Calorimeters

Showers & Detectors,

Signal Treatment & Commissioning,

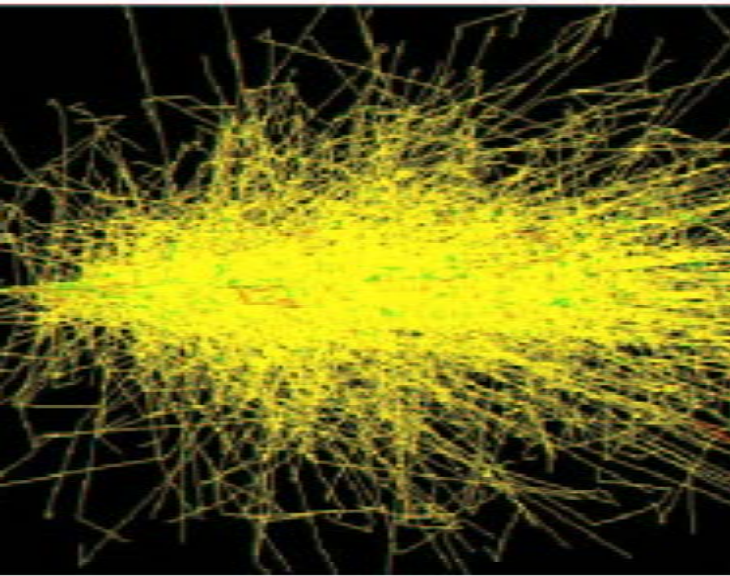**Calibration & Reconstruction**

Overview

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
  - Signal Treatment
  - Online Calibration
  - Commissioning
- Calibration & Reconstruction
  - Cell level calibration
  - Electrons/photons
  - Jets
  - Missing E_T
  - E-flow

Longitudinal shower profiles


Simulation of 1 GeV electron in copper

• Multiplication of e/γ up to max shower depth where most particles reach E_c

• Exponential fall off of the shower afterwards

• Maximum shower development ~6 X_0

• Quasi universal behavior wrt X_0 but :

- Shower maximum deeper at high Z

- Slower decay at high Z

→Critical energy $\propto 1/Z$

The depth of a calorimeter goes as ln(E)

Longitudinal Development EM Shower

Longitudinal development EM showers (EGS4, 10 GeV e⁻)
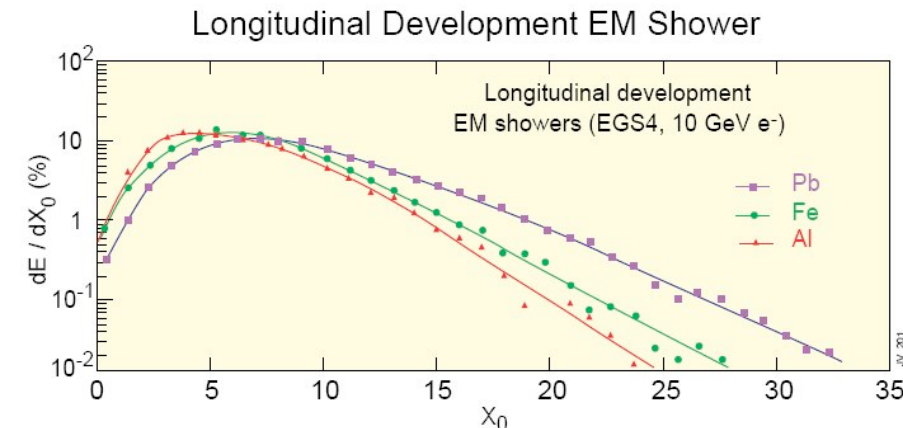
After 25 X_0 only 1% leakage for E up to 300 GeV ➔ compact detectors!

em Showers

- **Electron, photons produce em showers in a calorimeter:**

  - **em showers are compact:**
    - the shower maximum is at ~$6X_0$ longitudinally contained in ~$25\ X_0$,
    - laterally contained to 90% in 1 R_M, > 99% in 3 R_M

  - **Measured in homogeneous (crystal) or sampling calorimeters**
    - homogenous calorimeter have an excellent intrinsic resolution, but larger non-uniformities, no longitudinal segmentation
    - Sampling em calorimeters use either scintillator or liq. Noble Gas (liq. Argon) as active material, and mostely Pb or Ur as absorber: fine segmentation, large variety of design
    - Intrinsic resolutions of em calorimeters: 3-20%/$\sqrt{E}$

Hadron Calorimeters

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadron Calorimeters
    - Hadron Showers
    - Compensation

- Signal Treatment & Commissioning
  - Signal Treatment
  - Online Calibration
  - Commissioning

- Calibration & Reconstruction
  - Cell level calibration
  - Electrons/photons
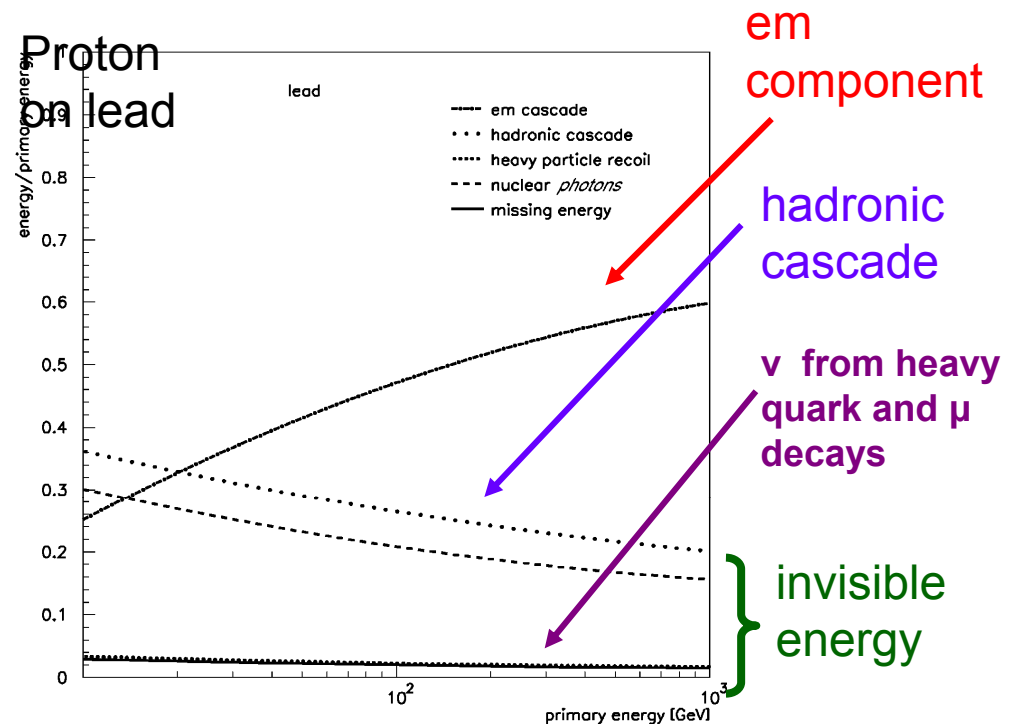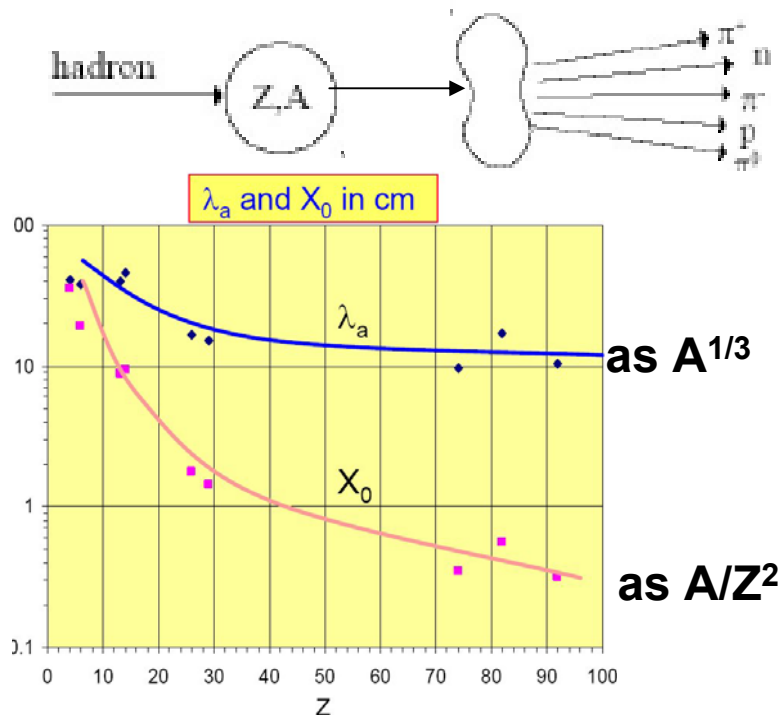 - Jets
  - Missing E_T
  - E-flow

Hadron showers
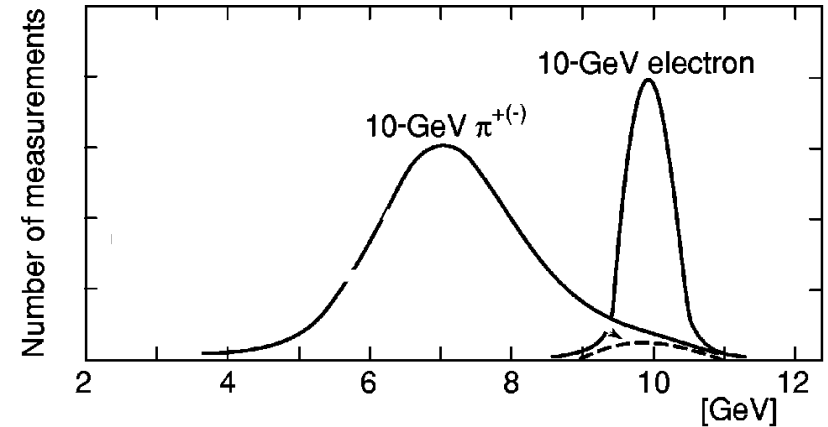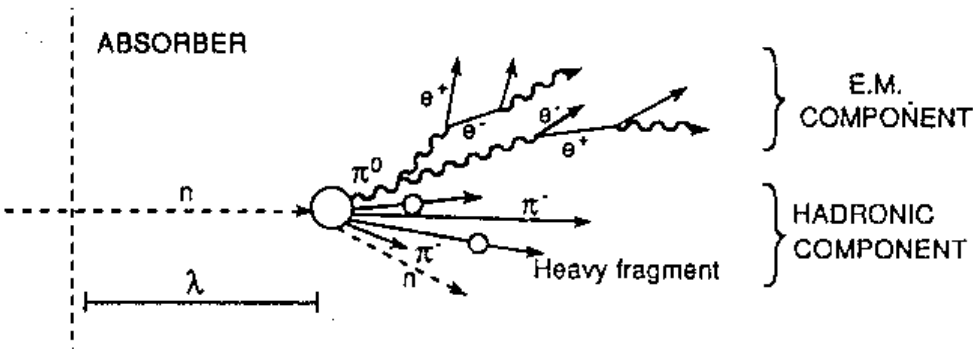
1. **Production of energetic secondary hadrons**
   - Number of particles produced ~ ln (E) with an "interaction length" $\lambda \approx 35\ A^{1/3}$
   - secondary particles produced: p, n, $\pi^{+/-}$, and
     $\pi^0 \rightarrow 2\gamma \rightarrow$ electromagnetic component of the hadron shower
   - Hadrons thermalize but only <10% energy loss through ionization
2. **Nuclear interactions $\rightarrow$ resulting in a few MeV photons**
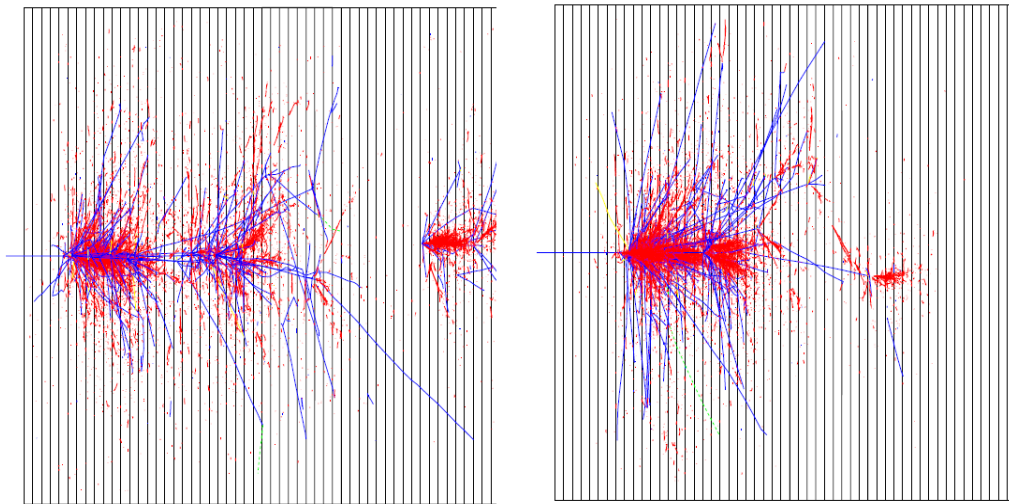   - Produced slowly ~µs $\rightarrow$ mostly invisible energy

λ_a and X_0 in cm

as $A^{1/3}$

as A/Z^2

Proton on lead

em component

hadronic cascade

ν from heavy quark and µ decays

invisible energy

Resolution for hadron calorimeters

ABSORBER

E.M. COMPONENT

HADRONIC COMPONENT

Heavy fragment

Number of measurements

10-GeV electron

10-GeV $\pi^{+(-)}$

[GeV]

Signal (in energy units) obtained for a 10 GeV energy deposit

red: em component   **blue: hadronic component**

- **not all the incident energy is measured : e/π > 1**
- very large event to event fluctuations between hadron and em component
- em component energy dependent→ non linear →resolution worse than for em showers!

