Calorimetry

concept & examples

European School of Instrumentation
in Particle & Astroparticle Physics
ESIPAP

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

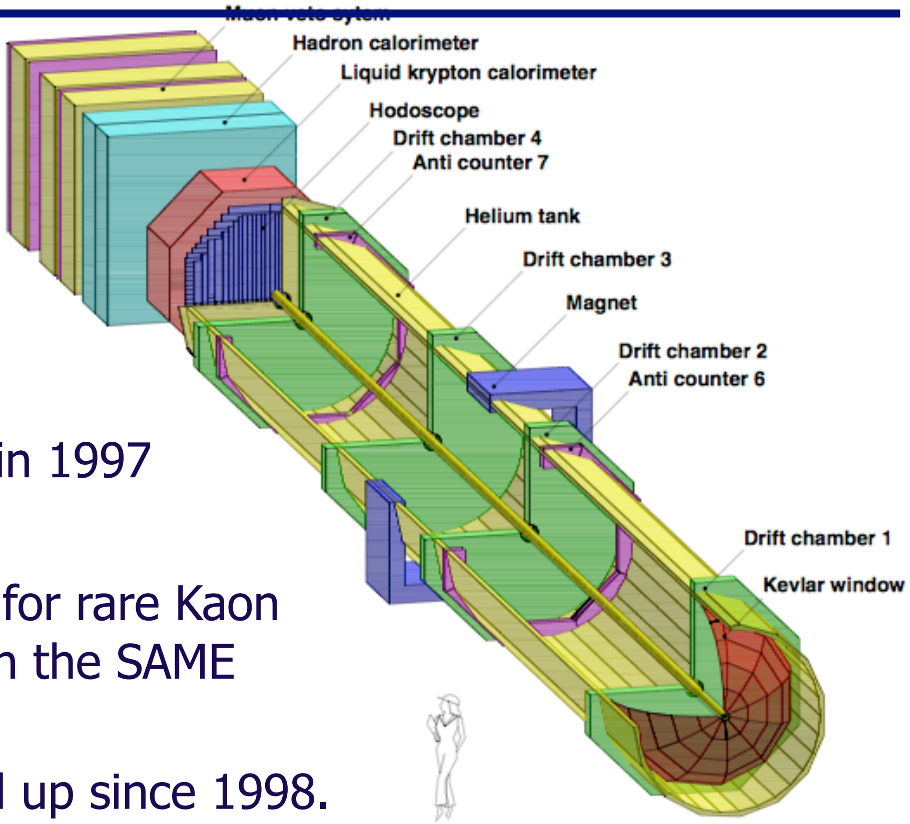
Calorimeter R&Ds for future colliders

H→γγ & the EM calorimeter

Tutorial

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.

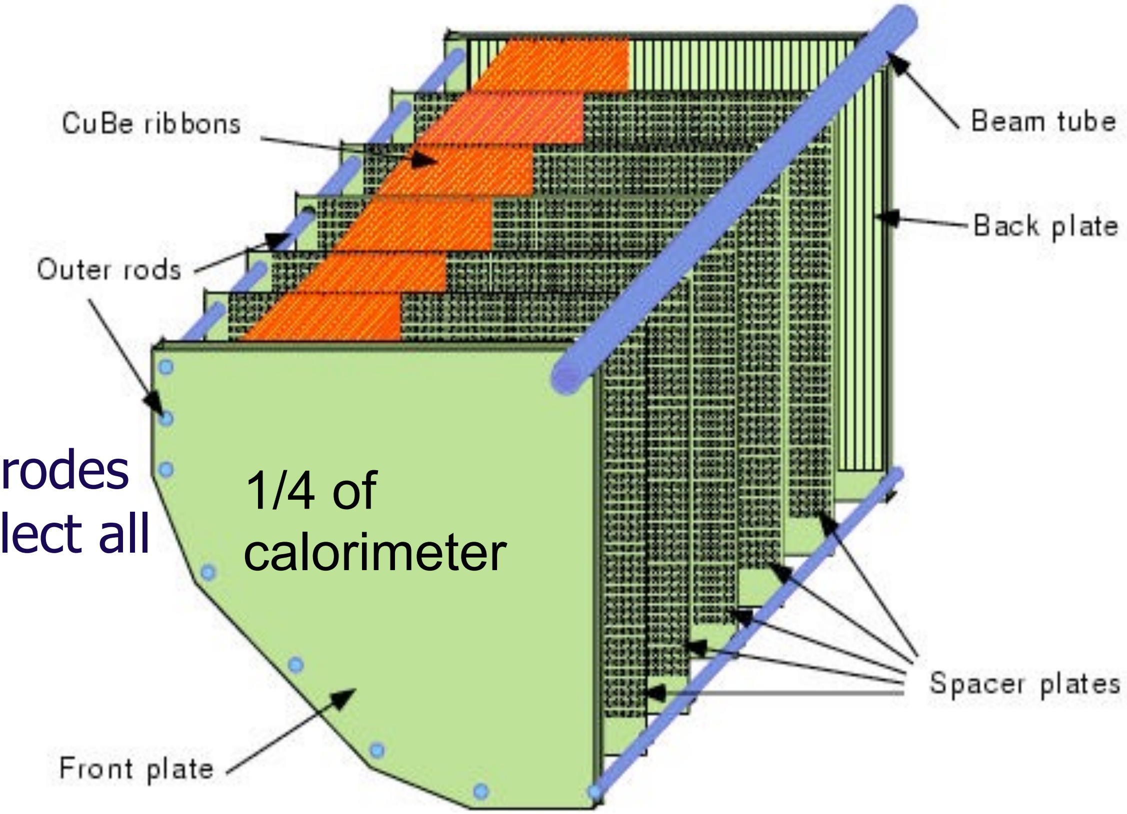
The calorimeter has not been warmed up since 1998.

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

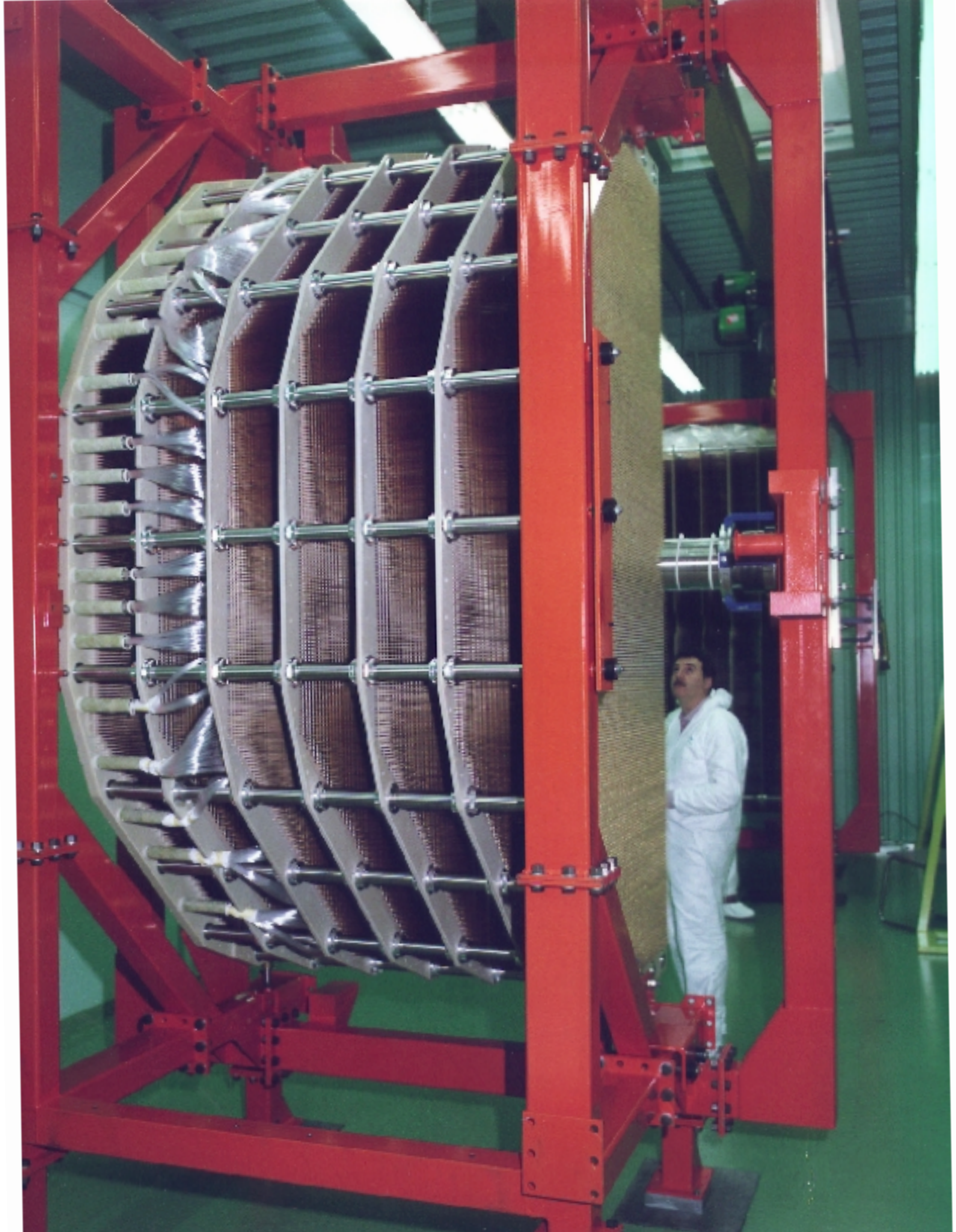
Le calorimètre à Krypton liquide de NA48

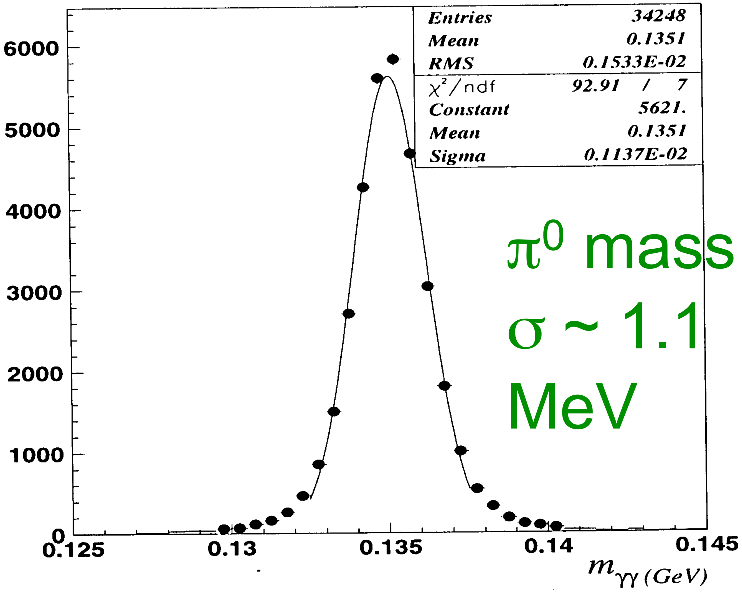
Liquid Krypton T = 120 ^{0}K

- NA48 has measured Re(ε'/ε) ~10^{-4} identifying the modes $K_S \rightarrow \pi^0\pi^0$ et $K_L \rightarrow \pi^0\pi^0\pi^0$
- Mass resolution on m(π^0): 1MeV (m(π^0) = 135MeV)
- Energy resolution 5%/√E
- LKr instrumented with electrodes with zig-zag geometry to collect all the charges.



