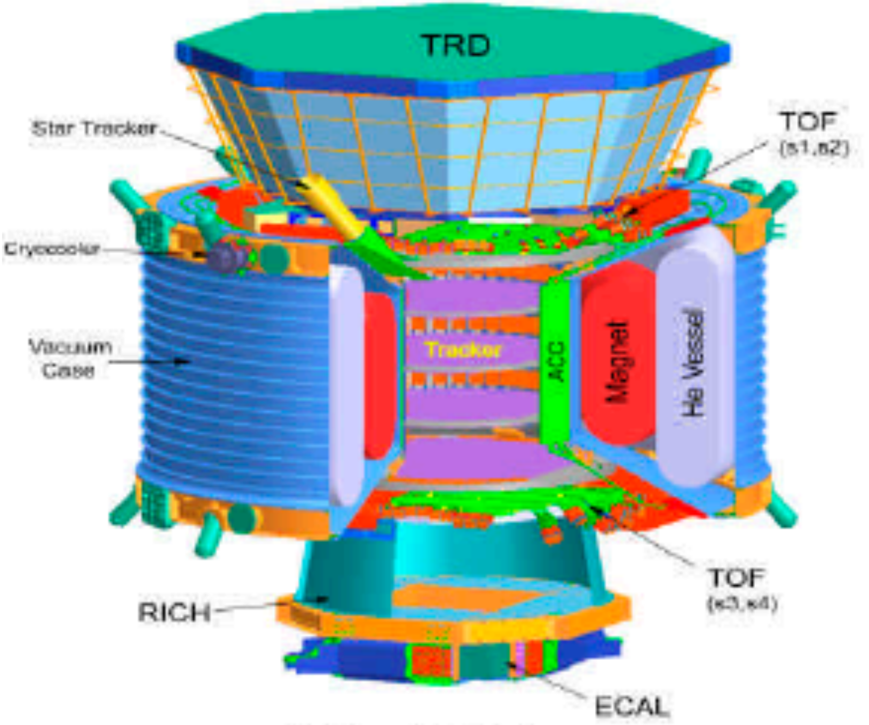


Alpha Magnétique Spectrometer



- AMS est conçu pour étudier les rayons cosmiques de haute énergie.
- AMS s'intéresse en particulier à la recherche d'anti-matière (anti-He)
- AMS peut aussi mesurer les photons de haute énergie grâce au calorimètre.

Alpha Magnétique Spectrometer

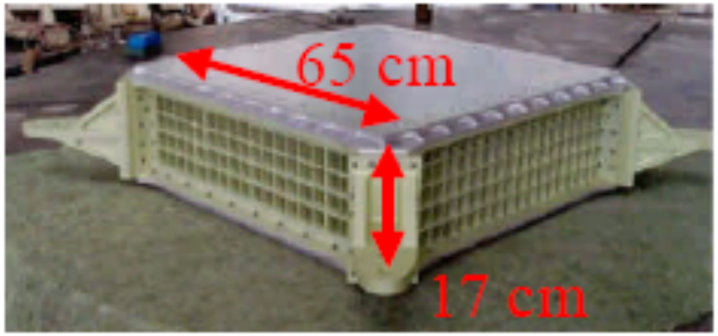


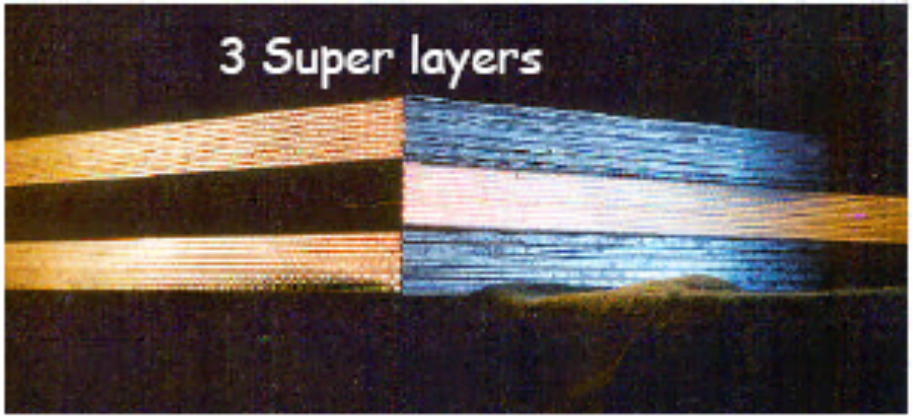
AMS on ISS for 3 years

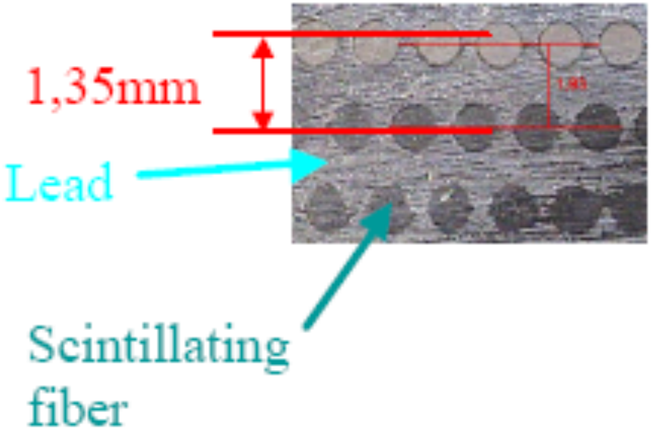
- Transition Radiation Detector
  - Foam + drift tubes (Xe/CO$_2$)
- Time of Flight (trigger)
  - Scintillators, fine mesh PMT's
  - $\sigma_t \sim 120$ ps
- Superconducting magnet (0.86 T·m^2)
- Tracker (8 layers, 6m^2)
  - 6 double-sided silicon strips
  - $\sigma_x = 10\ \mu m$ in bending plane
- RICH
  - Radiator (Aerogel+NaF)
  - PMT's (16 pixels)
- 3D-sampling ECAL
  - Lead+Scintillating-fibers
  - PMT's (4 pixels)

ECAL Structure

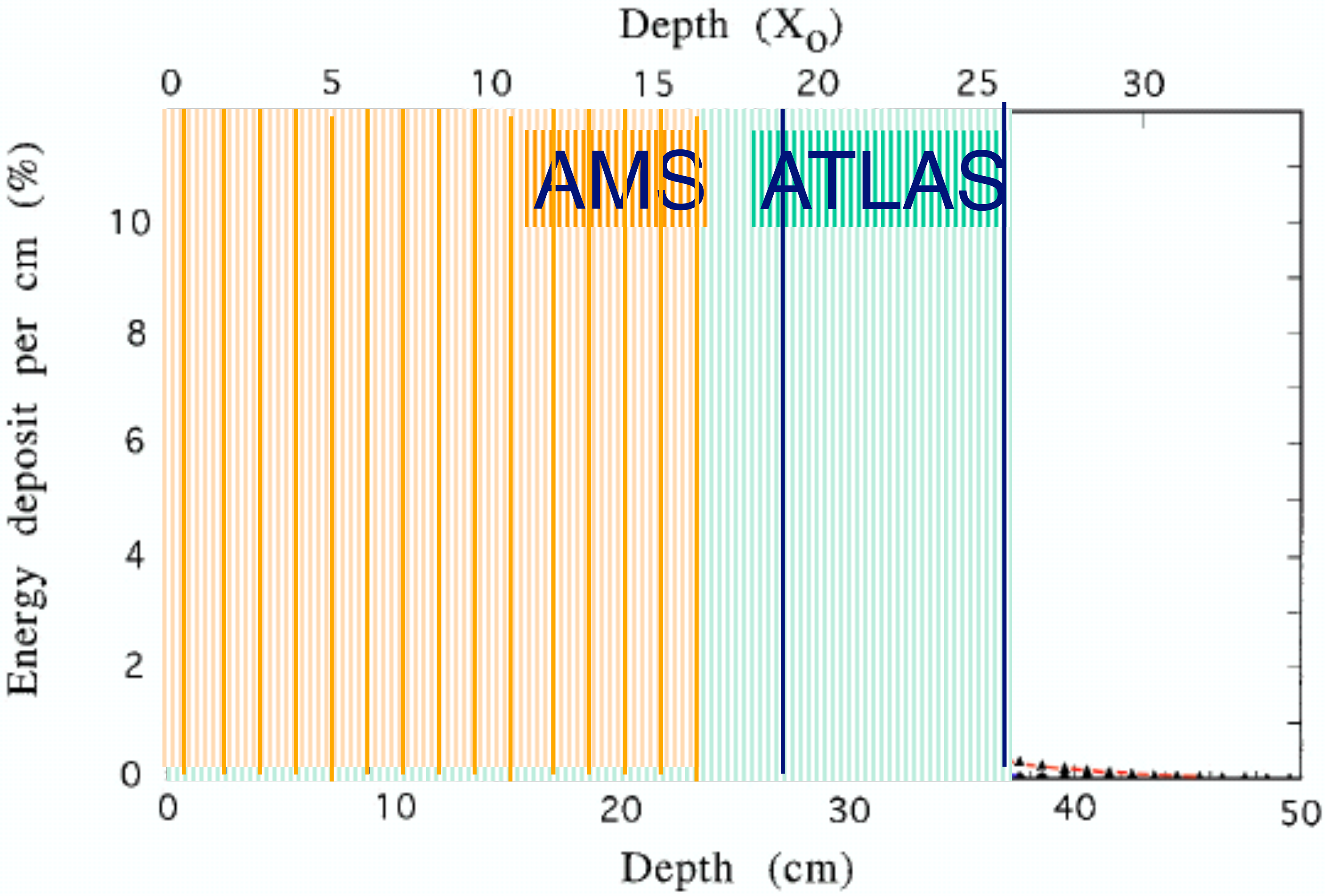
- 9 super layers ($16X_0$) alternatively oriented along X and Y axis
- 1 Super layer:
  11 grooved Pb foils (1mm thick) interleaved with 10 layers of scintillating fibers (∅=1mm) glued by an epoxy resin



