Crystal Calorimetry at LHC

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Particle Physics

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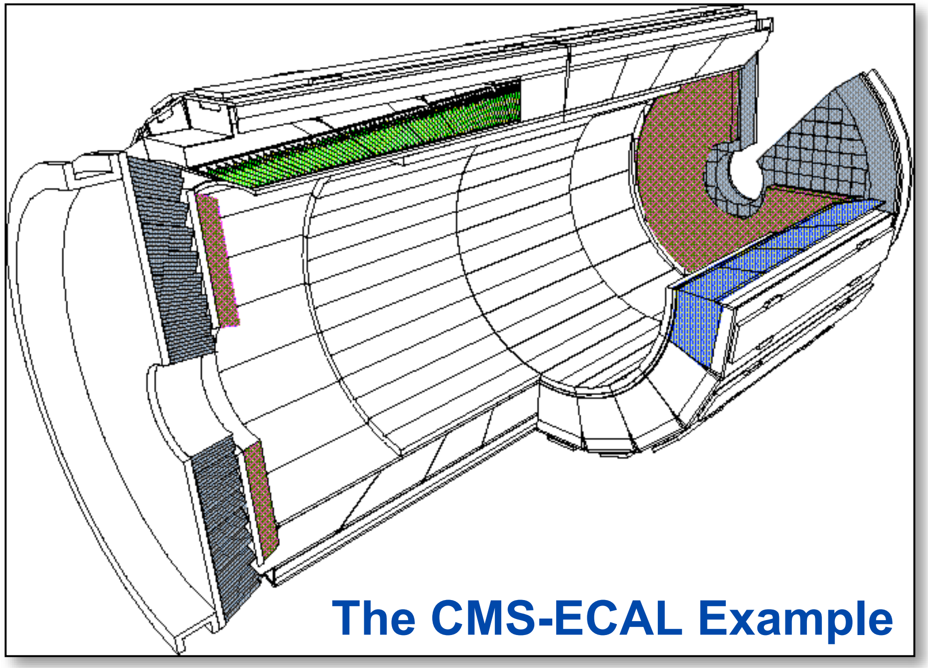
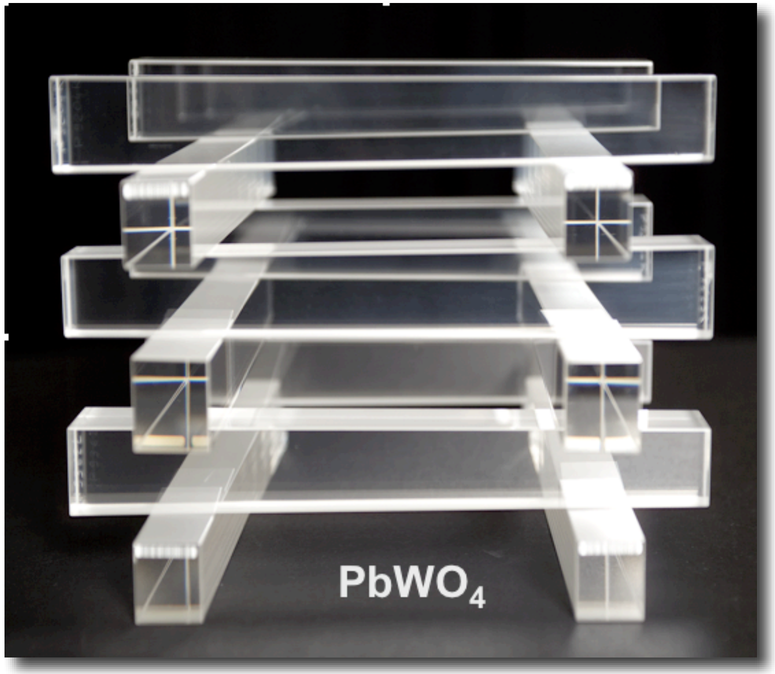
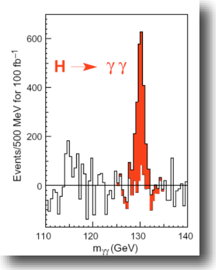

The CMS-ECAL Example

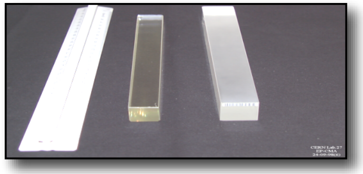


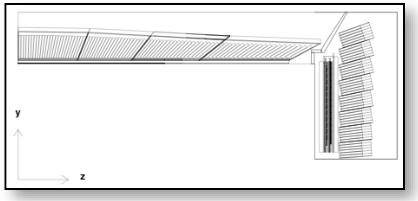
ACT, CERN, March 1, 2005

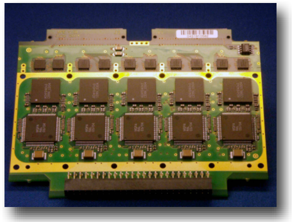
Contents

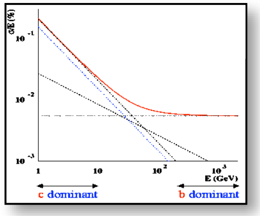
- The requirements
- Choosing crystals
- A possible detector layout
- Readout electronics
- Performance
- Summary







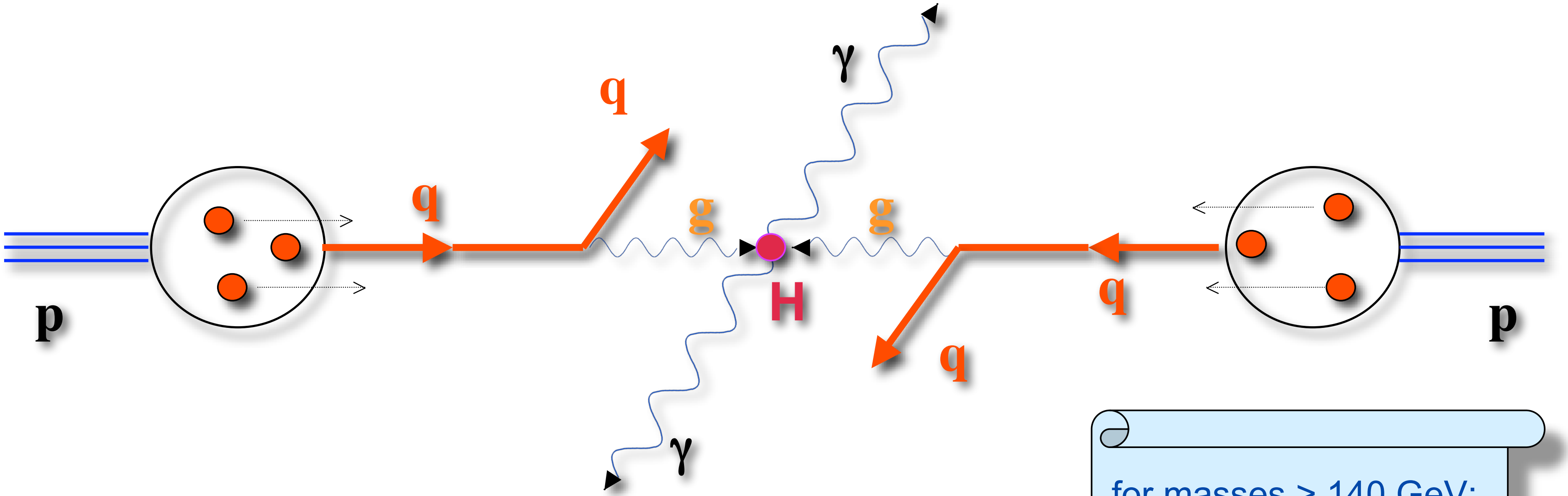




The requirements

Higgs Search at LHC

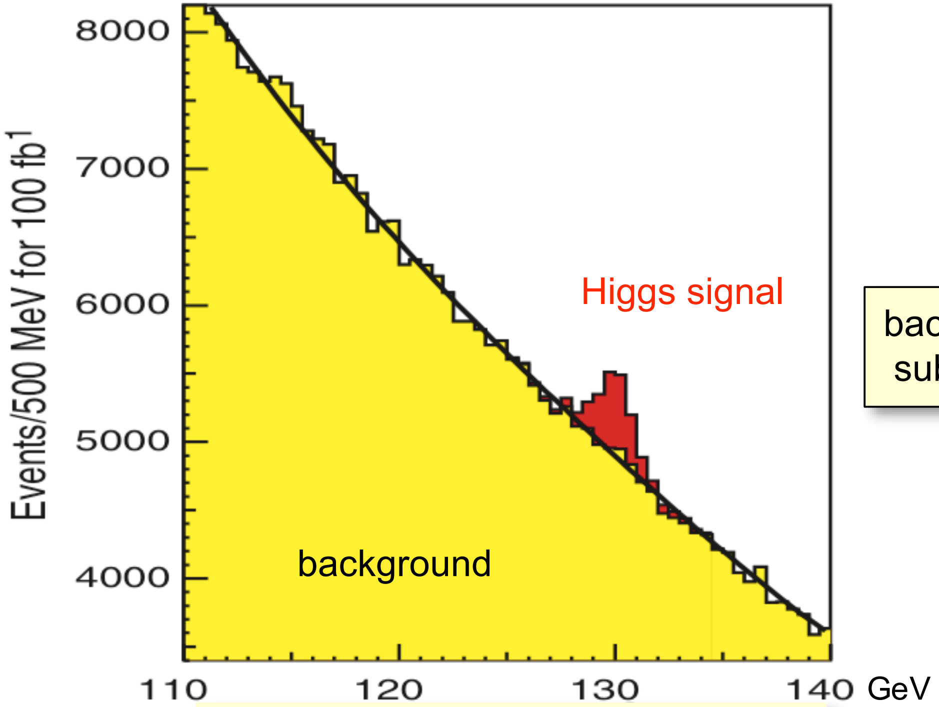
- LEP/EW data : preferred Higgs mass range = 115 — 260 GeV
- Most important discovery channel for the low-mass range : **H → γγ**



- Very low event rate, but clear signature above large background
- Required : excellent experimental mass resolution
- Benchmark channel for electromagnetic calorimetry

for masses > 140 GeV:
Other important channels:
H → WW → e ν e ν
H → ZZ → e e e e

Higgs Search : H → $\gamma\gamma$

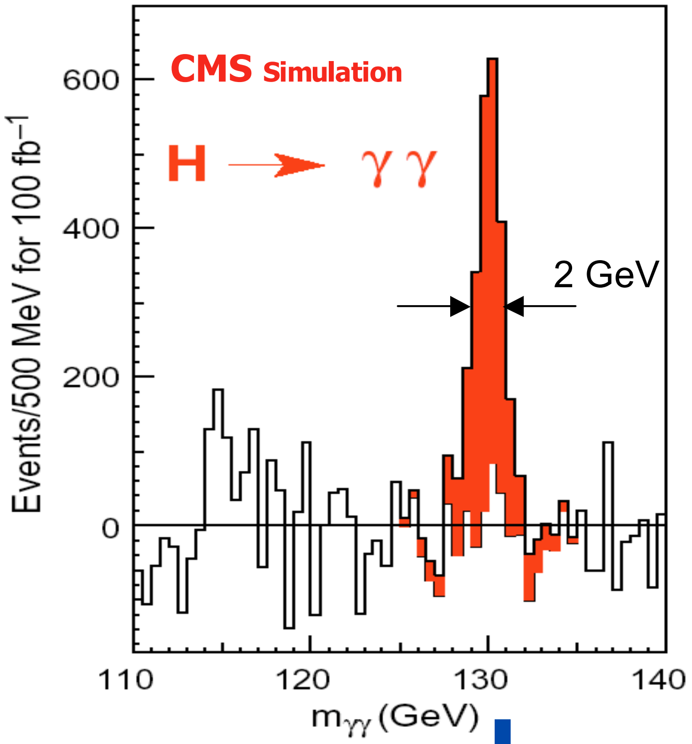


$$m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}\left(1-\cos\theta_{\gamma 1,\gamma 2}\right)}$$

$$\Downarrow$$

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan\left(\theta_{\gamma\gamma}/2\right)}\right]$$