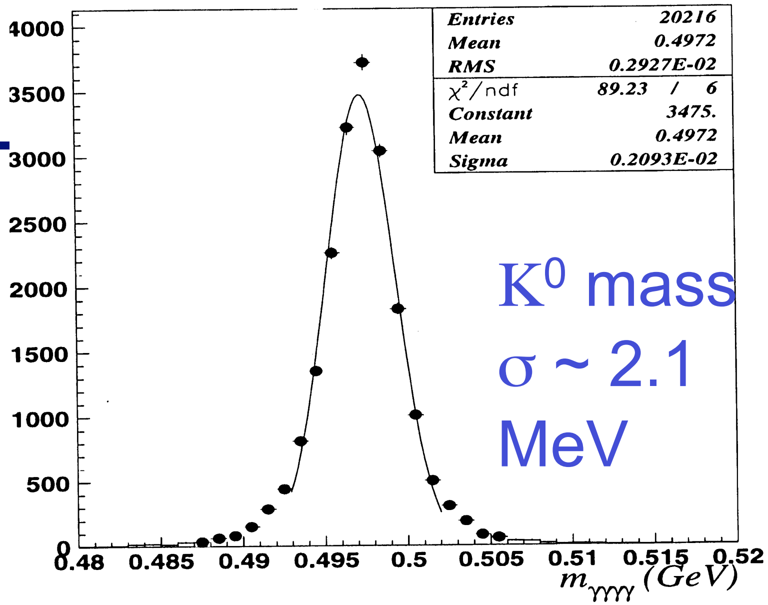
1/4 of calorimeter





π^0 mass

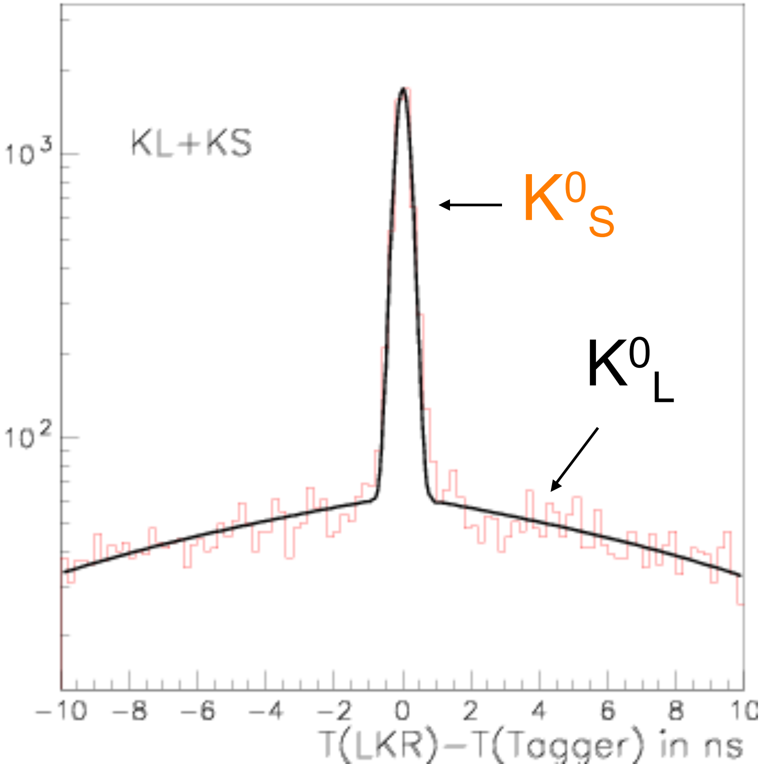
σ ~ 1.1 MeV



K^0 mass

σ ~ 2.1 MeV

NA48



Calorimeter time resolution

σ ~ 220 ps

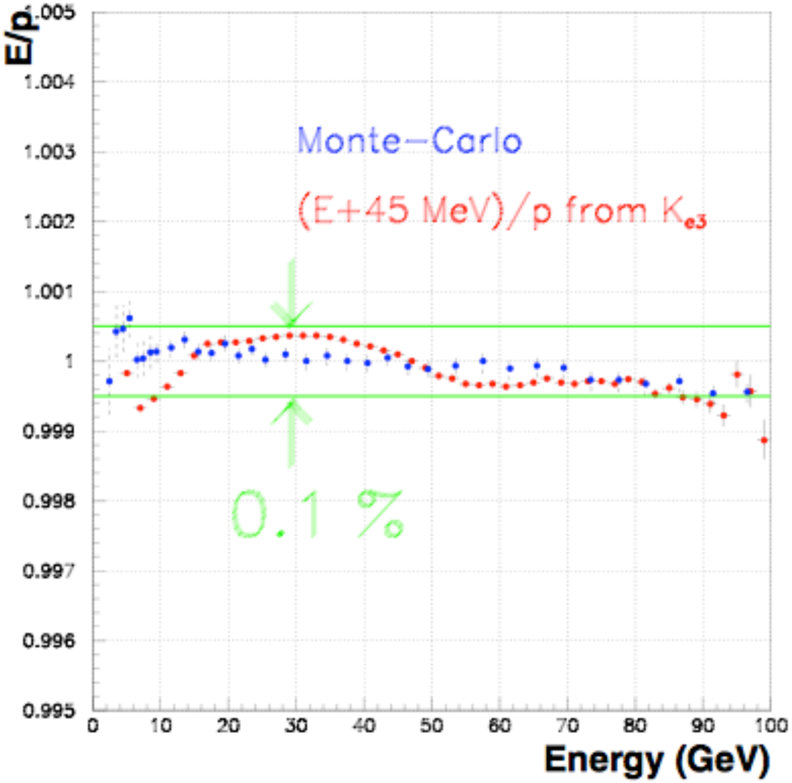
Energy Resolution

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

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

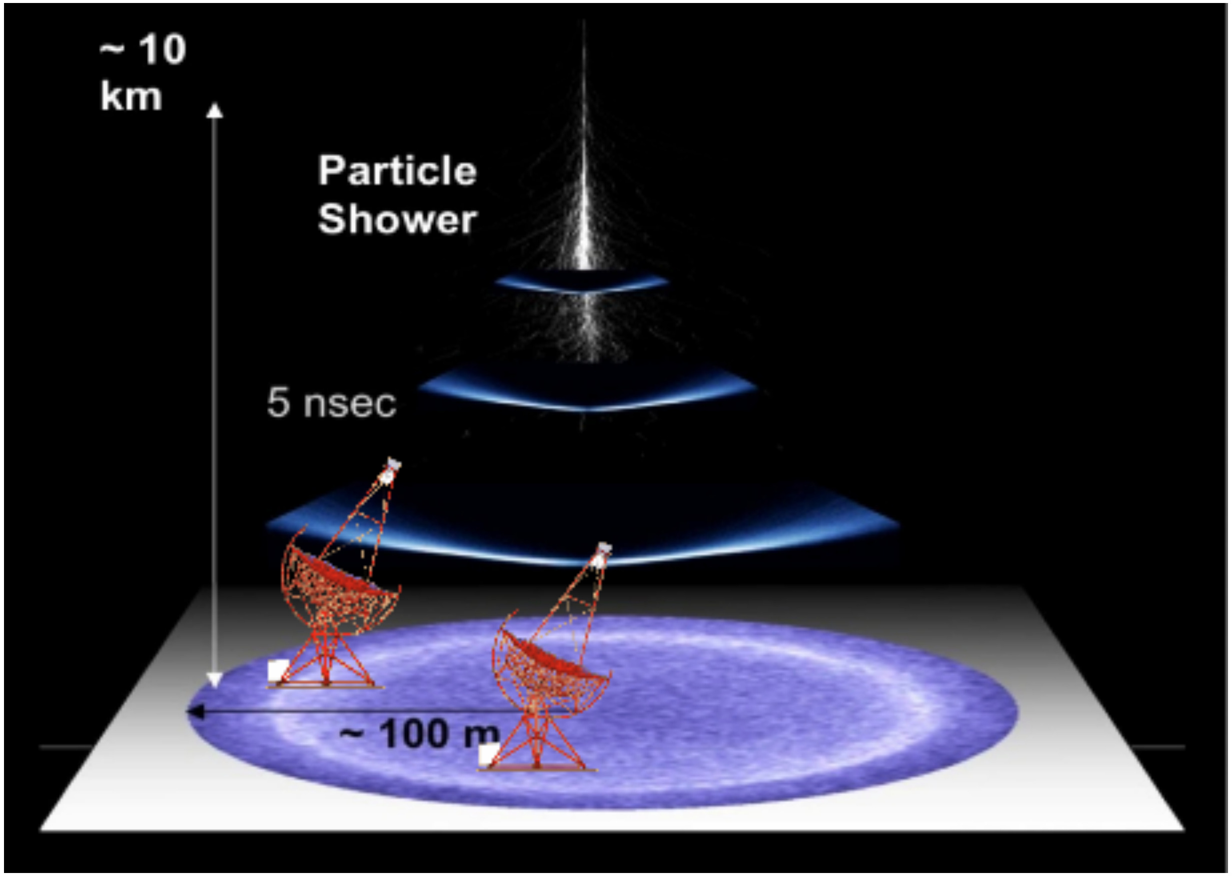
Spectrometer ⇒ Impulsion p (resolution ≈ 0.5% to 1%)
Calorimeter ⇒ Energy E

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

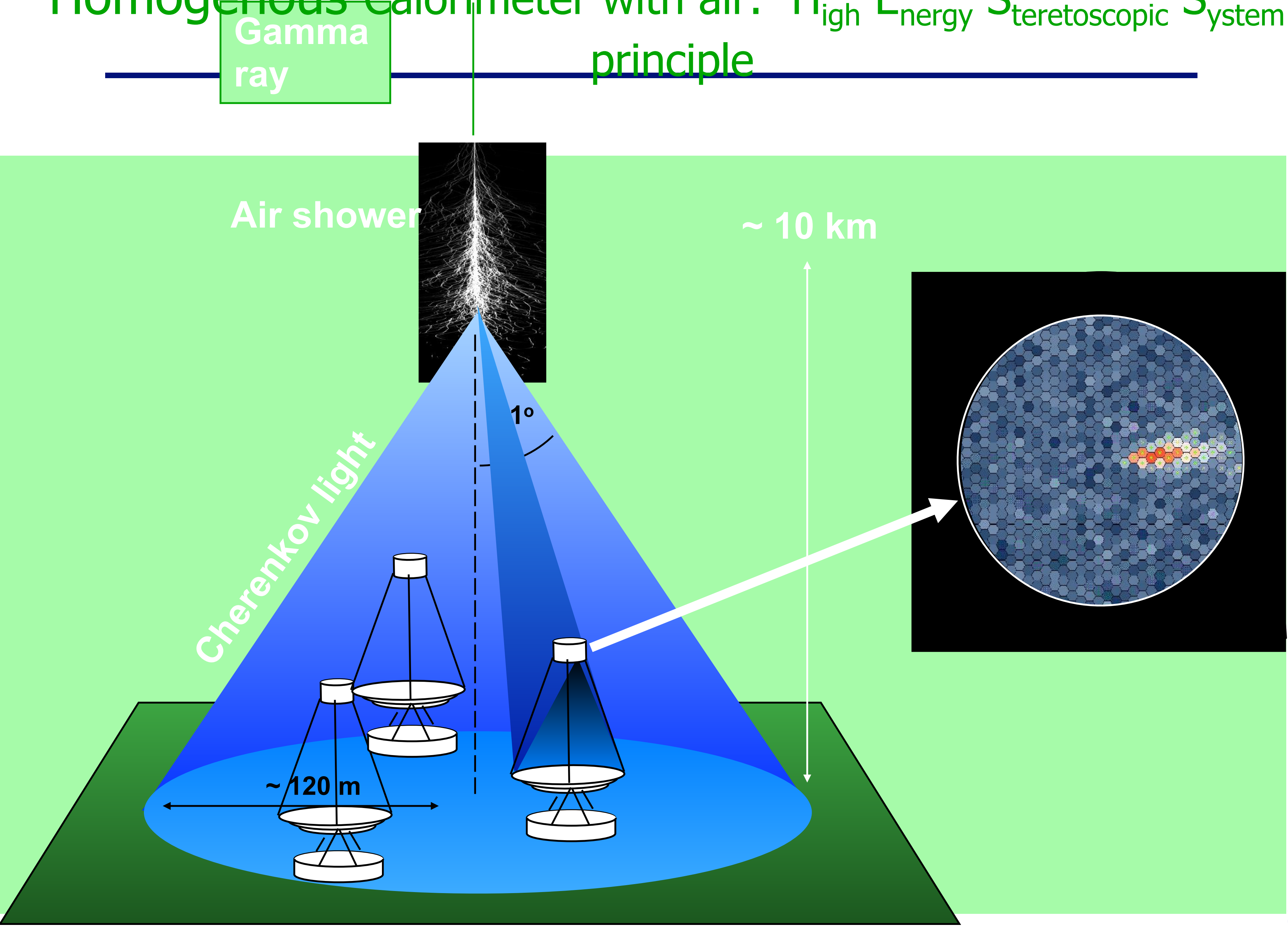


⇒ Non linearity ≈ 0.1%
(from 5 to 100 GeV)

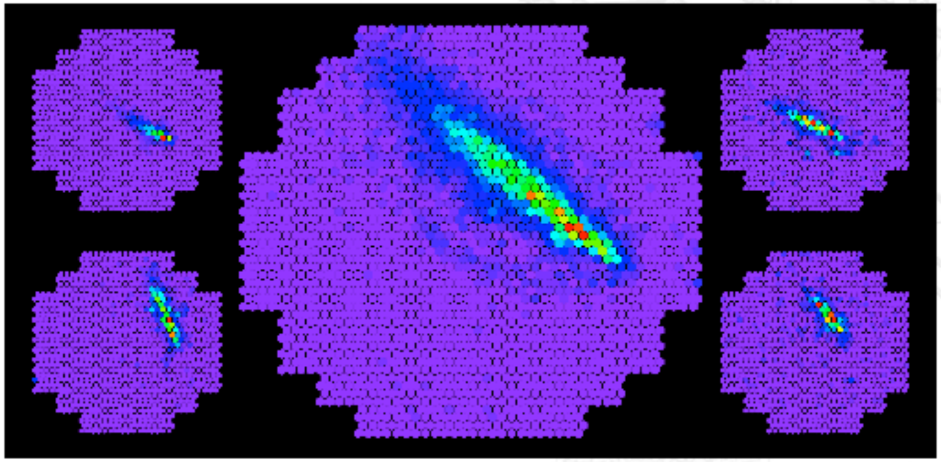
“Natural Calorimeter”

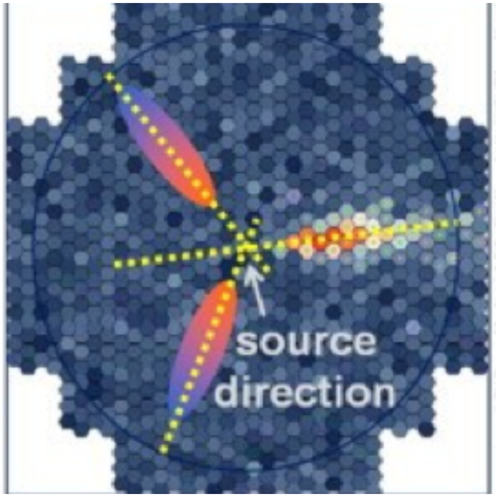


Homogenous Calorimeter with air: H_{igh} E_{nergy} S_{teretoscopic} S_{ystem}: principle

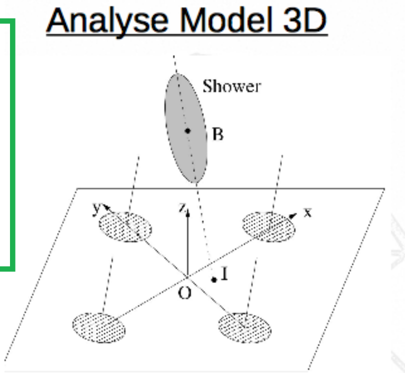


The method

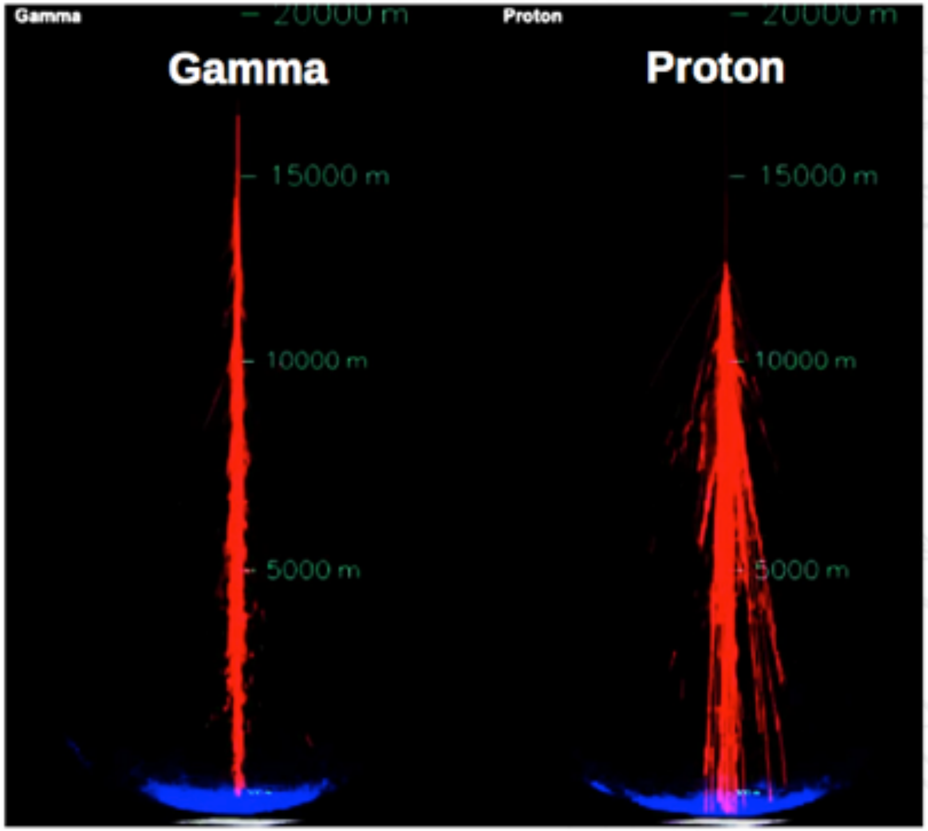




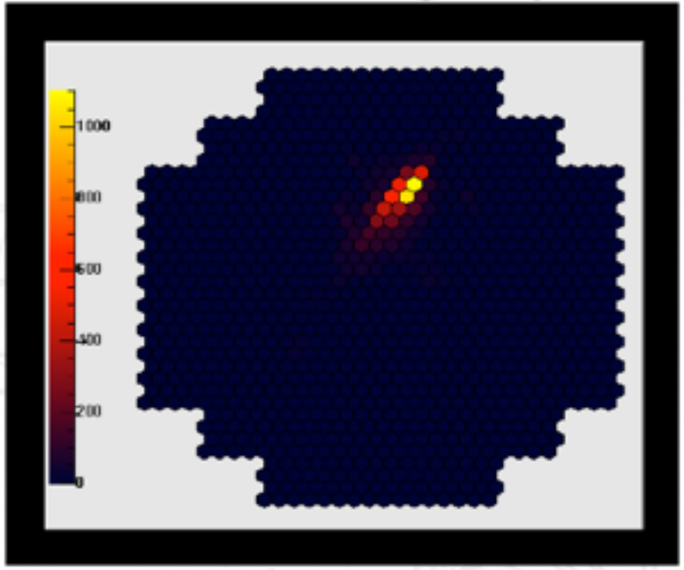
Reconstruct the shower position in atmosphere
Estimate the energy from signal in telepscopes +
simulation of air showers