Typical resolutions: $\dfrac{\sigma(E)}{E} \approx \dfrac{50-100\ \%}{\sqrt{E}} \oplus 3-5\% \ (\text{E en GeV})$

Compensation for hadron calorimeters

e/π ratio is a major component to the resolution !
- if e/π ≈ 1 the calorimeter is « compensated »

How to achieve compensation?
- impossible to have a similar response to e and hadrons in a homogenous calorimeter
- sampling calorimeters allow to optimize absorber and active materialfor the hadron cascade,
- active material containing hydrogen (Scintillator) sensitive to neutrons!
- long integrations times…

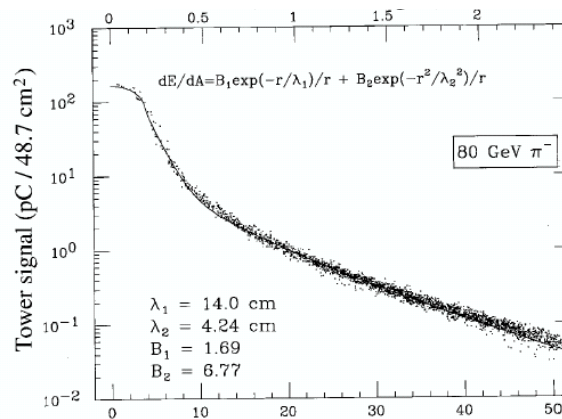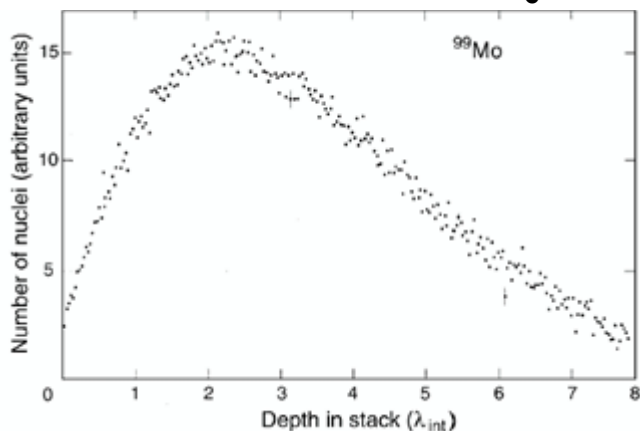- **High Z absorber material: U, Pb, but difficult due to mecanical constraints**

- Tuning of the thickness between absorber and active material!
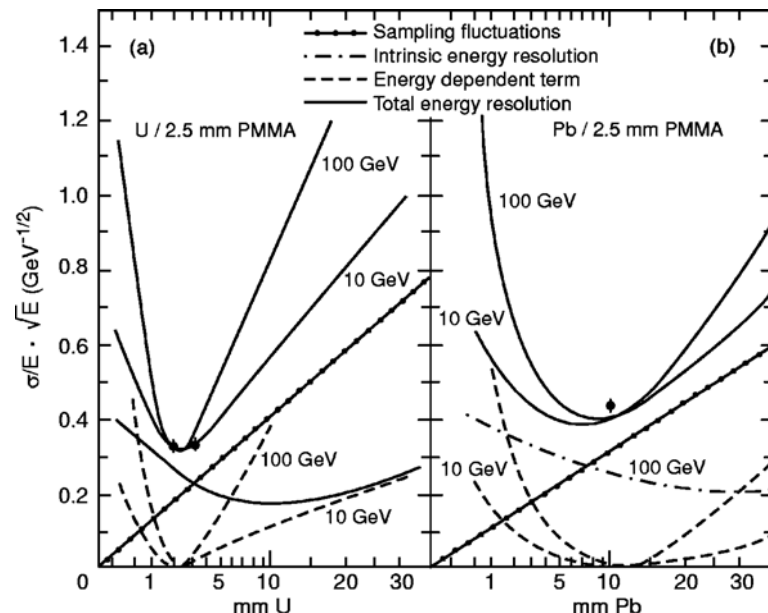
Shower profiles

300 GeV pion, 95% in 8 λ_{int} (85 cm of U)
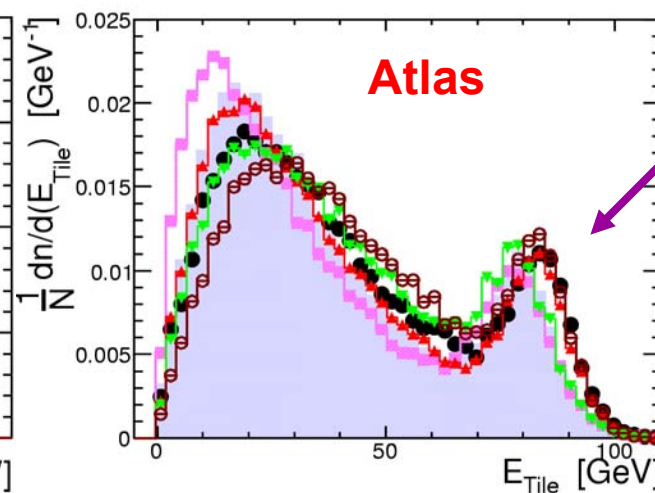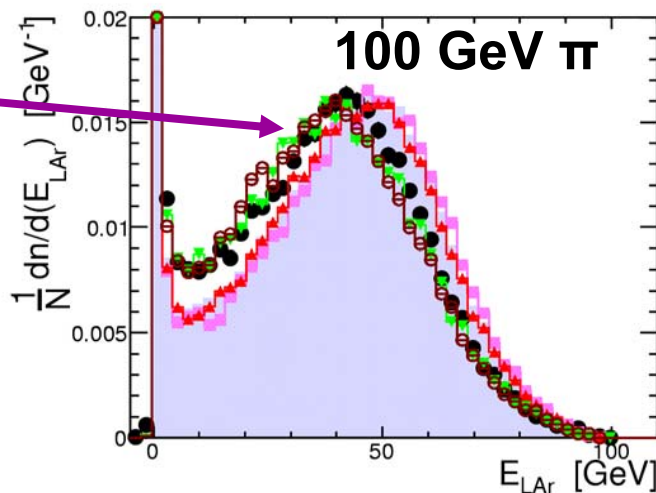**300 GeV electron , in 30 X_0 (Pb 9cm)**

80 GeV pion, 95% in 1.5 λ_{int} (32 cm)
80 GeV electron (3.5cm)

• typically factor ~10 on shower sizes, shower max at ~2λ

➜ a large energy fraction of the hadron shower is in the em sections !

peak of events starting to shower in e.m. calo.

100 GeV π

Atlas

peak of events starting to shower after e.m. calo.

HCal generalities

- All the hadronic sections of the hadron collider experiments are sampling calorimeters
  - Possible optimization of e/π response, yet limited resolution of hadron showers
  - Jet radius rather large: coarser granularity, fewer longitudinal segmentation
  - big devices: mechanical considerations, cost consideration
  - Energy fraction deposited decreases with depth, radius of the device increases: less performing absorber material at the outside
  - ➔ use of robust and rather cheep absorber material
  - ➔ active material: either liquid Argon or scintillator

Tile calorimeters

- Atlas barrel HCAL : l=5.6m r=4.2m
- iron/scintillating tiles
- 10K readout channels in 3 layers (1.4λ, 3.9λ, 1.8λ, ~2λ from em) with a η x φ segmentation of 0.1x0.1 – except last layer 0.2x0.1 (TC)
- resolution: $\sigma/E=50\%/\sqrt{E} \oplus 3\%$

CMS: barrel HCAL: l=9m, r=6m
- brass-scintillator calorimeter
- 10k channels 5.2λ (10λ total) with a η x φ segmentation of 0.087x0.087
- HO: scintillator array in the central region outside the magnet to catch leakage energy
- resolution: $\sigma/E=100\%/\sqrt{E} \oplus 4\%$
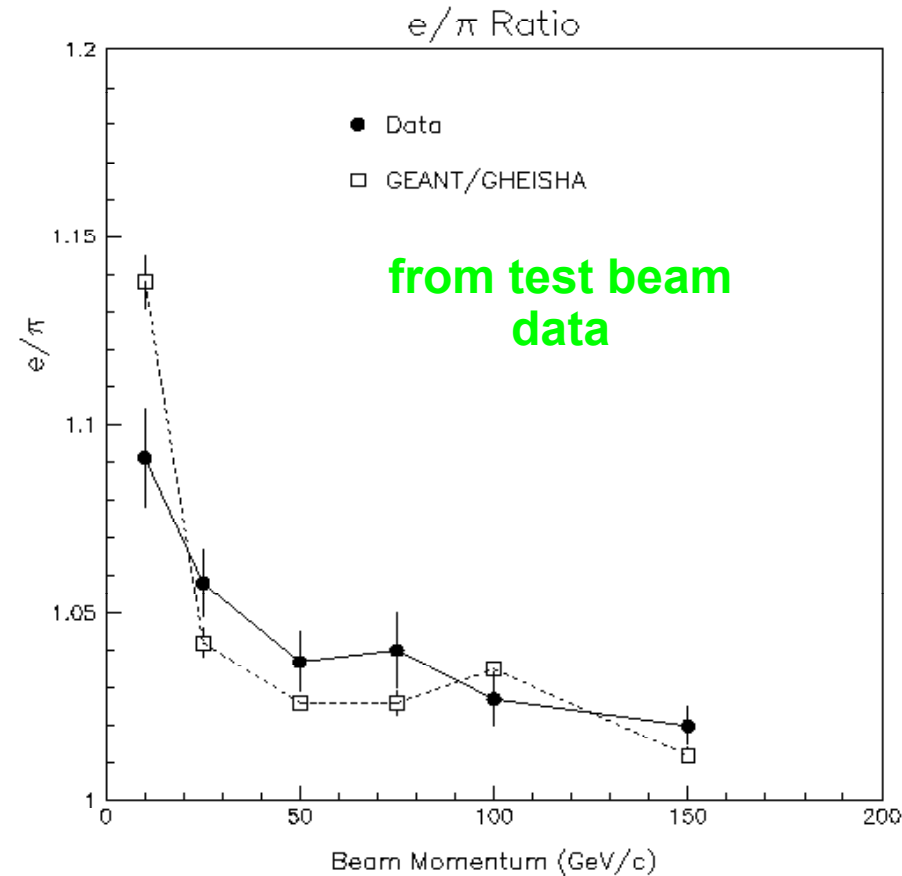
D0 - Calorimeter

- **4-5 hadronic layers (FH + CH)**
- **Uranium absorber in EM and Uranium-Nobium in FH**
- **Cu (CC) or Steel (EC) for coarse hadronic**

From test beam measurments:

- ◆ **compensating e/$\pi \sim$ 1 for Run I intergration time**

from test beam data

e: σ_E/E = 15% /$\sqrt{E}$ + 0.3%

π: σ_E/E = 45% /$\sqrt{E}$ + 4%

e/π Ratio

- ● Data
- □ GEANT/GHEISHA

e/π

Beam Momentum (GeV/c)

Summary on showers & detectors

- Electron, photons leave em showers in a calorimeter:
  - They are compact:
    - the shower maximum is at $\sim 6X_0$ longitudinally contained in $\sim 25\ X_0$,
    - laterally contained to 90% in 1 R_M, > 99% in 3 R_M
  - Measured in homogeneous (crystal) or sampling calorimeters
    - homogenous calorimeter have an excellent intrinsic resolution, but larger non-uniformities, no longitudinal segmentation
    - Sampling calorimeters use either scintillator or liq. Argon as active material, and Pb or Ur as absorber: fine segmentation, large variety of design
    - Intrinsic resolutions 3-20%/$\sqrt{E}$
- **Hadrons produce showers, where the energy contributes**
  - **20-30% hadronic cascade**
  - **30-60% electromagnetic cascade**
  - **20-30% of the initial energy is lost in slow nuclear interactions, with large fluctuations**
  - **Intrinsic resolution: 50%-100%/$\sqrt{E}$**
  - **Hadronic calorimeters complete the em-sections: shower max at $\sim 2\lambda$**
  - **Sampling calorimeters which have to be solid, robust and rather cheap**