background subtracted

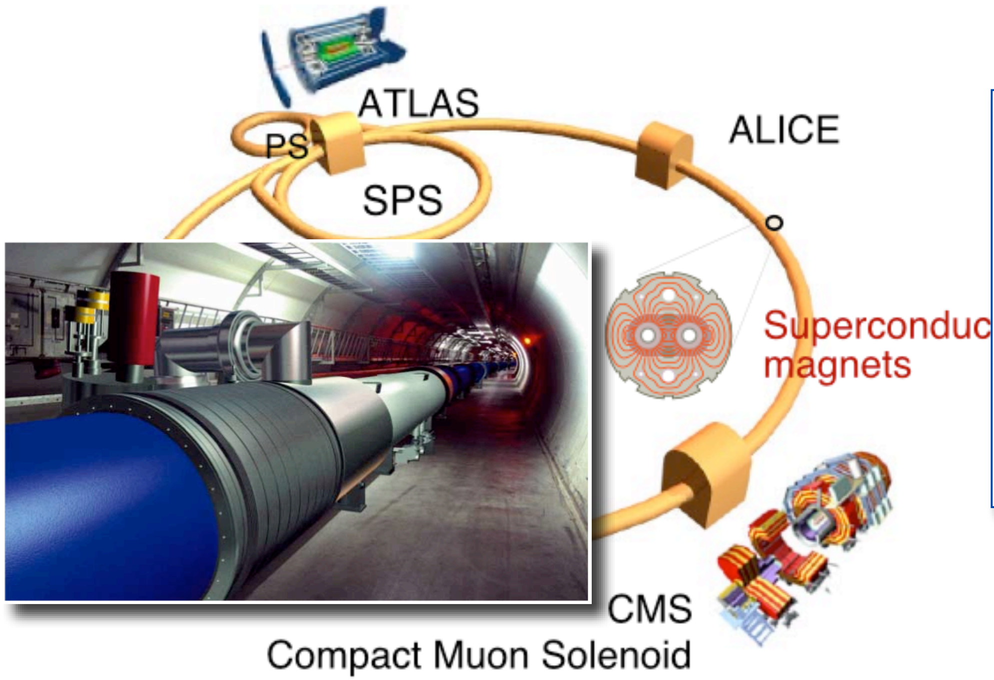


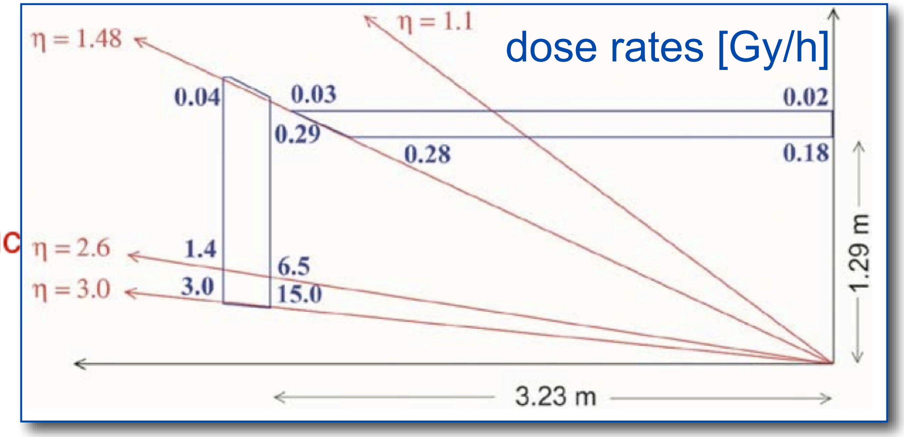
Need energy resolution

ΔE/E < 1%

for E ≈ 50 GeV

The LHC environment





Expected radiation levels
for CMS-ECAL

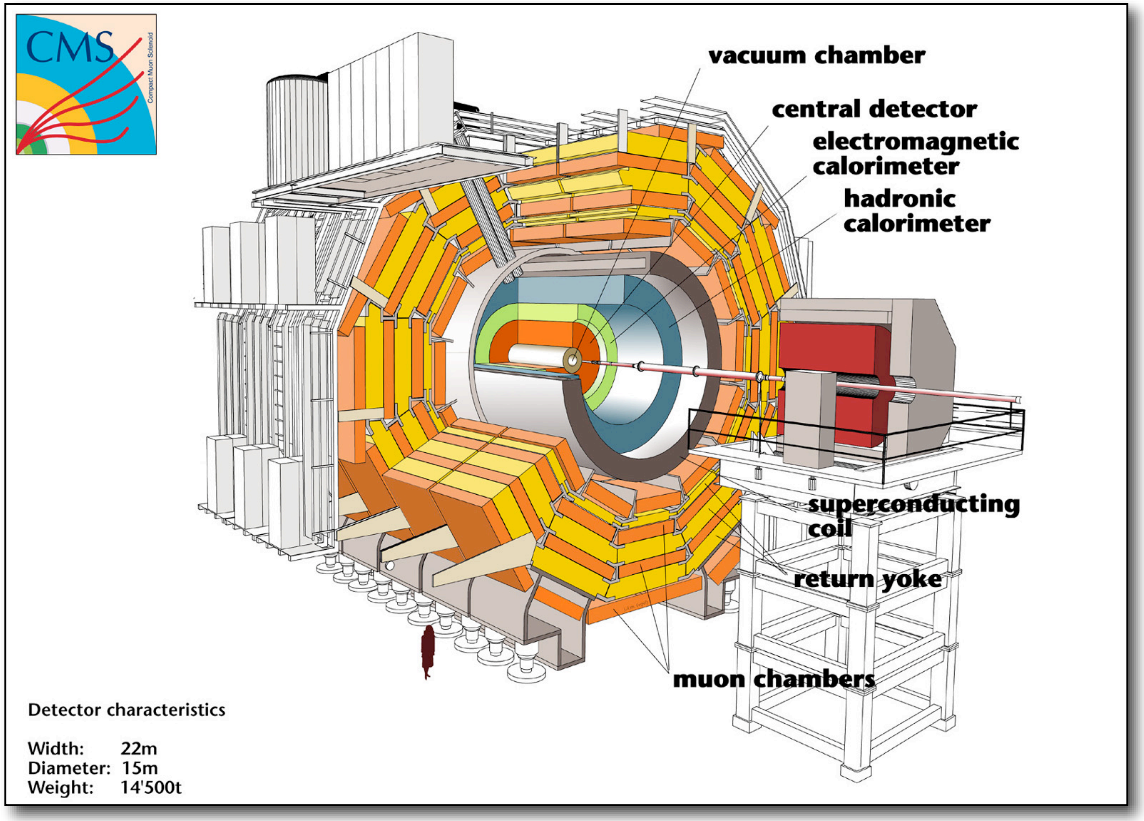
Bunch crossing rate : 40 MHz
Every 25 ns : up to 20 p-p interactions
up to 1000 charged particles

Over LHC lifetime :
10^{13} - 10^{14} neutrons/cm^2

Need fast and
highly granular detectors

Need radiation-hard
detectors

The experiment's design criteria



- Example: CMS
  - **C**ompact
  - **M**uon system
  - One magnet coil (**S**olenoid)
  - Tracking and calorimetry **inside** the magnet coil
- Physics performance:
  - Excellent tracking
  - **Excellent electromagnetic calorimetry (photons, electrons)** over large acceptance
  - Excellent muon detection

⇒ Need very compact calorimeter, with excellent energy resolution at the same time

Summary : Requirements

Fast

Excellent energy resolution, over large dynamic range
(50 MeV - 1.5 TeV)

Highly granular

Which Calorimeter ?

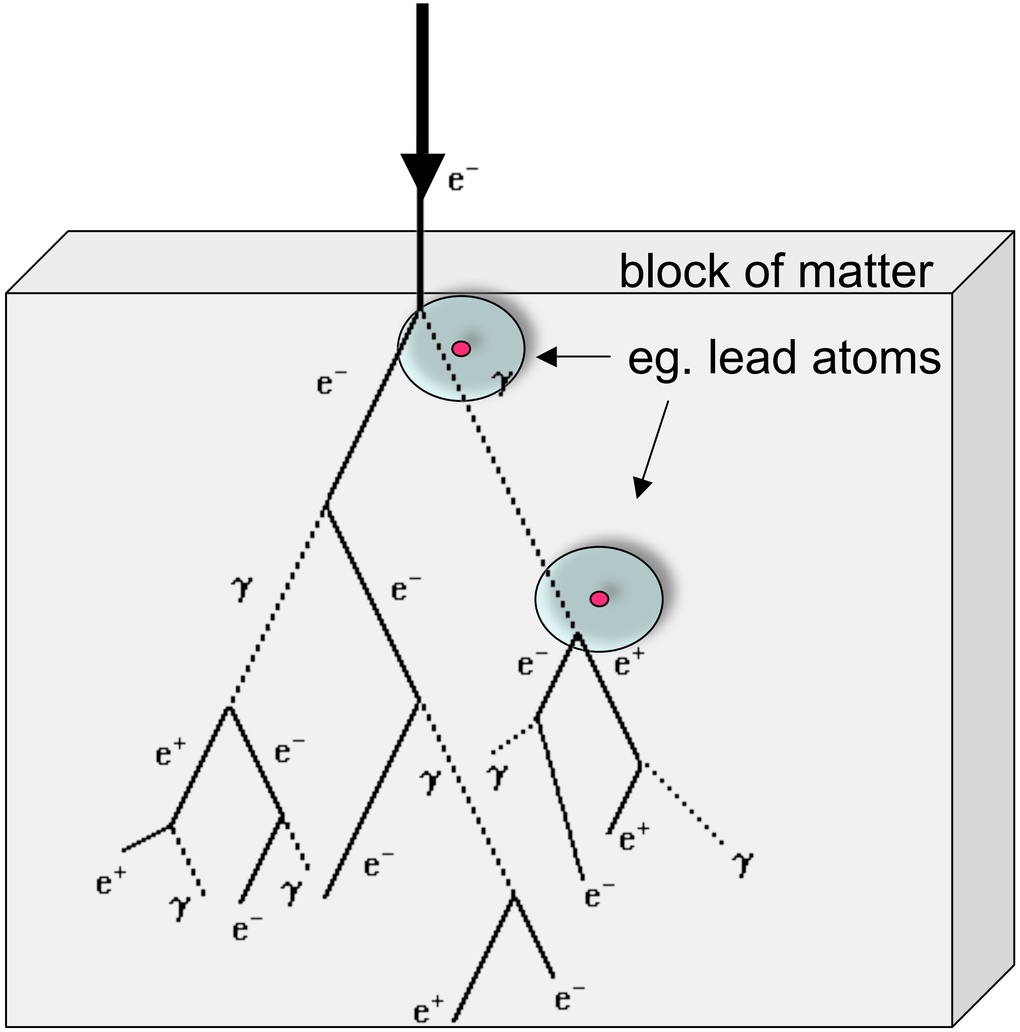
Radiation hard

Compact = Short radiation length

Operates inside strong magnetic field

Choosing crystals…

Calorimetry : Basics



Ionization, scintillation, Cherenkov light

Relevant quantities:

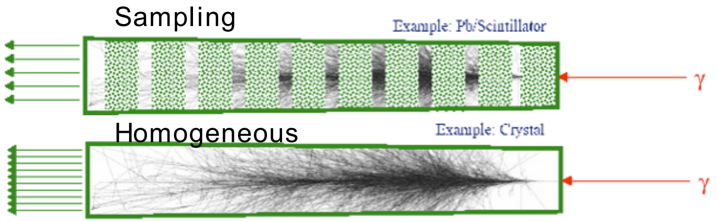
Radiation length X_0 :

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

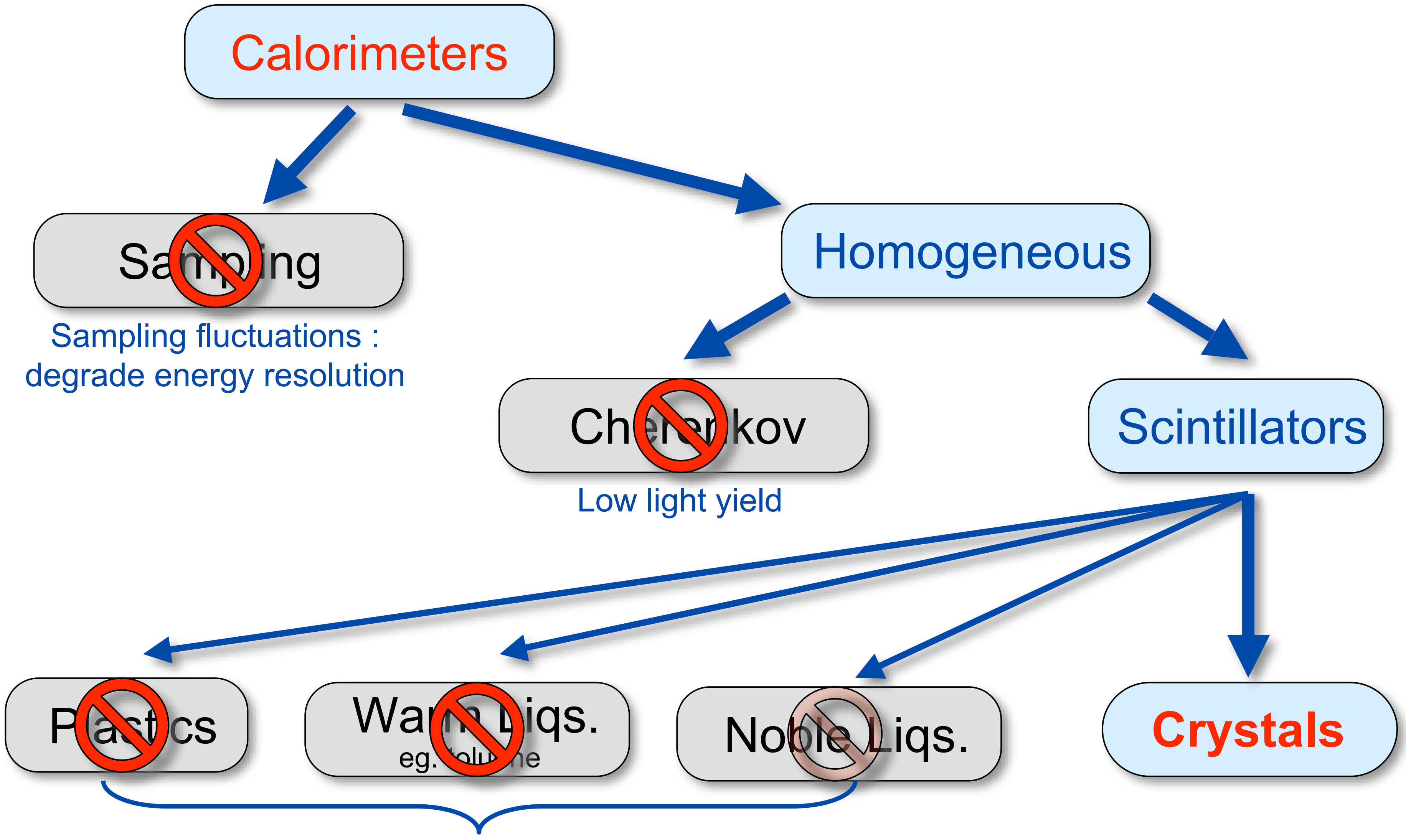
Moliere radius ρ_M :

- 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



Choosing a calorimeter type



Calorimeters

Sampling

Sampling fluctuations :
degrade energy resolution

Homogeneous

Cherenkov

Low light yield

Scintillators

Plastics

Warm Liqs.
eg. toluene

Noble Liqs.