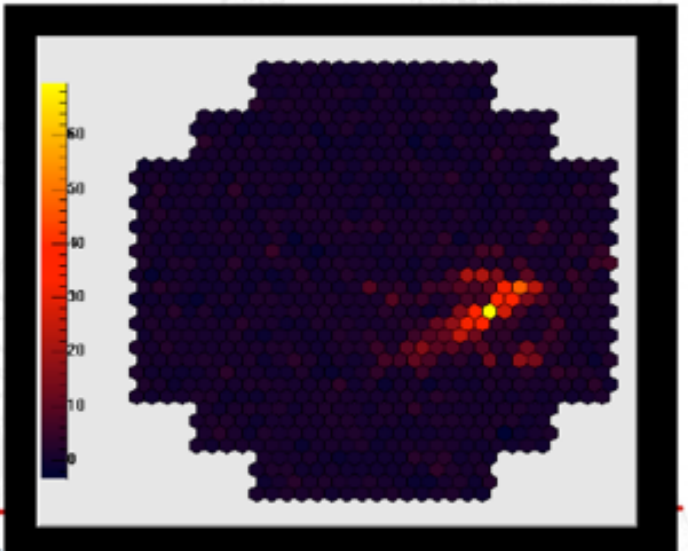
Détection des rayons γ



Gerbe électromagnétique

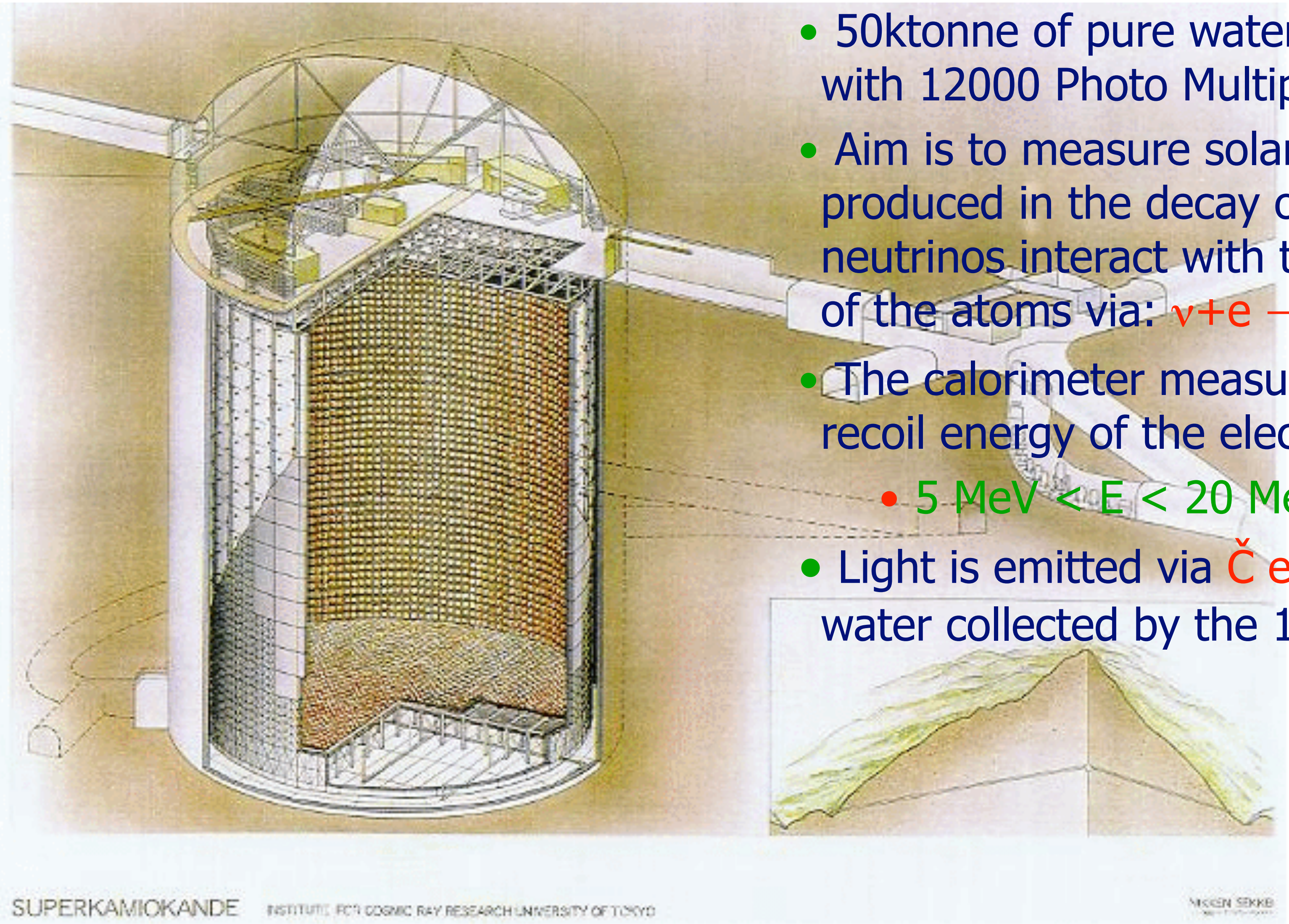


Gerbe hadronique



Homogenous Calorimeter with air: H_{igh} E_{nergy} $S_{teretoscopic}$ S_{ystem}: installed in Namibia

Super-Kamiokande: Čerenkov dans l’eau

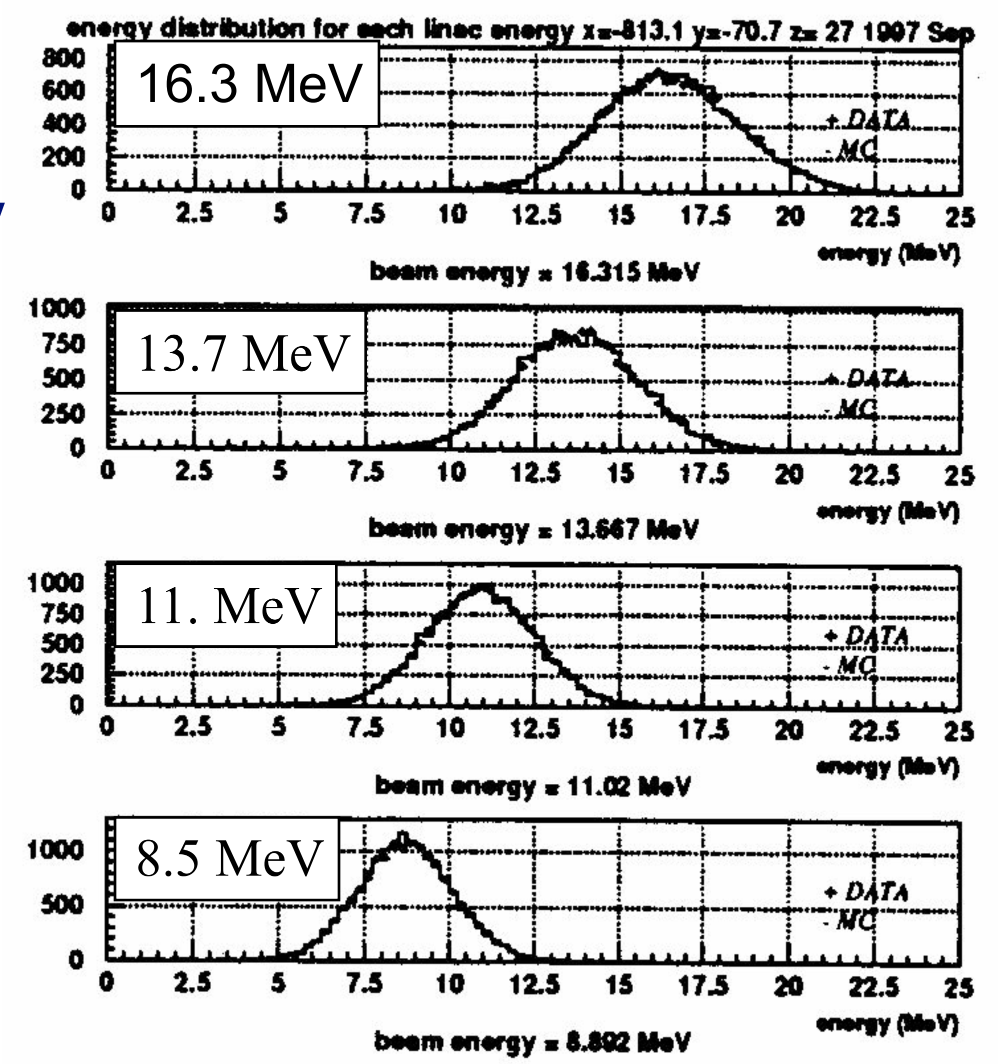


- 50ktonne of pure water – readout with 12000 Photo Multipliers
- Aim is to measure solar neutrinos produced in the decay of ^{8}B; neutrinos interact with the electrons of the atoms via: $\nu + e \rightarrow \nu + e$
- The calorimeter measures the recoil energy of the electron:
  - $5\ \mathrm{MeV} < E < 20\ \mathrm{MeV}$
- Light is emitted via Č effect in water collected by the 12000 PMs

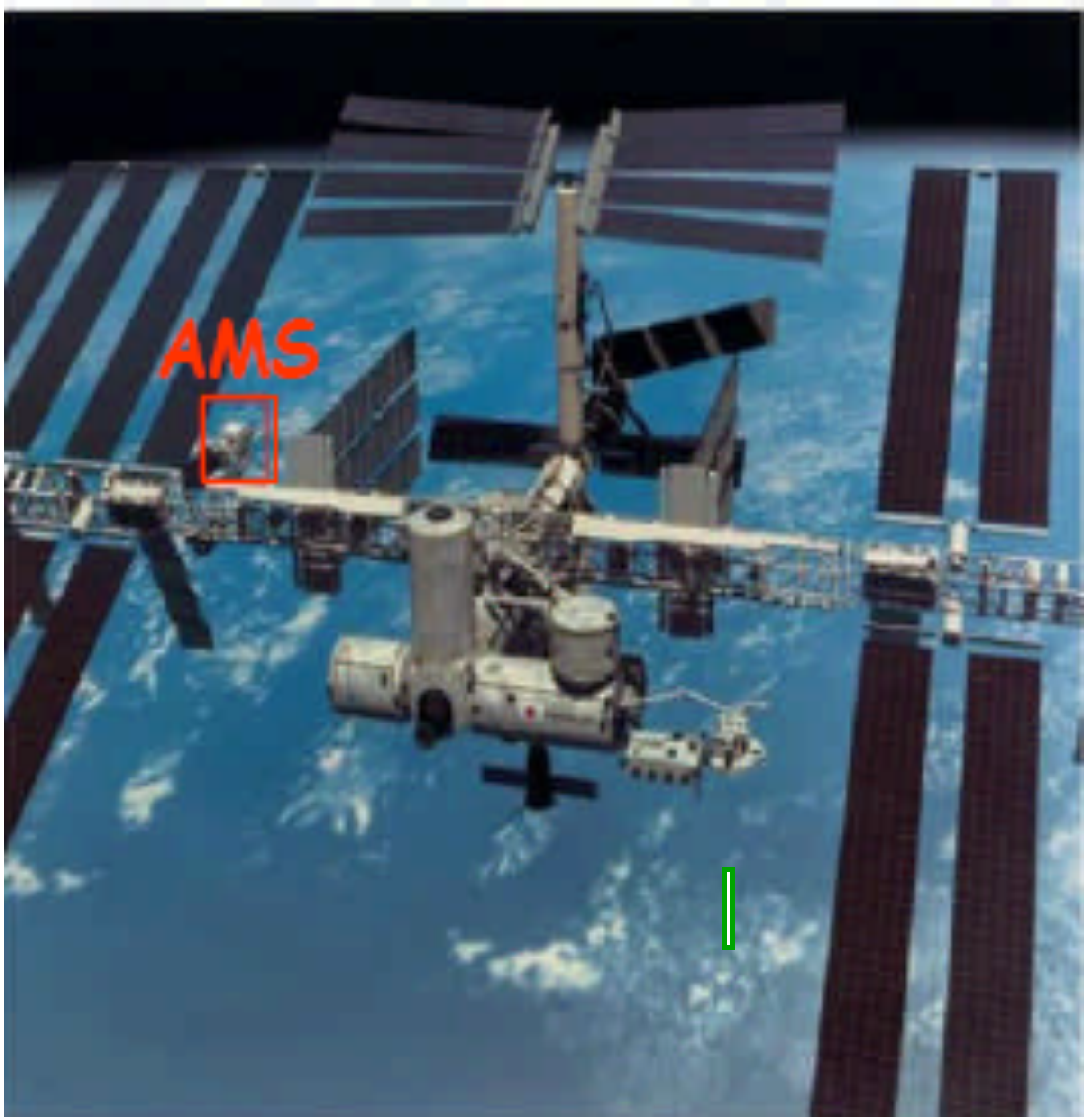
Performance Super-Samiokande

- Prior to data taking: testbeam
- Response and time uniformity better than 0.5%

- 10% à 10MeV

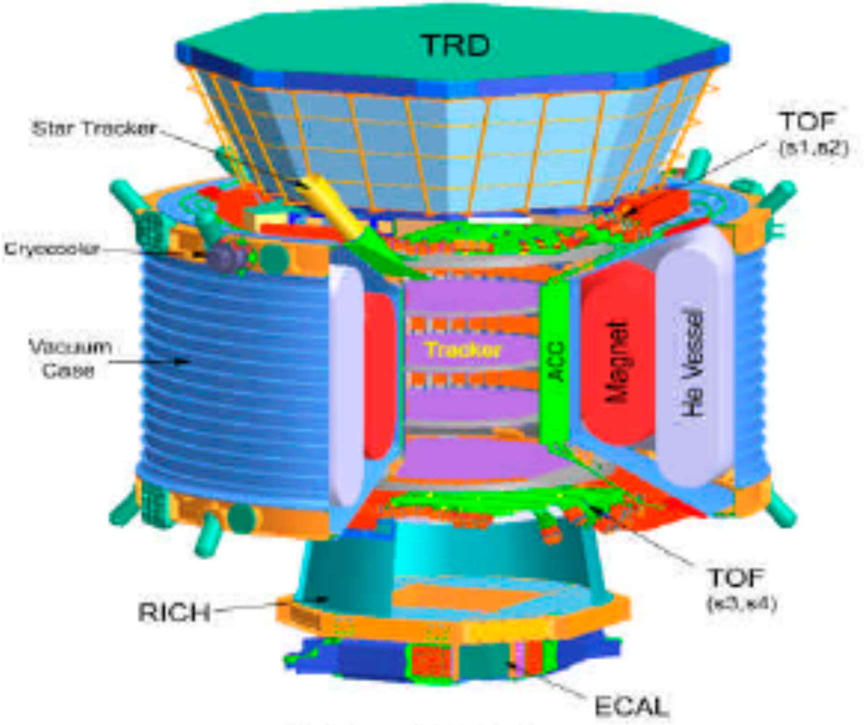


Alpha Magnétique Spectrometer



- AMS was conceived to study very high energy cosmic rays.
- AMS is searching for presence of anti-matter in cosmic rays (e.g. anti-He)
- AMS also measures high energy photons with its calorimeter