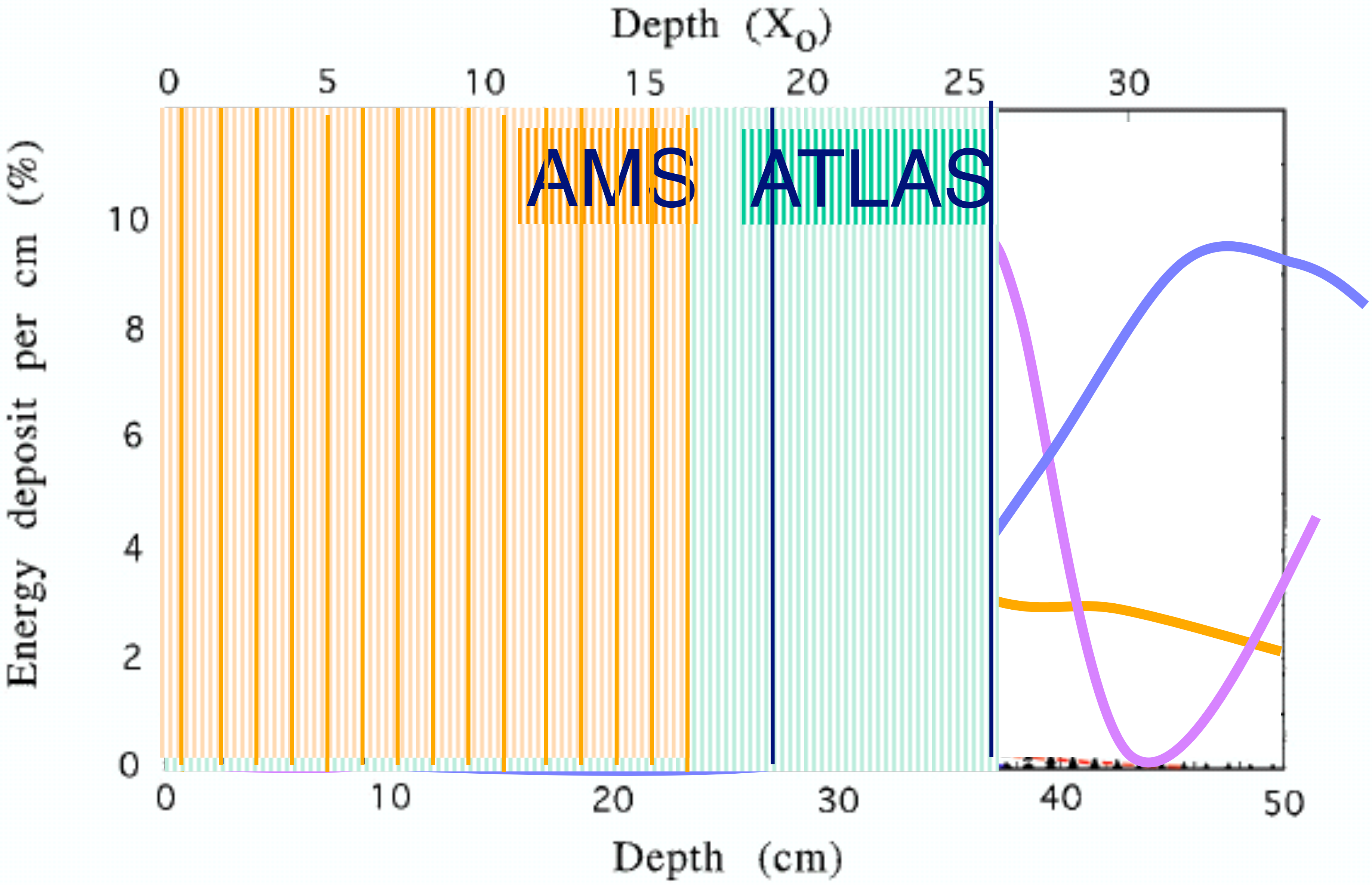




Gerbes Electromagnétiques/Calorimètres EM



Gerbes Hadroniques/Calorimètres EM



Calorimeters R&D for Linear Colliders

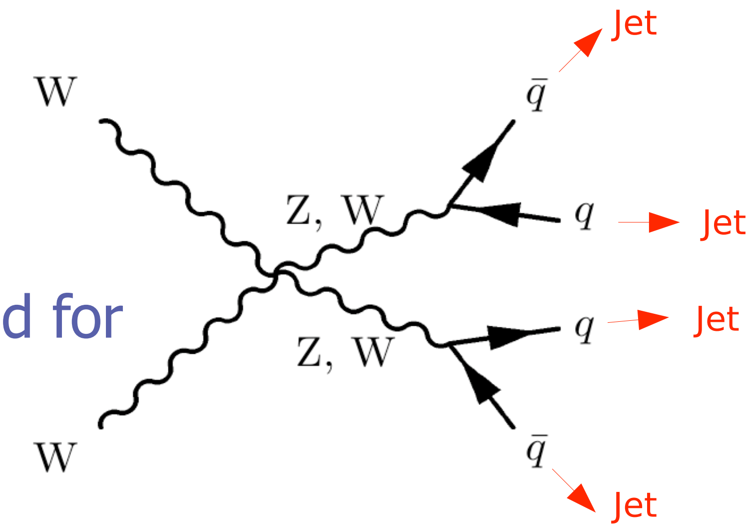
Some ideas for future calorimeters (Linear Colliders)

Boson-Boson scattering

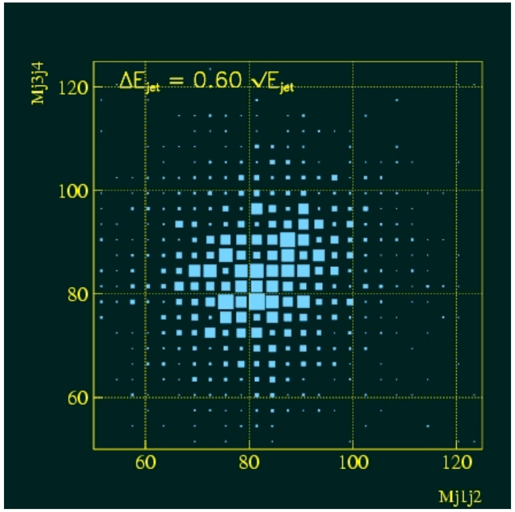
 Hadronic Decay of W & Z

Needs improved energy resolution

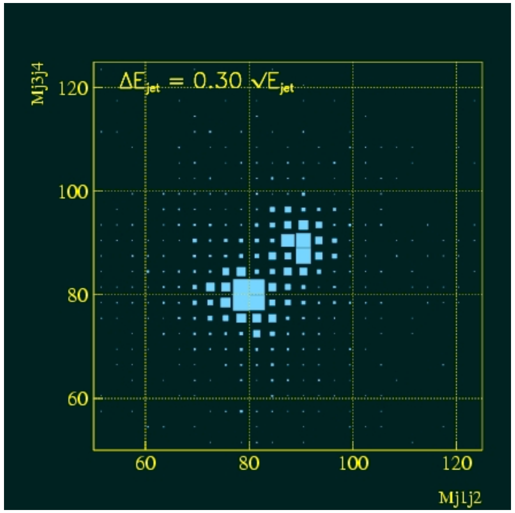
 Higly granular calorimeters optimized for particle flow