Crystals

Radiation length too large (2-20 times w.r.t. crystals), except LXe, but avail., purity

Courtesy : S. Gascon-Shotkin

Scintillating crystals

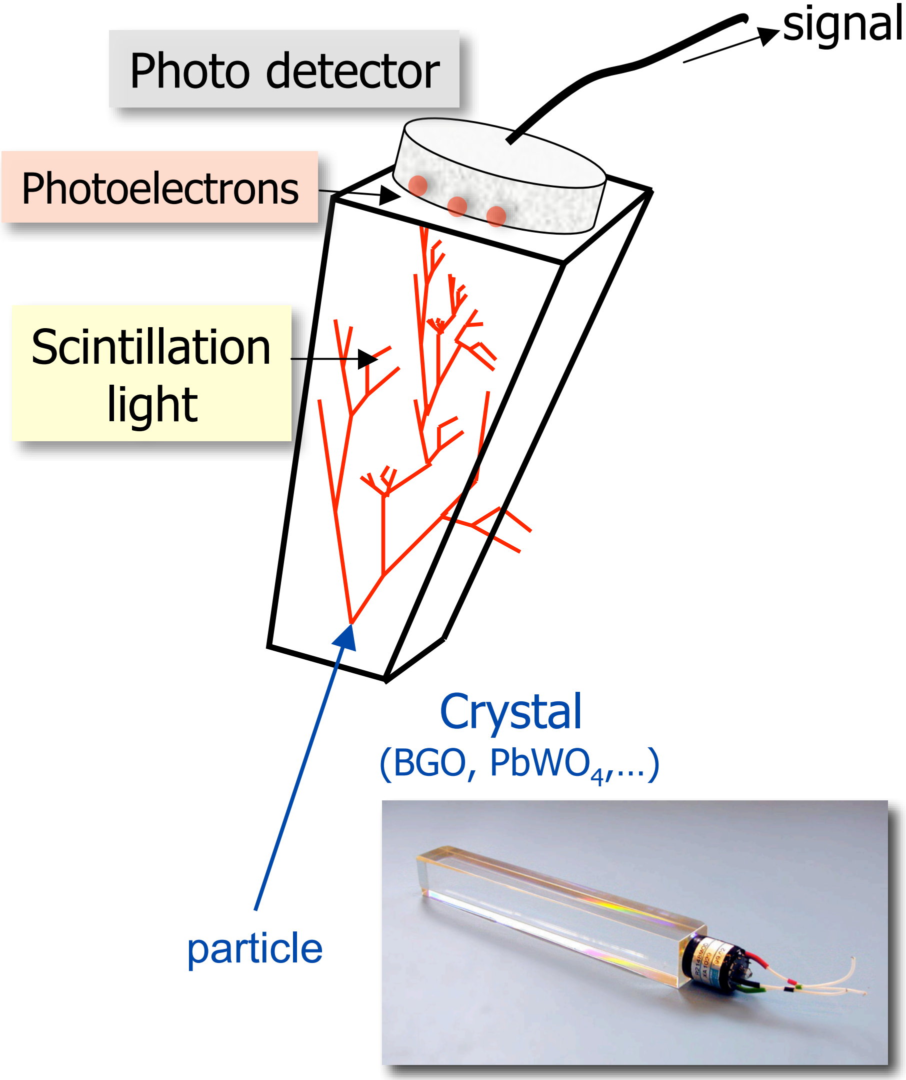


Photo detector

signal

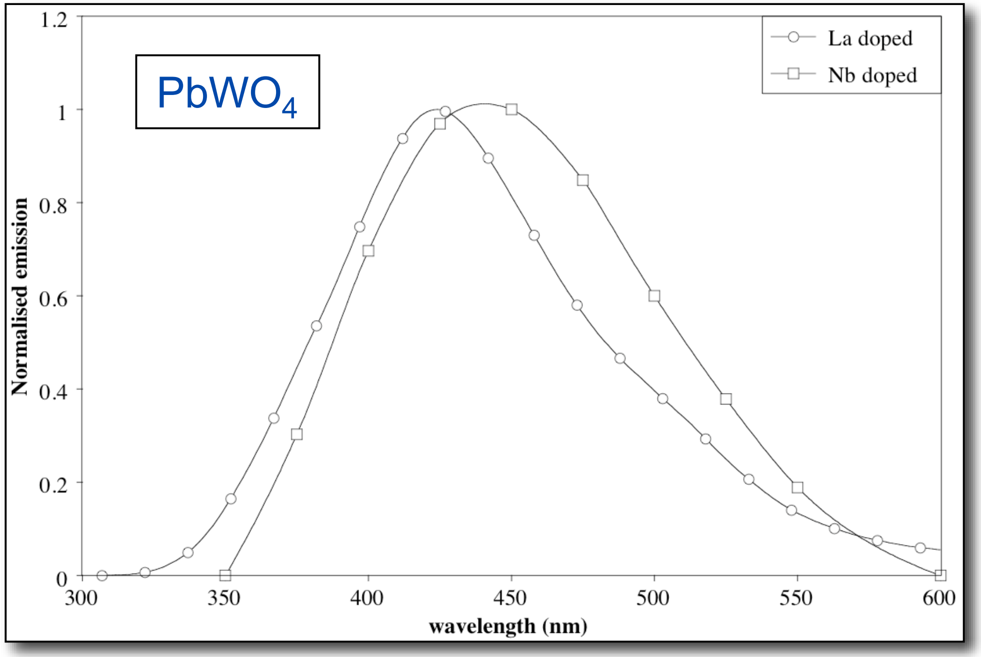
Photoelectrons

Scintillation light

particle

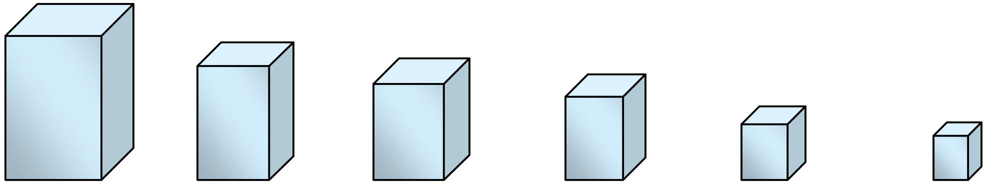
Crystal (BGO, $PbWO_4$,...)

- Relevant quantities:
  - Scintillation spectrum



  - Light yield : Photoelectrons / MeV
  - Light decay time
  - Refractive index n
  - Transmission curve

The Crystal Market



	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59 ☹	2.03 ☹	1.86 😐	1.66 😐	1.12 🙂	0.92 🙂
ρ [g/cm^3]	3.67 ☹	4.89 ☹	4.53 ☹	6.16 🙂	7.13 🙂	8.2 🙂
τ [ns]	230 ☹	0.6 🙂 620 ☹	1050 ☹	30 🙂	340 😐	15 🙂
λ [nm]	415 🙂	230 🙂 310 😐	550 🙂	310 😐 340 😐	480 🙂	420 🙂
$n@\lambda_{max}$	1.85 😐	1.56 🙂	1.80 😐	1.68 🙂	2.15 ☹	2.3 ☹
LY [%NaI]	100 🙂	5 ☹ 16 ☹	85 🙂	5 😐	10 🙂	0.5 ☹

→ CMS ECAL

and

ALICE PHOS

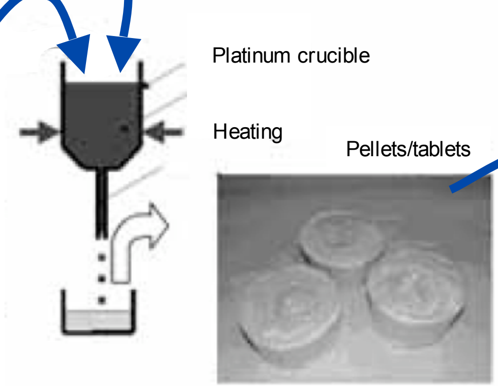
+ radiation hardness : 🙂

Courtesy : P. Lecoq / P. Denes

How to grow a crystal

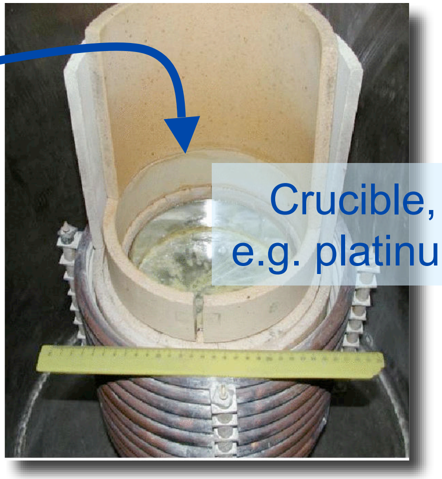
Science,art, alchemy

Very pure raw materials
e.g. PbO + WO_3



Pre-reaction : melt and
grow quickly a crystal,
Then crunch again to powder

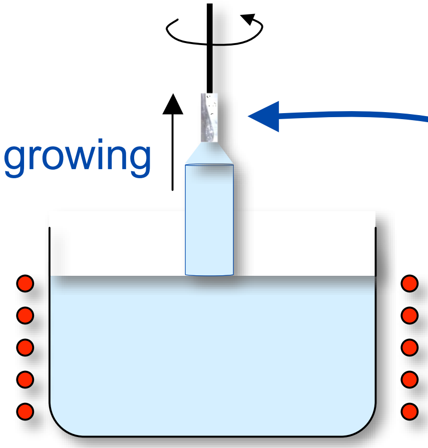
densified



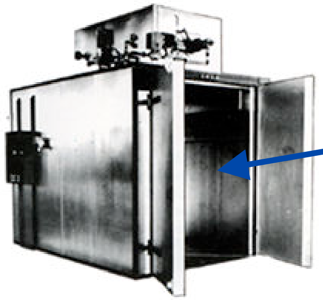
Crucible,
e.g. platinum

Preparation of **seed :**
little crystal, with well
defined orientation!

growing



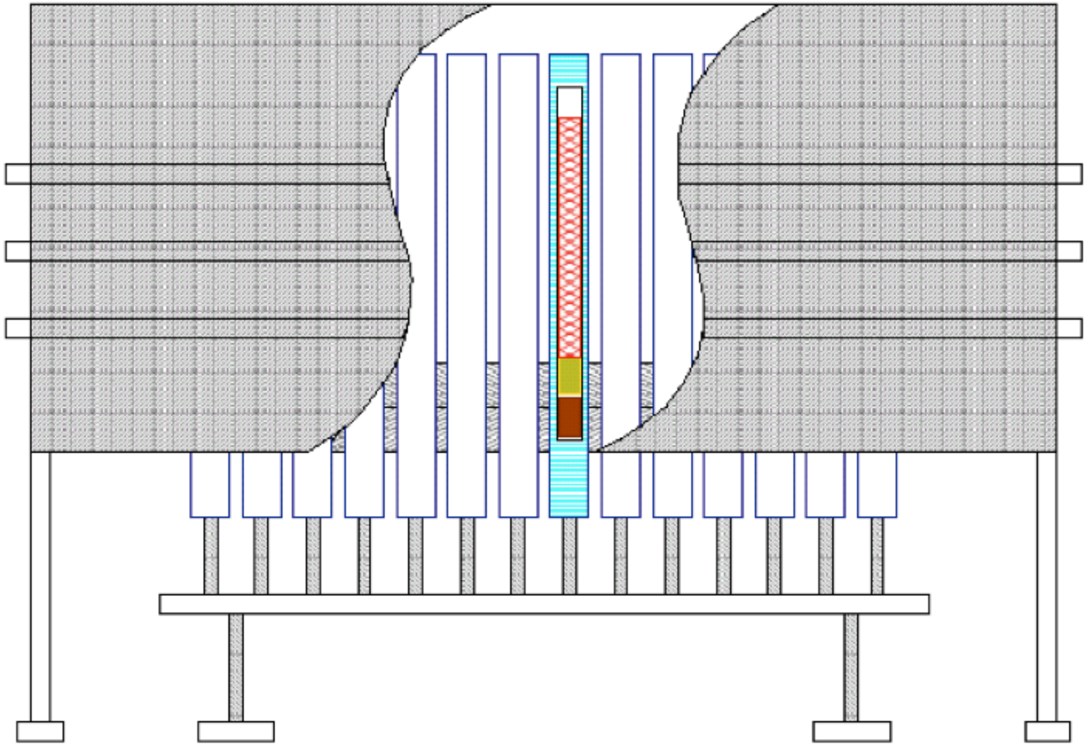
Heating
1165 ^{o}C



Annealing :
Reduce mechanical stresses,
distribute tension and defects

Growing methods

Czochralski - Method:
Bogoroditsk Techno-Chemical Plant,
Tula, Russia



Modified Bridgman - Stockbarger - Method:
Shanghai Institute for Ceramics,
China

Courtesy : P. Lecoq / Q. Deng

R&D for crystals

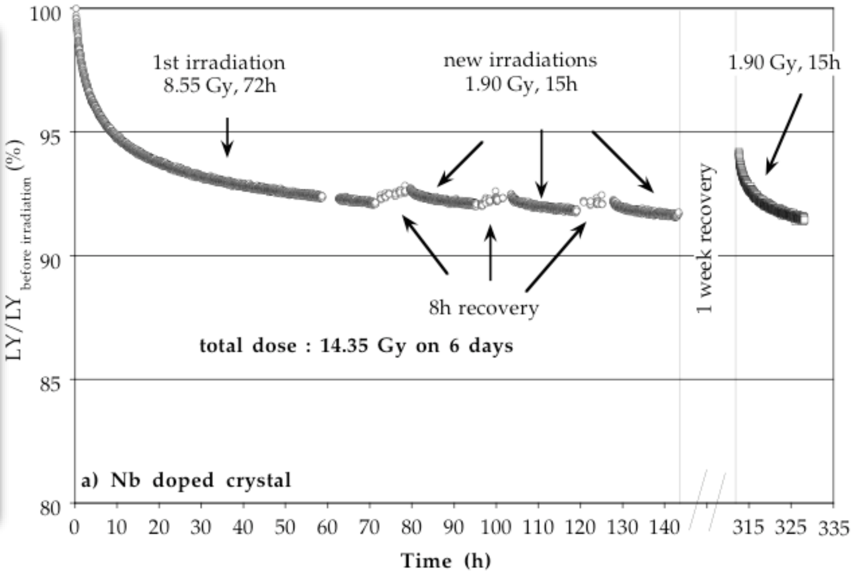
- Optimization of :

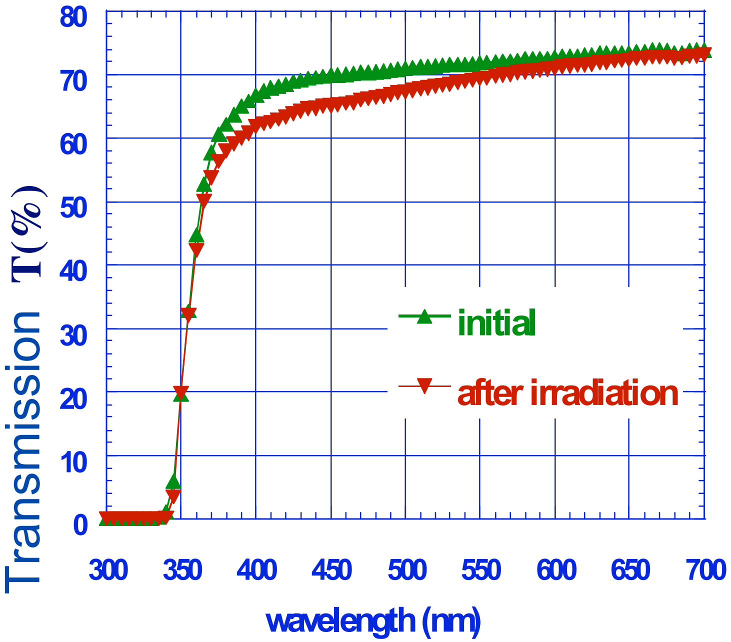
Light collection uniformity

- Stringent requirements on growing process, partial de-polishing of crystal faces