Signal Treatment & Calibration

Noble liquids

Scintillators

incident particle

shower development

detection

amplification, shaping and digitization
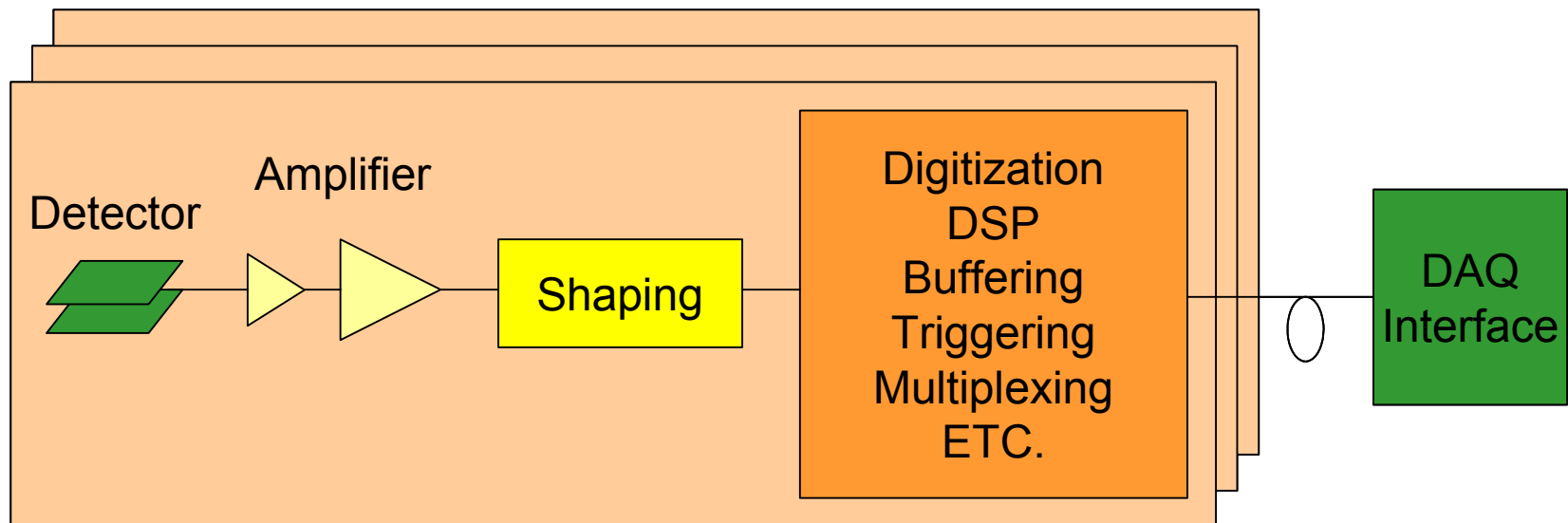
conversion from digital signals to energies
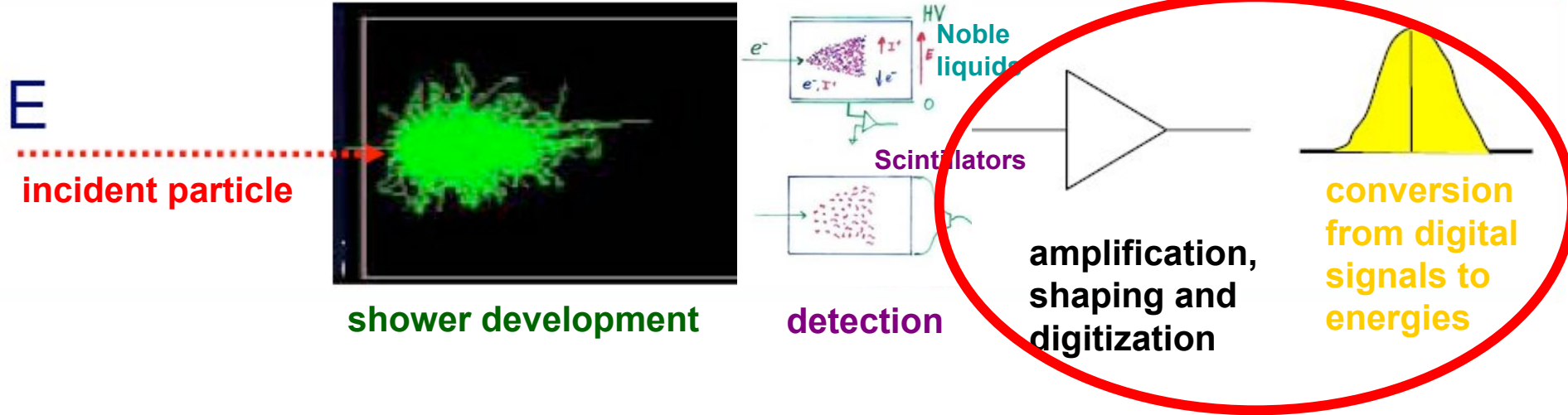
- how to go from the collected charge or photons to ADC counts?

  ➔ Basics on FrontEnd and ReadOut electronics

- how to go from ADC counts to GeV deposited in a calorimeter cell?

  ➔ How to determine the conversion factors?

  ➔ How to ensure that the measurements are linear and uniform?

  ➔ Effects from the detectors and the electronics

Signal Treatment

- **Showers & Detectors**
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- **Signal Treatment & Calibration**
  - Signal treatment
    - Basic Front-End
    - Examples of calorimeter ReadOut
    - Noise Treatments
  - Online Calibration
  - Commissioning
- **Simulation & Reconstruction**
  - Cell level calibration
  - Electrons/photons
  - Jets
  - Missing ET
  - E-flow

Basic Front-end

- Pre-amplifier interfacing the detector with additional gain stages if needed.

- Shaping – filtering: defines a signal form, which height is proportional to the deposited energy

- Further treatment:
  - Buffering: store the signal to take a trigger decision
  - Triggering: summation of rapid signals send to the trigger system
  - Digitization: conversion of analog signal in digital signal (ADC counts)
  - DSP:may apply online correction, elaborated 0 suppression, etc.

Calorimeter electronics: example D0

Interaction time: 396ns

BLS board

4 * L1 SCA (48 deep)

Trig. sum

Calibration

LAr cell

Preamp/ Driver

PreAmp Board

Filter/ Shaper

x1

x8

Analog Storage

BLS

L2 SCA

AD

Detector signal

Signal from preamp

After shaper

320 ns

amplitude

0   400   800   1200   **ns**
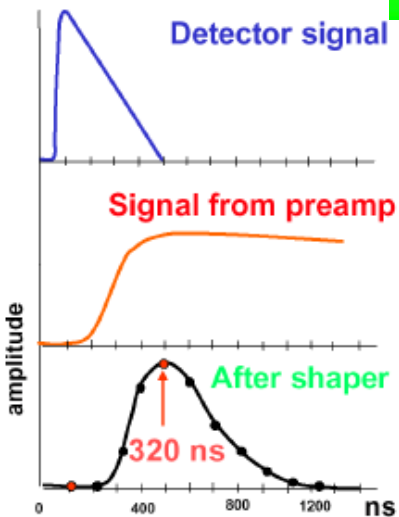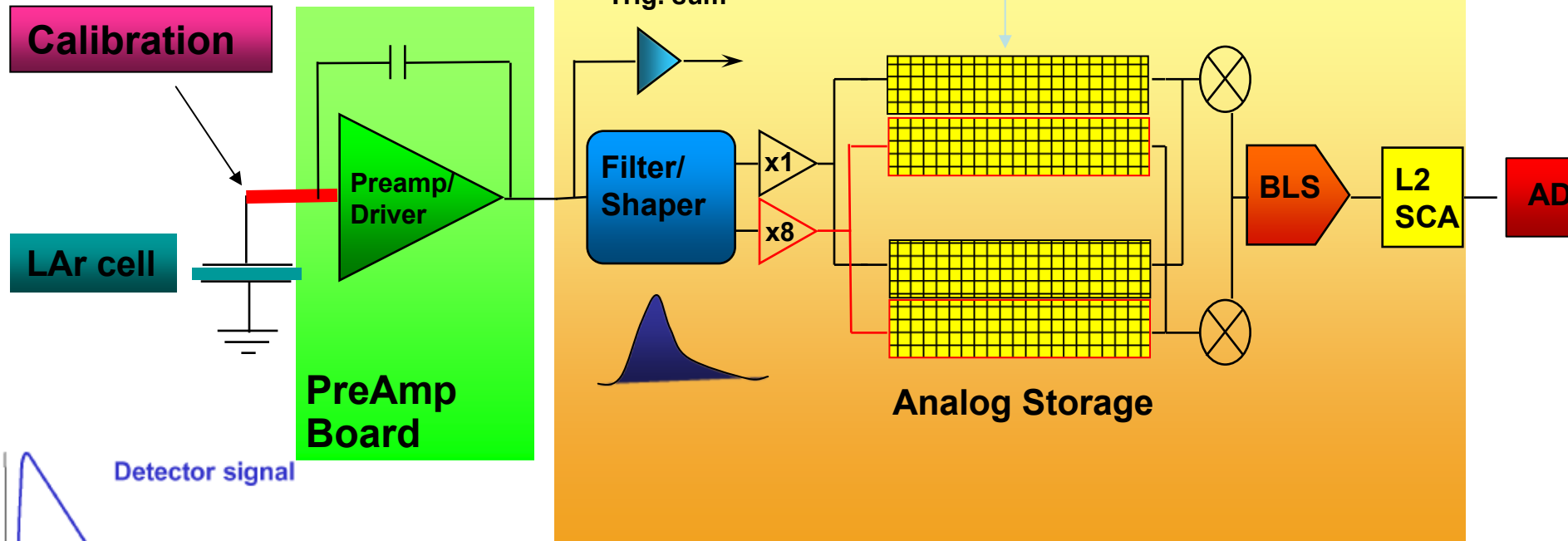
BLS (Base Line Subtraction):
- **shaping**
- **analog memories**
- **base line subtraction**
- **gain selection**

ADC:
- digitization
- 0-suppression

Noise measurements

Measurement of the the electronics output without any signal: example D0

σ of the distribution gives the noise level
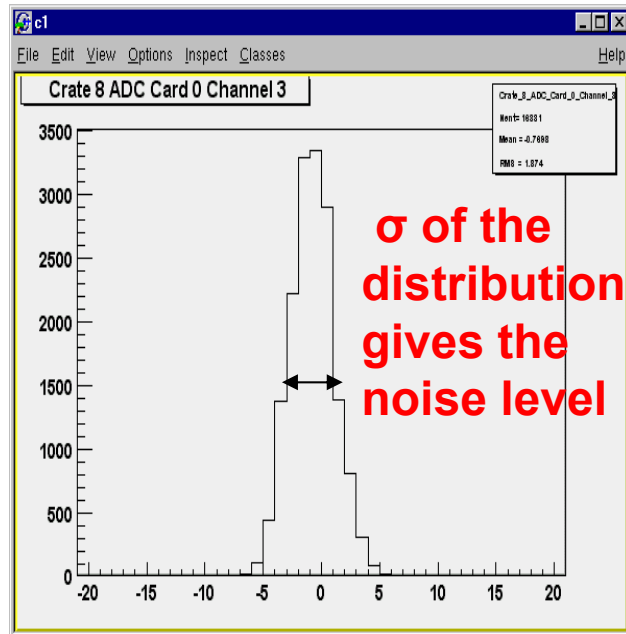
Electronics noise:
- Cell capacitance, Uranium, preamplifier
- varies as $\sqrt{t}$

gain 8

sigma8/(capa/1000.) vs. channel

gain 1

ECNW CCW ECSW ECSE CCE ECNE
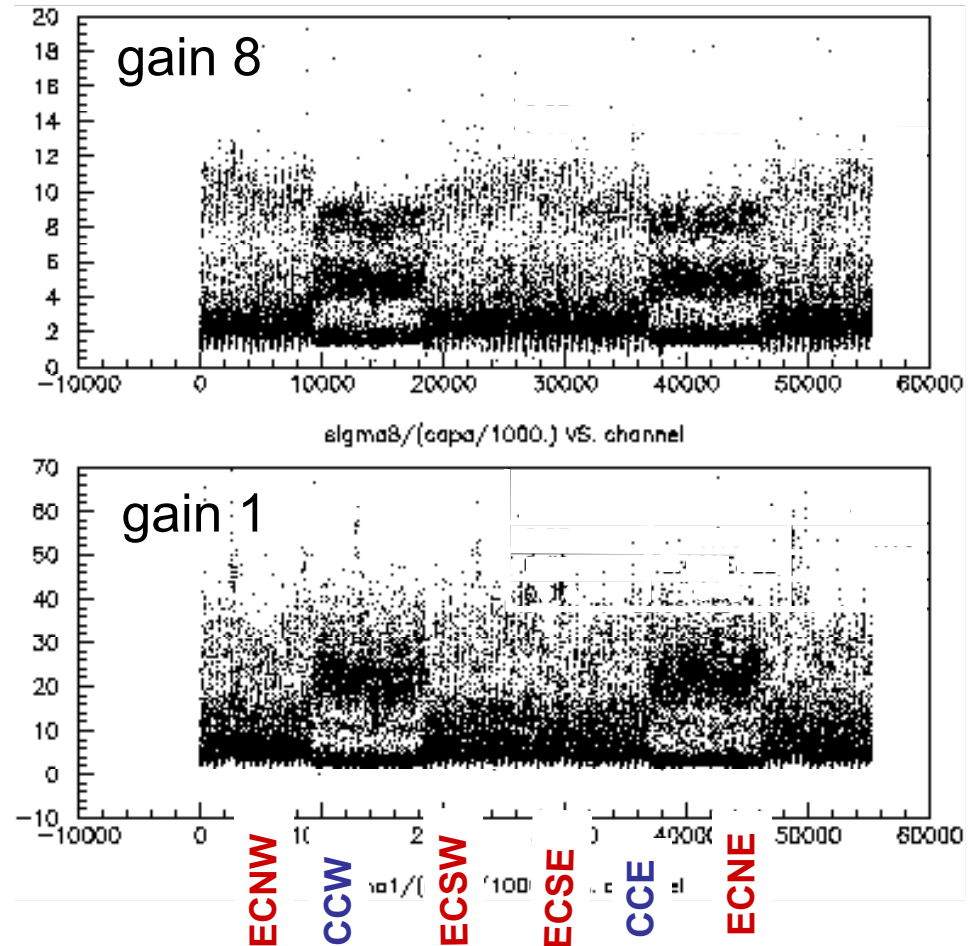
σ/C vs. channel