$\boxed{\Delta(M_Z,M_W) \sim 10\ \text{GeV}}$



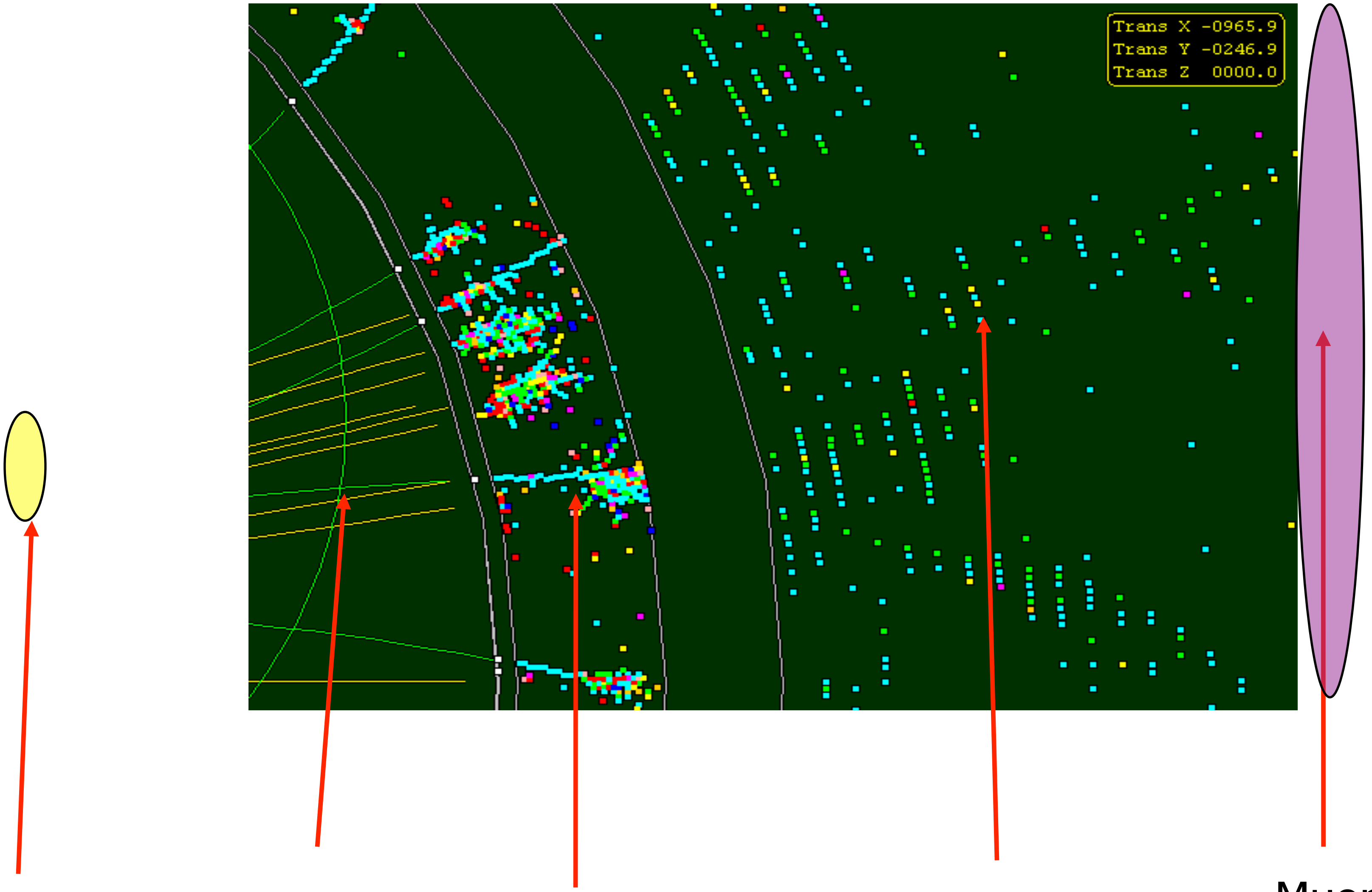
60%/√E



30%/√E

c.f. R. Pöschl for the CALICE collaboration - SPSC January 2011

Calorimeters developed for Linear colliders



VXD
tag b,c jets

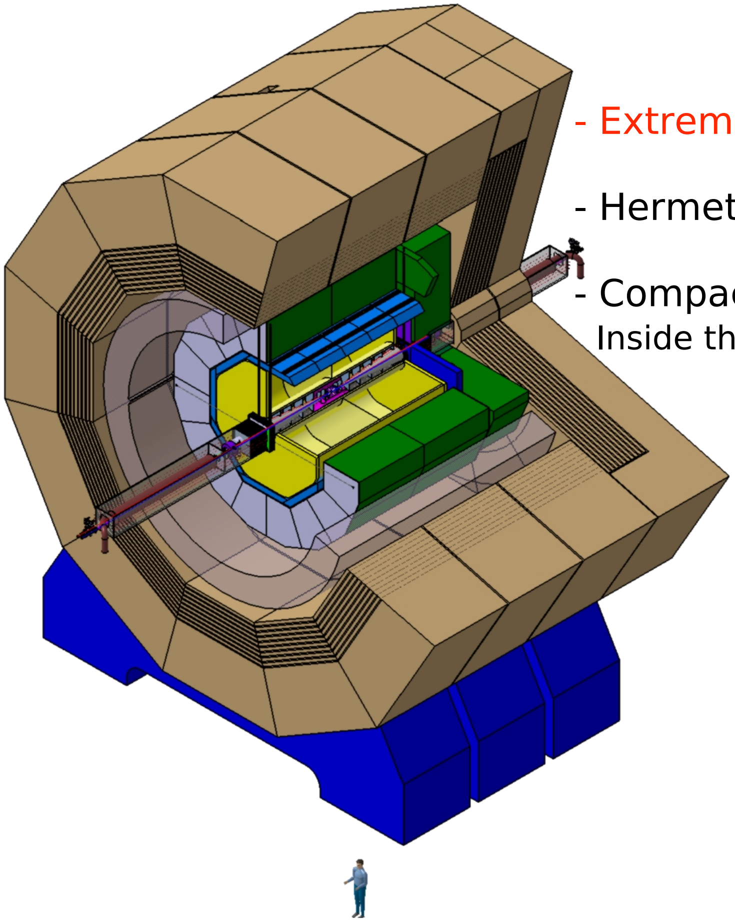
Tracking system

EM Cal

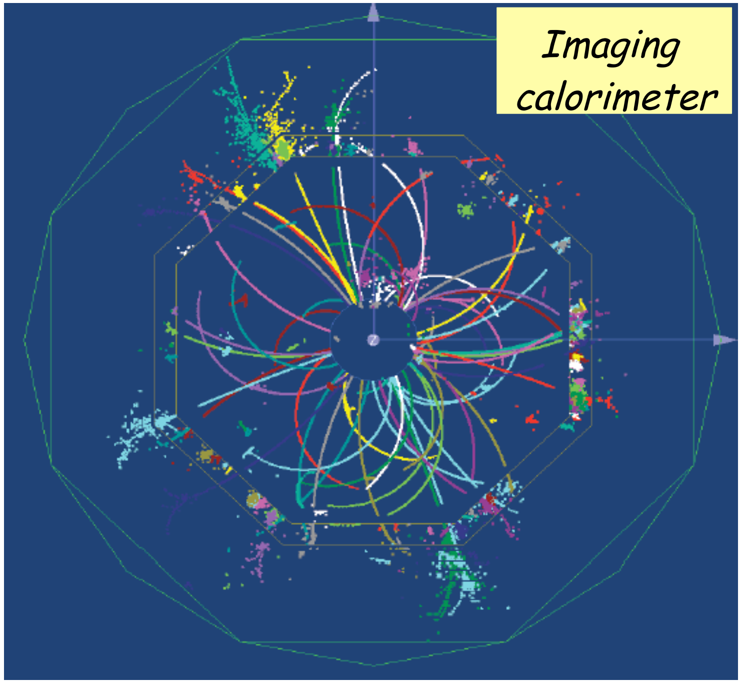
HAD Cal

Muon system

Calorimeter requirements

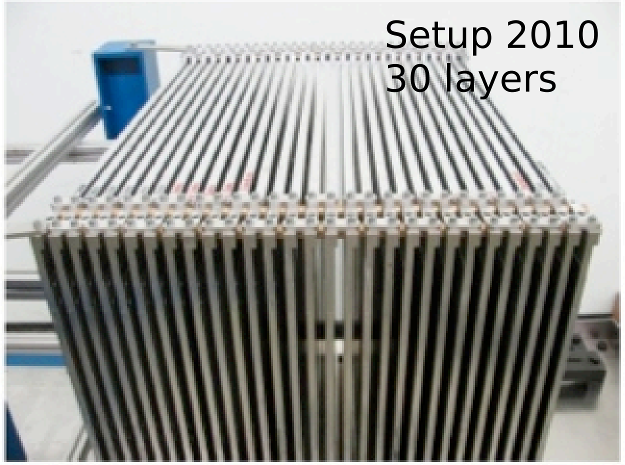


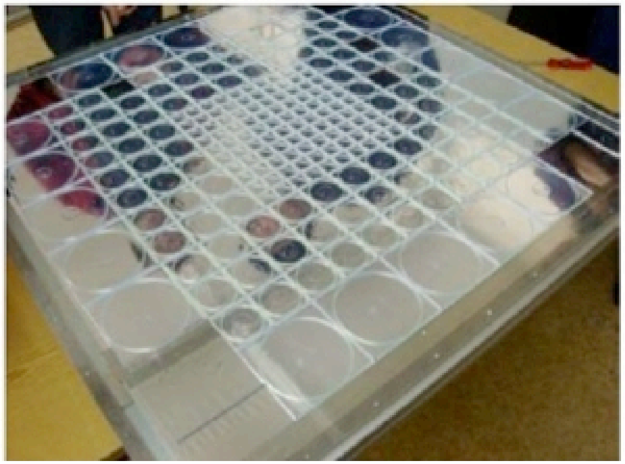
- Extreme high granularity
- Hermetic
- Compact
  Inside the coil of the solenoid



Imaging calorimeter

Many ongoing testbeams (e.g. CALICE)





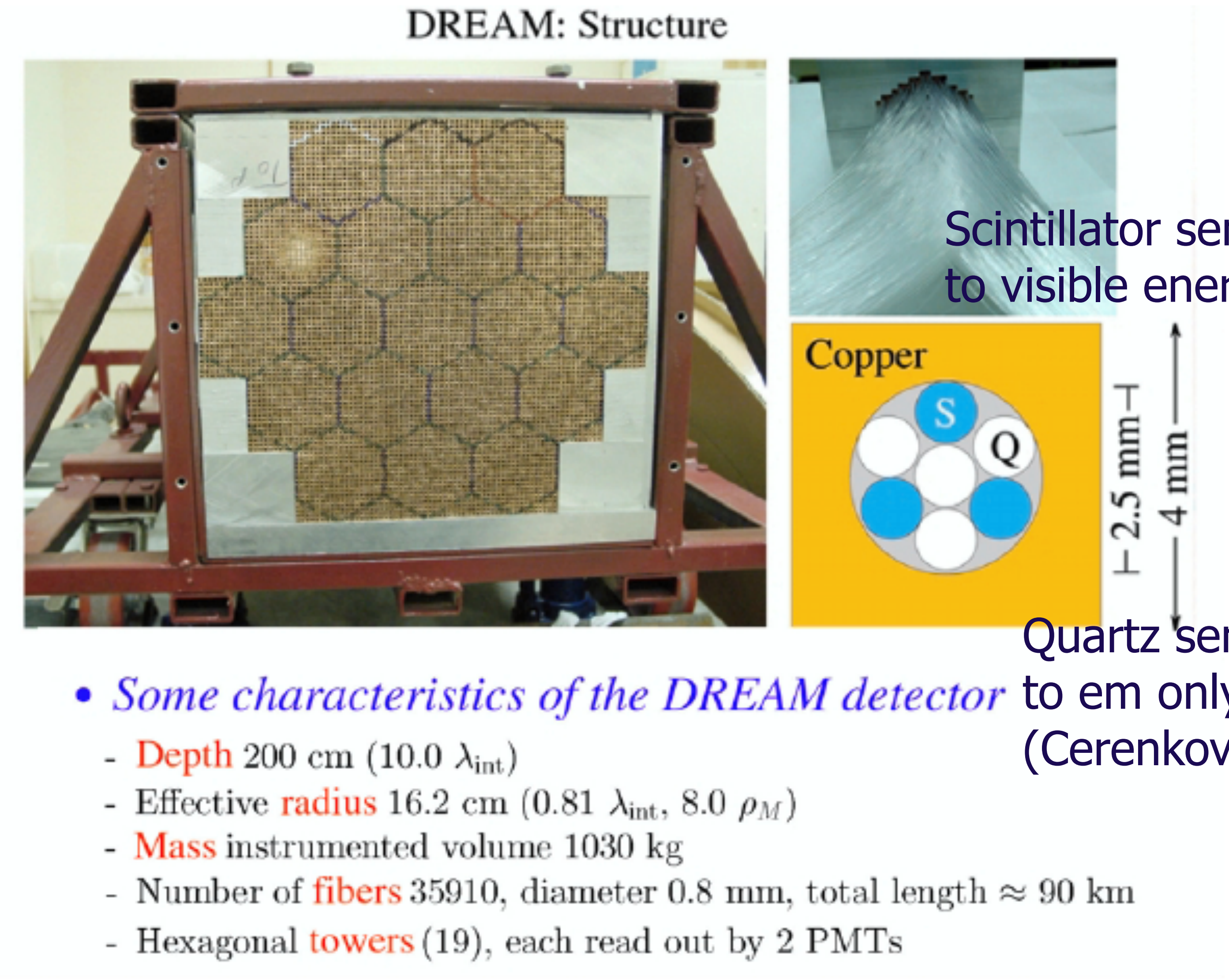
Linear Collider Calorimeters Development:

- Fine segmentation (also for HAD)
  - Both longitudinal and lateral
- Self-suporting calorimeter
  - Minimize dead zones
- Semi-digital readout
  - Electronics embedded inside the calorimeter
  - Development of Power Pulsing

Example: DHCAL

Dual readout for hadronic showers DREAM

Intermezzo: DREAM (ongoing R&D)