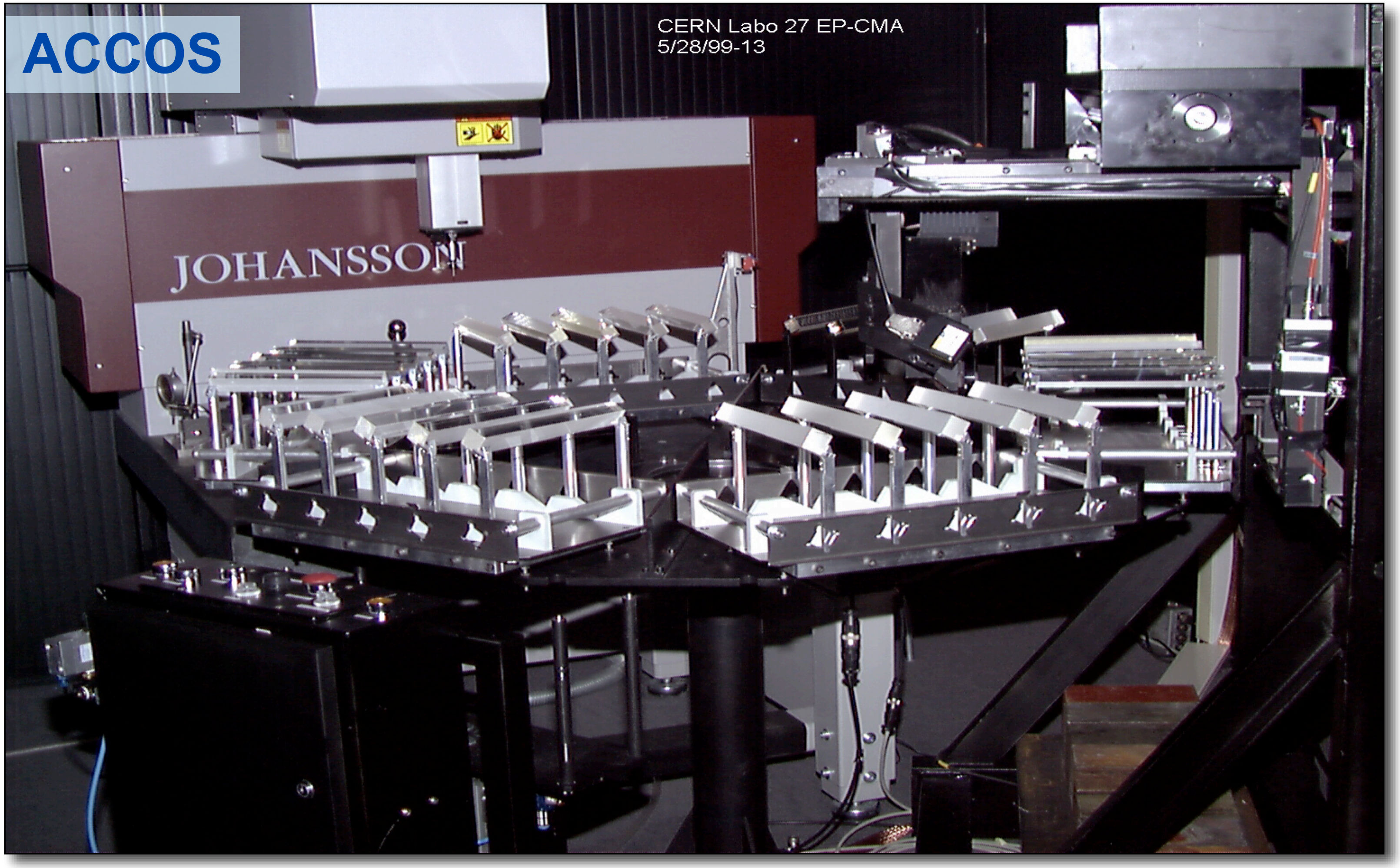
Radiation hardness:

- γ-irradiations have shown : scintillation mechanism is not altered
- Light transmission is reduced, because of radiation-induced colour centers (e.g. oxygen vacancies)
- Partial auto-recovery





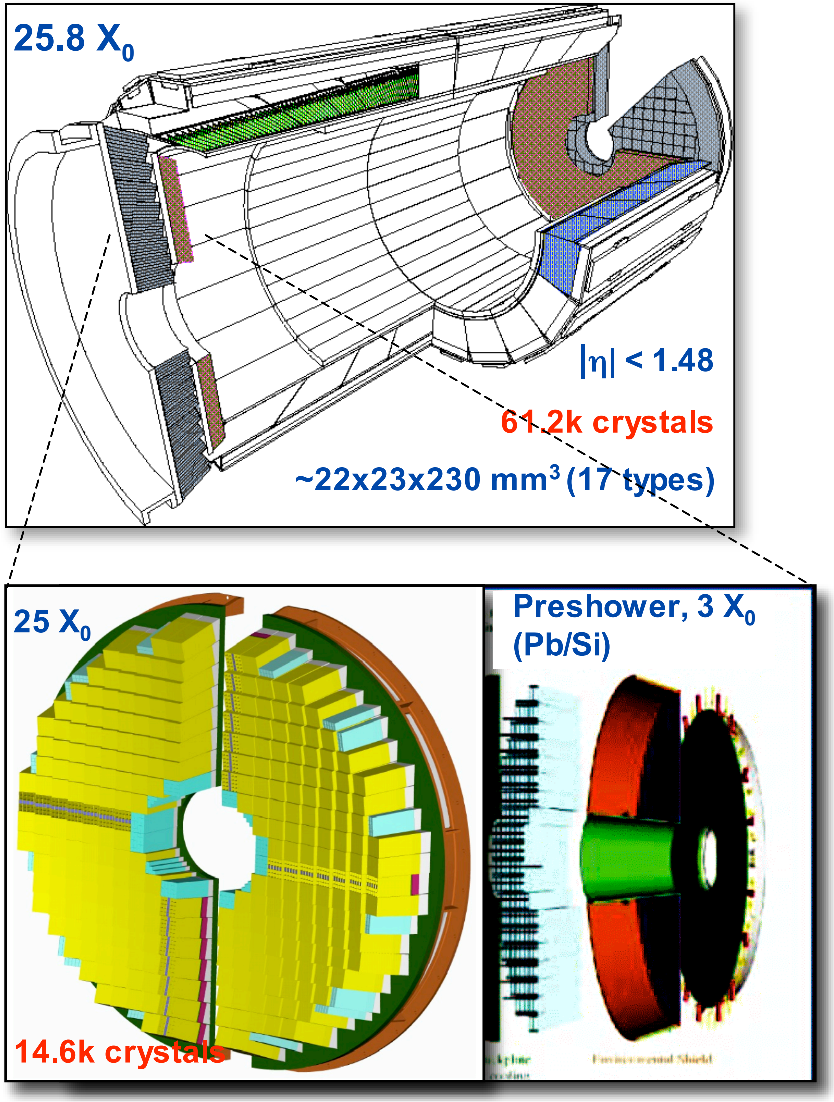
Quality Control



For CMS-ECAL (at CERN and in Rome):
Automatic testing of dimensions, transmission, light yield and uniformity

A possible detector layout:
The CMS-ECAL example

The CMS electromagnetic calorimeter



25.8 X_0

$|\eta| < 1.48$

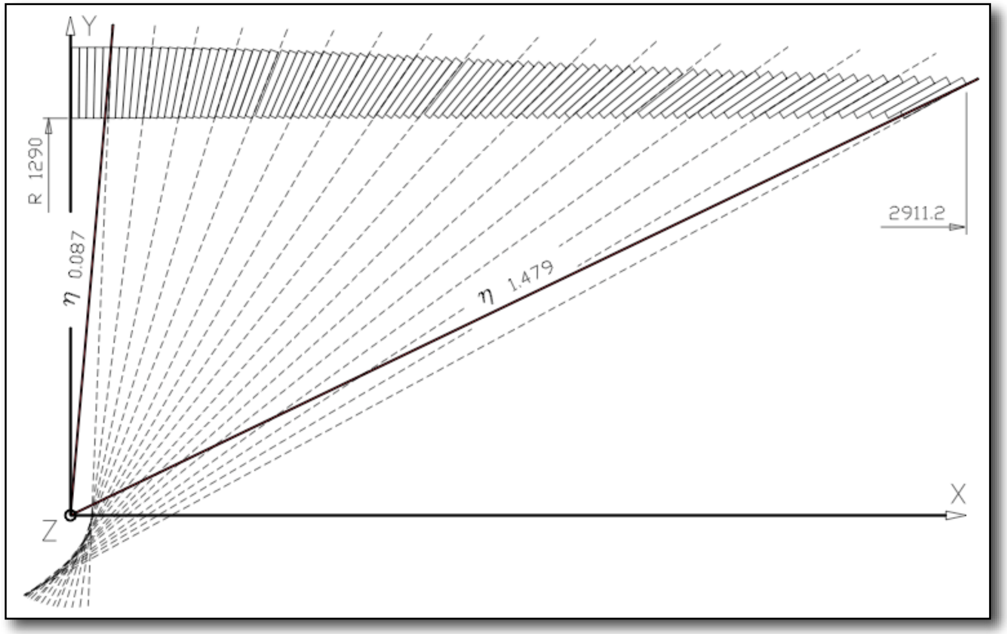
61.2k crystals

~22x23x230 mm^3 (17 types)

25 X_0

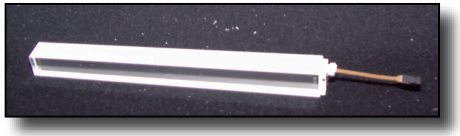
14.6k crystals

Preshower, 3 X_0 (Pb/Si)

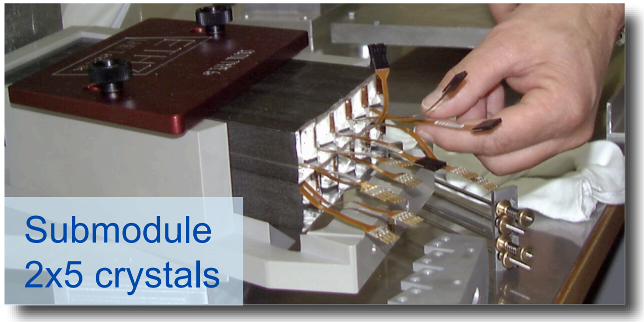


- Some numbers
  - 75848 crystals in total
  - Barrel : 36 supermodules
  - Endcaps : 4 Dees
  - Crystal volume : 10.8 m^3, 90.3 tons