Noise studies in physics events

0-biais **QCD** $\eta < 0.8$

Cell energies
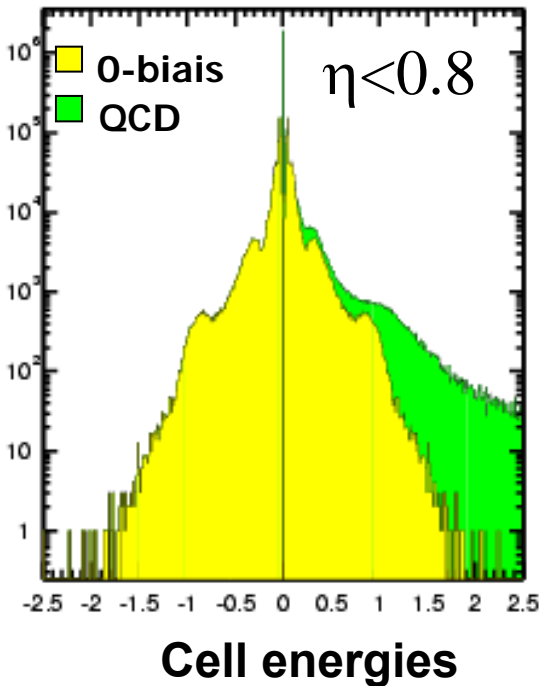
How to study the effect of noise suppression?

Most sensitive quantities: missing E_T and scalar ET

0-bias events are collected during beam crossings at fixed rate without trigger requirements

→ Those events contain about 1/3 of elastic interactions
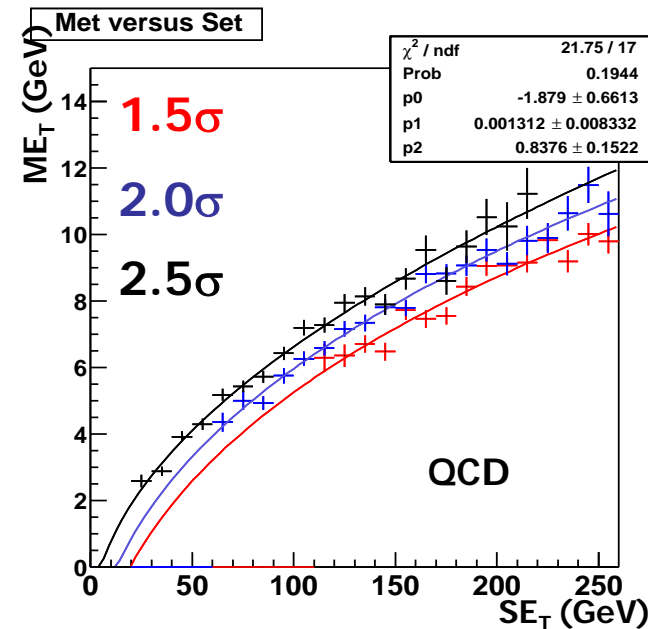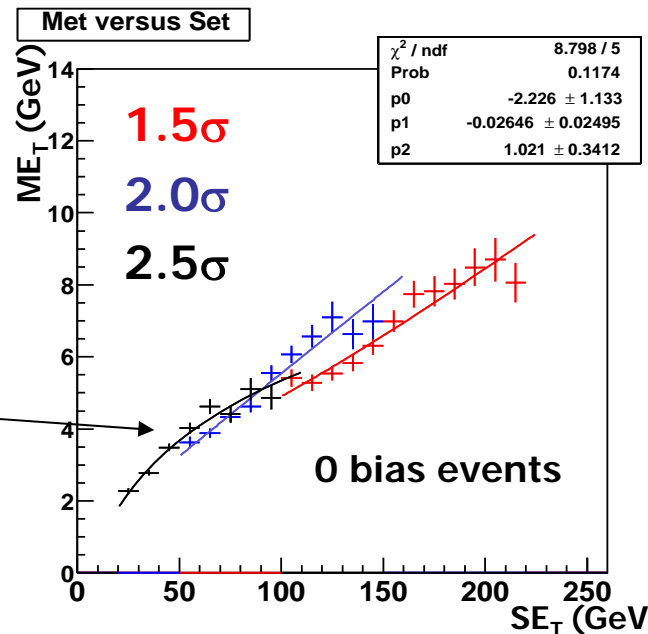
The typical correlation for signal between mET and sE$_T$ starts to appears for a 2.5σ cut

Met versus Set

χ^2 / ndf	8.798 / 5
Prob	0.1174
p0	-2.226 ± 1.133
p1	-0.02646 ± 0.02495
p2	1.021 ± 0.3412

1.5σ
2.0σ
2.5σ

0 bias events

Met versus Set

χ^2 / ndf	21.75 / 17
Prob	0.1944
p0	-1.879 ± 0.6613
p1	0.001312 ± 0.008332
p2	0.8376 ± 0.1522

1.5σ
2.0σ
2.5σ

QCD

Sophisticated noise suppression

- Online noise suppression: only energies $|E| > 1.5\text{-}2.5\,\sigma$ are read out
- Offline T42 algorithm is applied:
  - All cells with $E > 4\sigma$ are kept
  - all cells with $2\sigma < E < 4\sigma$ and a neighbor with $E > 4\,\sigma$
  - Reduction of number of cells kept: 40%

What neighbours means

global_Ebef

global_Ebef	
Entries	7449272
Mean	1.886
RMS	2.701
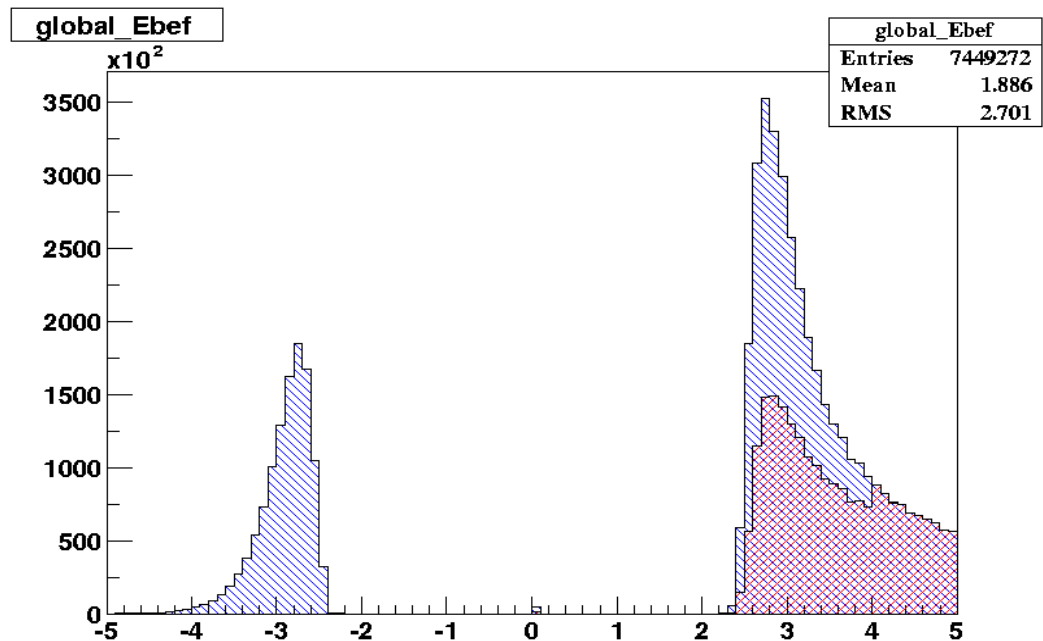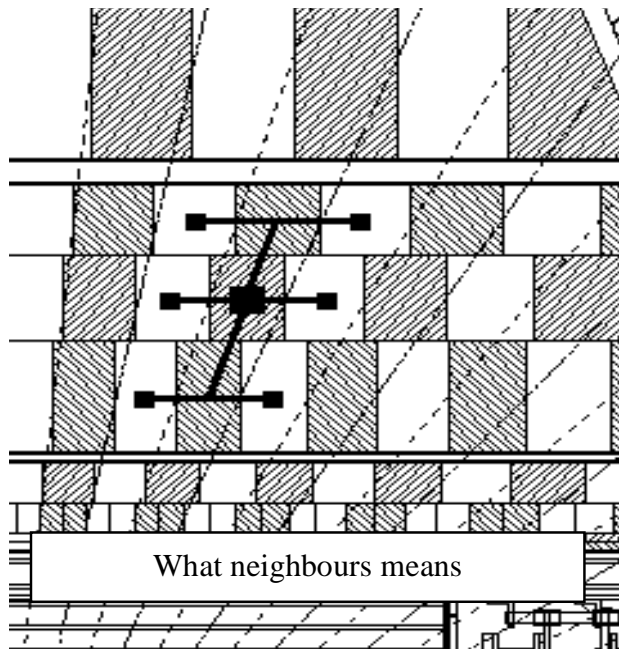
Effect of T42 noise suppression

no t42

with t42
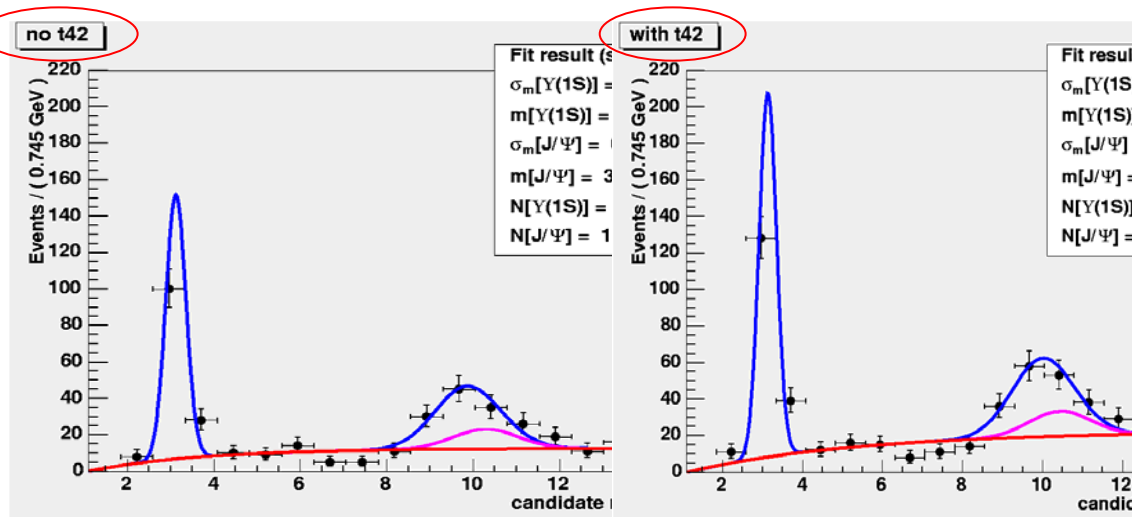
Effect on low energy electrons:

- **better reconstruction efficiency,**

- **better energy resolution,**

- **slightly higher backgrounds which need cuts to be re-optimized**

without T42

with T42
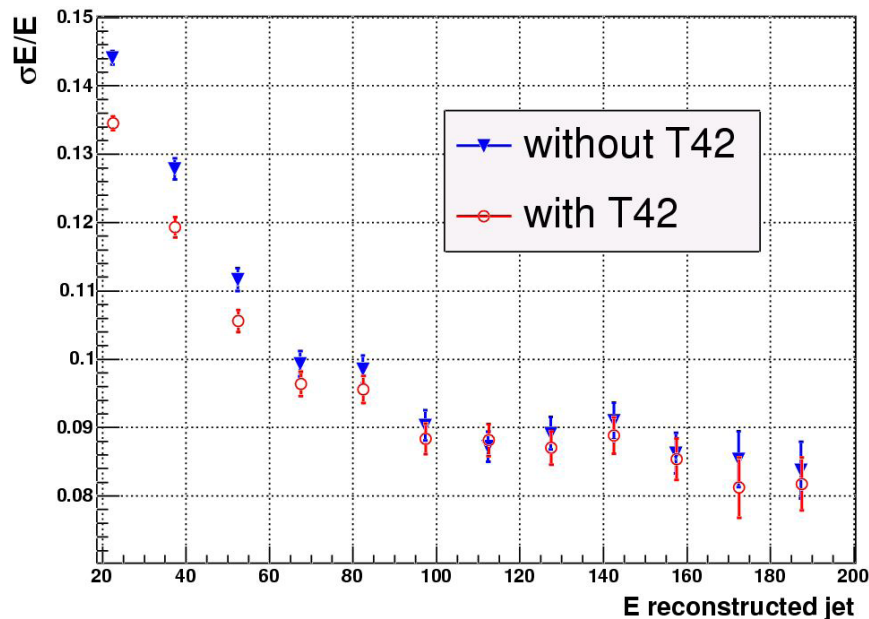
Effects on jet resolution:

Improvement at low energy without degrading jet resolution at high energy!