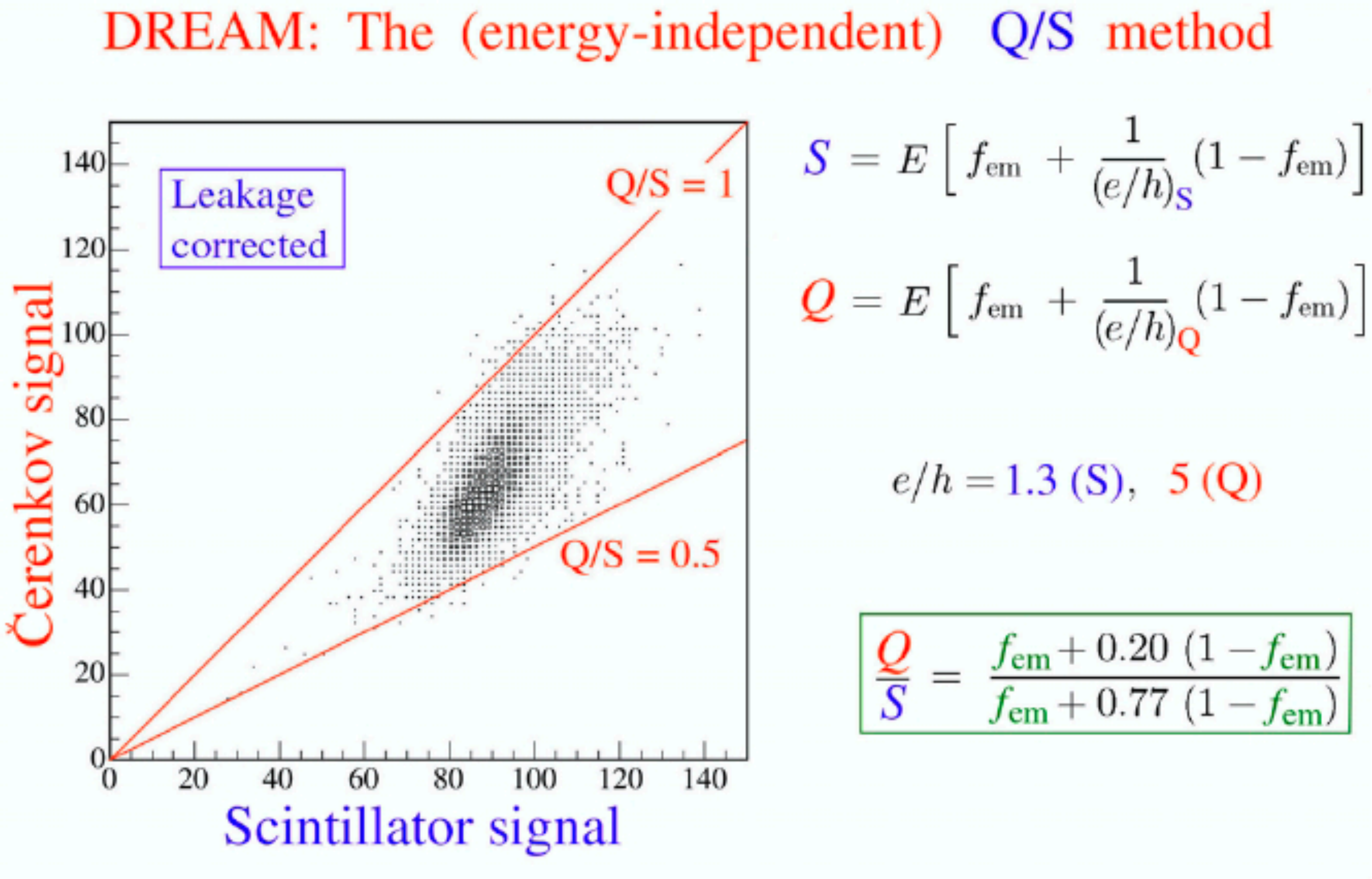
DREAM: Structure

- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

Scintillator sensitive
to visible energy only

Quartz sensitive
to em only
(Cerenkov light)

DREAM: The principle



DREAM: The (energy-independent) Q/S method

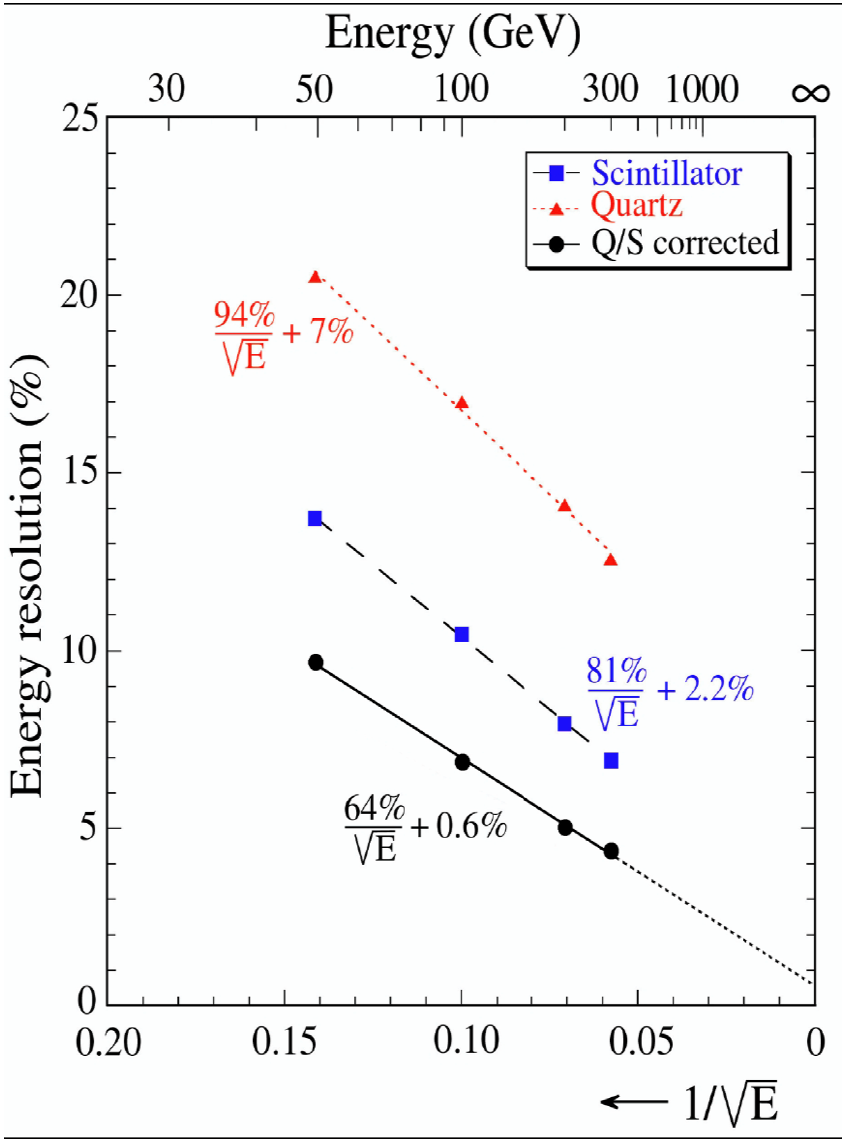
$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_S}(1 - f_{\mathrm{em}})\right]$$

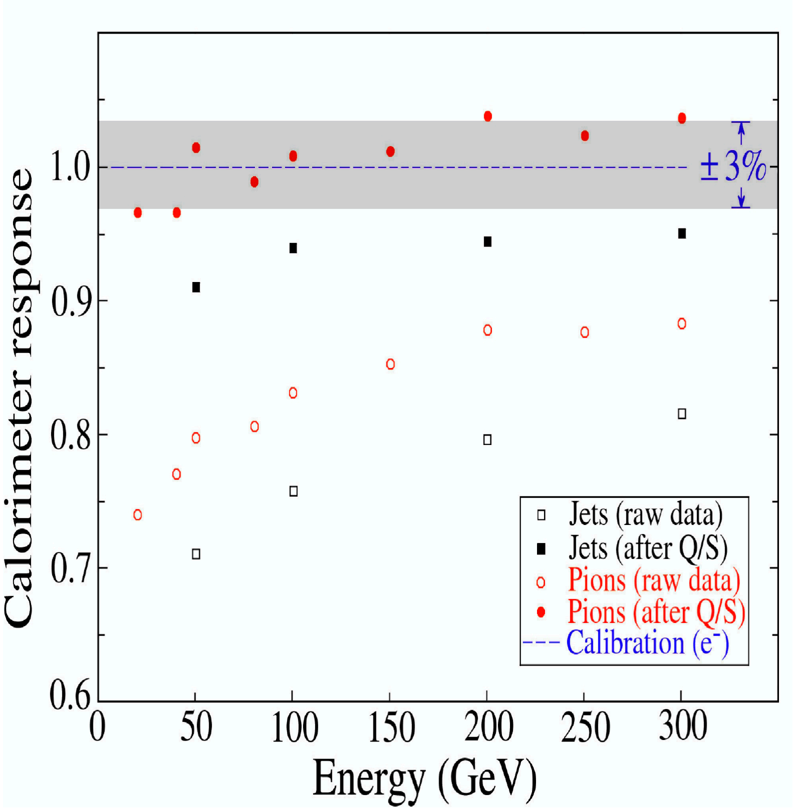
$$Q = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_Q}(1 - f_{\mathrm{em}})\right]$$

$$e/h = 1.3\ (\mathrm{S}),\quad 5\ (\mathrm{Q})$$

$$\boxed{\frac{Q}{S} = \frac{f_{\mathrm{em}} + 0.20\ (1 - f_{\mathrm{em}})}{f_{\mathrm{em}} + 0.77\ (1 - f_{\mathrm{em}})}}$$