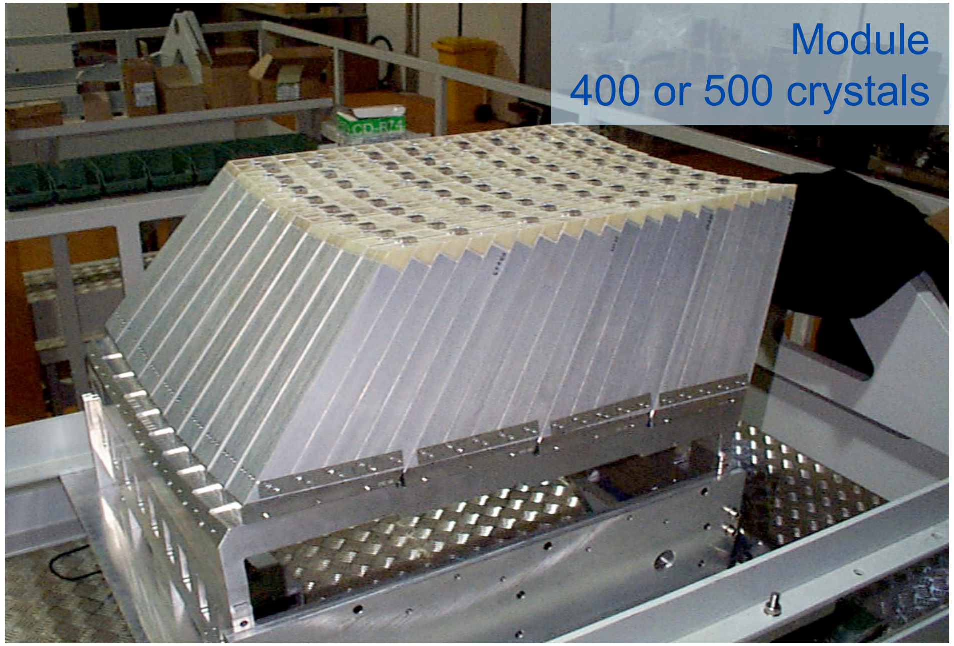
From crystals to supermodules



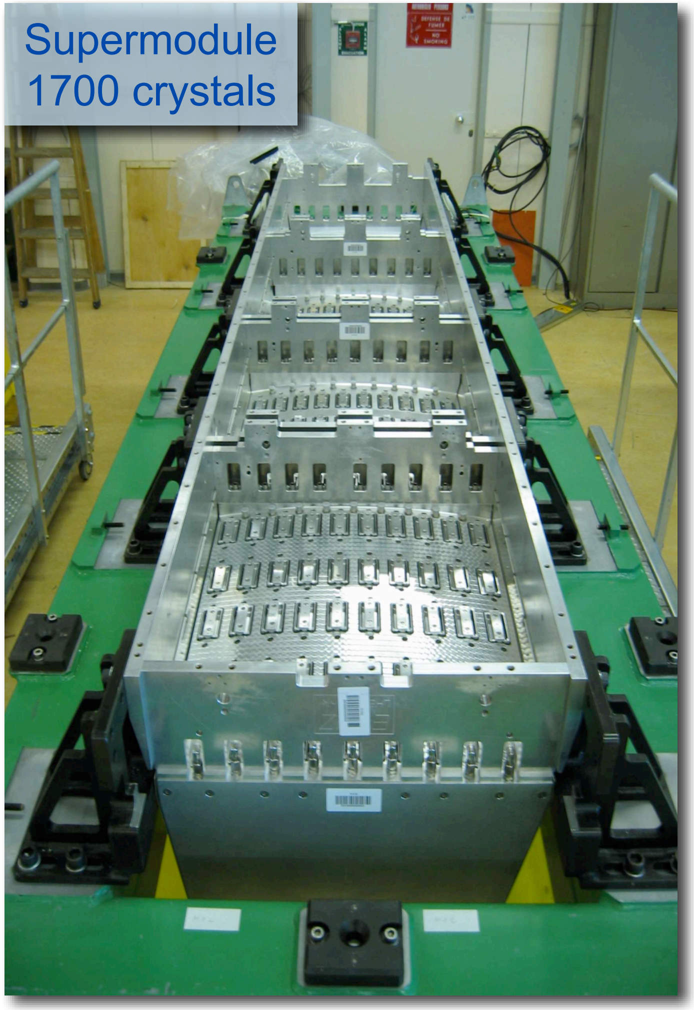
Subunit



Submodule
2x5 crystals



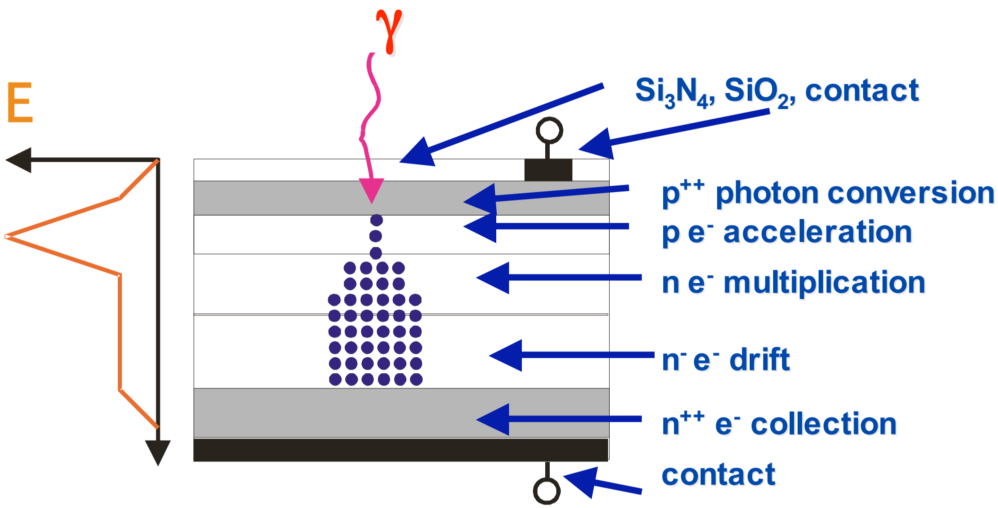
Module
400 or 500 crystals



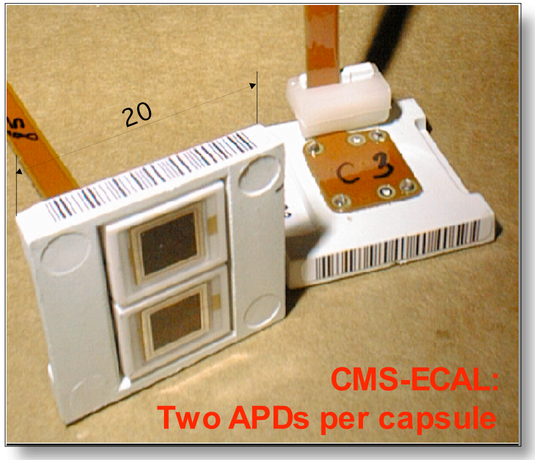
Supermodule
1700 crystals

The readout electronics

Photo Detectors



Internal gain=50 for V=380 V



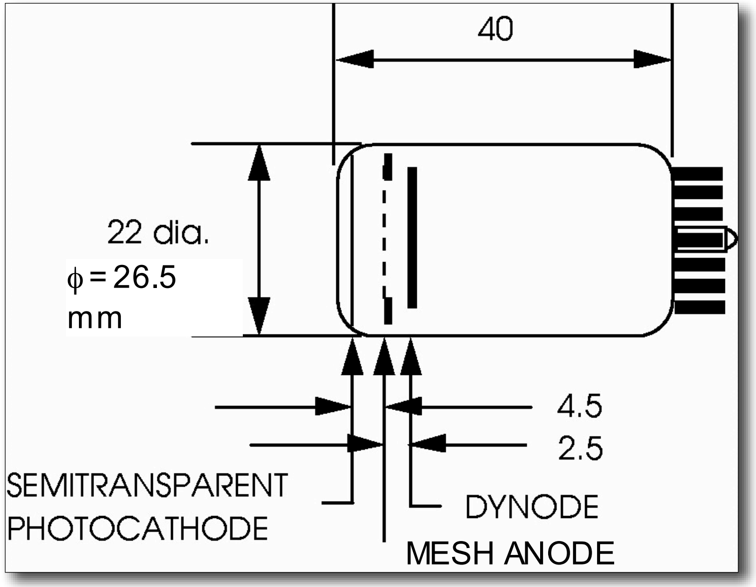
CMS-ECAL:
Two APDs per capsule

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

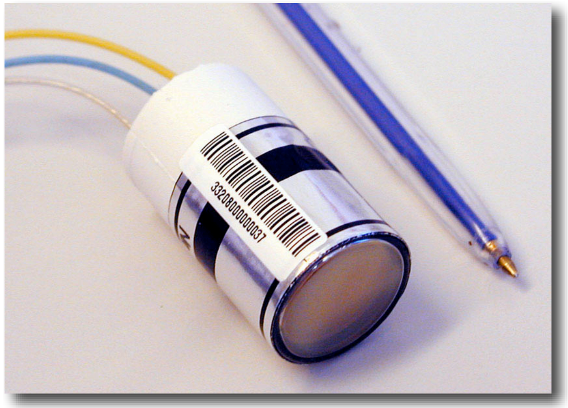
- Drawback of $PbWO_4$:
  Low light yield
  - Need photodetectors **with intrinsic gain** (+radiation hard, +insensitive to magnetic field)
- Choice for CMS-ECAL Barrel and ALICE PHOS:
  Avalanche Photo Diodes (APD)
  - rad. hard, fast (few ns)
  - Quantum efficiency (QE, photon conversion into electrons) : ~75% at 430 nm
  - Active Area : 25 mm^2
  - Excess noise factor F≈2 (see later)
  - **But :**
    strong sensitivity of gain to voltage and temperature variations!

    → Good stability needed!

Photo Detectors 2



Single stage photomultiplier tube



Other possible choice: Vacuum Photo-Triodes (VPT)

- For CMS Endcaps
- rad.hard (better than APDs)

  neutron flux too high for APDs in forward region
- Uniform response for large range of orientations w.r.t. magnetic field
- QE ≈ 20 % at 420 nm
- Active area : 280 mm^2
- Gain : 8 - 10

Electronics Readout Chain

- Requirements:
  - From photo-detectors : charge / current
  - To be amplified and shaped, digitized, trigger information built, transported off-detector
  - All this : every 25 ns ! (i.e. at 40 MHz)
  - With large dynamic range:
    linear amplification for ~ 50 MeV — 1.5 TeV (90 dB)
  - In a harsh radiation environment
  - Many channels
  - without excessive power consumption (< few Watt / channel)
  - Still affordable…

?

The Multi-Gain Approach

Dynamic range *R* : 50 MeV — 1.5 TeV

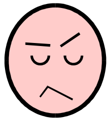
$$R = \frac{1500}{0.05} = 30000 \approx 2^{15} \Rightarrow 15 \text{ bits}$$

But : fast, low power, radiation hard : feasible only 12-bit ADC
➔ this would imply a least-significant bit (LSB) of:

$$\text{LSB} = \frac{1500}{2^{12}} \approx 360 \text{ MeV}$$

If we have a calorimeter with very good intrinsic resolution, a = 3%:

$$\sigma = a\sqrt{E} \oplus \sigma_{\text{LSB}} = 3\%\sqrt{E} \oplus 360 \text{ MeV}$$
$$\text{for } E = 100 \text{ GeV} : \sigma = 300 \text{ MeV} \oplus 360 \text{ MeV}$$



The Multi-Gain Approach

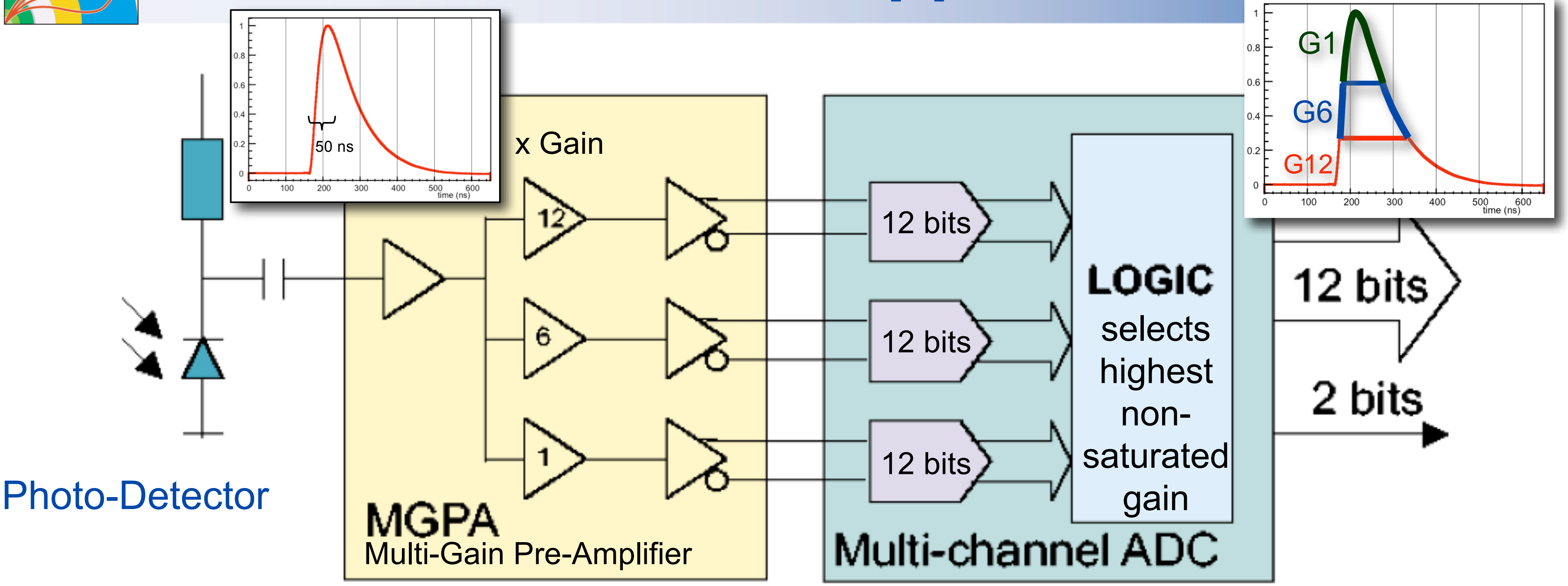


Photo-Detector

x Gain

MGPA
Multi-Gain Pre-Amplifier

12 bits
12 bits
12 bits

LOGIC selects highest non-saturated gain

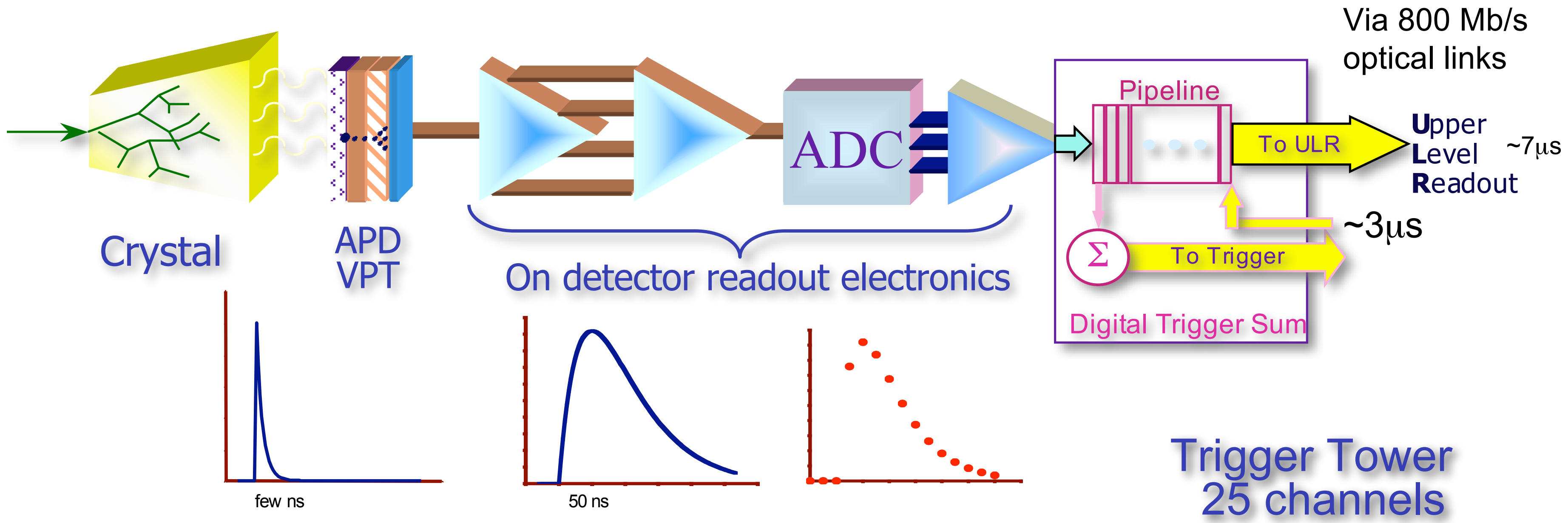
Multi-channel ADC

12 bits

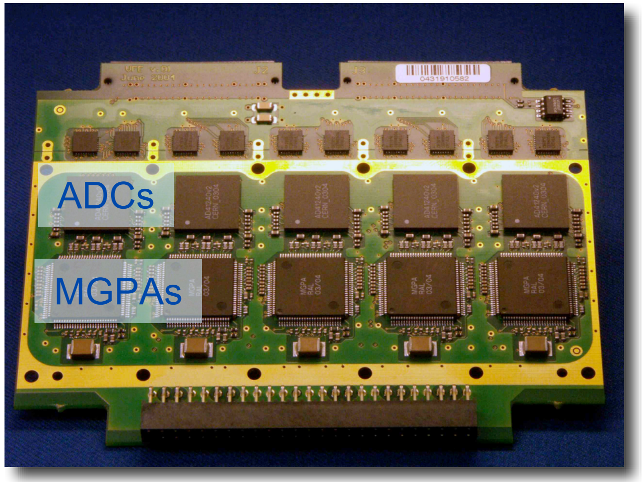
2 bits

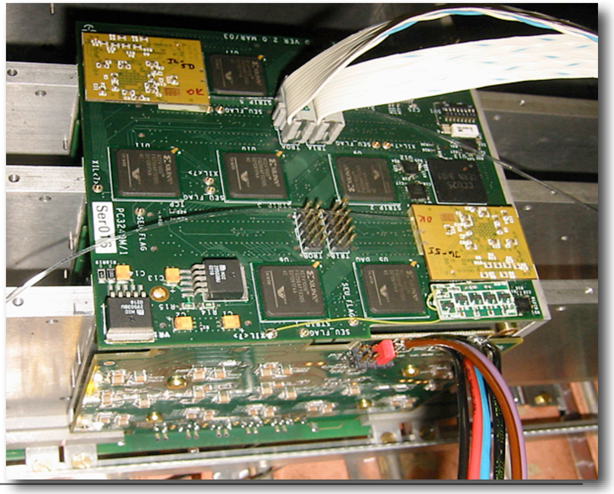
Gain	Maximum Range: 1500 GeV / Gain	Effective LSB: max. range / 2^{12}
12	125 GeV	30 MeV
6	250 GeV	60 MeV
1	1500	360 MeV