Alpha Magnetic Spectrometer

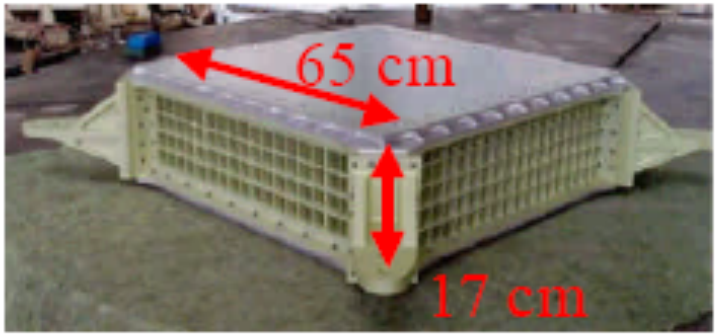


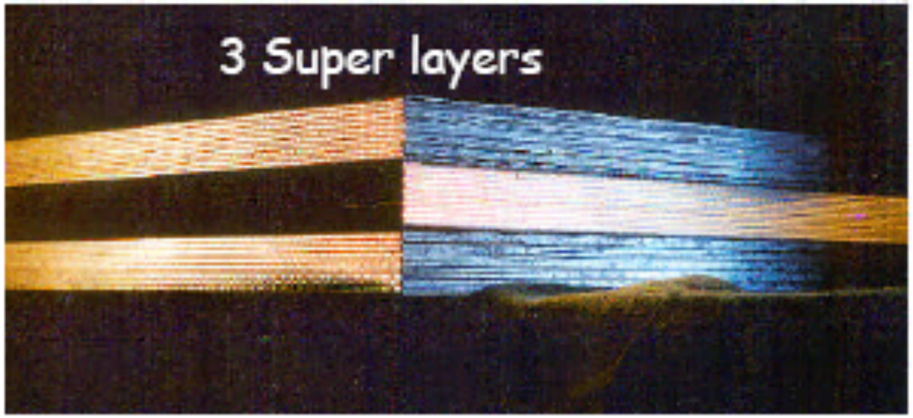
AMS on ISS for 3 years

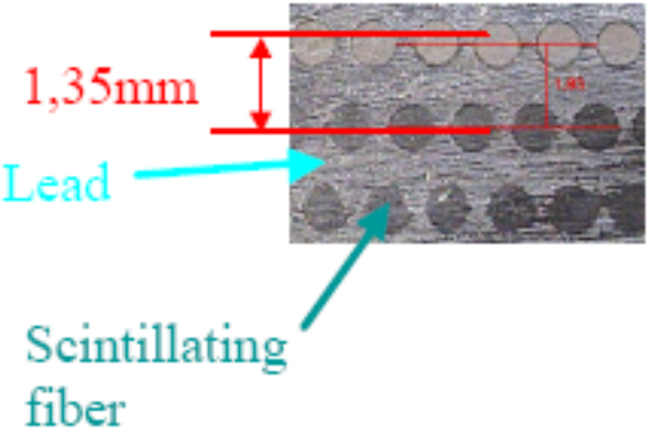
- Transition Radiation Detector
  - Foam + drift tubes (Xe/CO_2)
- Time of Flight (trigger)
  - Scintillators, fine mesh PMT's
  - $\sigma_t \sim 120$ ps
- Superconducting magnet ($0.86\ T{\cdot}m^2$)
- Tracker (8 layers, $6 m^2$)
  - 6 double-sided silicon strips
  - $\sigma_x = 10\ \mu m$ in bending 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



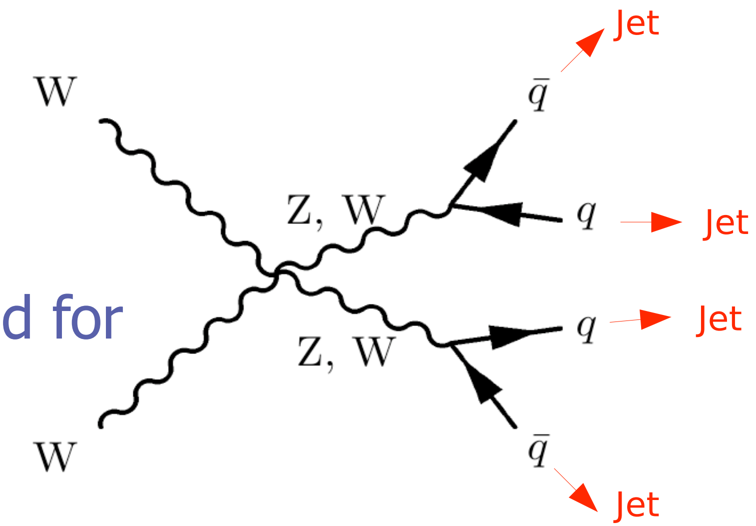




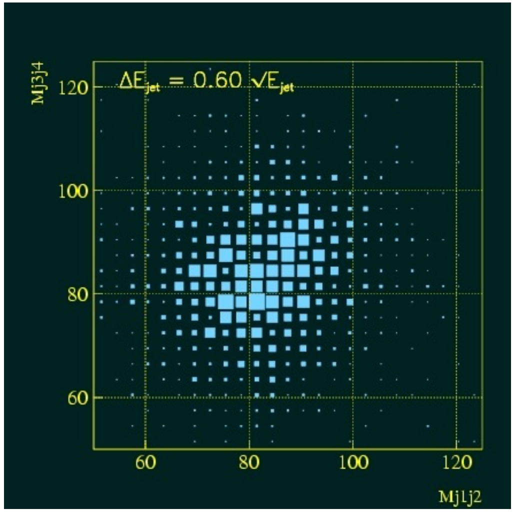
Calorimeters R&D for Linear Colliders

Some ideas for future calorimeters (Linear Colliders)

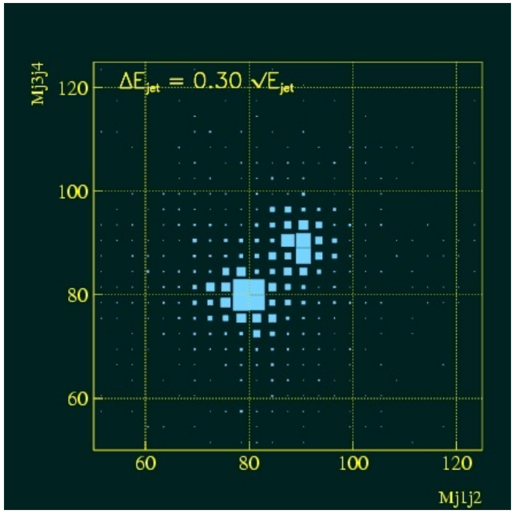
- Boson-Boson scattering
  - Hadronic Decay of W & Z
- Needs improved energy resolution
  - Higly granular calorimeters optimized for particle flow



$\Delta(M_Z,M_W) \sim 10$ GeV



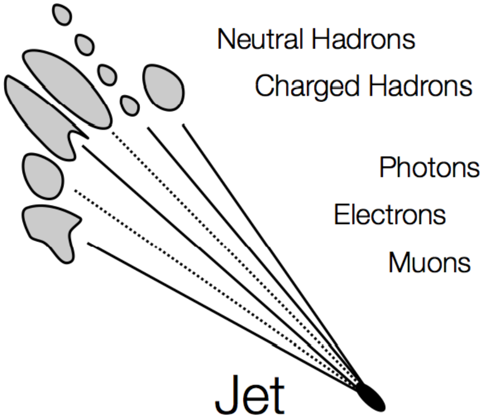
60%/√E



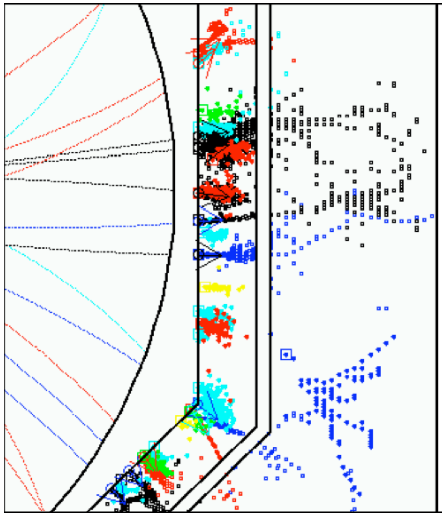
30%/√E

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

LINEAR COLLIDER: JET ENERGY MEASUREMENT



Component	Detector	Fraction	Part. resolution	Jet Energy Res.
Charged ($X^{\pm}$)	Tracker	60%	$10^{-4} E_X$	negligible
Photons (γ)	ECAL	30%	$0.1/\sqrt{E_\gamma}$	$.06/\sqrt{E_{jet}}$
Neutral Hadrons (h)	E/HCAL	10%	$0.5/\sqrt{E_{had}}$	$.16/\sqrt{E_{jet}}$



Difficulties

- Non-compensation
  - hadronic vs electromagnetic energy
- Missing energy
  - e.g. muon tracks
- Double counting
  - when using track momenta

Solutions

- Particle Flow Calorimetry
  - Reduce the role of *hadron* calorimetry to measurement of neutrons, K^0
- Compensating Calorimetry
  - Correcting hadronic energy to nuclear-binding energy loss

Particle Flow Analysis

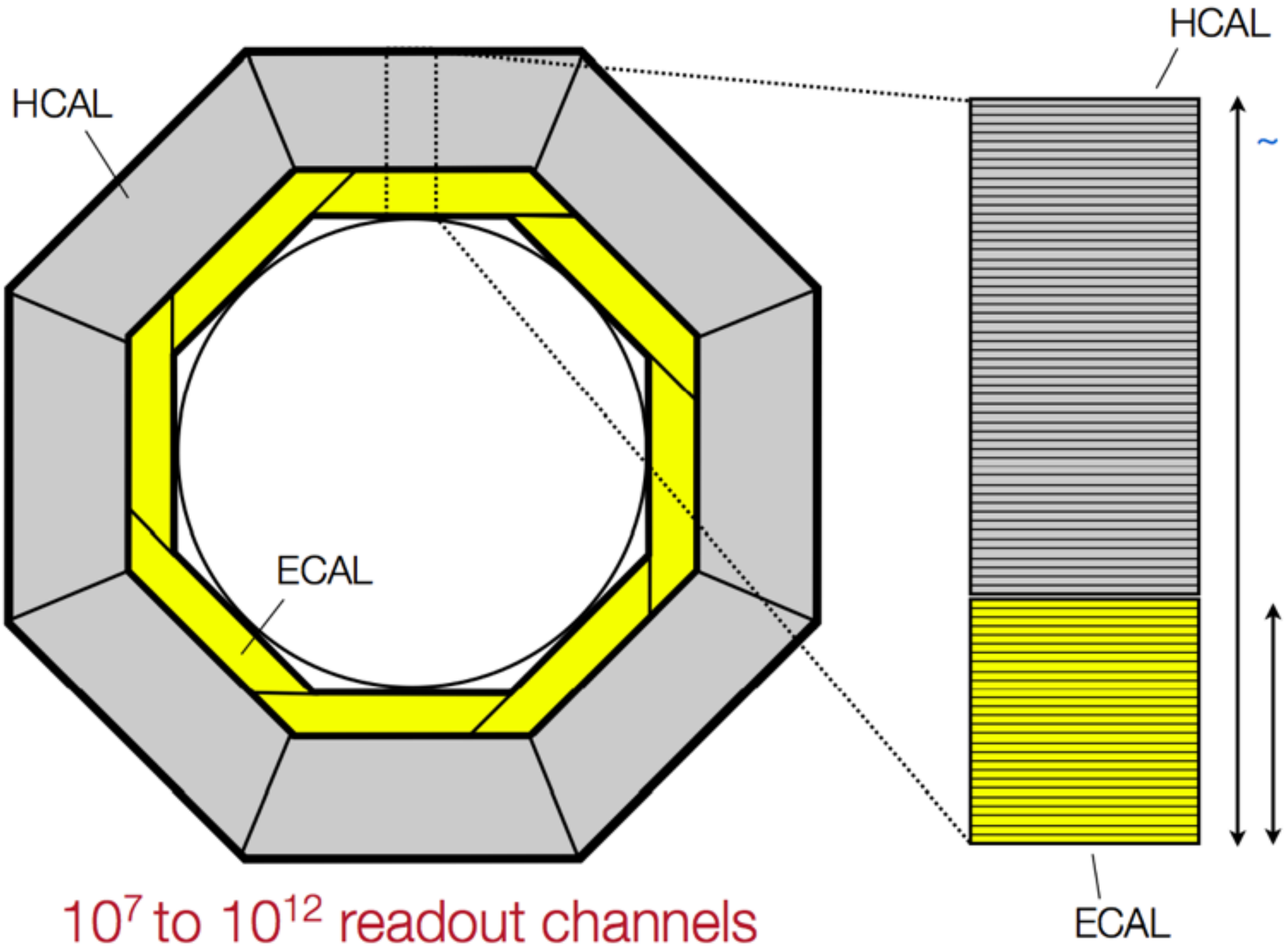
Choose detector best suited for particular particle type

use tracks and distinguish *charged* from *neutral* energy to avoid double counting

SEGMENTATION

distinguish electromgnetic and hadronic energy deposits for software compensation

LINEAR COLLIDER: OVERALL DESIGN



~ 5 λ

40 extra layers
[2.5 cm/layer]

Granularity:
- $3x3 \text{ cm}^2$ to $20x20 \text{ cm}^2$ (analog)
- $1x1 \text{ cm}^2$ (digital)

~ 24 X_0

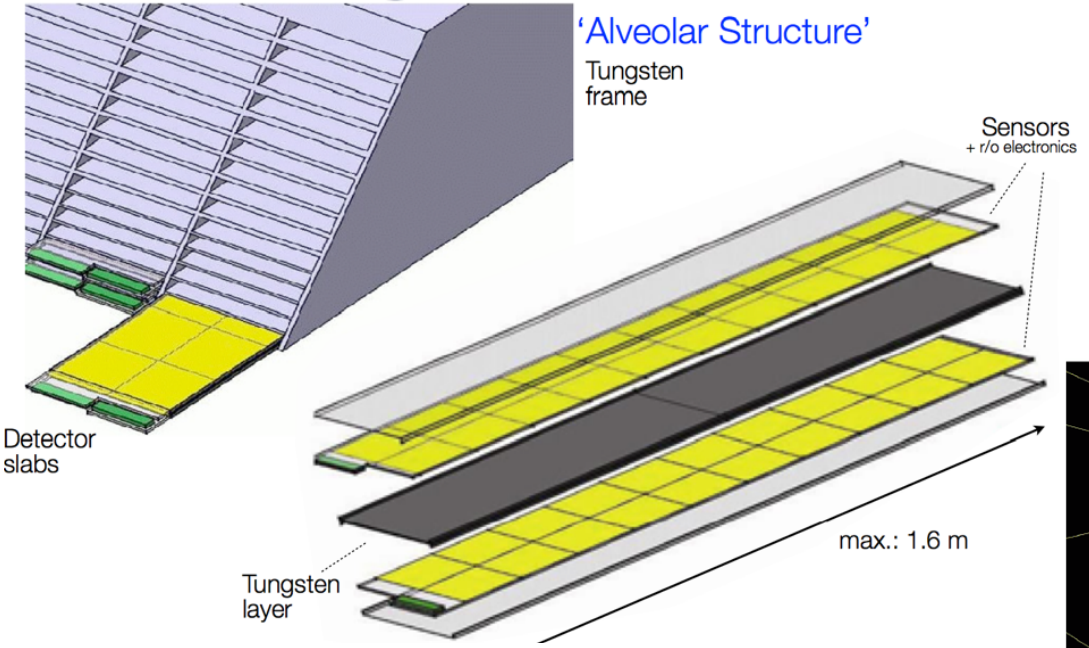
30 - 40 layers
[0.6 – 1.2 X_0]