DREAM: some results





Systèmes de lecture

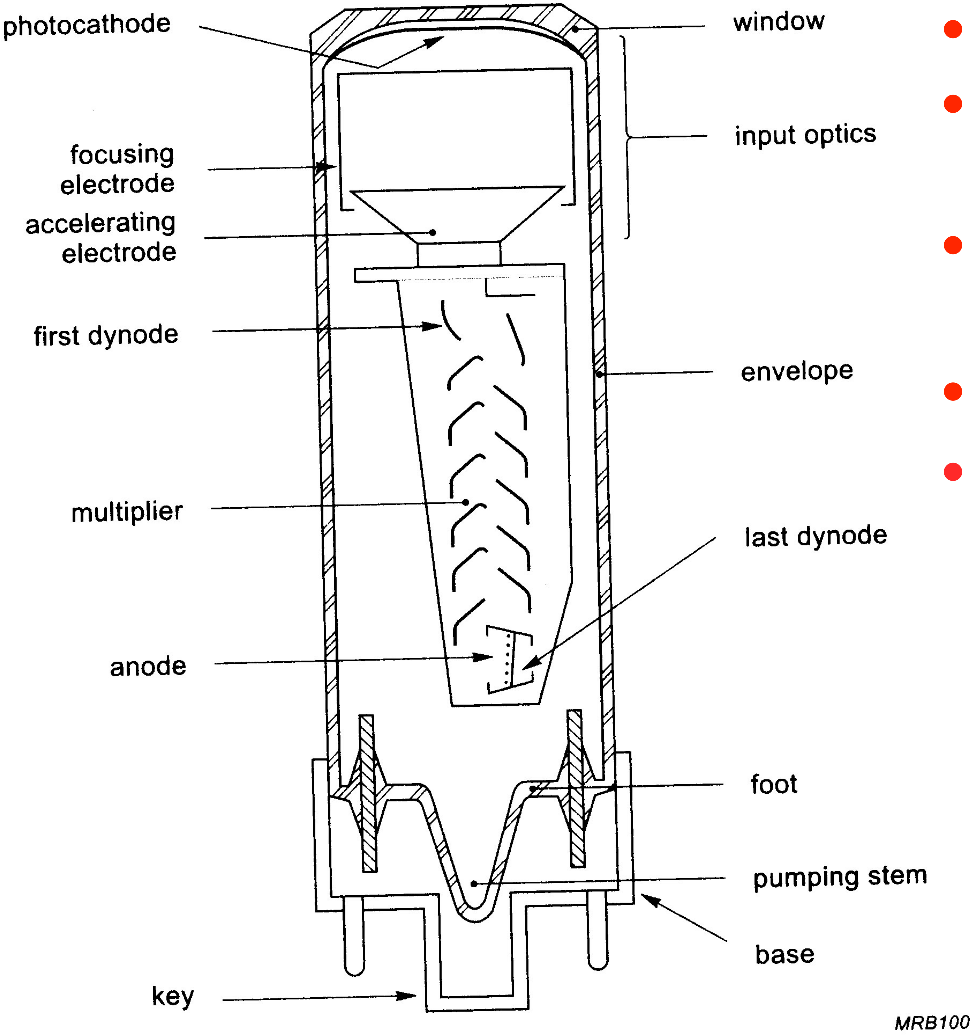
Les systèmes de lecture

- Pour collecter le signal:
  - collection de la lumière
  - collection des charges

- Il faut des détecteurs
  - de lumière
  - de courant

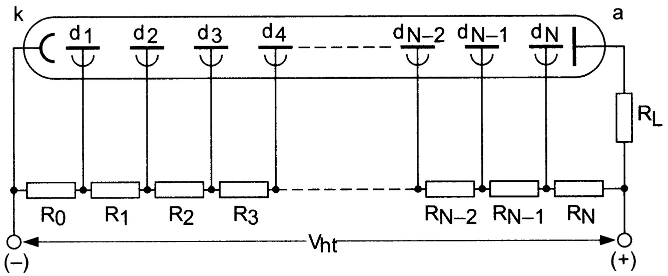
- On utilise
  - photoMultiplicateurs
  - photodiode à avalance
  - preamplificateurs

Photomultiplier tubes

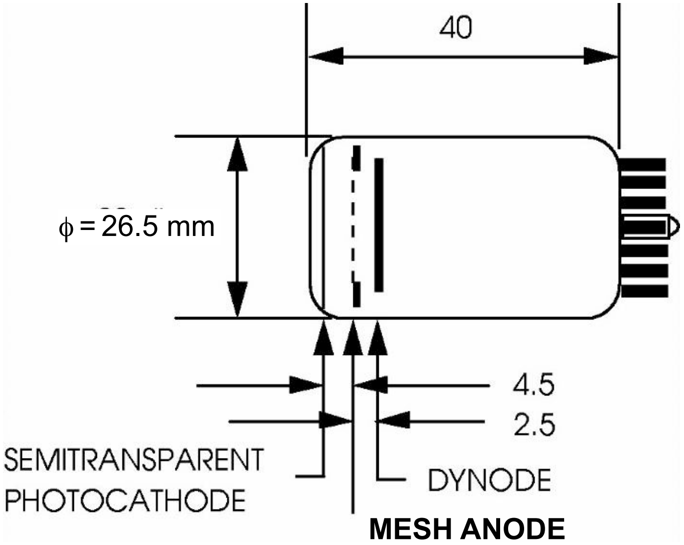


Light signal transformed to electrical signal

- Vacuum device
- Emission of photoelectrons from a photocathode
- Acceleration and multiplication at dynodes
- Gain $G=\Pi g_i$ ($10^4 - 10^8$)
- Sensitive to magnetic fields



Vacuum Phototriodes (VPTs)



Single stage photomultiplier tube with fine metal grid anode

Can be arranged to be largely insensitive to ~axial magnetic fields

- ***In CMS ECAL:***
- B-field orientation favourable
- Gain 8 -10 at B = 4 T
- Radiation hard (UV glass window)
- Active area of ~ 280 mm^2
- Q.E. ~ 20% at 420 nm

Avalanche Photodiodes (APDs)

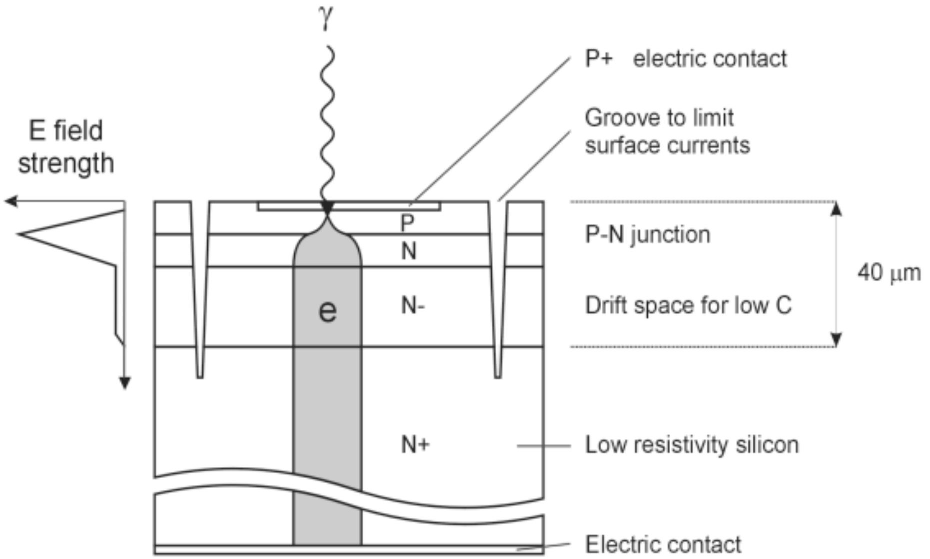
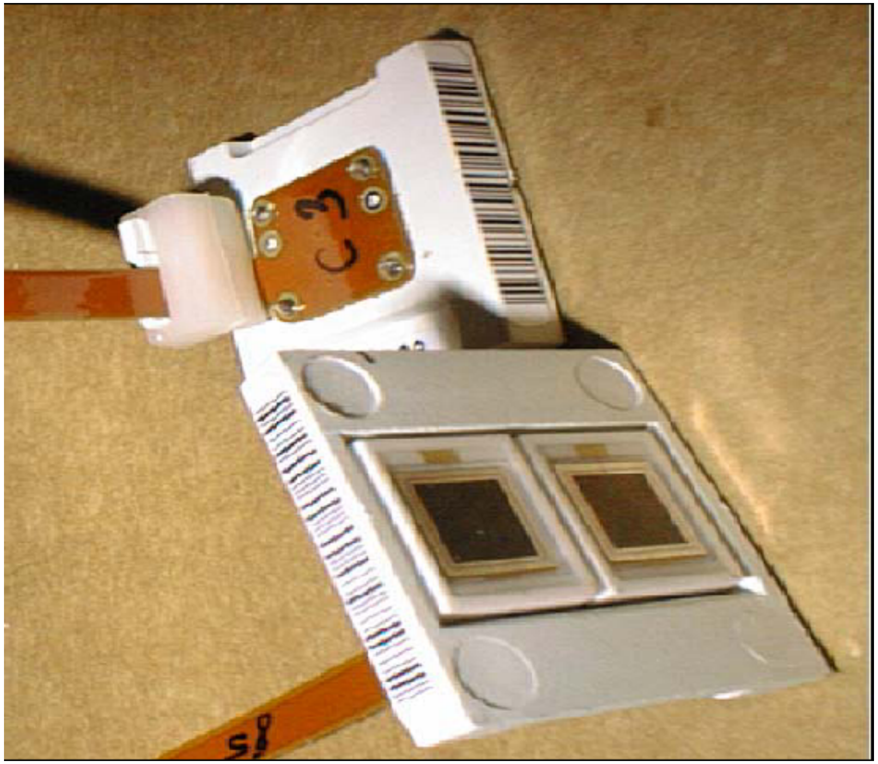