Example : ECAL Readout Chain



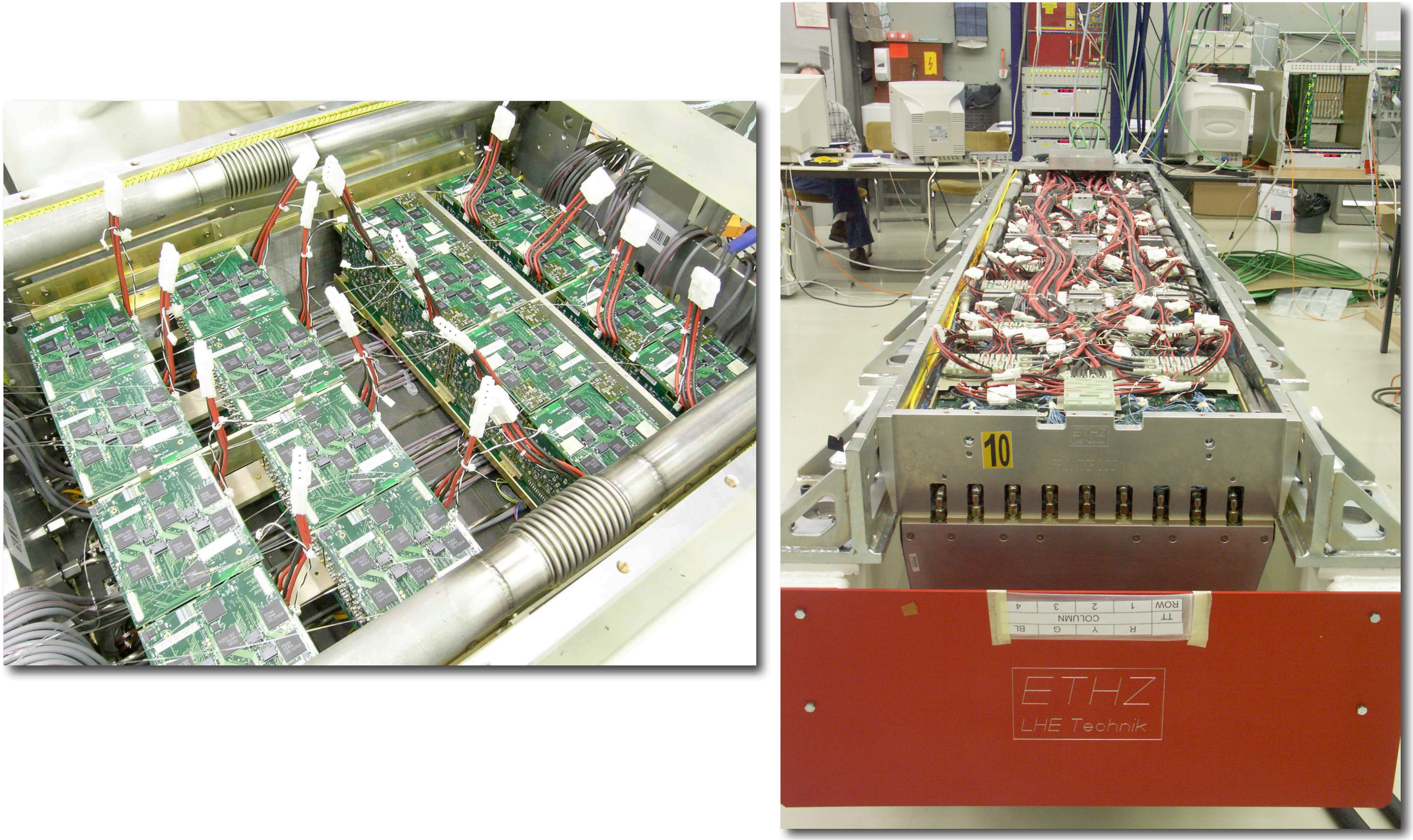
Trigger Tower
25 channels





VFE and FE Boards:
Contain custom-designed
ASICS in IBM 0.25 μm technology

The full beauty…

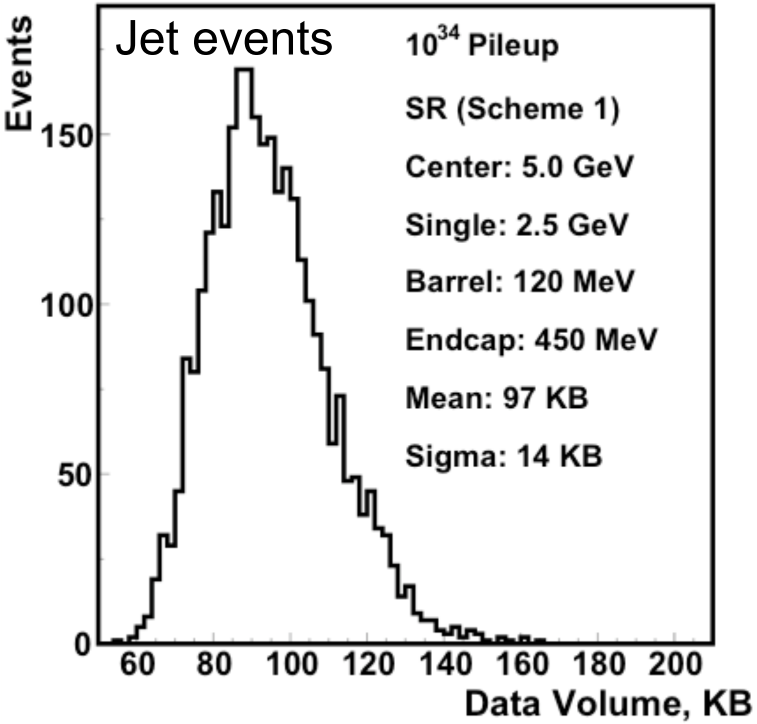


Data Rates and Volume

- Typical trigger rates, Level 1, at Luminosity=2x10^{33} /cm^2/s

Trigger	Threshold [GeV]	Rate [kHz]
Inclusive isolated electron/photon	29	3.3
Di-electrons/di-photons	17	1.3

- Data volume
  - Total ECAL ≈ 1.8 Mbyte
  - Acceptable ≈ 100 kByte !
  - Can fully read out only about 5% of all channels
  - Selective Readout Processor: Algorithm to decide which channels to be read out, with which level of zero-suppression, eg.
    ALL crystals in region of high E_T shower read out; other areas zero suppressed at ~2-3 σ_{noise}

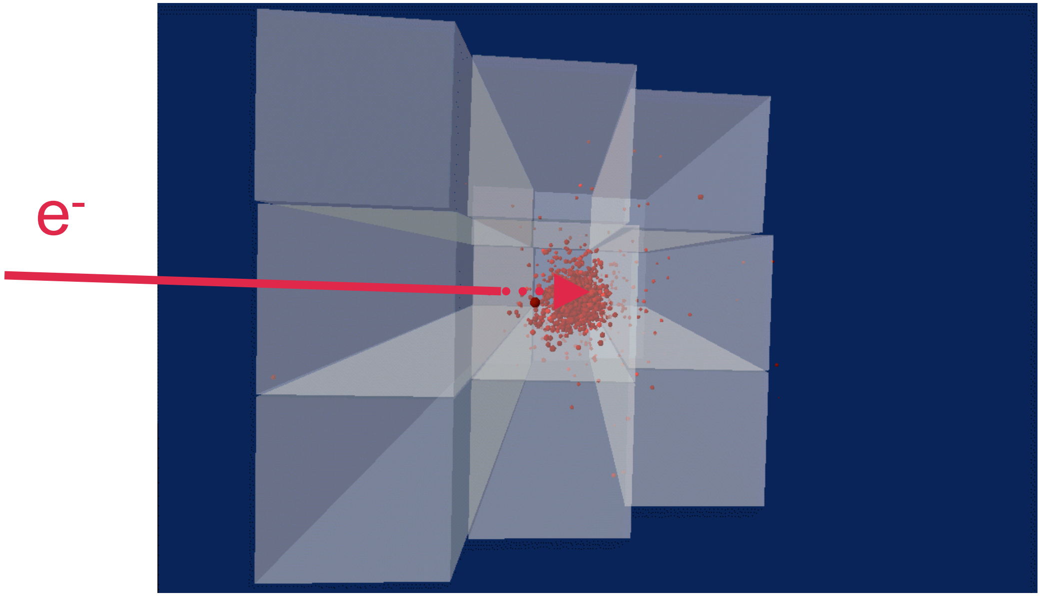


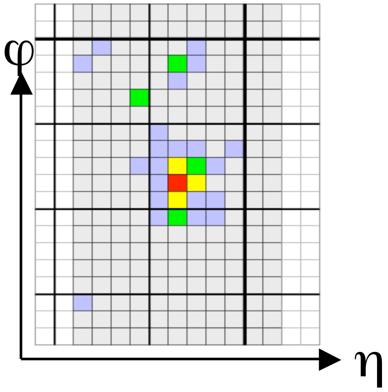
The performance

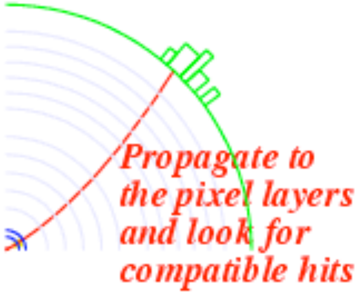
How to reconstruct particles?

Basic principle

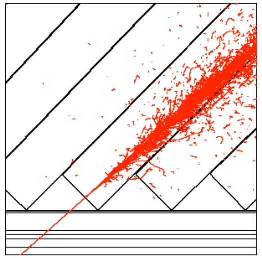
- Energy in central crystal : ~80 %, in 5x5 matrix : 96 %
- Look for “seed”-crystals with energy deposit above some threshold
- Look at the (n x n)-cluster of crystals around this seed
- Study $E_{central}/E_{(n\ x\ n)}$, study isolation, look for associated tracks
- Look at ratio of energies deposited in ECAL and HCAL



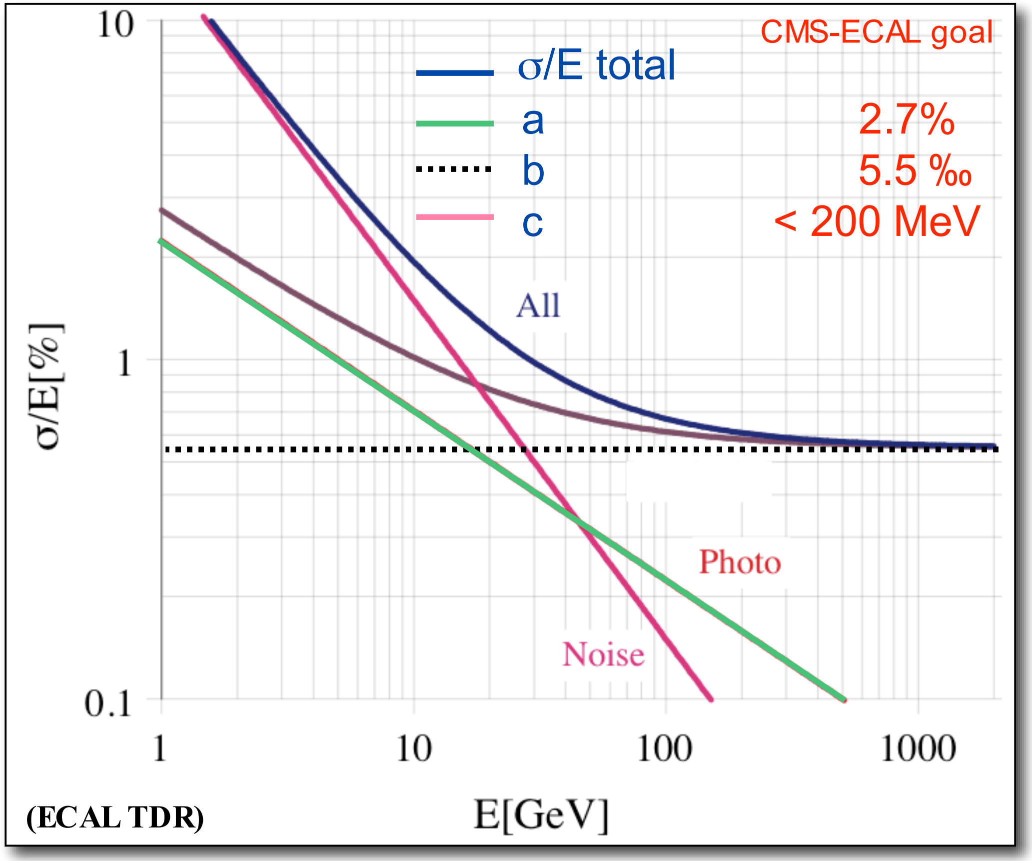




Propagate to the pixel layers and look for compatible hits



Focus on energy resolution



(ECAL TDR)

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

If you want precision, you have to take a lot of care...

- Longitudinal and lateral shower containment
- Light production, collection uniformity
- Channel to channel intercalibration
- Electronic noise
- Stability of Photo-Detector gain and crystal response
  ➔Temperature stability and uniformity
- Radiation damage
- Nuclear counter effect
- Pileup
- ...