Typical LHC front-end

- 40MHz sampling rate
- Triggered at few kHz - 1MHz rate
- Constant latency buffer of a few µs (few hundred samples at 40MHz)
- On-detector:
  - Analog front-end
  - Extraction of data for trigger
  - Latency buffer
  - Readout via optical links (many)
  - Timing and trigger control
  - Controls and monitor interface
  - Difficulties: radiation, space, cooling access, magnetic fields
- Off-detector:
  - Trigger systems
  - DAQ interface
  - Global readout and trigger control
- Digitization: **on-detector** or off-detector
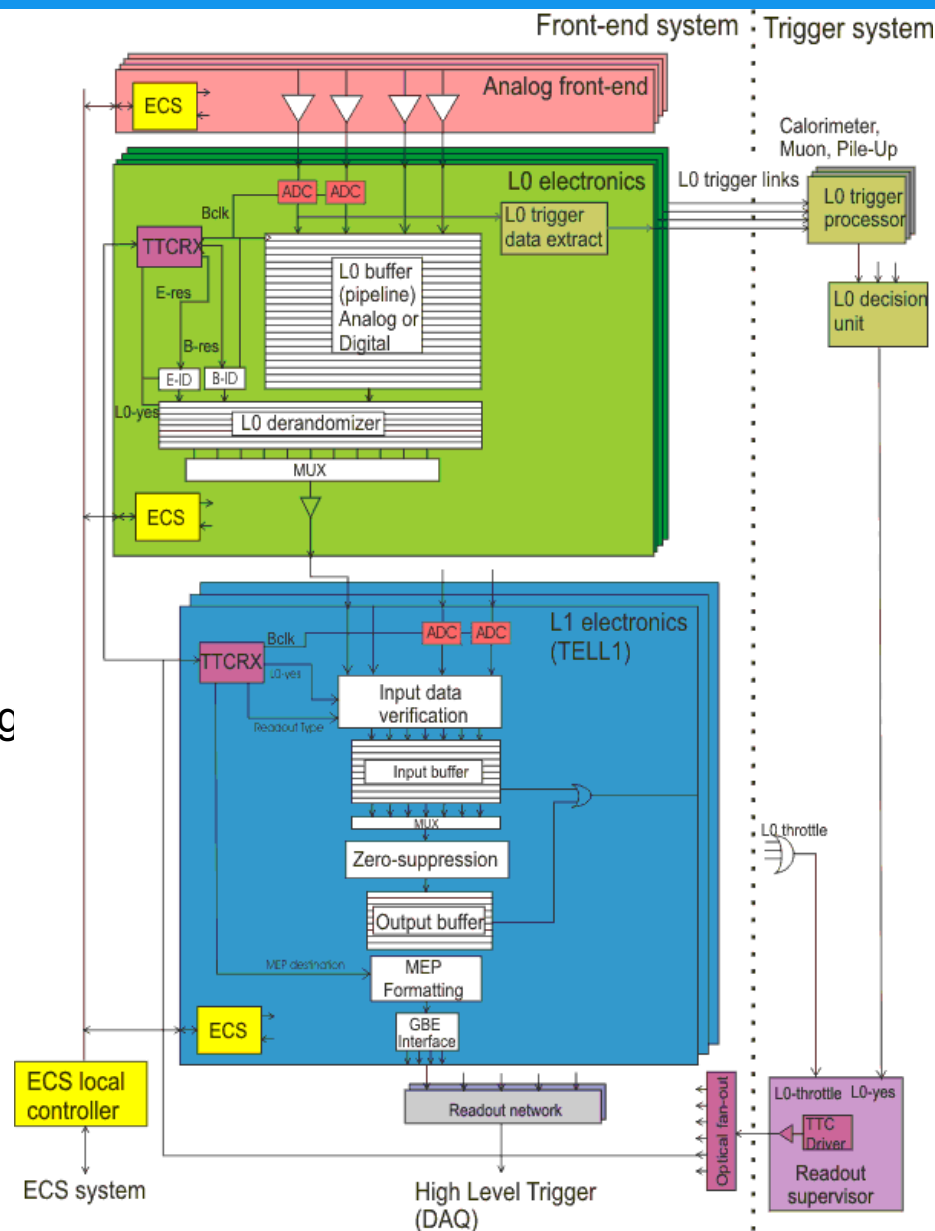
CMS: detector electronics

Energy → Light | Light → Current | Current → Voltage | Voltage → Bits | Bits → Light | Clock & Control

x12 · x6 · x1 · MGPA · 2 · 1 · Logic · 0 · 12 bit ADC · FE · Trigger data · SRP · DAQ data

PbWO$_4$ Crystal | APD VPT | Multi-Gain (x 1, x 6, x 12) Pre Amplifier | multi-channel 12-bit ADC 40 MHz | Data pipeline Trigger primitives
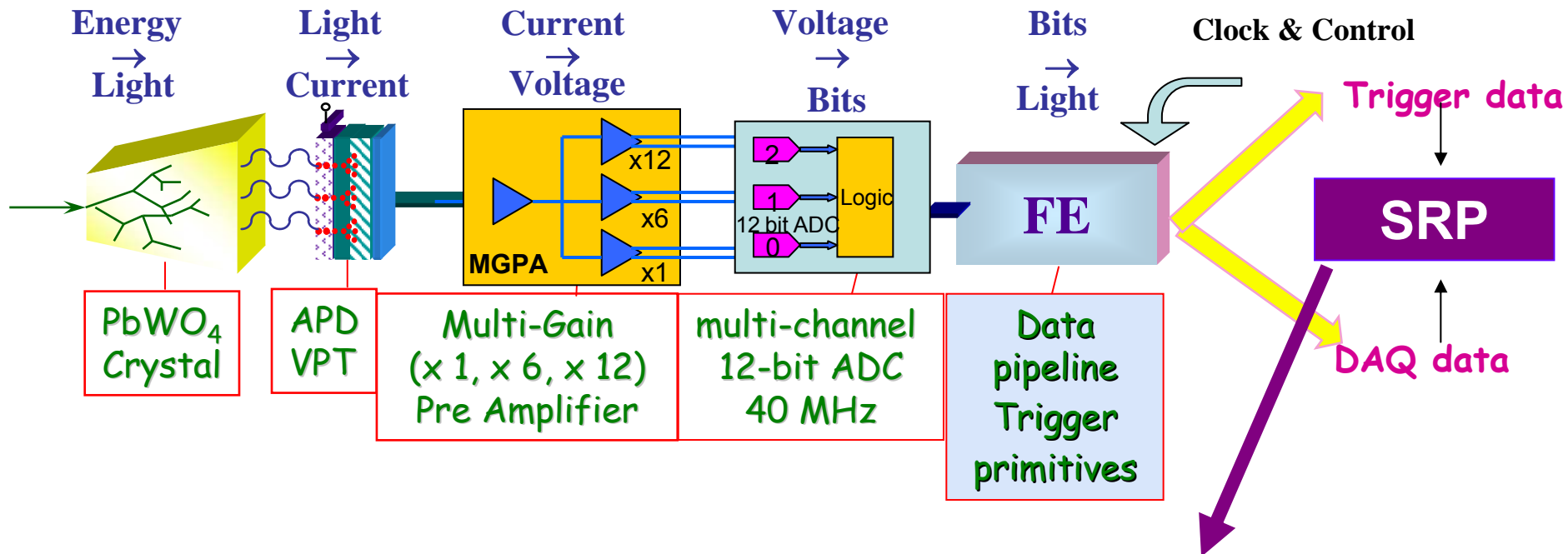
SRP: Selective Read Out Processor

- allows for "event topology dependent online noise suppression": from the trigger information calorimeter regions with interesting signal are determined and the only one read-out

- data flow reduction: x15-20

Detector cell

SHAPER · SCA · MUX · ADC 12b 15M AD9042 · Gain Selector · MUX · Glink · SCA controller · Config. Control · TTCRx · SPAC Slave · Layer Sum

Front End Board

A_{max}

Triangular ionization signal in LAr cell

FEB output after shaping

Sampling time Δt: 25 ns
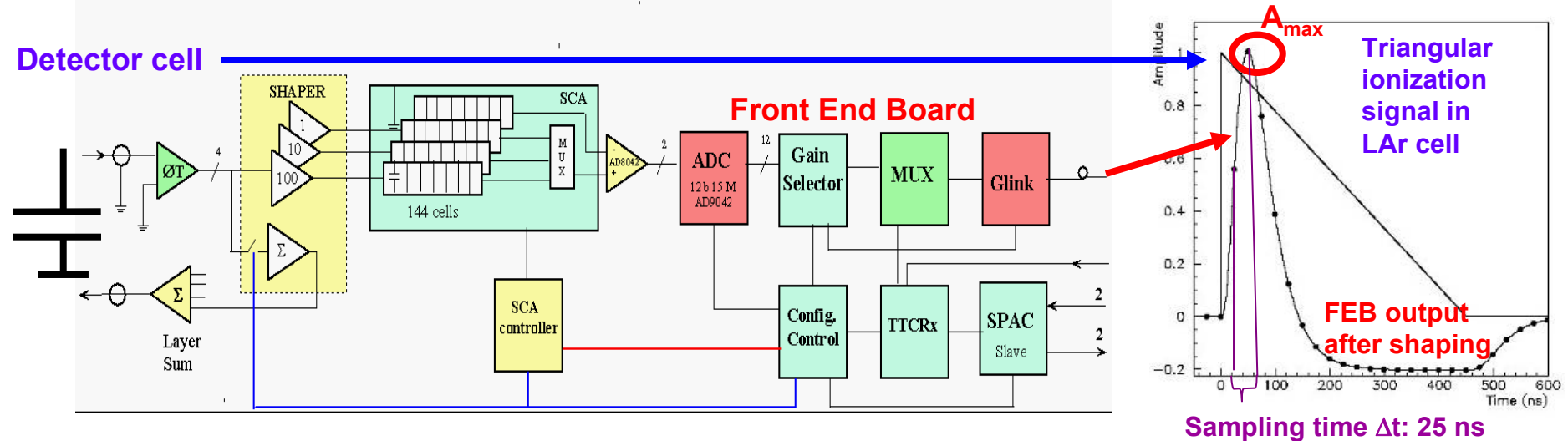
Optimal Filtering: determination of maximum signal amplitude A_{max} and temporal position Δt

$$A_{max} = \sum_{i=1}^{n} a_i S_i \qquad \Delta t = \frac{\sum_{i=1}^{n} b_i S_i}{A_{max}}$$

Coefficients a_i and b_i are calculated from the signal shape of each cell in order to minimize noise and pileup

➔ Dynamic pedestals subtraction and pile-up suppression

Online Calibration

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Calibration
  - Signal Treatment
  - Online Calibration
    - Electronics response
    - Monitoring
  - Commissioning
- Calibration & Reconstruction
  - Cell level calibration
  - Electrons/photons
  - Jets
  - Missing ET
  - E-flow

Online Calibrations

"**I**nject a know signal and measure the response"

(**I** suppose) from liquid Argon Calorimeter "slang":

• "Cold calibrations": inject signal at the calorimeter cell

• "Warm calibrations": inject signal at the preamplifier level

• Light Yield monitoring: injects light signal

Allows to measure:

> • channel to channel variations
>
> • variations in time
>
> • linearity of the electronics response
>
> • also heavily used during commissioning