Photo-electrons from THIN 6 μm p-layer induce avalanche at p-n junction

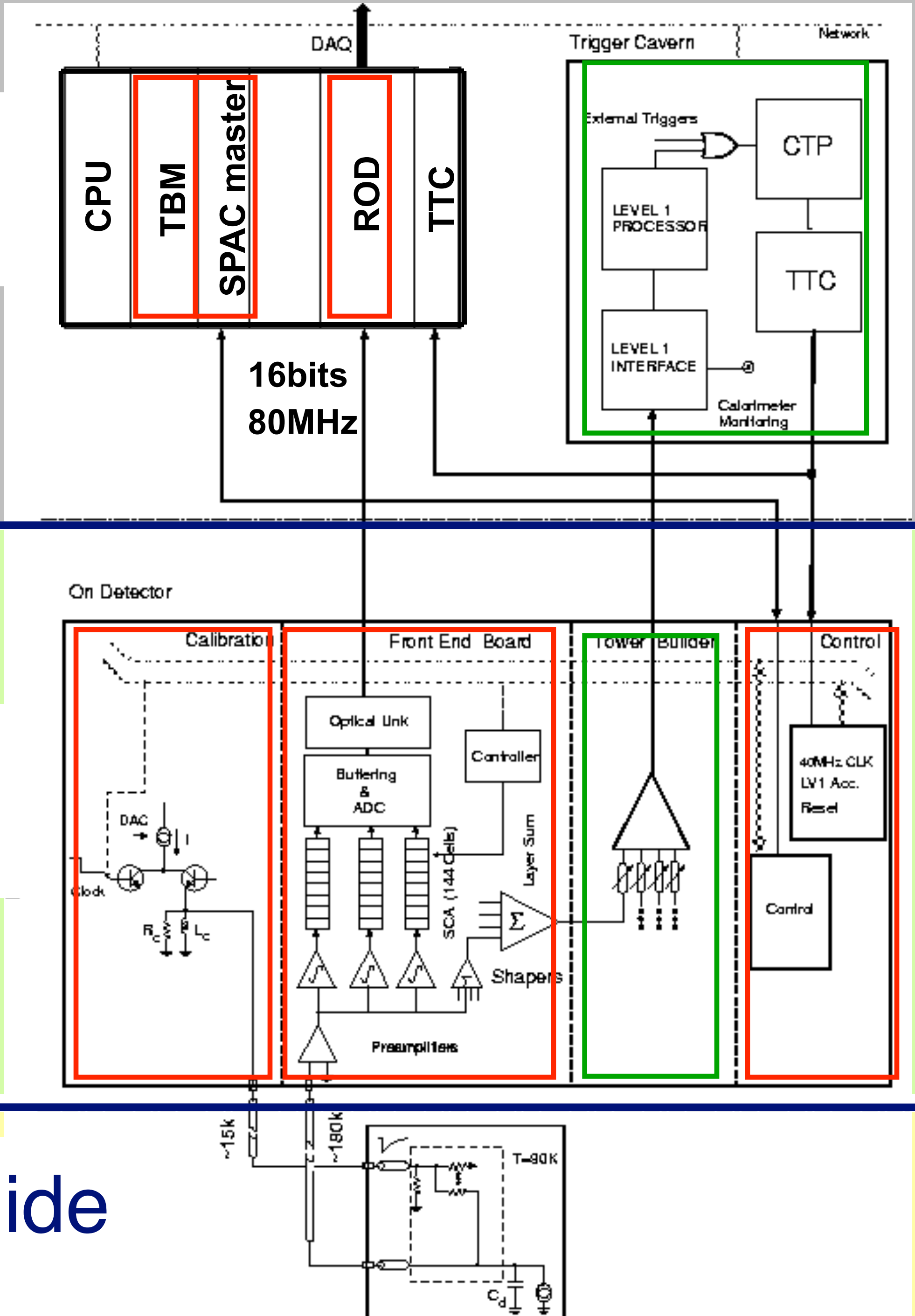
Electrons from ionising particles traversing the bulk NOT amplified [(insensitive to shower leakage)]

APD & VPTs de CMS



Barrel:
Avalanche Photodiodes (APDs)

Endcap:
Vacuum PhotoTriodes (VPTs)