Resolution Terms

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

Stochastic term:

Shower fluctuations
(photo-statistics + lateral)

$$E \propto N_{\text{p.e.}}$$

$$\sigma(N_{\text{p.e.}}) \propto \sqrt{N_{\text{p.e.}}}$$

$$\Rightarrow \quad \frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

Including gain fluctuations of photo-detector (*F*) :

$$\frac{\sigma(E)}{E} = \sqrt{\frac{F}{N_{\text{p.e.}} \cdot E}}$$

$$F = 2-3; \quad N_{\text{p.e.}} \geq 4000/\text{GeV}$$

$$\Rightarrow a = 2-3\%$$

Constant term:

Intercalibration of crystals

Rear leakage

Non-uniformity of light collection

Noise term:

Electronics noise

Leakage currents

Pile-up noise

Calibration steps

- **Precalibration:**
  - Lab measurements **< 5%** (from measurements of light yield)
  - Test beam **< 2%**

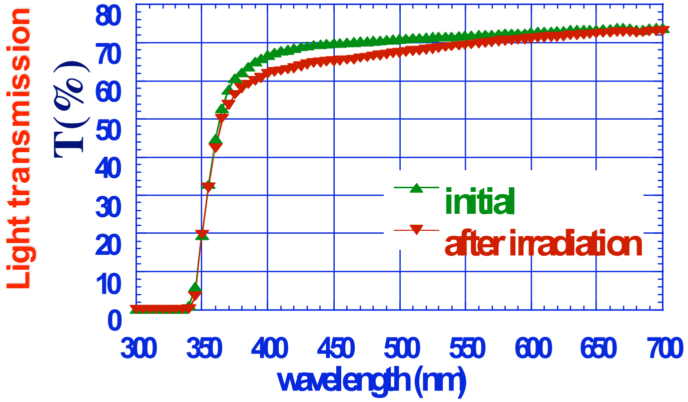
- **In-situ calibration:** at low Lumi
  - A) using Φ - **symmetry** of energy deposition **≈2%** **few hours**
  - B) Use **$Z \rightarrow e^+e^-$** for intercalib. in η and absolute E scale **few days**
  - C) When tracker fully operational : E/p from **$W \rightarrow e\nu$** **few months**

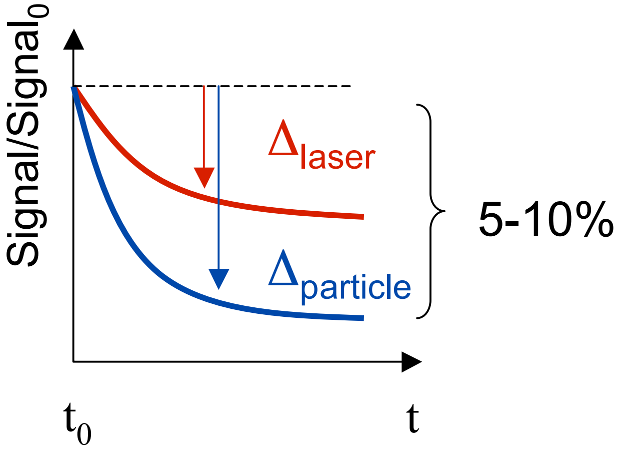
    Final goal : 0.5%

- **Online Laser monitoring:**
  - Correct for variations in crystal transparency due to irradiation

Laser monitoring

Why is the laser monitoring so important?

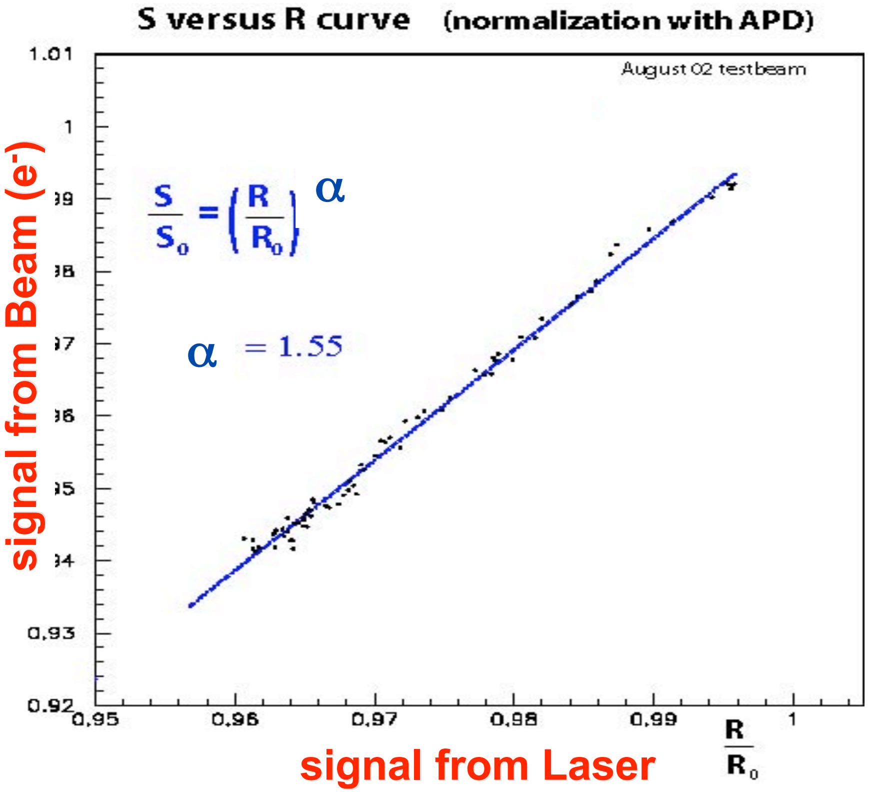




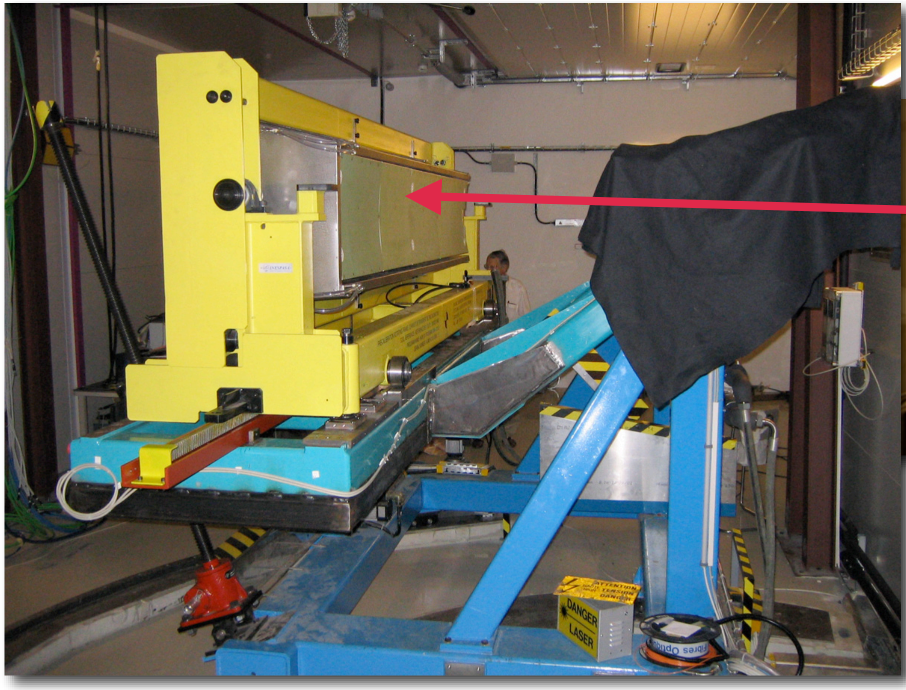
$\Delta_{particle}$ vs Δ_{laser} ?

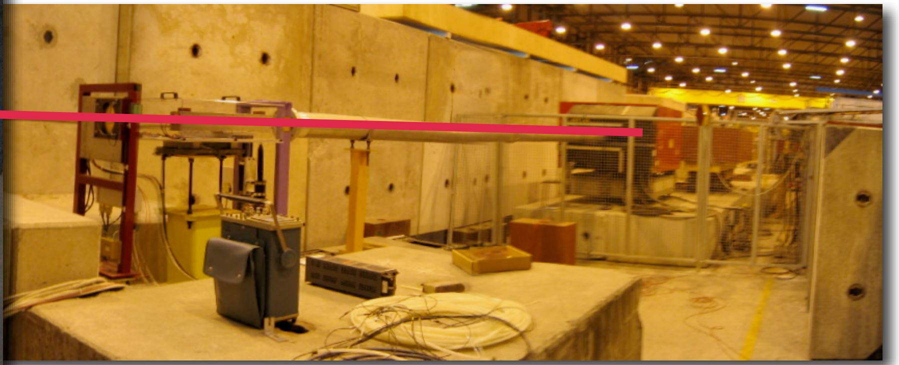
Thus the idea is:

- Inject laser light to monitor crystal transparency
- Follow signals from beam and laser
- Determine “slope” laser vs. beam
- Correct the data using this slope

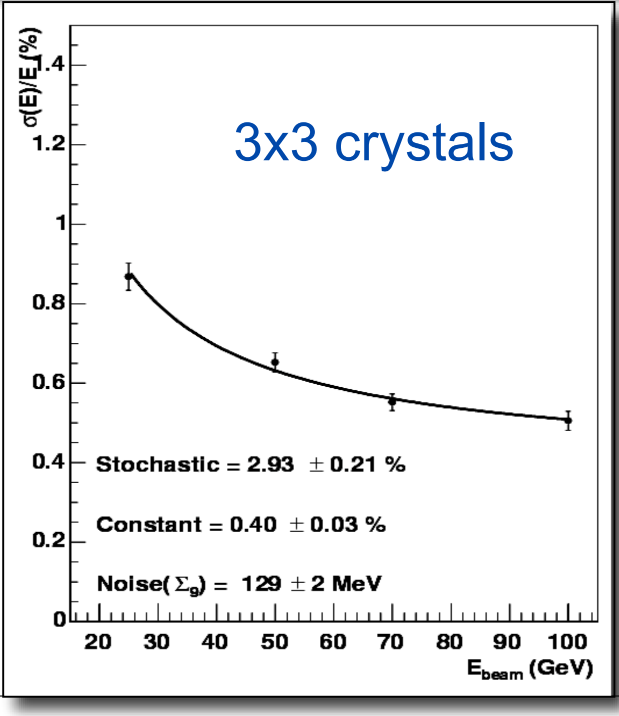


Testbeam measurements





H4-Beamline, CERN



3x3 crystals

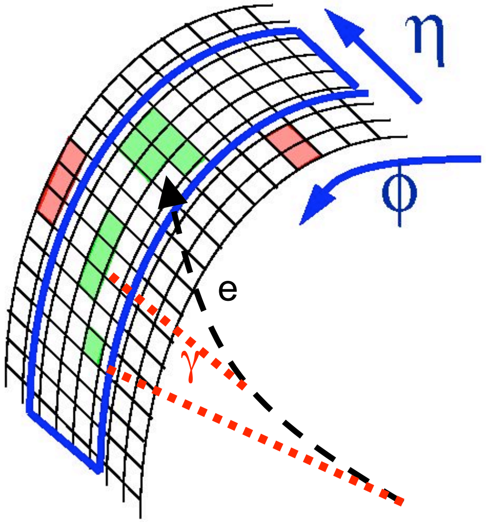
CERN-SPS beam:

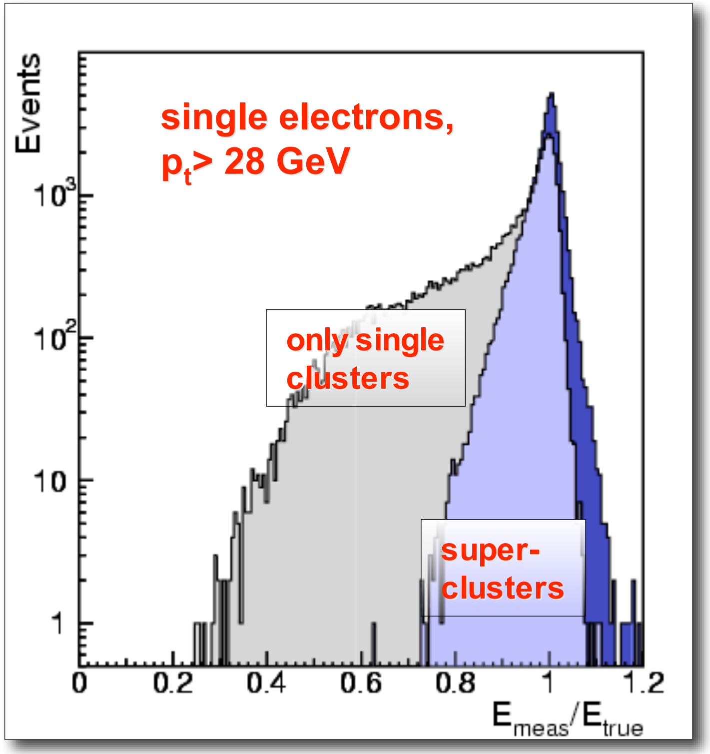
- Electrons, pions, muons
- Precisely known energies
- Supermodules on moveable table
- Study of energy resolution, irradiation effects reconstruction issues

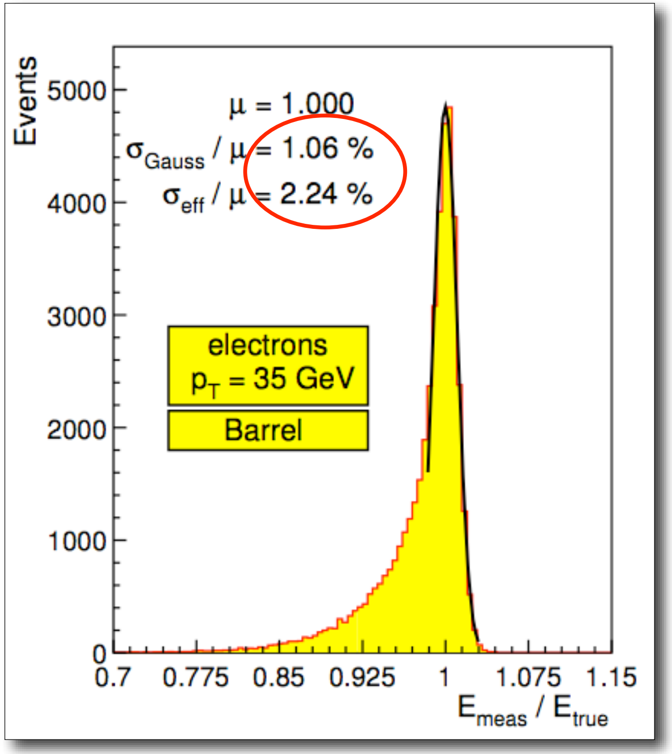
Reconstruction Issue : Bremsstrahlung

- **Main difficulty** : tracker material ⇒ **bremsstrahlung**

  $\langle E_{brems}/E \rangle = 43.6\ \%,\ P_t = 35\ \text{GeV},\ |\eta| < 1.5$
- Recover by reconstructing clusters of clusters (**super-clusters**)
- Essential for $Z \rightarrow ee$ and $W \rightarrow e\nu$ reconstruction