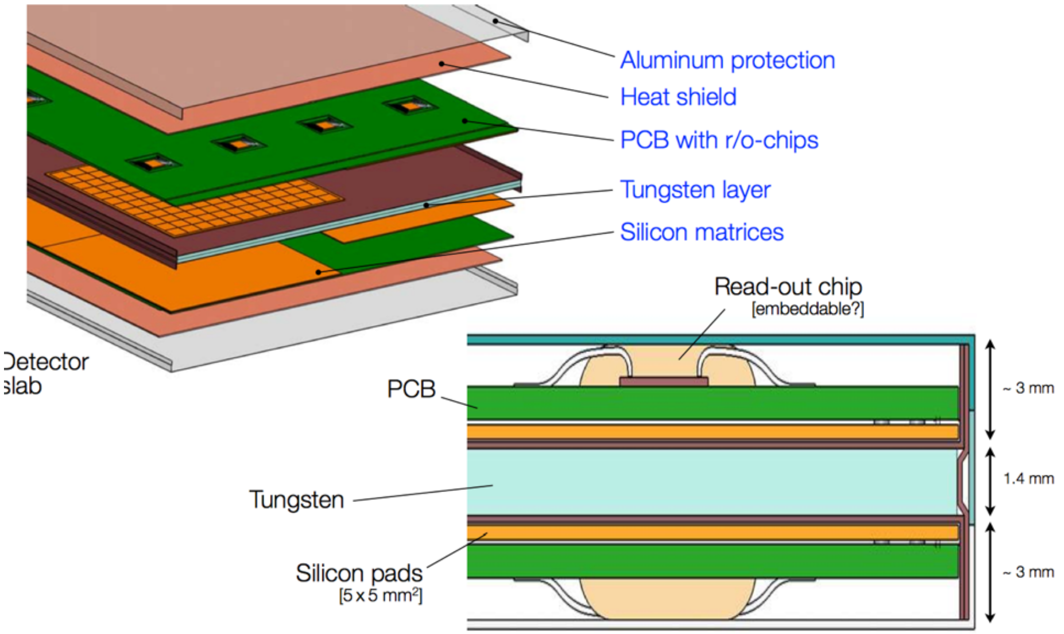
Granularity:
- $5x5 \text{ mm}^2$ (analog)
- $50x50 \ \mu\text{m}^2$ (digital)

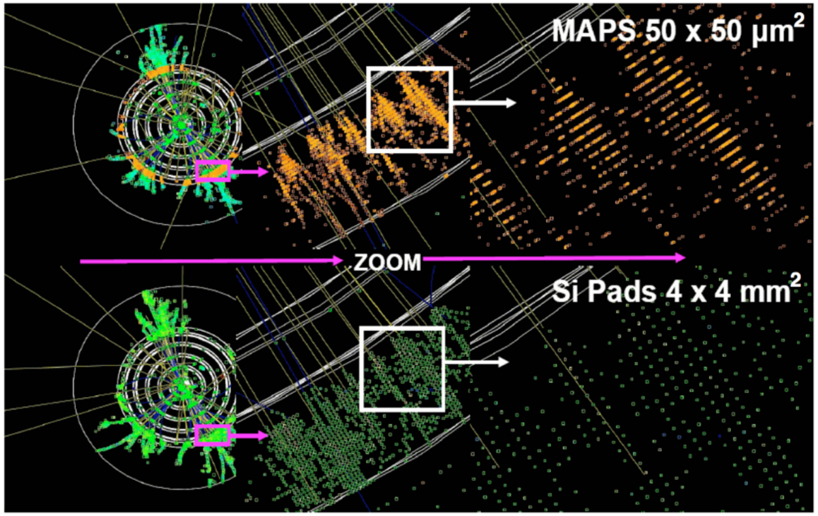
10^7 to 10^{12} readout channels

[high-level of integration, low power consumption]

LINEAR COLLIDER ECAL design





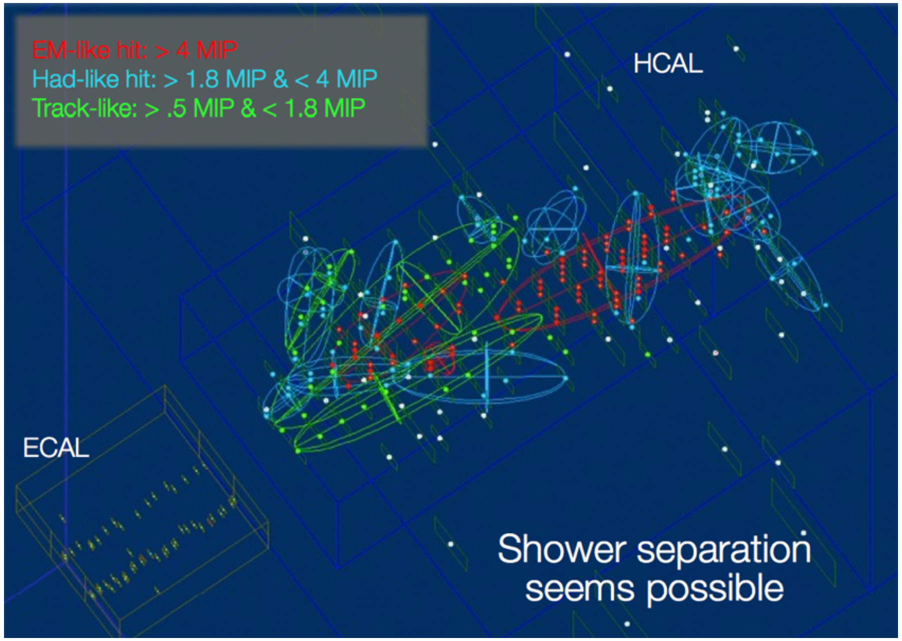


Simulation

LINEAR COLLIDER HCAL design

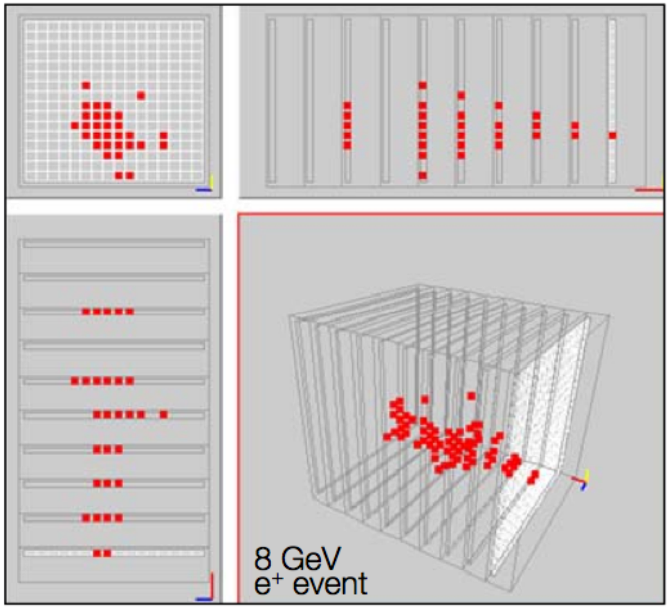
Why digital ?
- Better PFA performance
- *Cheap*, robust detector
- Small total thickness

Used technologies
- GEMs
- μMegas
- RPCs



Shower separation seems possible

Slice Test Setup [Fermilab]



8 GeV e^+ event

Example RPCs:

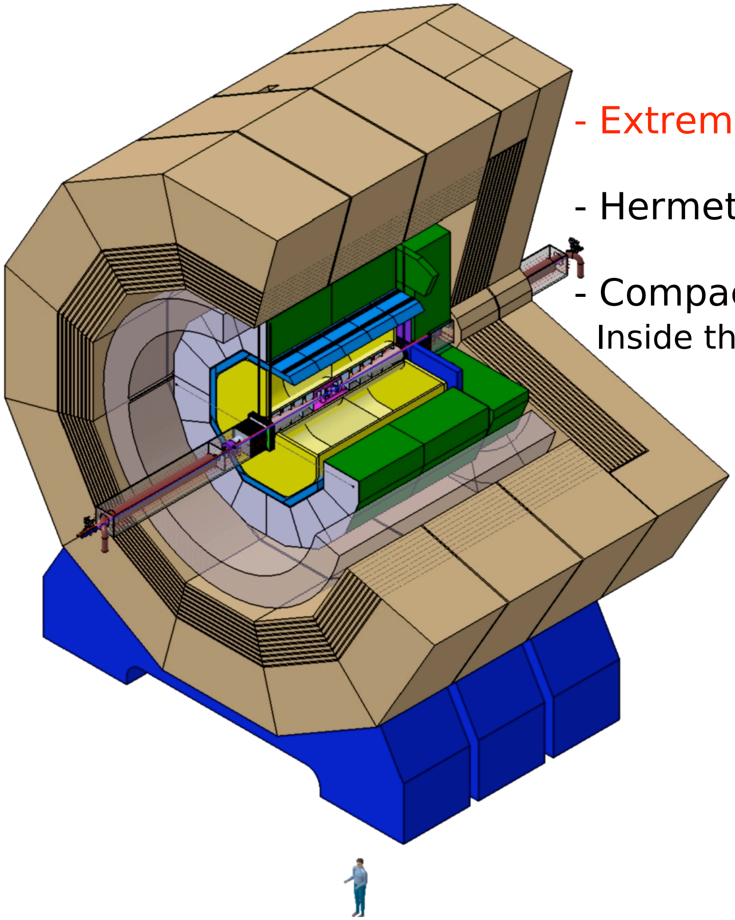
Pad Size: 1 x 1 cm^2

Total thickness: < 6 mm possible

Vertical Slice Test with 9 small chambers successful

Large Prototype to be built

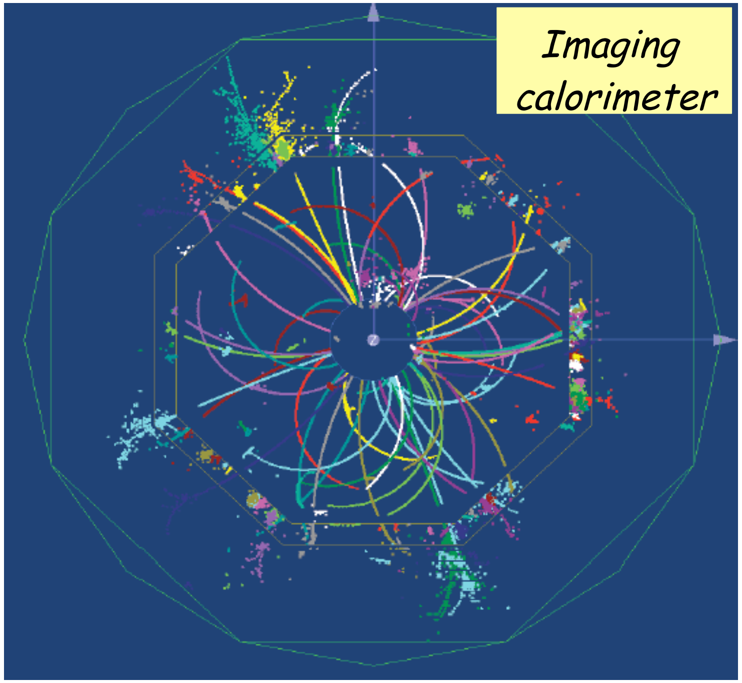
Calorimeter requirements



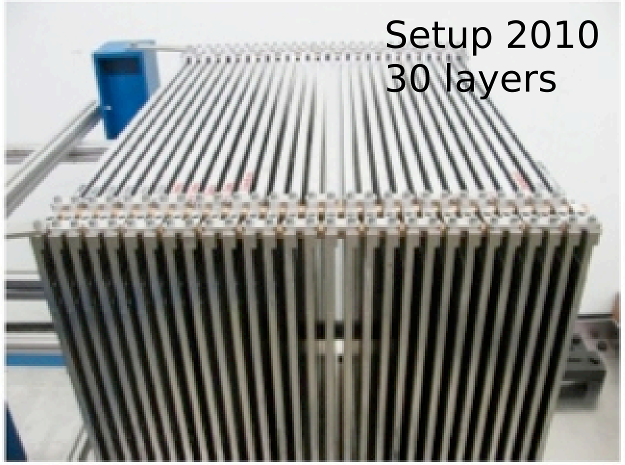
- Extreme high granularity

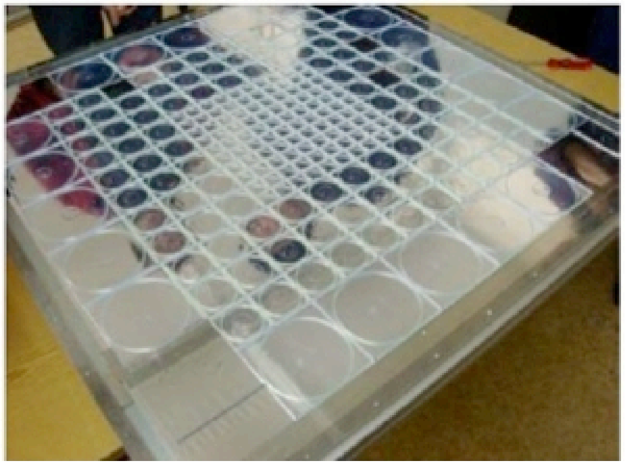
- Hermetic

- Compact
  Inside the coil of the solenoid



Many ongoing testbeams (e.g. CALICE)


Setup 2010
30 layers



Linear Collider Calorimeters Development:

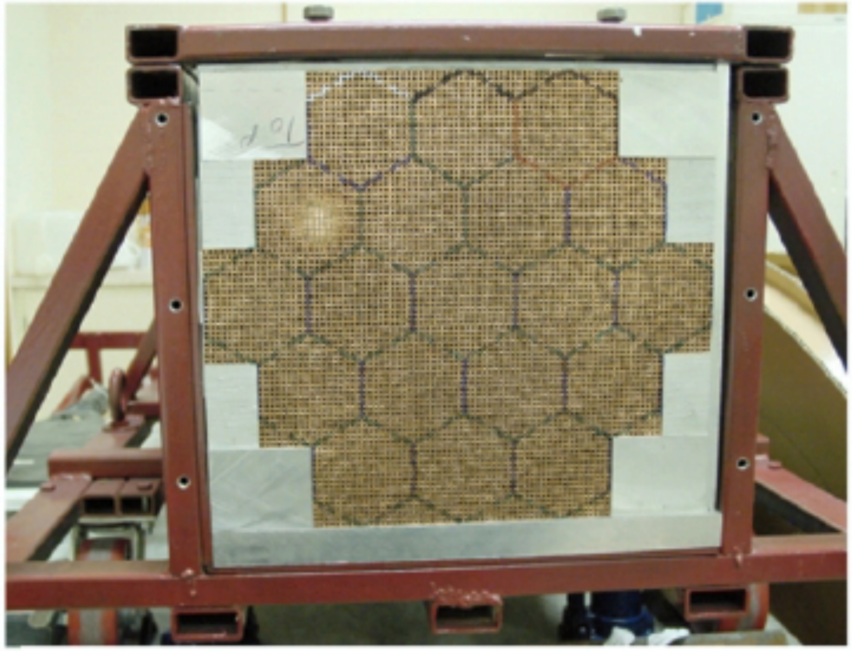
- Fine segmentation (also for HAD)
  - Both longitudinal and lateral
- Self-suporting calorimeter
  - Minimize dead zones
- Semi-digital readout
  - Electronics embedded inside the calorimeter
  - Development of Power Pulsing

Example: DHCAL

Dual readout for hadronic showers DREAM

Intermezzo: DREAM (ongoing R&D)