D0 Electronics calibration
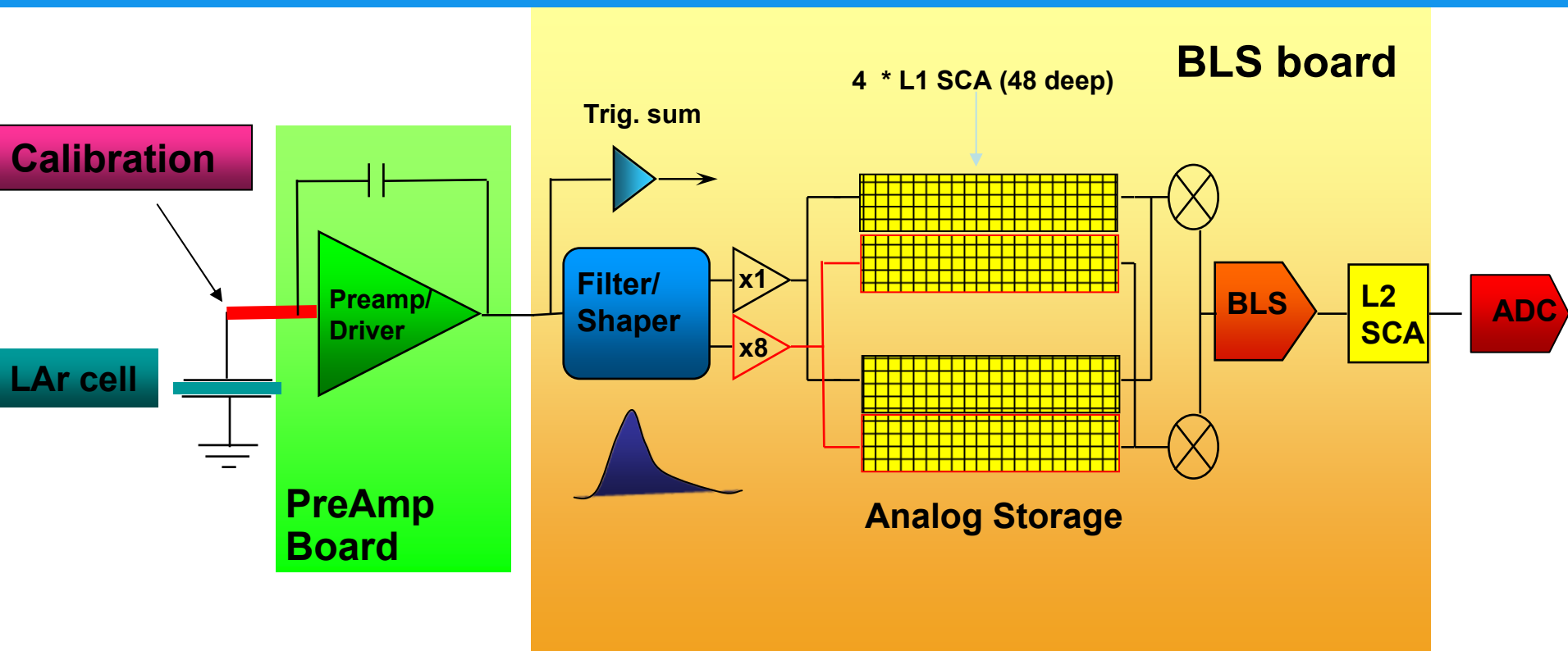
- Calibration system allow to inject signals covering the entire dynamic range of the calorimeter read-out electronics

- Calibrations are done separately for gain 1 and gain 8 read-out

- Operations point of view: done ~monthly and whenever a hardware component is changed

Signal shapes: calibration vs physics

Em channel

pulser Preamp

data Preamp

Pulser shaper

data shaper

effect of signal reflection
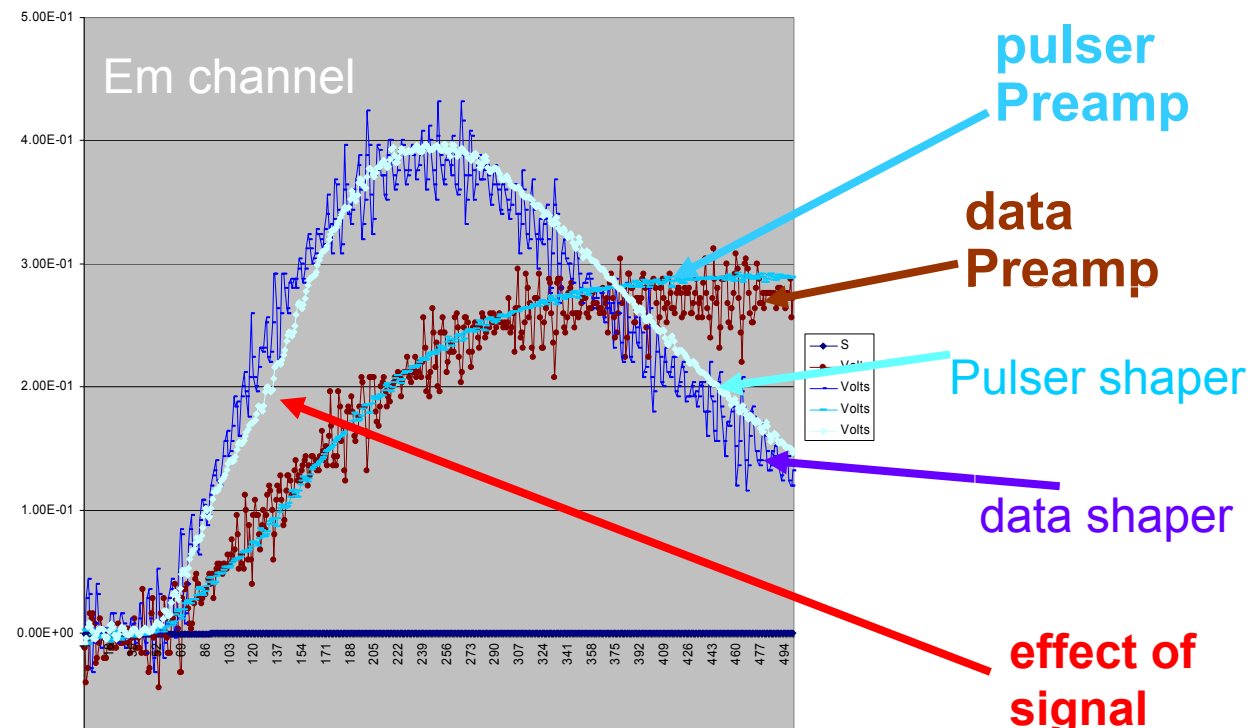
Calibration signal should be close to physics signal

Calibration signal has to vary in the same way to variations in the electronics chain as physics signal

➜ Difficulty of "warm" calibrations: signal reflection towards the calorimeter cell

➜ effect much stronger on hadronic cells which have a large capacitance

Atlas has a similar system, but the charge is injected much closer to the electrode: less effects of reflexion

em channels:

hadronic channels :
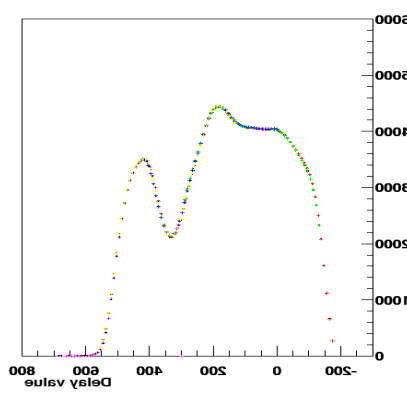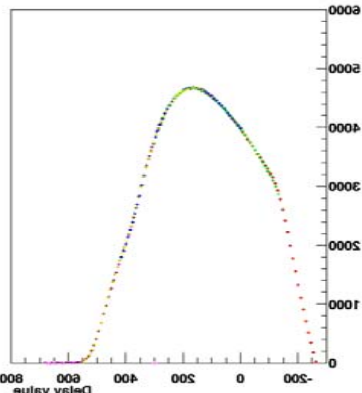
Linearity measurements

ADC

D0

saturation

gain 1

gain 8

DAC/1000

Residuals

ADC

±10

DAC/1000

● **gain ×1**

● **gain ×8**
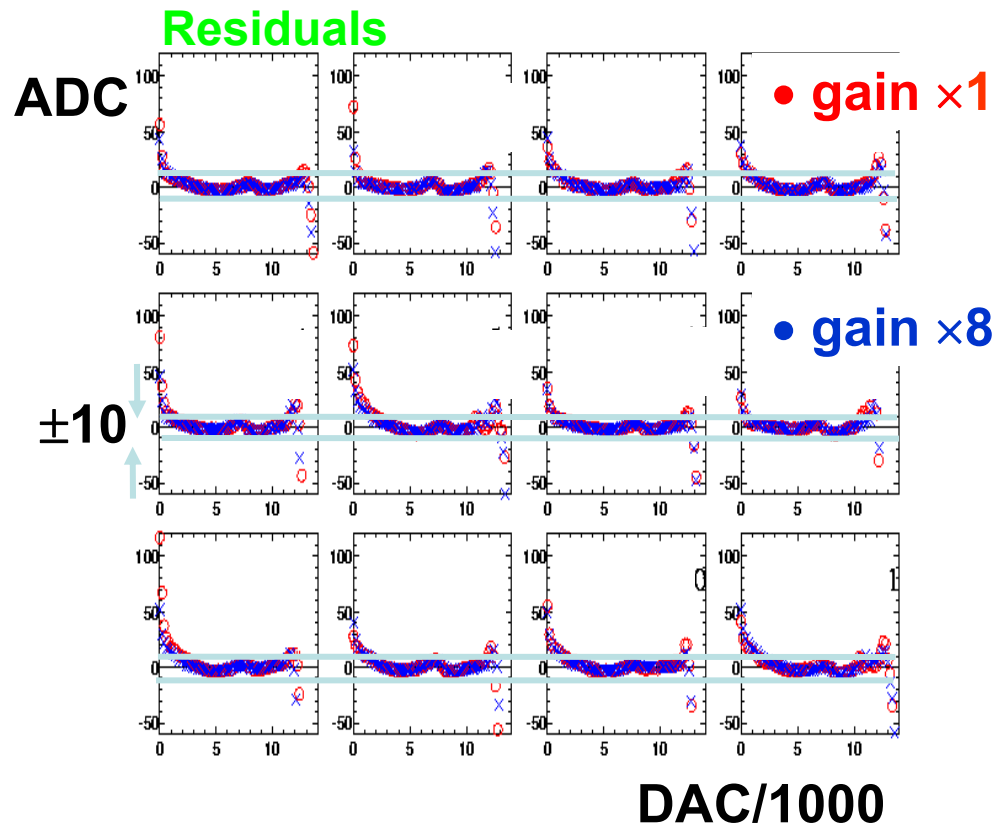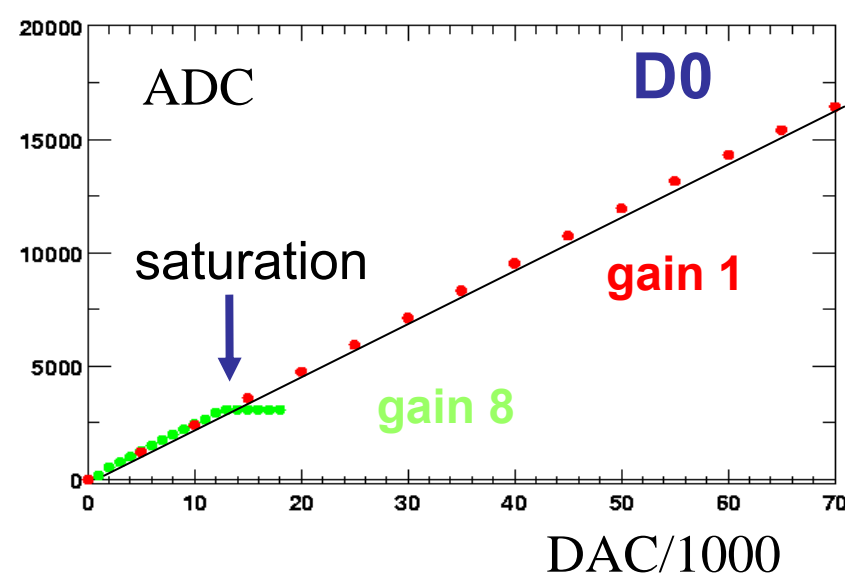
- **residuals from a linear fit**
- **non linearity similar for all channels: cause traced to saturation effects in SCA**