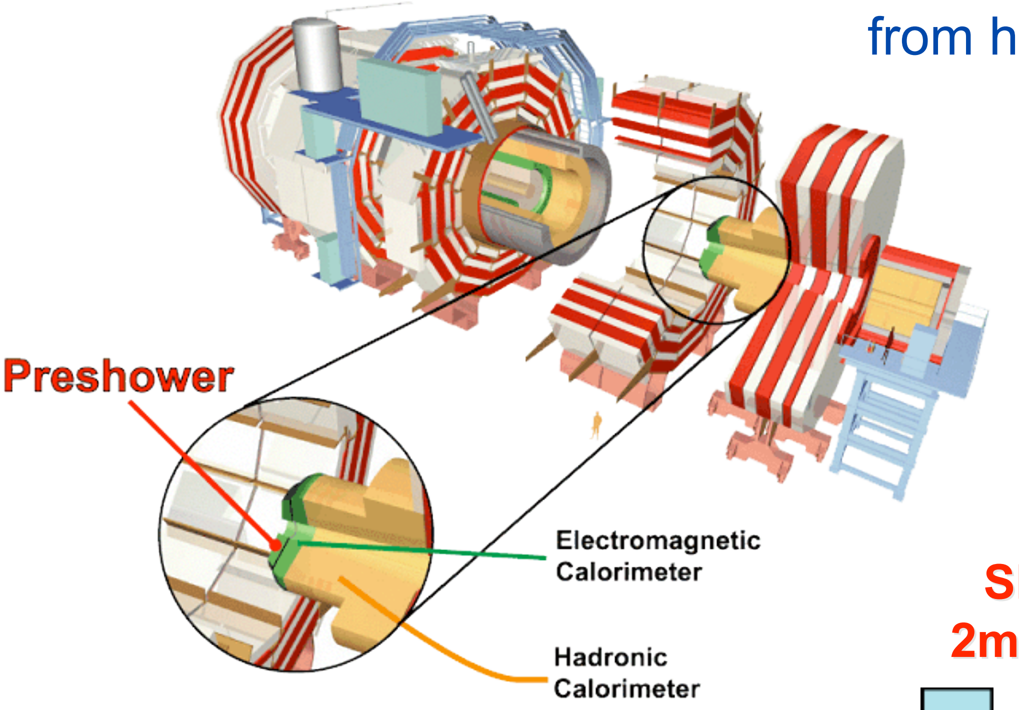


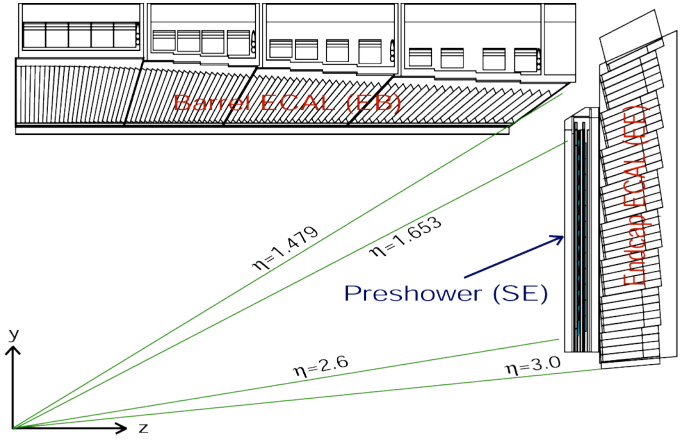


Reconstruction Issue : π^0 separation

ETH Institute for Particle Physics

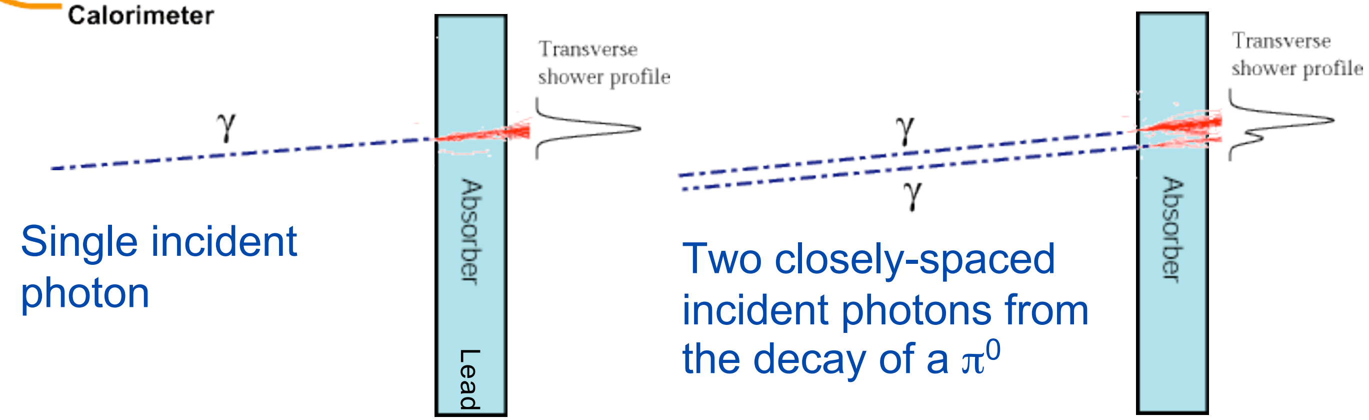
How to separate single photons from highly-energy $\pi^0 \rightarrow \gamma\gamma$ decays ?





Shower profile measured by 2mm-pitch silicon strip sensors

Idea of Preshower:



Single incident photon

Two closely-spaced incident photons from the decay of a π^0

$H \to \gamma\gamma$: some performance numbers

From ECAL-TDR:

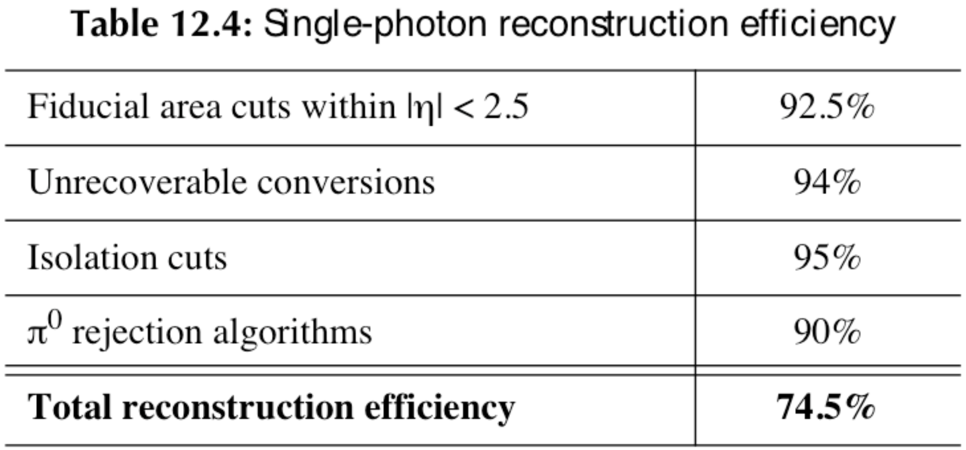
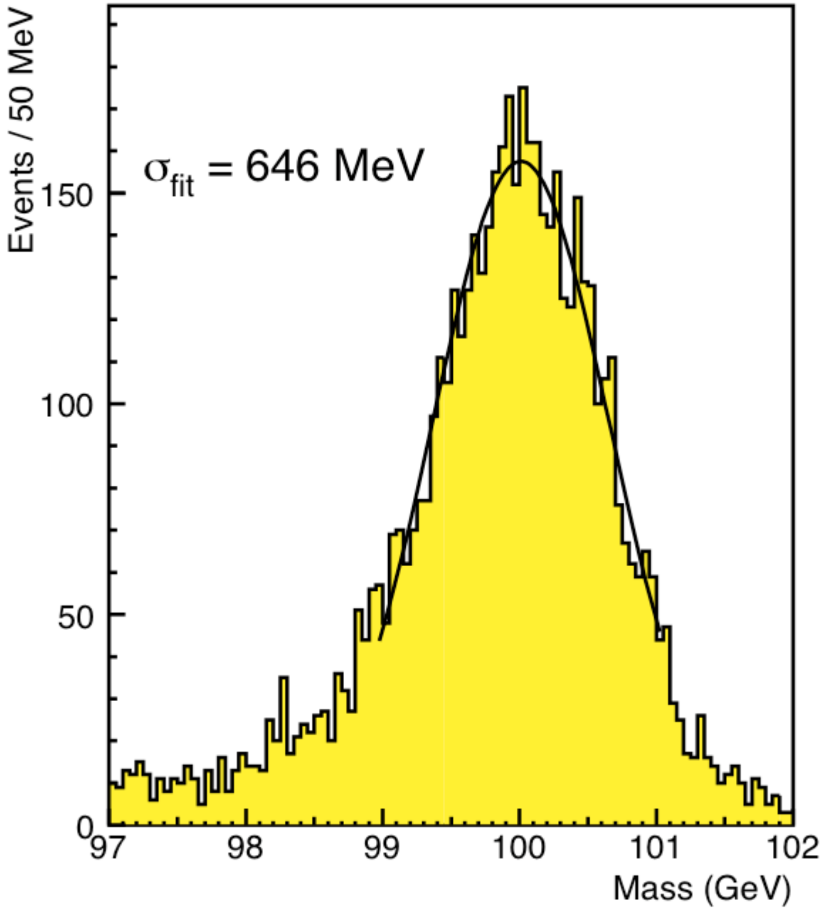


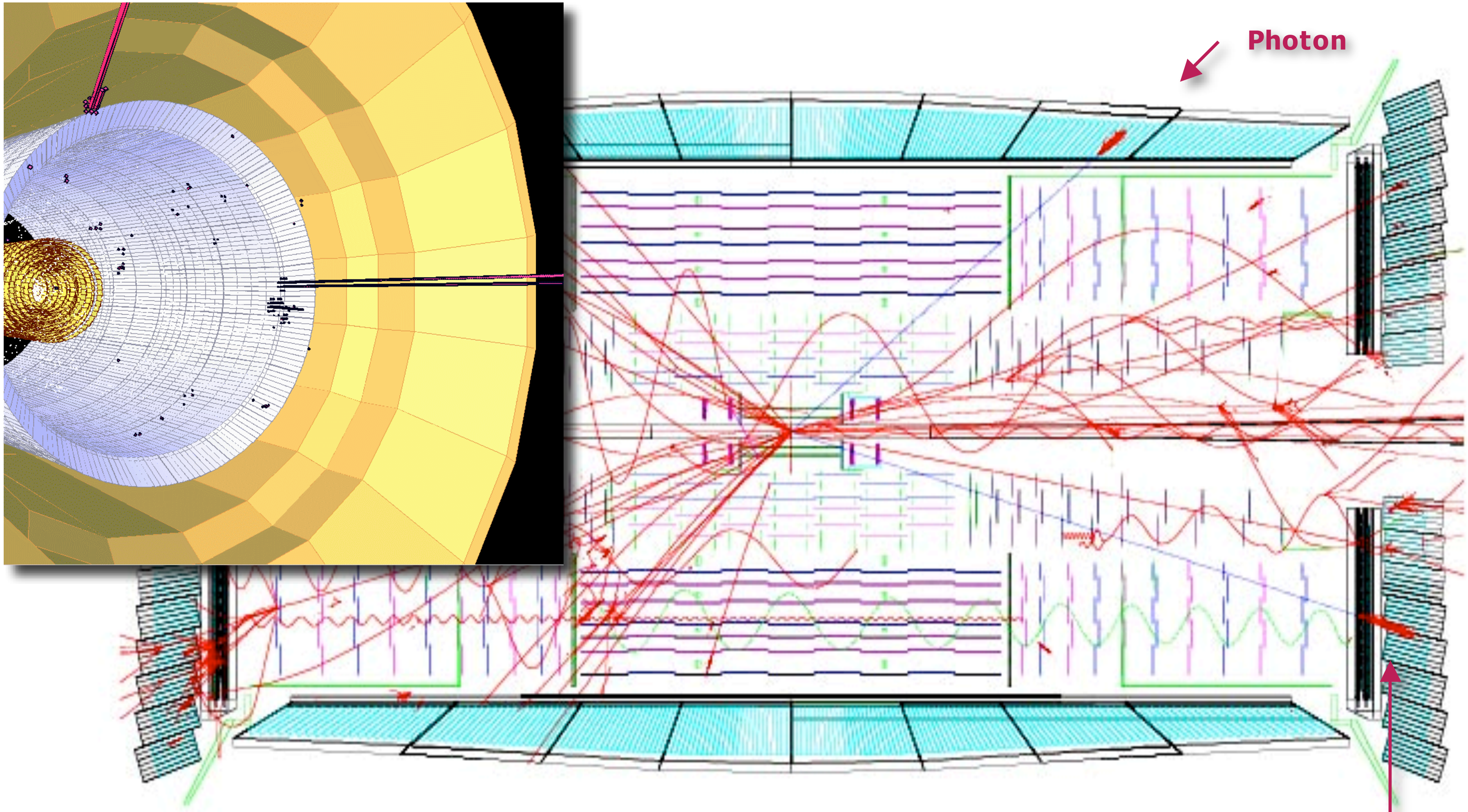
Table 12.4: Single-photon reconstruction efficiency

Fiducial area cuts within $\lvert\eta\rvert < 2.5$	92.5%
Unrecoverable conversions	94%
Isolation cuts	95%
π^0 rejection algorithms	90%
Total reconstruction efficiency	**74.5%**



Reconstructed Higgs mass resolution, for m_H=100 GeV and Luminosity=$10^{33}/cm^2/s$.
Vertex found from additional high-p_T tracks in event

In the future…



Summary

- One of the major design principles of the LHC detectors:
  - Best possible electromagnetic calorimetry
  - Driven by requirements from benchmark channels of the low-mass Higgs search
- Focus on energy resolution:
  - Homogeneous calorimeters are the first choice
  - If it has to be compact : go for scintillating crystals
- Many years of R&D
  - Needed to adapt the chosen crystals, photo-detectors and readout electronics to the harsh LHC environment
- Now under construction
  - A lot of effort, need control of many details in order to make sure that design goals are met
  - Concerns hardware, software and physics reconstruction

Acknowledgements/Literature

- Many thanks to all those who helped me for the preparation of this presentation

  S. Gascon-Shotkin, P. Lecoq, F. Pauss, M. Dittmar, W. Lustermann, C. Seez, A. Holzner, G. Davatz, J. Ehlers, ...

- Suggested literature
  - CMS-ECAL Technical Design Report, CERN-LHCC/97-33
  - "The CMS TriDAS Project", Technical Design Report, Vol. 2, CERN-LHCC/02-26
  - R. Wigmans
    "Calorimetry : Energy Measurement in Particle Physics"
    Oxford University Press.