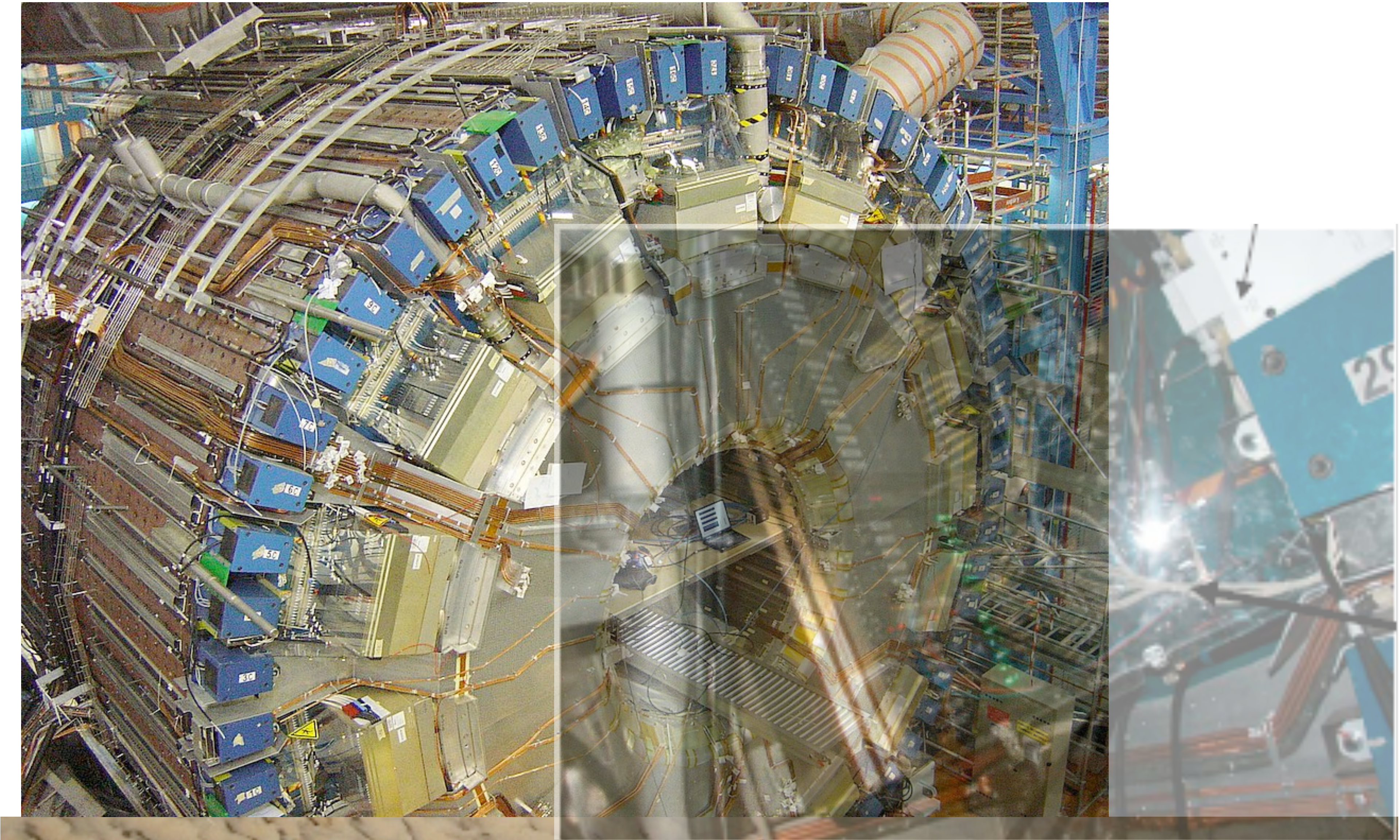
Salle de comptage

sur le cryostat

Argon liquide

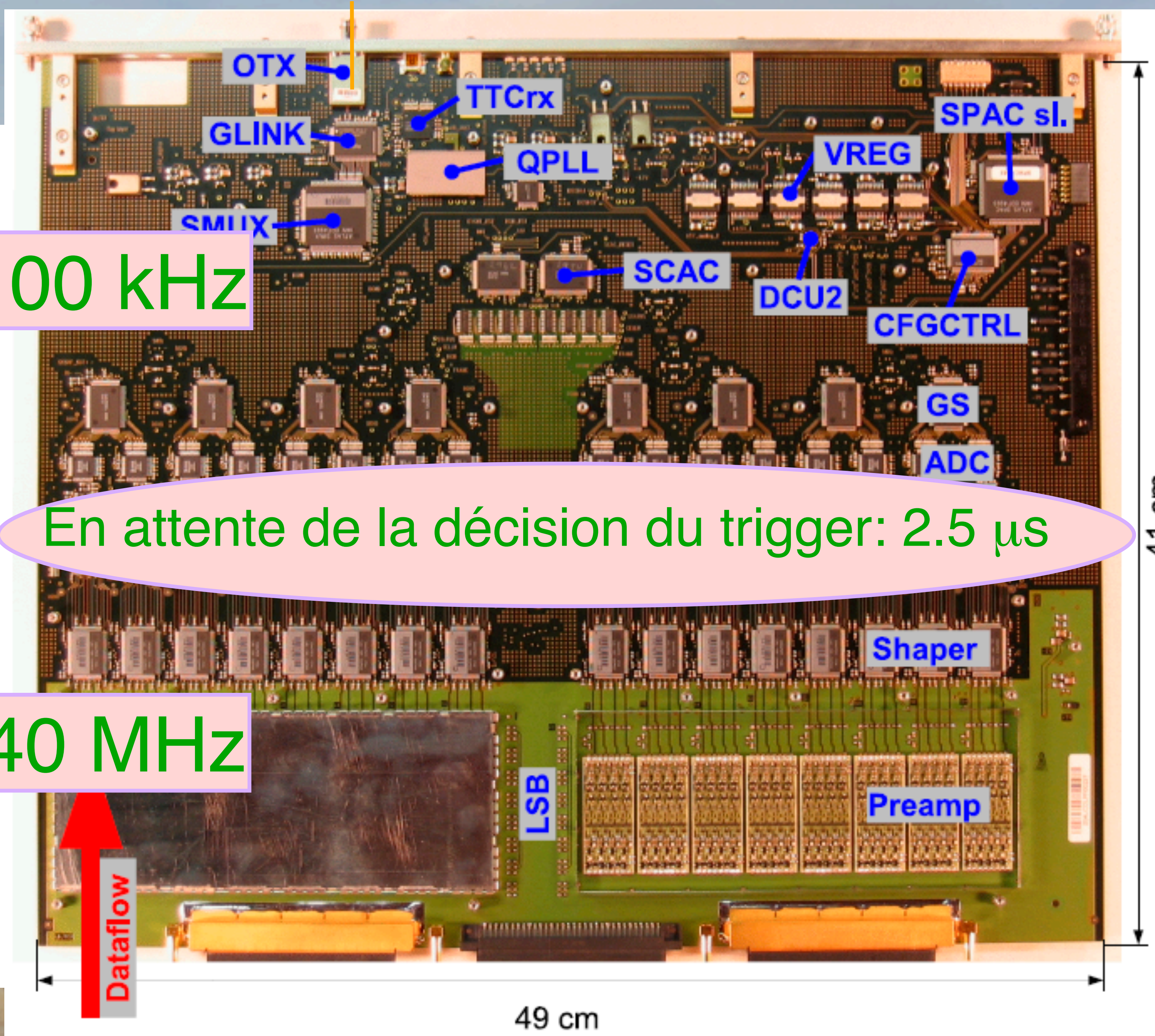
Chaîne de lecture de l'accordéon

Electronique ON DETECTOR



Carte FrontEnd pour le calorimètre EM d'ATLAS

ON DETECTOR

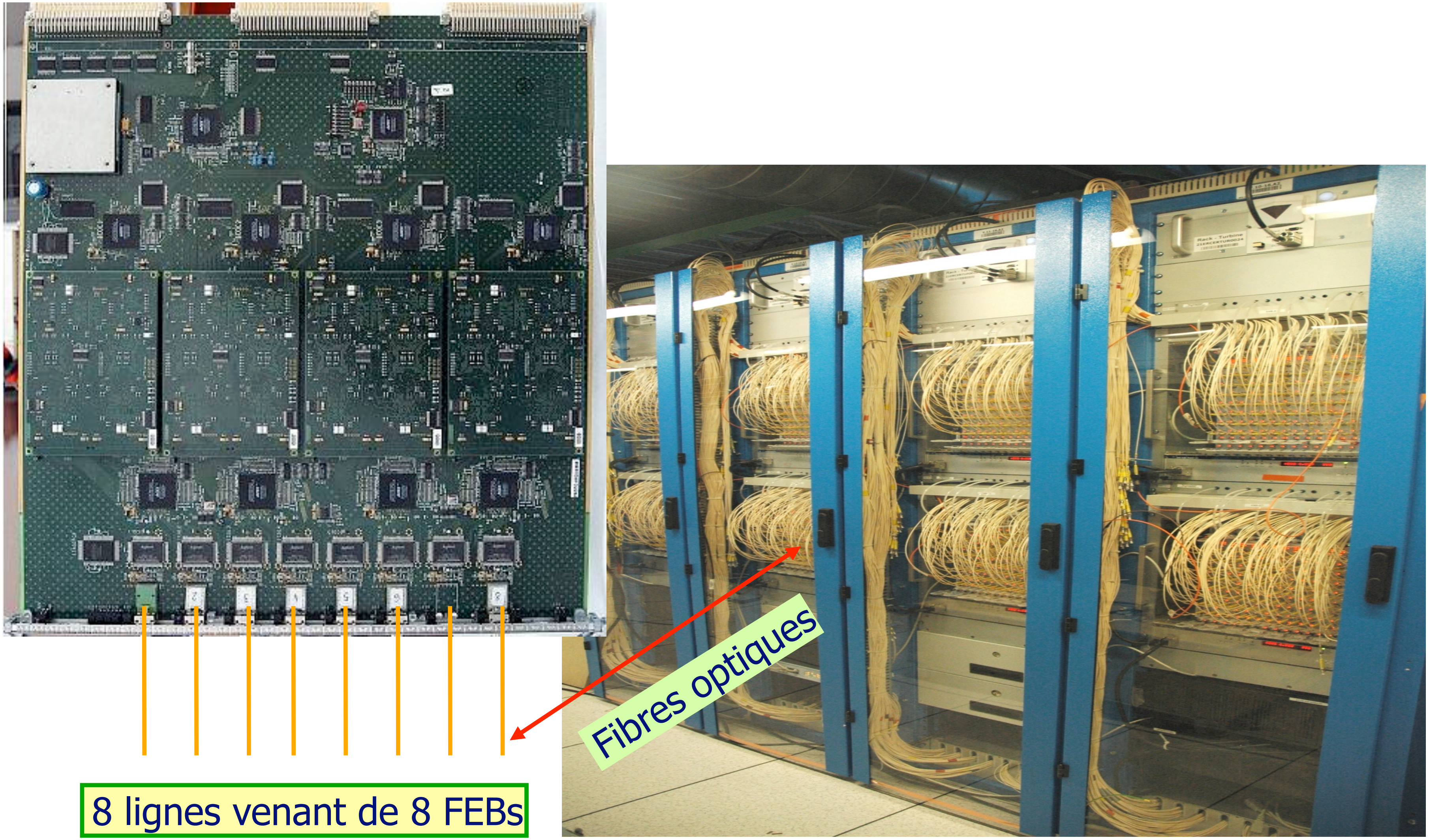


100 kHz

En attente de la décision du trigger: 2.5 μs

40 MHz

Le système BackEnd pour les calorimètres EM+HAD de ATLAS
OFF-DETECTOR

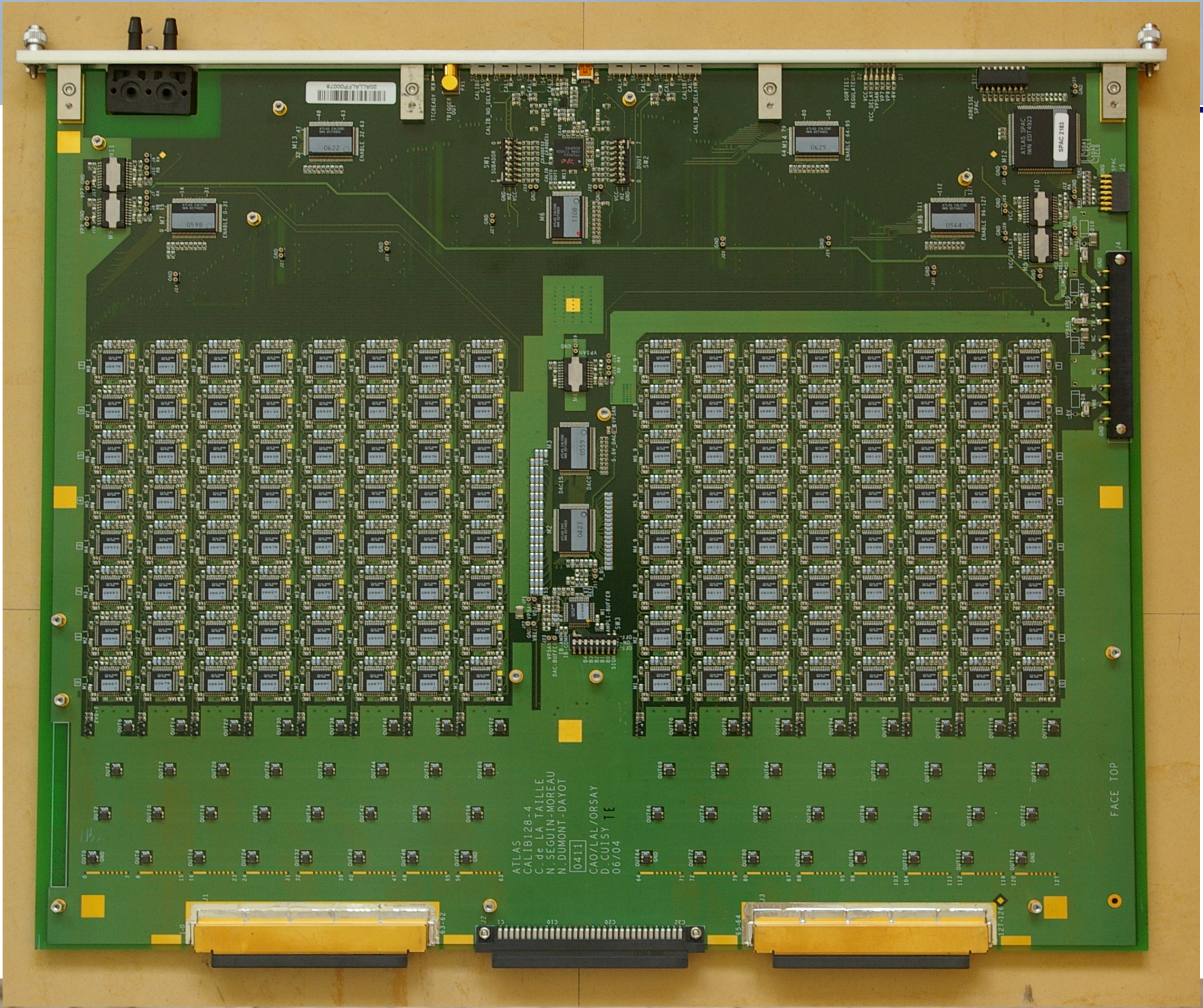


Fibres optiques

8 lignes venant de 8 FEBs

Carte Calibration pour le calorimètre LARG d'ATLAS

ON DETECTOR



In the cavern

In the counting room

Some conclusions

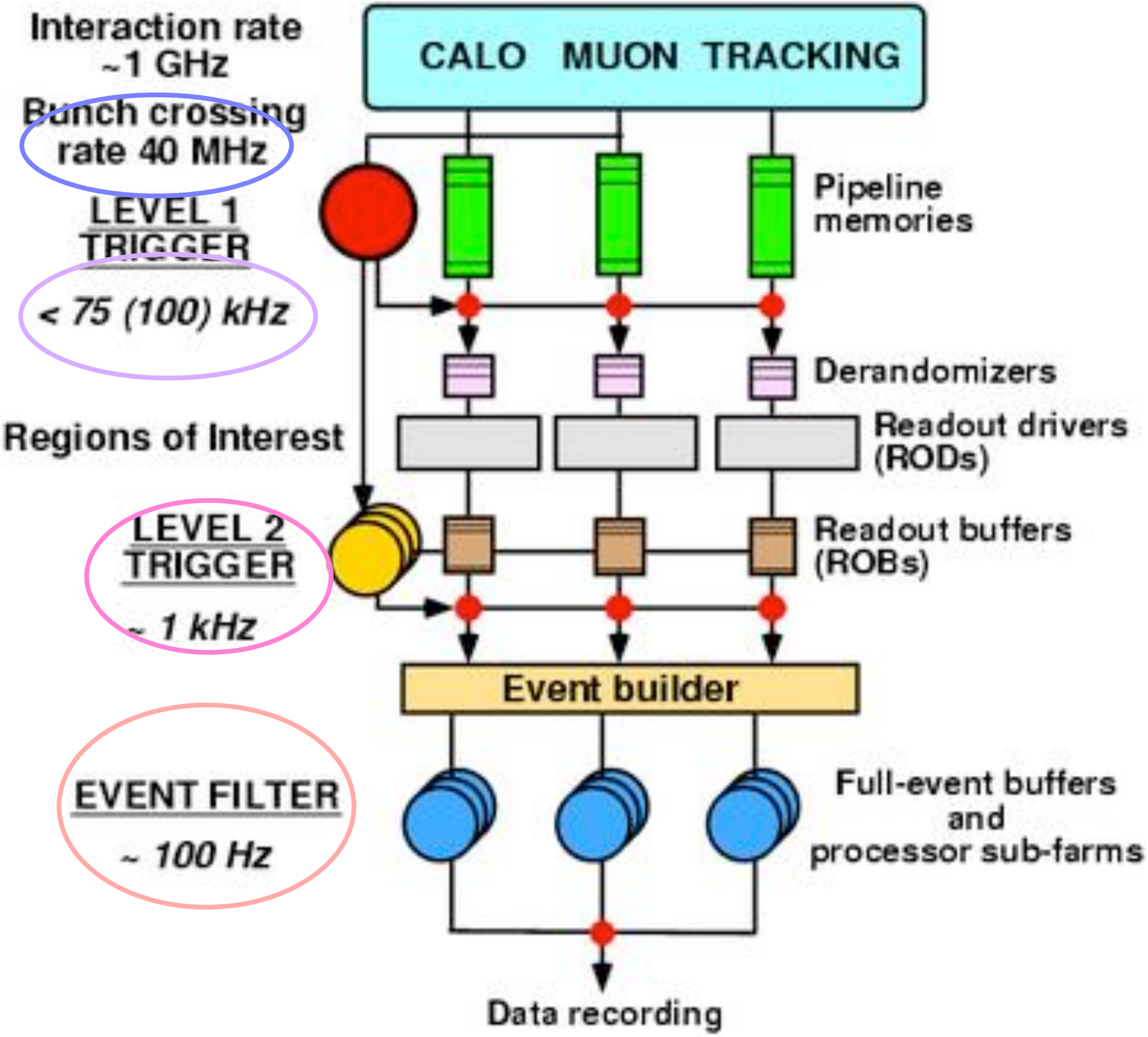
Calorimeters are playing a critical role large detectors such as the LHC ones