➔ **ADC to energy conversion corrected with a universal function**

Commissioning with calibration

Status of the D0 calorimeter channels in March 2001:
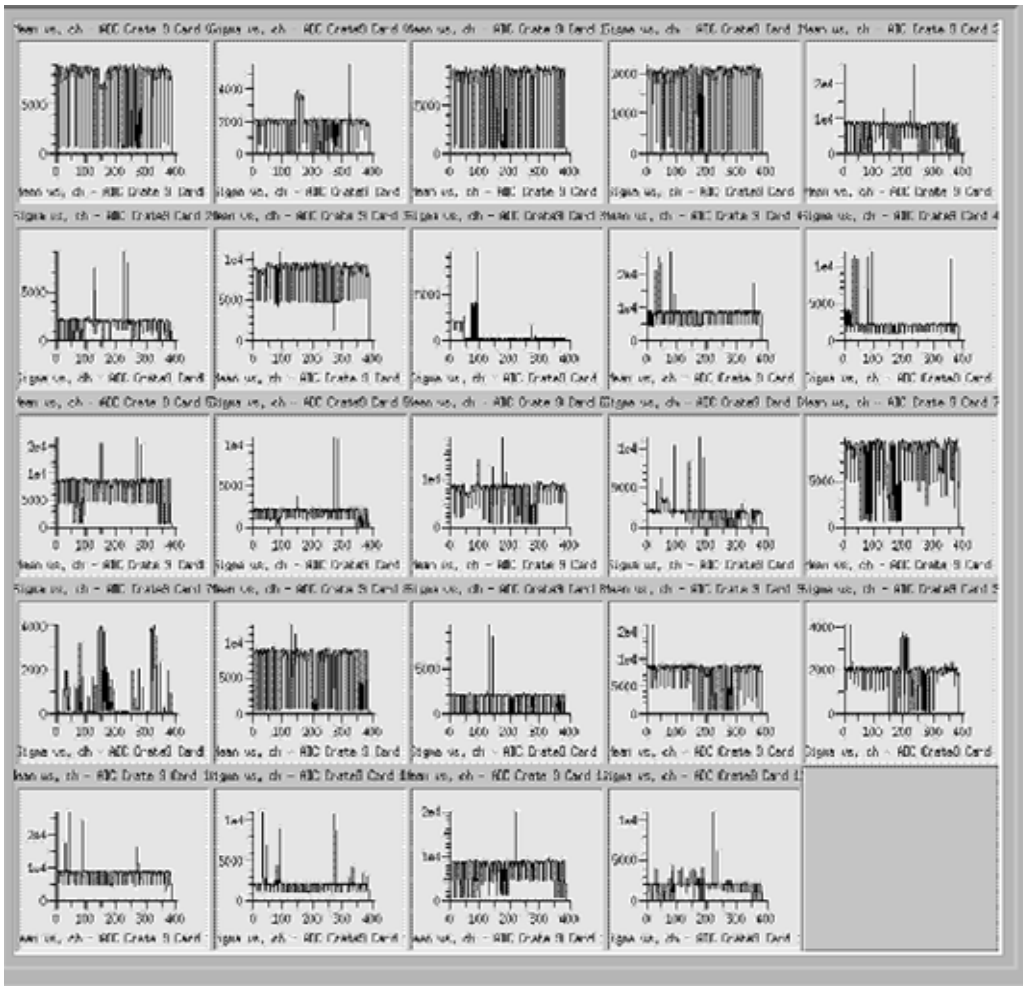
Online calibration systems are heavily used during the commissioning phases

- Test functionalities of the whole read-out chain

- From pattern of malfunctioning channels often the failing electronics component can be determined and mostely repaired!

CMS: ECAL monitoring system

Expected γ dose-rate on crystals at LHC high luminosity:
0.2-0.3 Gy/h (EB) $\rightarrow$ 15 Gy/h (EE)

During LHC cycles,
a continuous variation
of signal is expected

Simulation of signal evolution
η=0.9 - Low Lumi
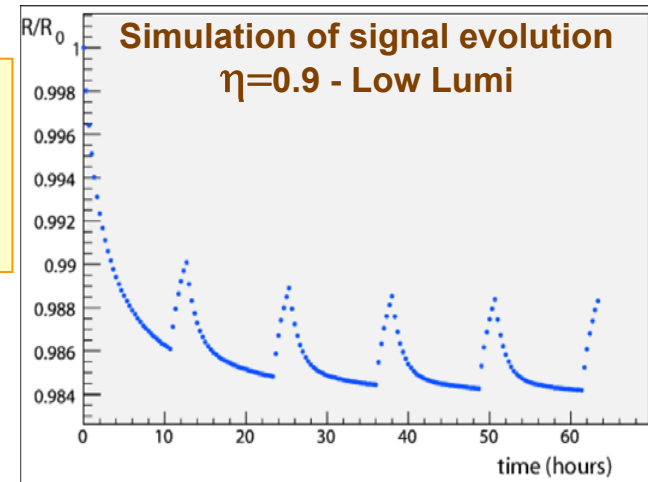
To follow and correct this effect,
a fiber-distributed Laser system
monitors the light response of each crystal

Laser fluctuations measured by PIN diodes. Stability 0.1%.

PWO

PIN   FE

F1   F2   S   Laser   440 nm
796 nm

χ^2 / ndf	73.85 / 68
Prob	0.2928
p0	5560 $\pm$ 0.626

test beam data

laser
correction
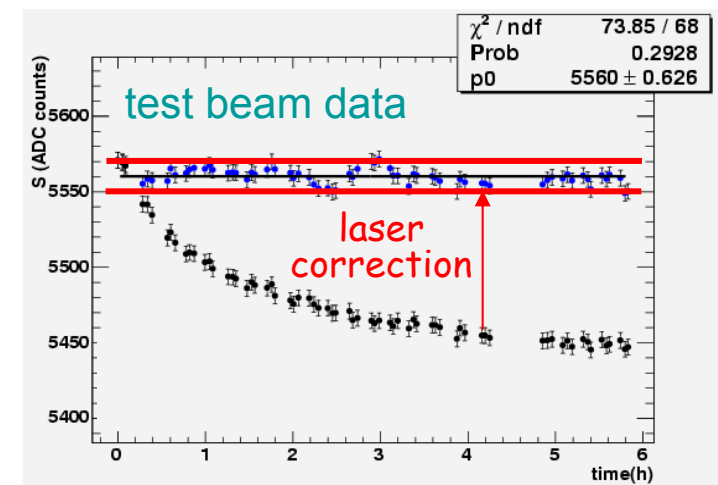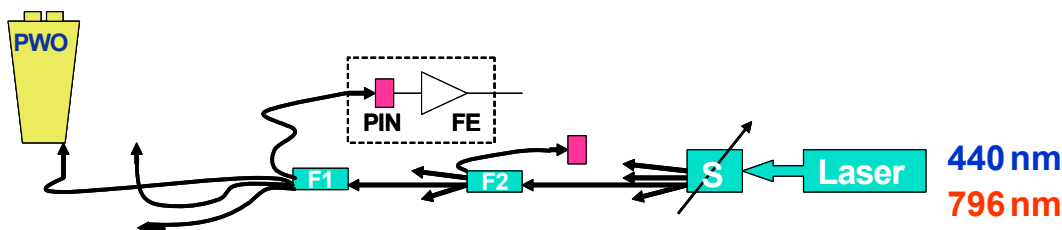
LHCb LED monitoring
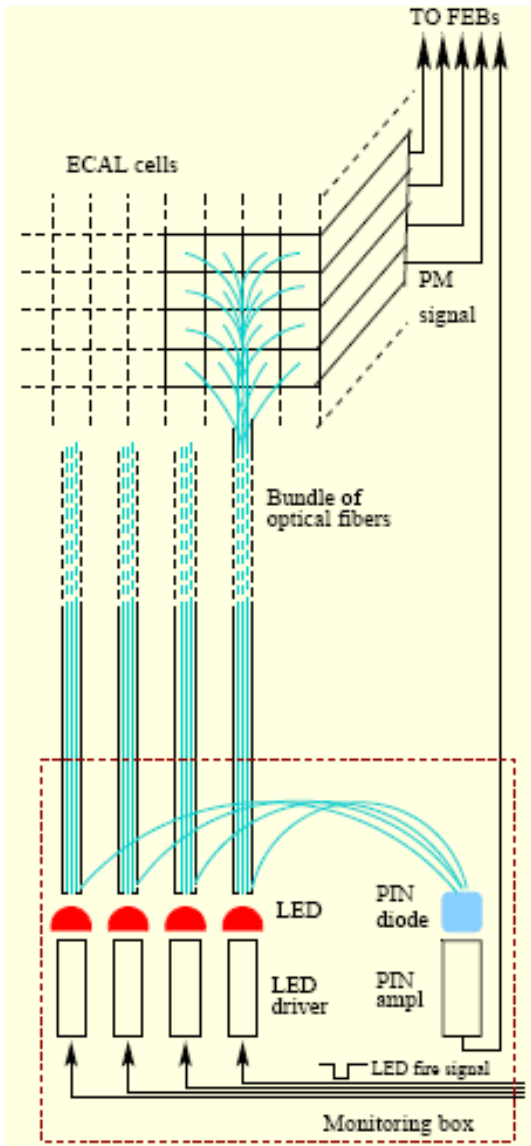
LED signals are injected into a group fo cells during "empty bunches" via optical fibers

LED intensity is controllable spanning a good part of the ADC dynamic range

Stability of LEDs is traced by PIN photodiods
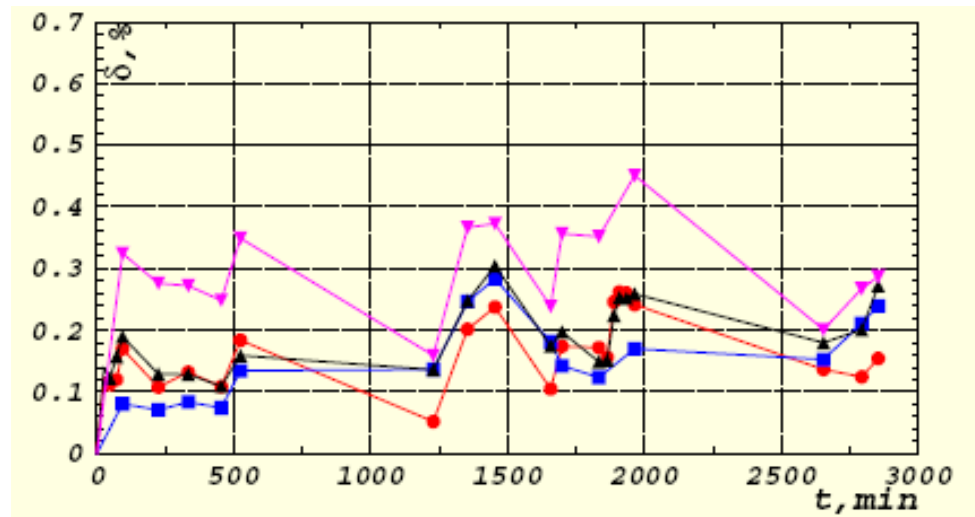
4 LEDs: stability measure over 2 days

LHCb(Atlas) ^{137}Cs Calibration

Six stainless steel pipes pass through the centers of each tile row (27 m per module)

All modules of each half calorimeter are connected.
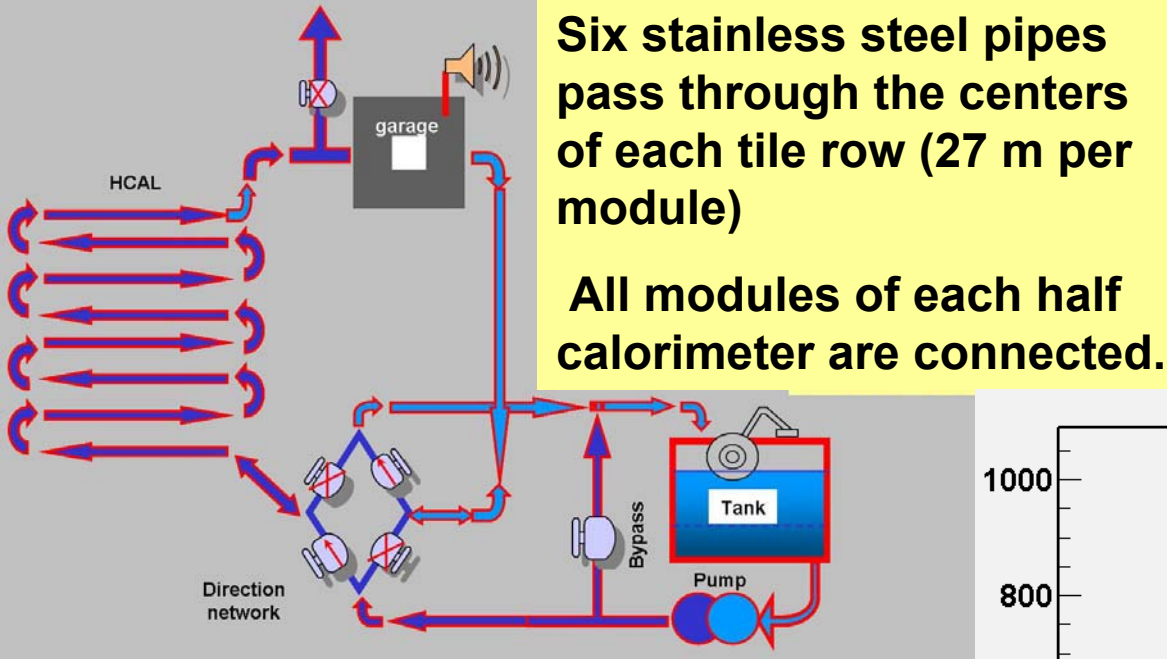
Similar system for Atlas Tilecal
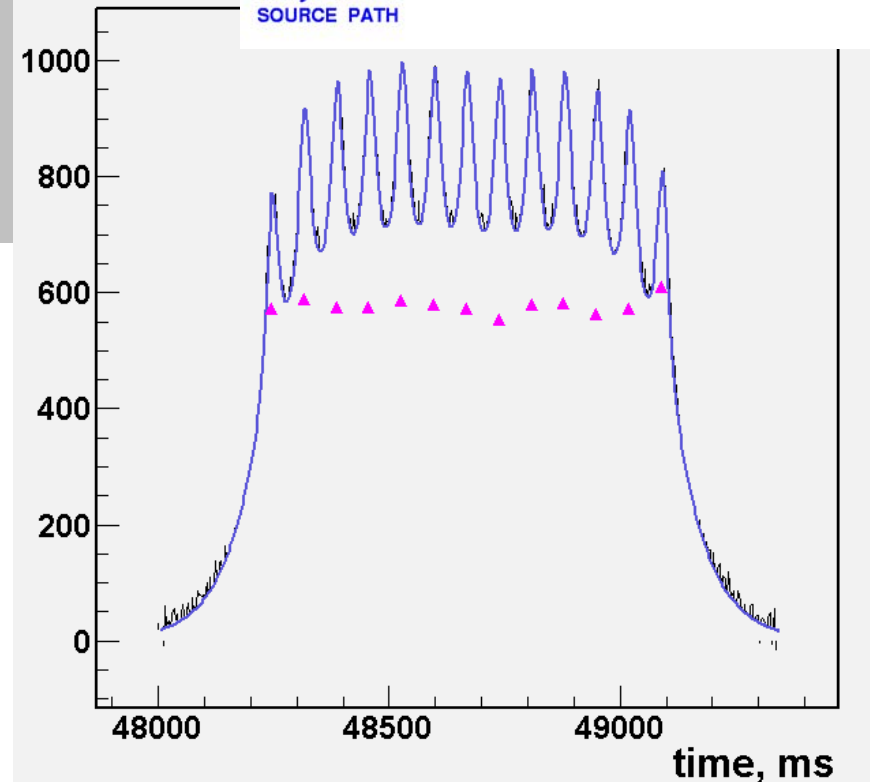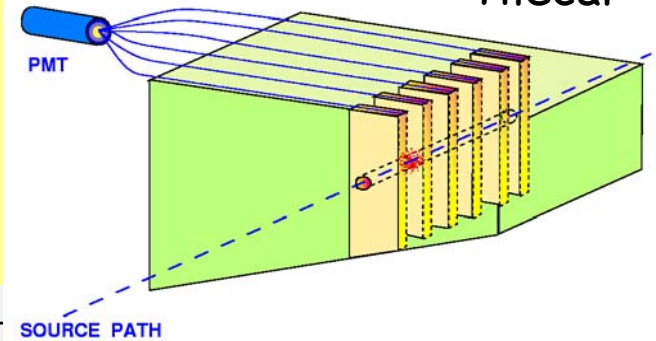
The ^{137}Cs source moves at constant speed 20-30cm/s