DREAM: Structure

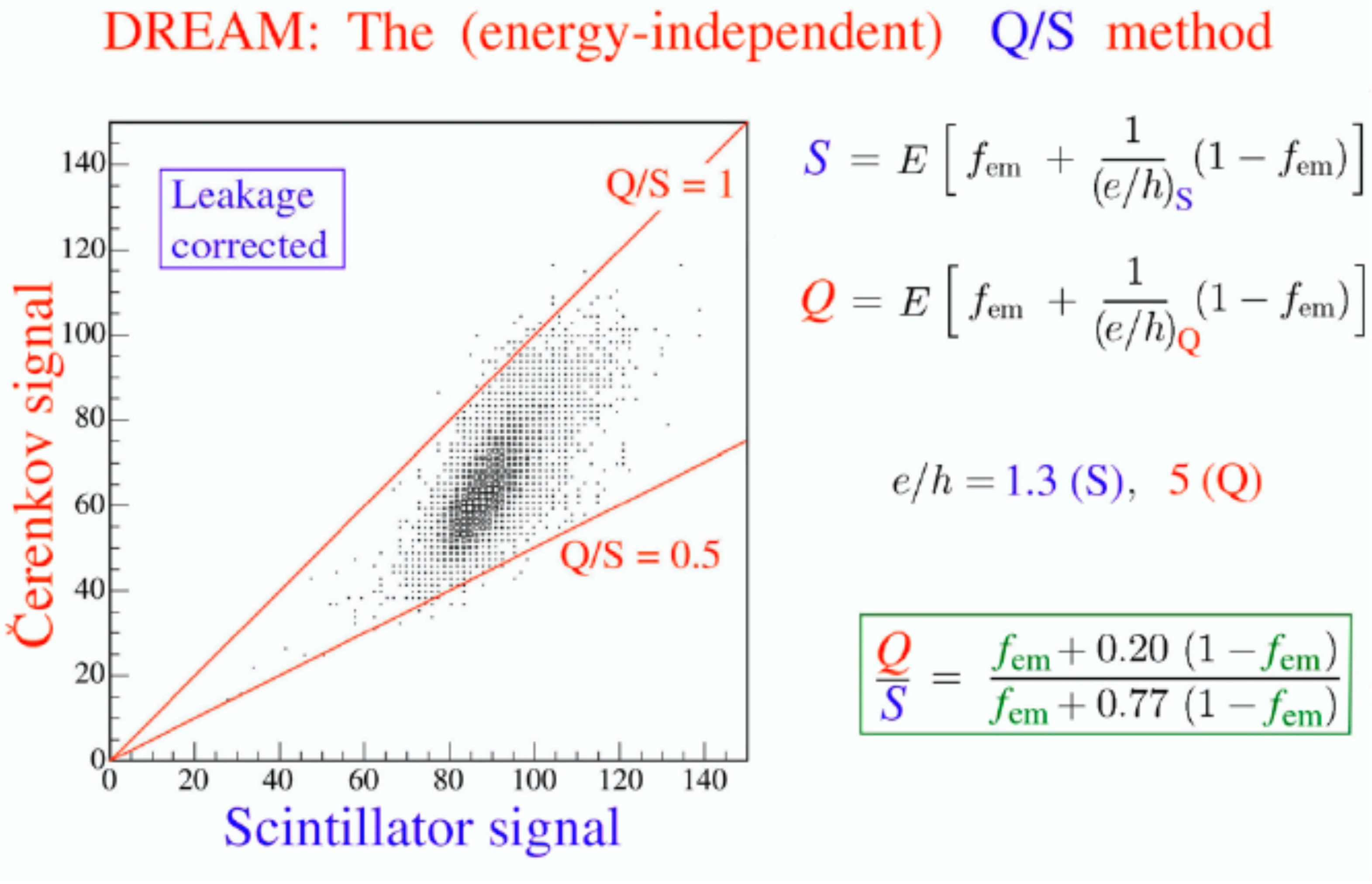


Scintillator sensitive to visible energy only

Quartz sensitive to em only (Cerenkov light)

- *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 ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM: The principle



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

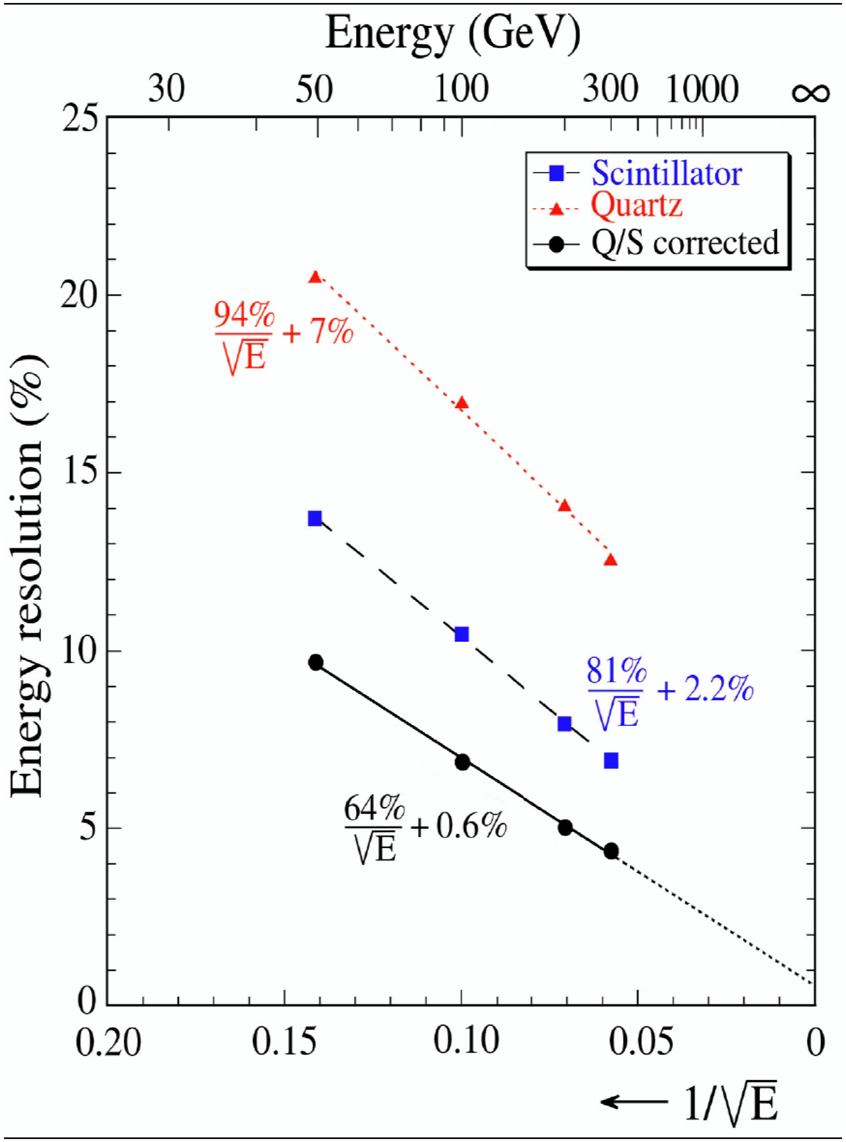
$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_S}(1 - f_{\rm em})\right]$$

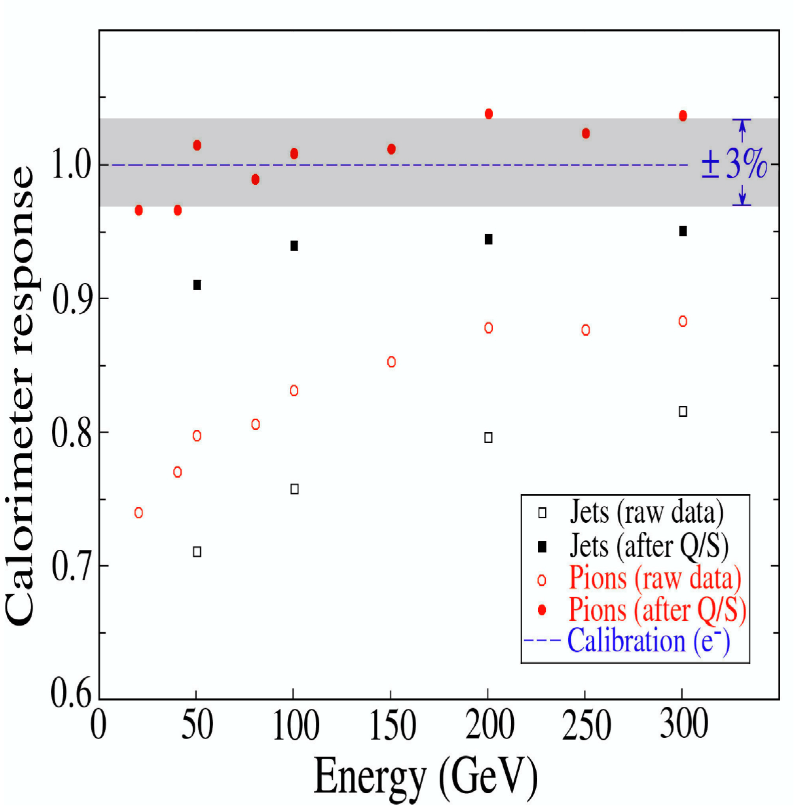
$$Q = E\left[f_{\rm em} + \frac{1}{(e/h)_Q}(1 - f_{\rm em})\right]$$

$e/h = 1.3$ (S), 5 (Q)