- Electron/Photon - Jet - E_T^{miss} reconstruction
- Background rejection $e^{\pm}$/jets - γ/π^0
- Triggering

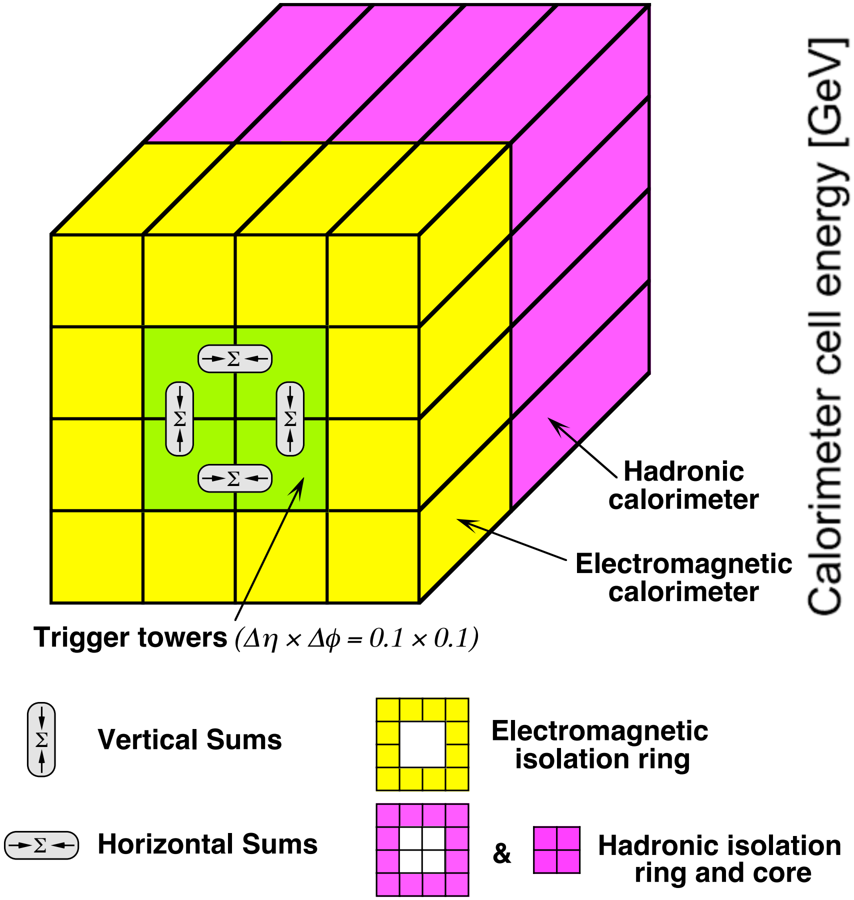
Detector design & construction have (obviously) a direct impact onto the physics

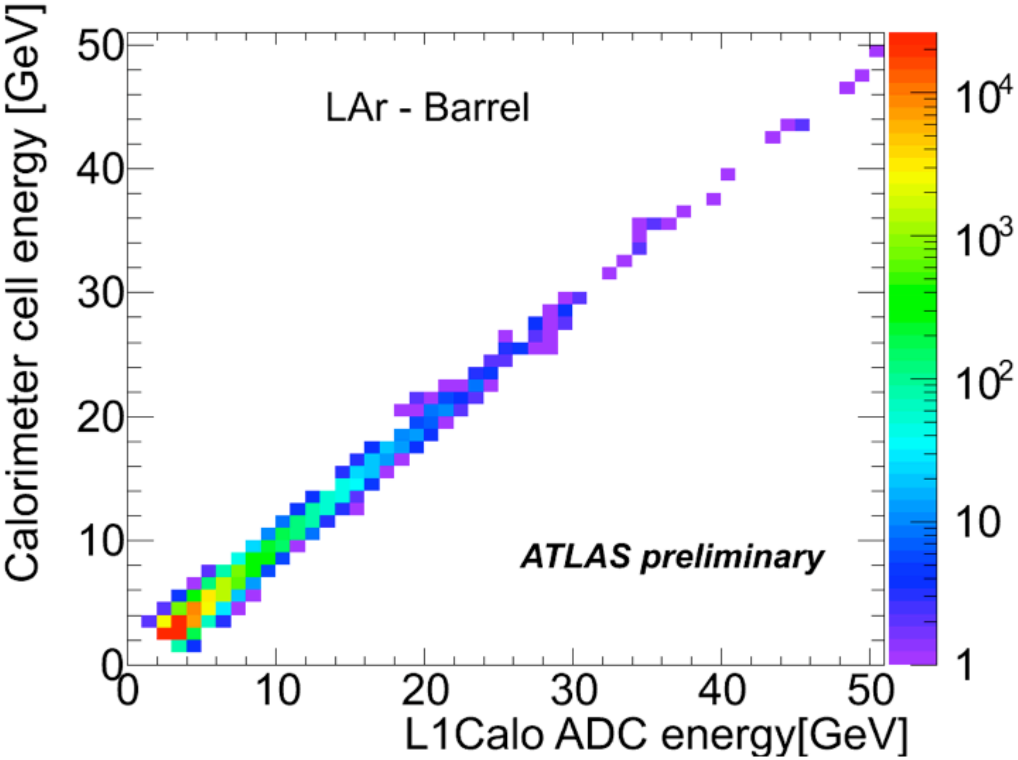
- Cell segmentation 0.1x0.1 at Tevatron, 0.025(0.003)x0.025 at LHC, semi-digital R/O for Linear Collider
- More and more precise simulation (interaction with matter, detector geometry) allows to understand quickly and very efficiently the detector performance

ATLAS Trigger chain

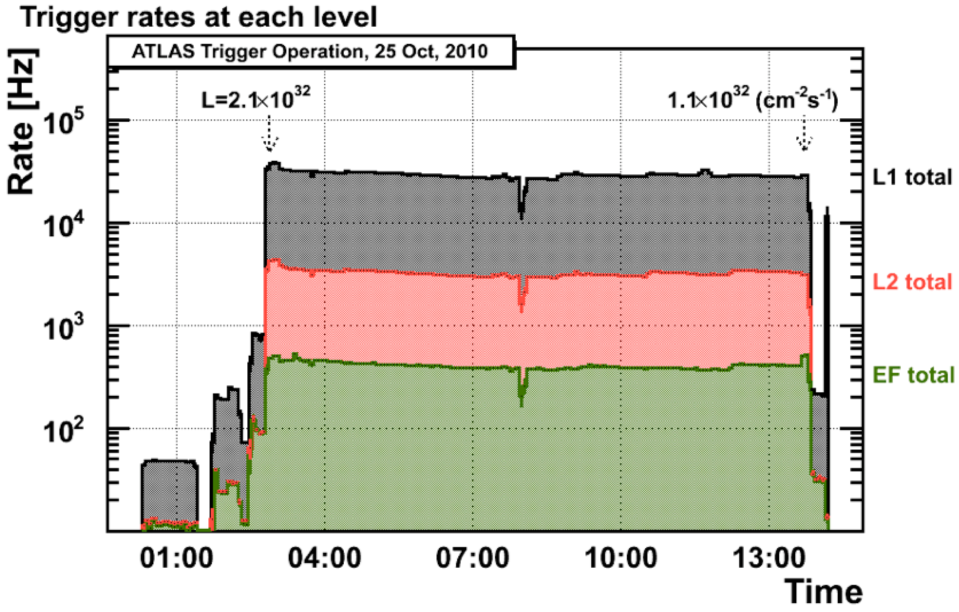


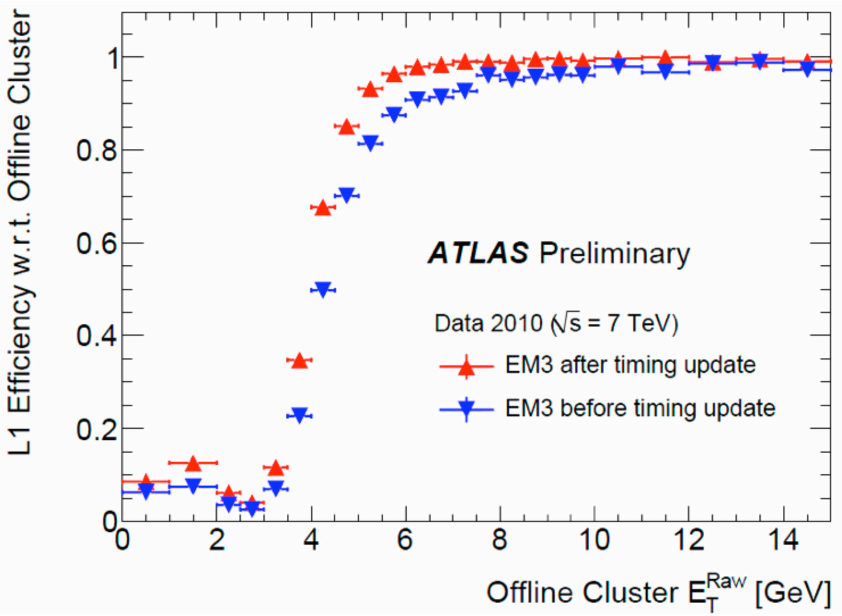
Level 1 calorimeter trigger





Calorimeter Trigger Efficiency





Trigger performance and “menus” are a key element towards physics results

- Balance between the various channels are regularly adjusted vs instantaneous luminosity
- For calorimetry:
  - Get calibrated energy for L1
  - Use “final” energy calibration (à la offline) for HLT