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

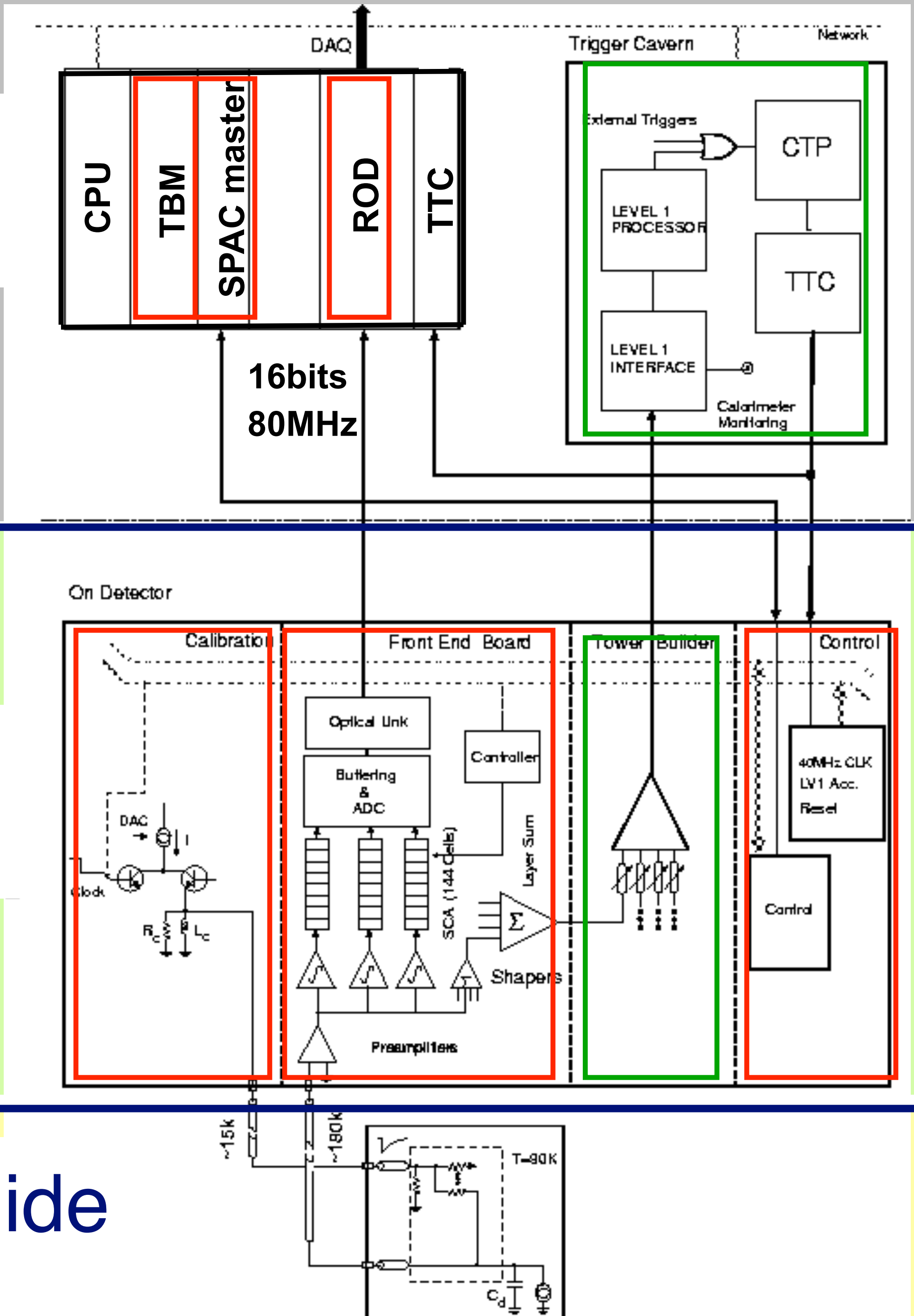
DREAM: some results





Chaîne de lecture de l'accordéon

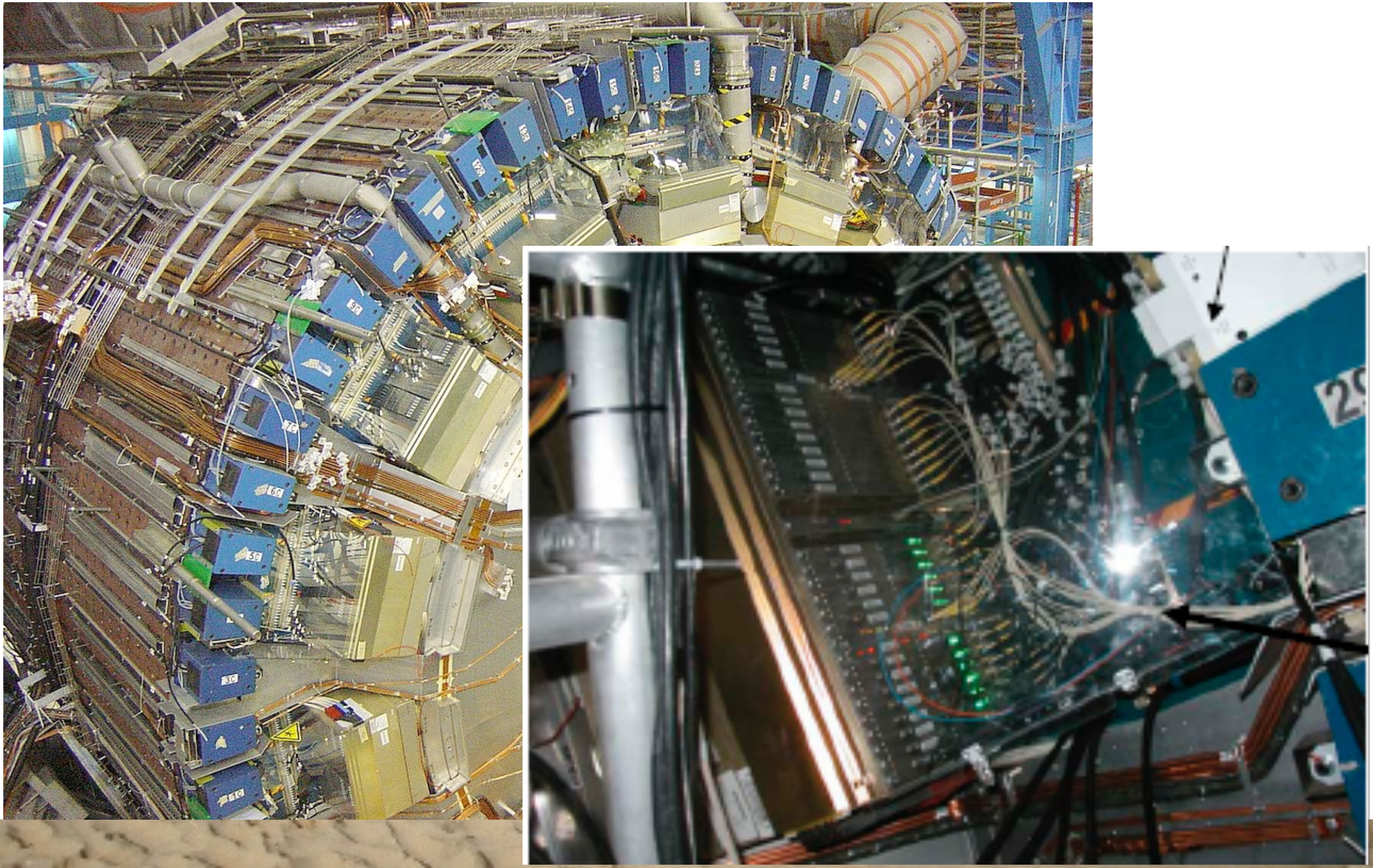
Salle de comptage



sur le cryostat

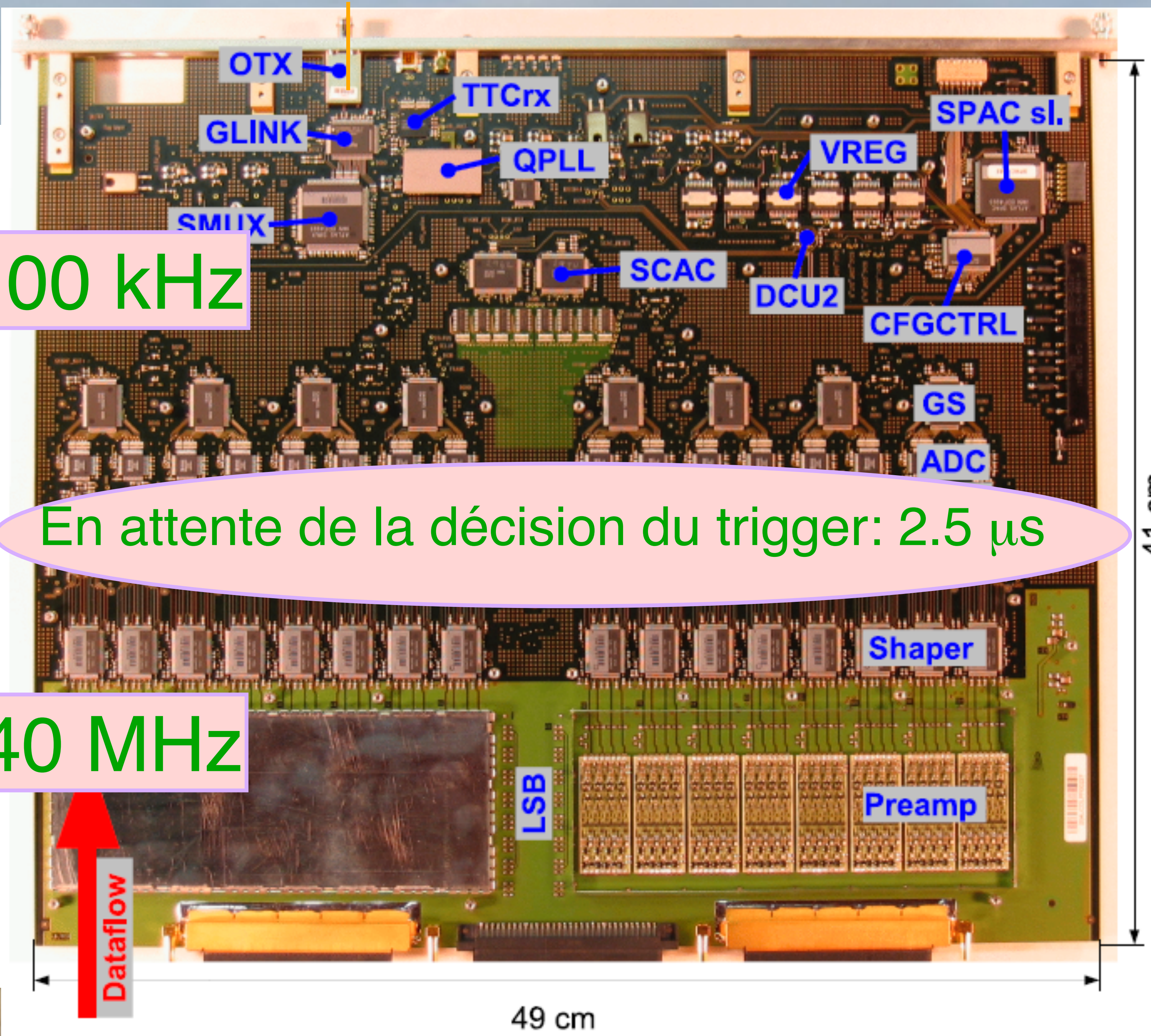
Argon liquide

Electronique ON DETECTOR



Carte FrontEnd pour le calorimètre EM d'ATLAS

ON DETECTOR



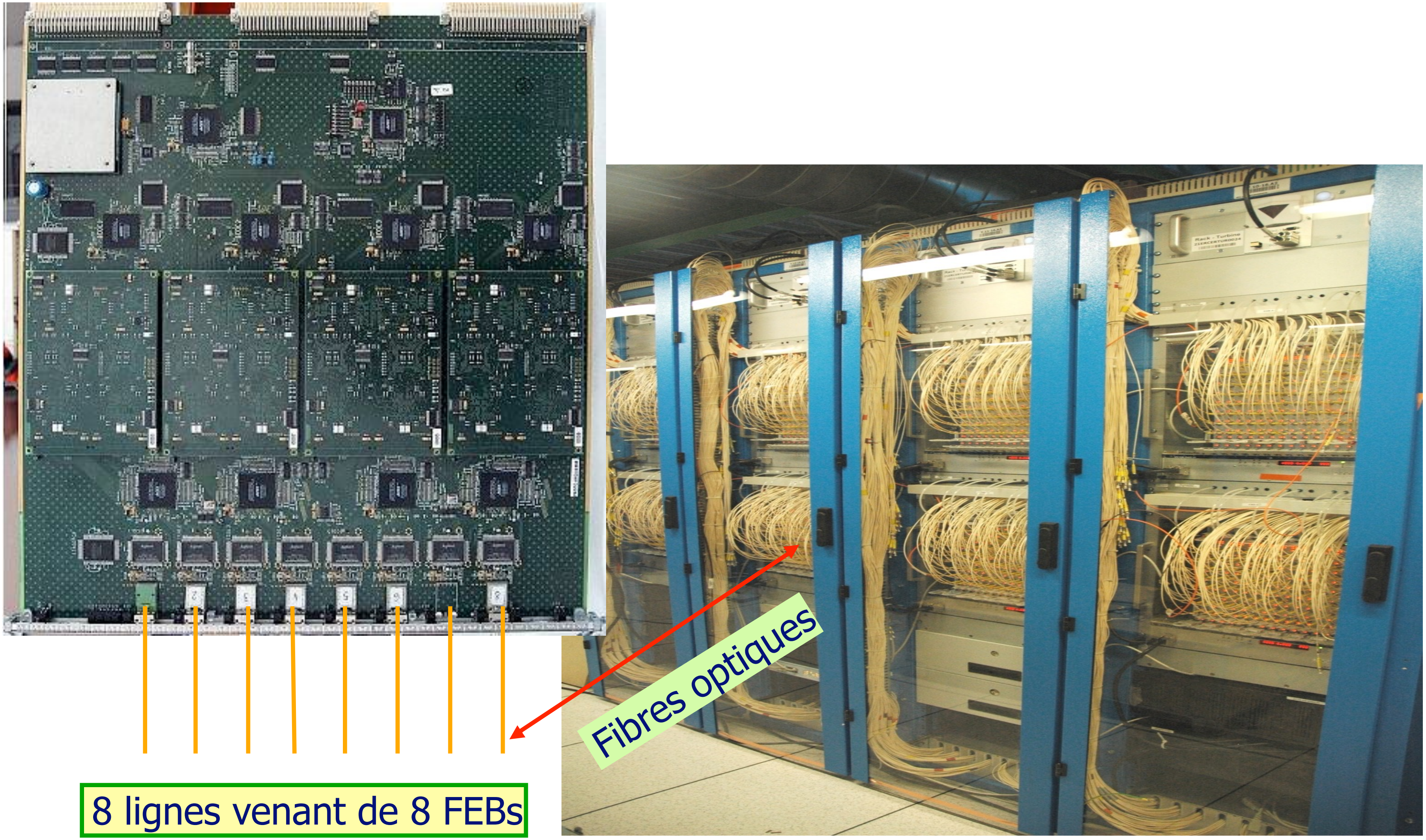
100 kHz

En attente de la décision du trigger: 2.5 μs

40 MHz

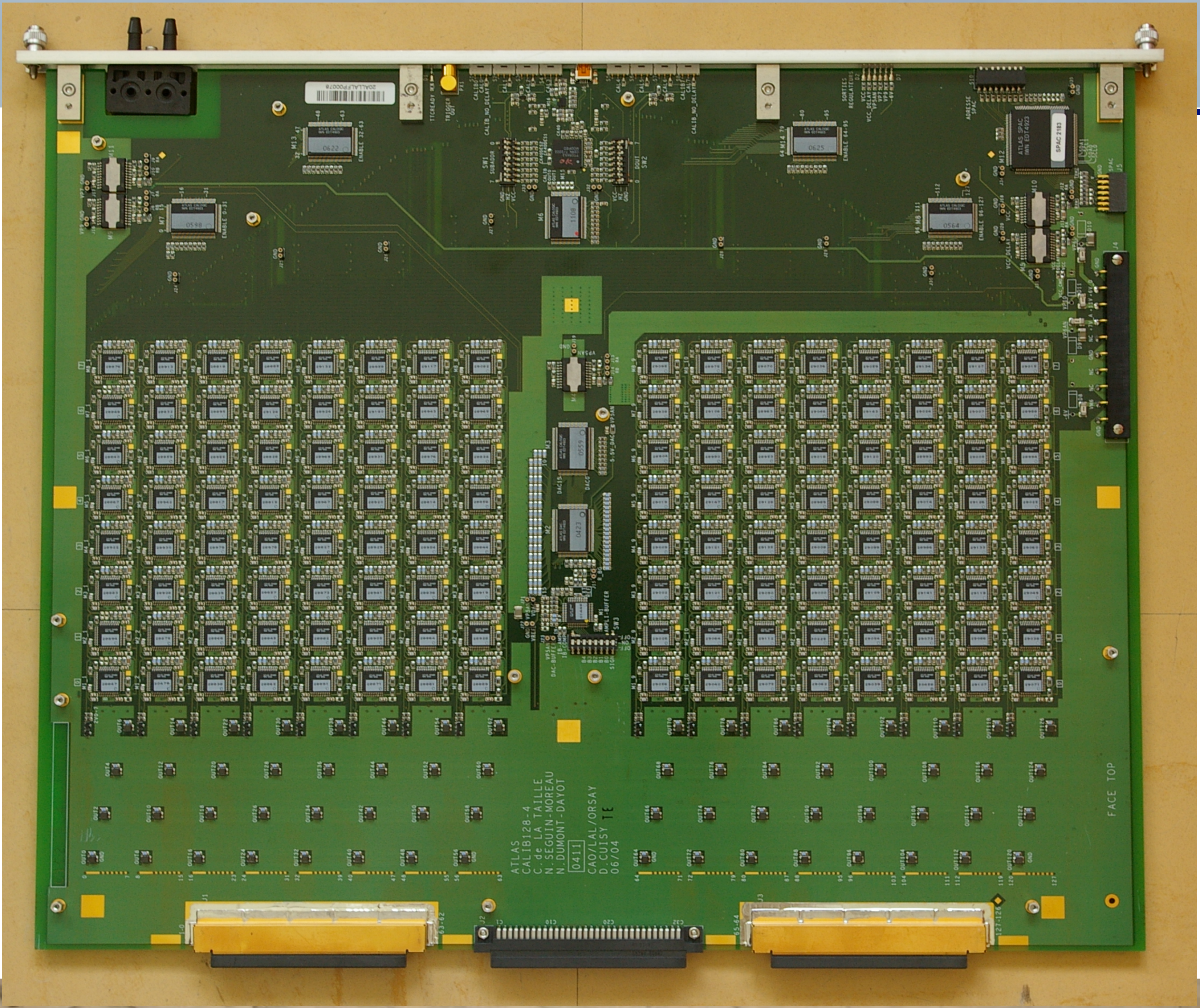
Dataflow

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



Fibres optiques

8 lignes venant de 8 FEBs



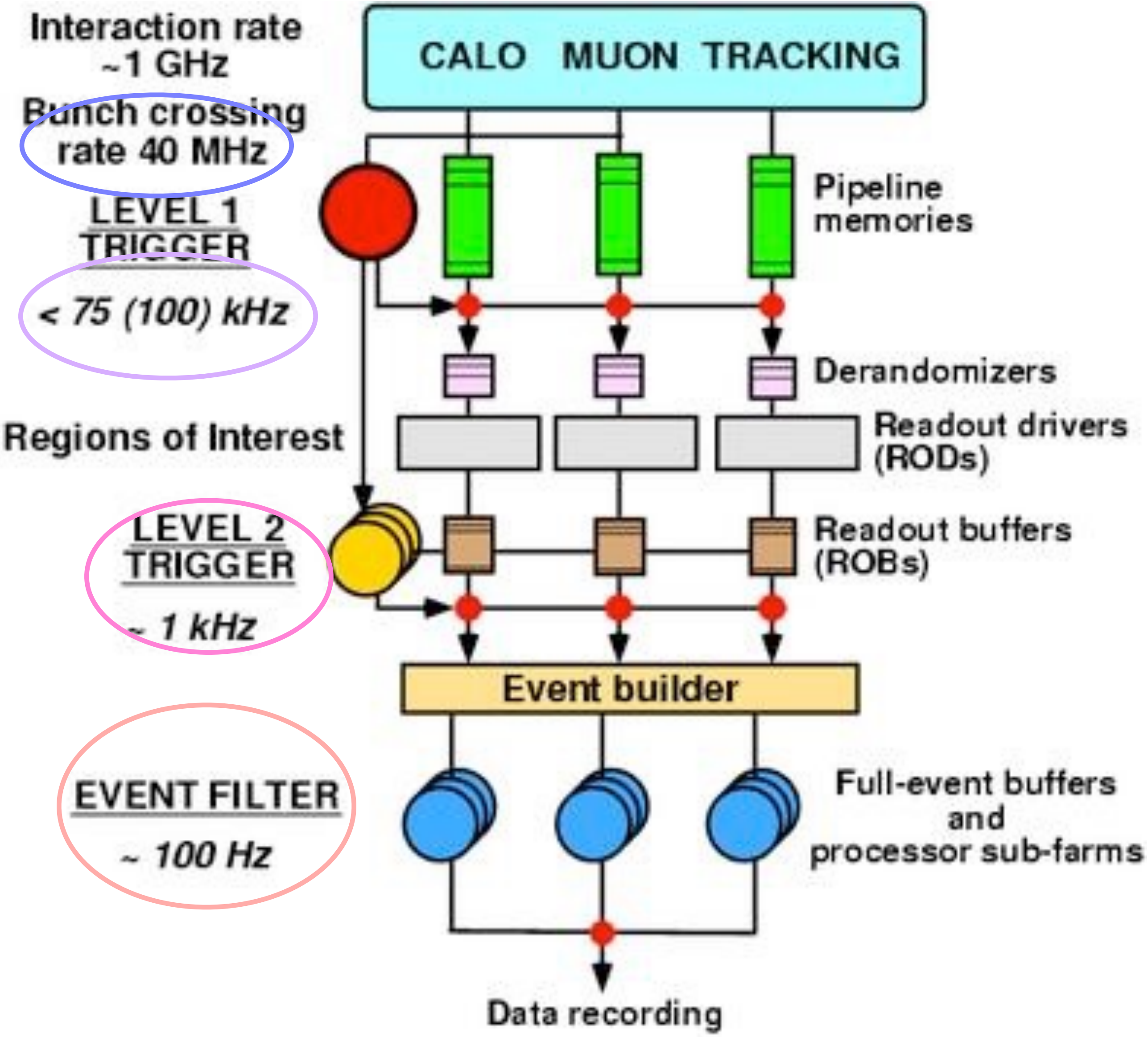
Carte Calibration pour le calorimètre LARG d'ATLAS

ON DETECTOR

In the cavern

In the counting room

ATLAS Trigger chain



Some conclusions

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

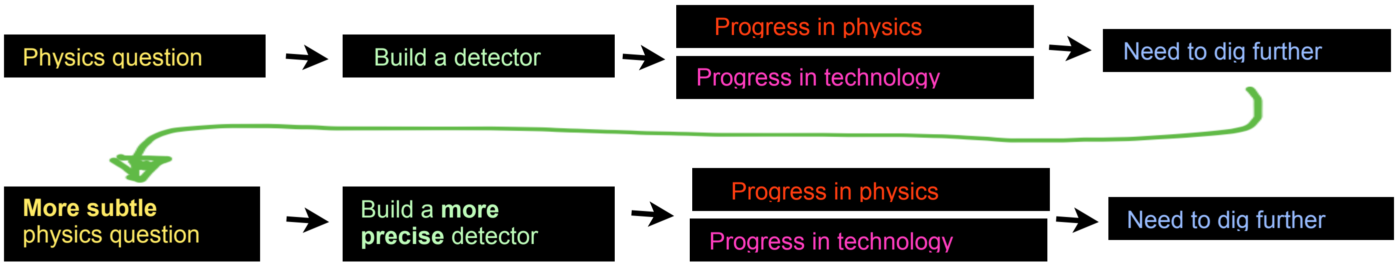
- Electron/Photon - Jet - E_T^{miss} reconstruction
- Background rejection $e^{\pm}$/jets - γ/π^0
- Triggering

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

SOME CONCLUSIONS

PHYSICS DRIVES the DETECTOR DESIGN

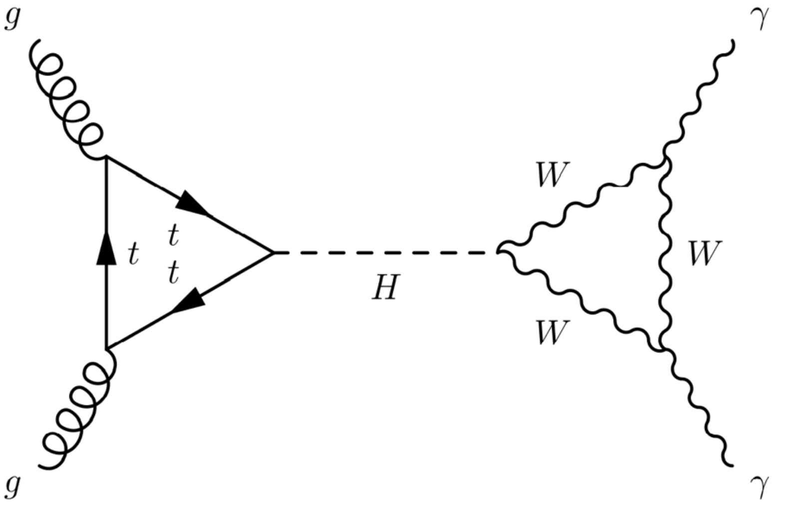


INSTRUMENTATION, DEVELOPMENTS PERMIT ADVANCE in PHYSICS

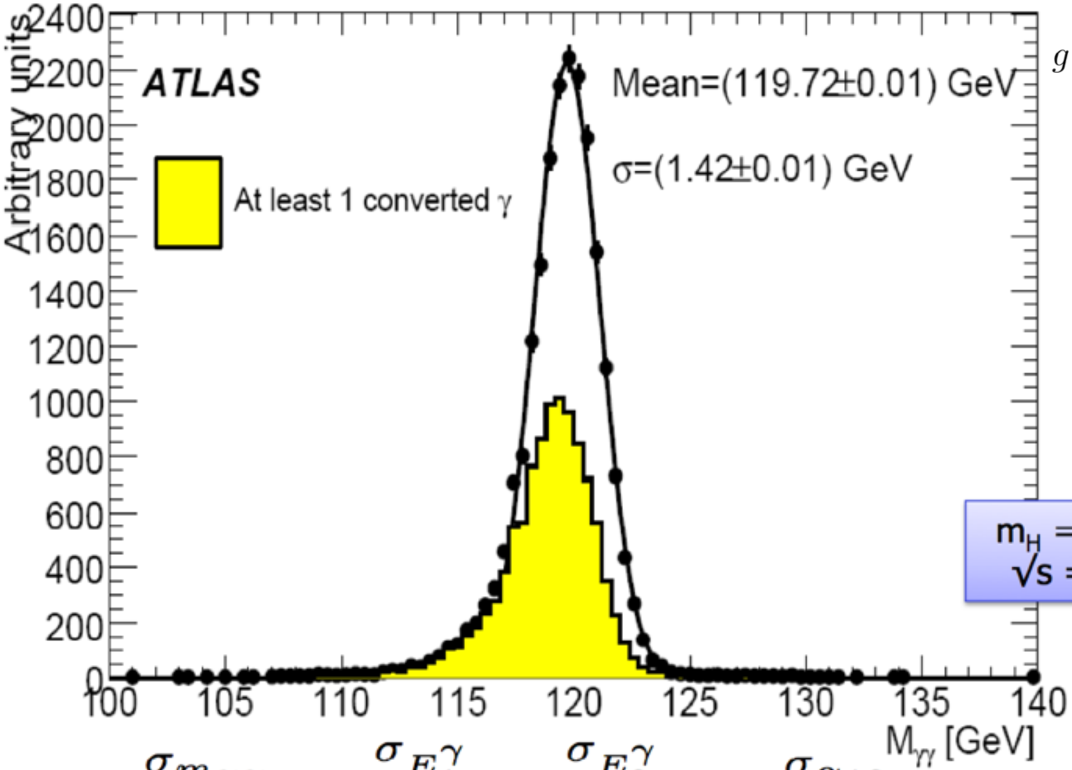
DETECTOR PERFORMANCE, IN HOSTILE ENVIRONMENT as LHC, REQUIRES THOROUGH DATA ANALYSIS

THESE LECTURES HAVE ONLY TOUCHED THE SURFACE of WHAT ALREADY EXISTS.

HIGGS MASS RESOLUTION



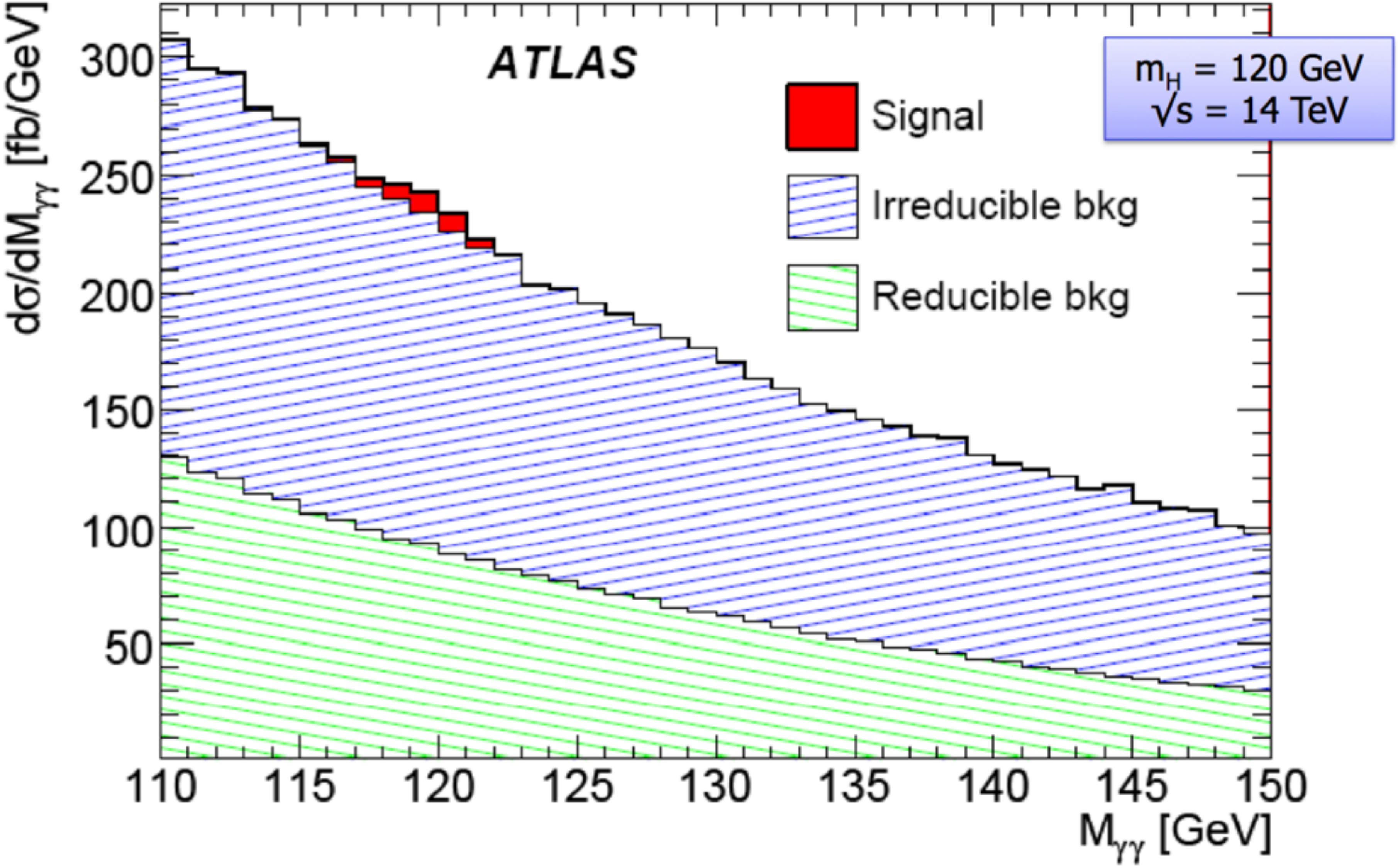
$$m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$$



$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{\sigma_{E_1^\gamma}}{E_1^\gamma} \oplus \frac{\sigma_{E_2^\gamma}}{E_2^\gamma} \oplus \frac{\sigma_{\alpha_{12}}}{\tan\alpha_{12}}$$

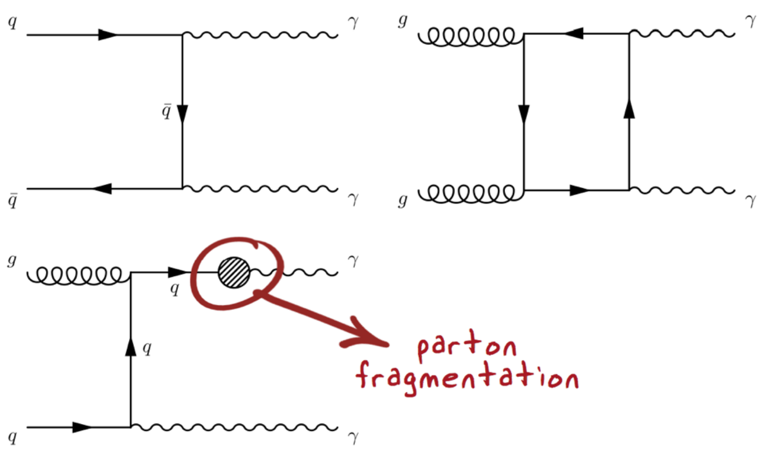
m_H = 120 GeV
$\sqrt{s}$ = 14 TeV

SIGNAL on a LARGE BACKGROUND



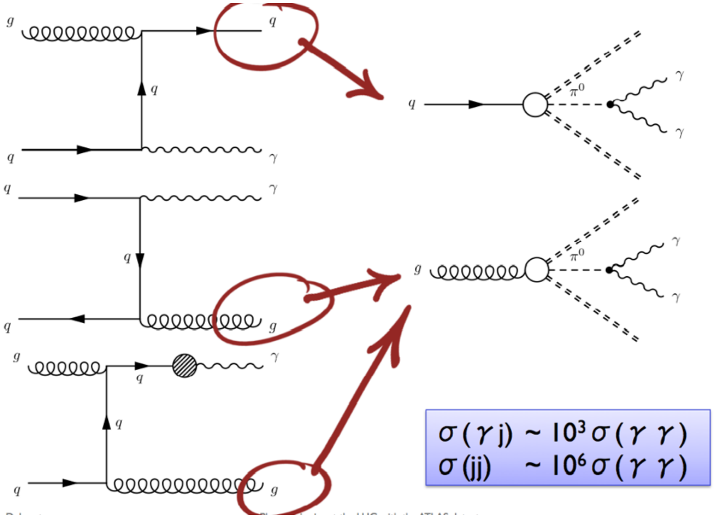
SIGNAL on a LARGE BACKGROUND

IRREDUCIBLE BACKGROUND
γ in the FINAL STATE

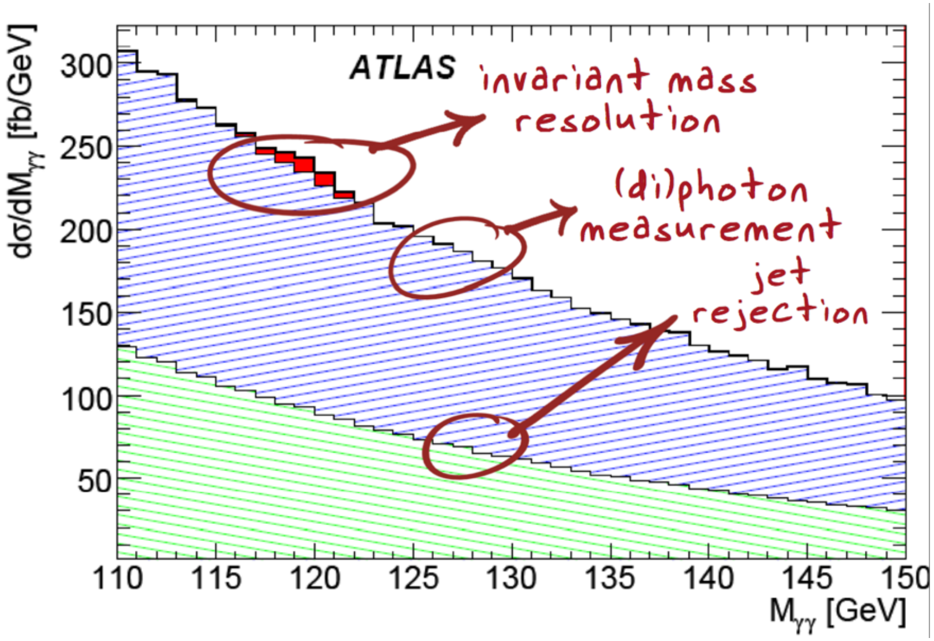


parton fragmentation

REDUCIBLE BACKGROUND
π^0 in the FINAL STATE



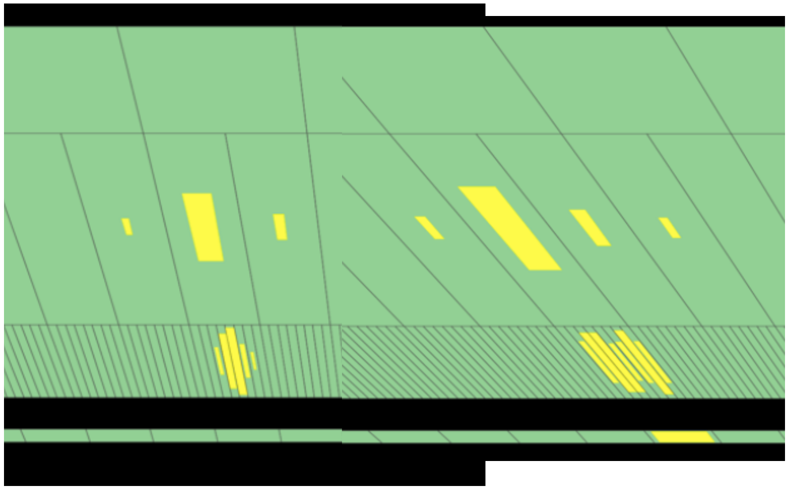
$\sigma(\gamma j) \sim 10^3 \sigma(\gamma\gamma)$
$\sigma(jj) \sim 10^6 \sigma(\gamma\gamma)$



invariant mass resolution

(di)photon measurement

jet rejection



H→γγ MASS SPECTRA & SIGNAL OBSERVATION