➔ dependence of current with time *I(t)* can be fitted with a weighted sum of (empirical) tile response functions placed at equal time intervals Δt

Commissioning

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
  - Signal treatment
  - Online Calibration
  - Commissioning
    - Test beam
    - Cosmic muons
- Calibration & Reconstruction
  - Cell level calibration
  - Electrons/photons
  - Jets
  - Missing ET
  - E-flow

Testbeam

Shoot with beams of different particles at different energies into calorimeter modules or combined modules from different subdetectors to measure various properties: energy response, linearity, uniformity

Setup for 2006 CMS testbeam:
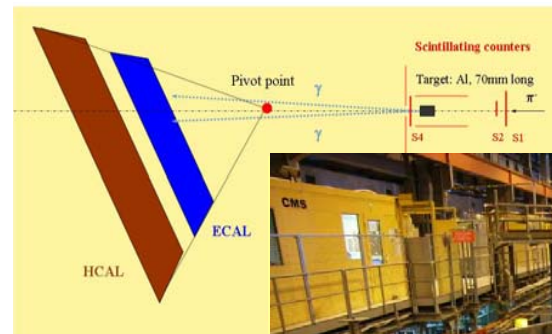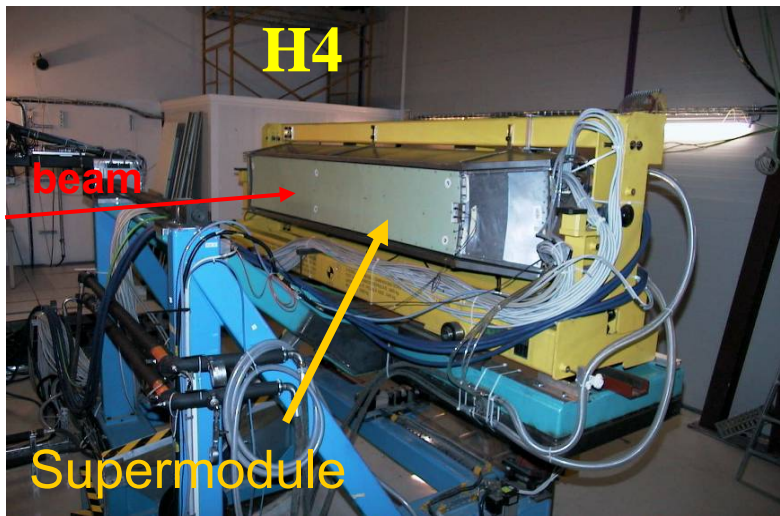
H4: 10 SM with different electron energies (15-250 GeV)

H2: combined ECAL/HCAL with positrons (1-100 GeV) and pions

- **detailed studies E, η behaviour**
- **combined test with HCAL: reconstruction and identification of electrons/pions**

Combined Testbeam

Atlas combined 2005 testbeam setup:
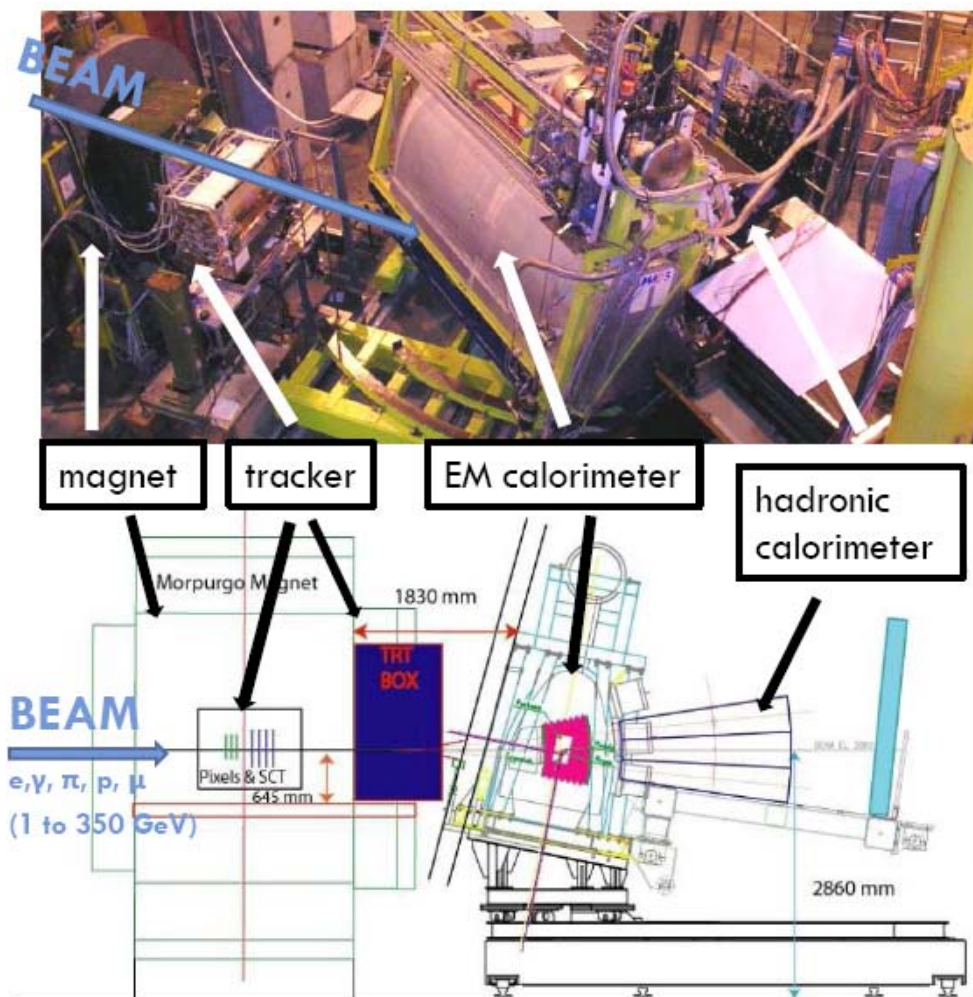
Setup contains a full slice of the barrel detector

➔**Test of detector performances as close as possible to real detector with as much "final" parts as possible**

➔**Validate Simulation**

➔**Test reconstruction and object-id algorithms**

CMS: measurements at various electron energies, reconstruction with 3x3 matrix
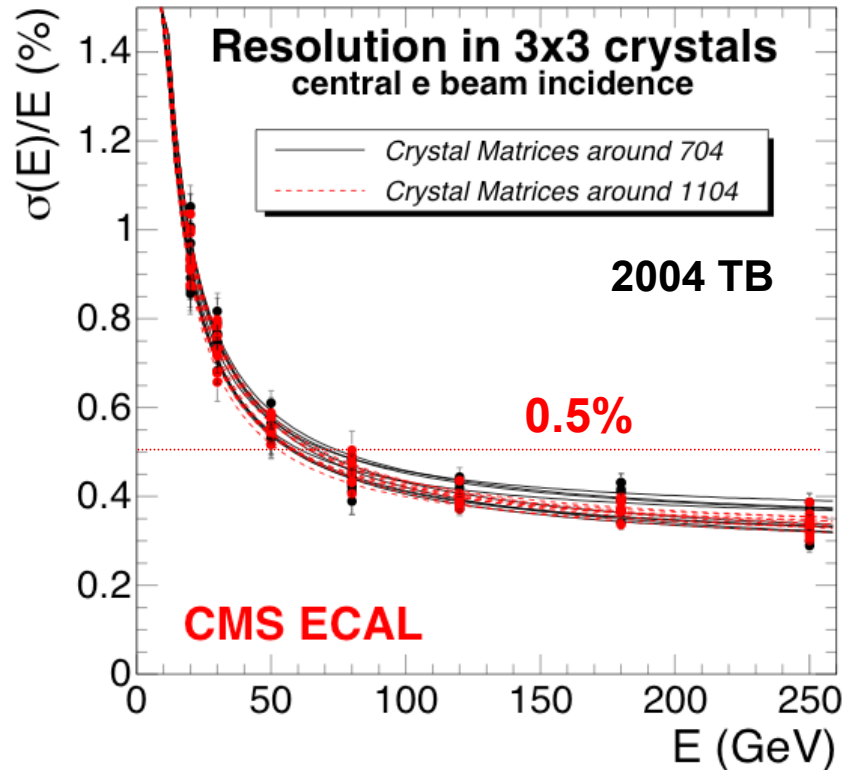
Linearity of the response:
Differential linerarity < 0.2% (20-180GeV)
<0.5% (2-9 GeV)
Electronics linearity <0.1%
Gain switch at 150 GeV

$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{125}{E(\text{MeV})} \oplus 0.3\%$$
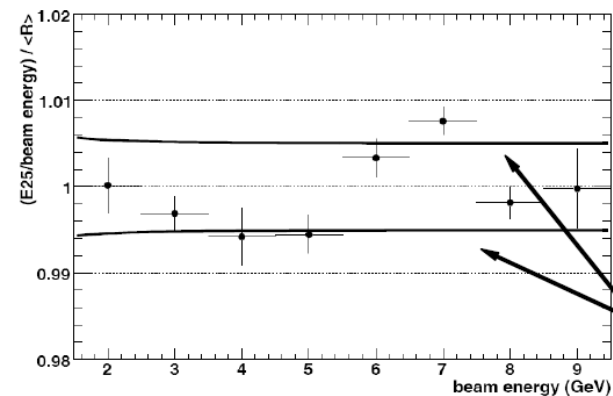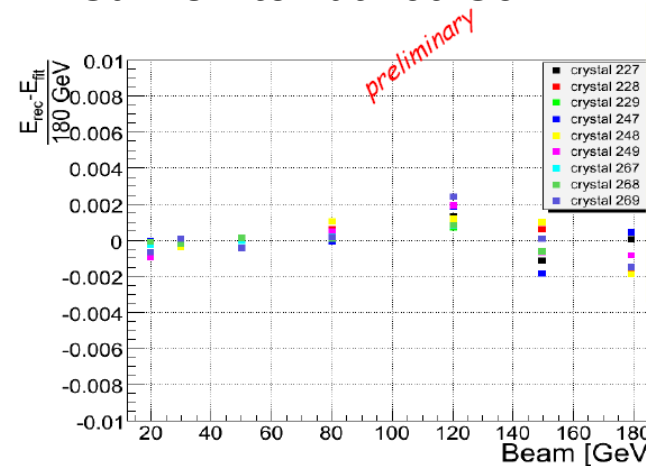
Beam energy uncertainty

position ( )

Test beam: uniformity

Impact point correction based on energy deposits in the crystal cluster position : should be usable for photons!
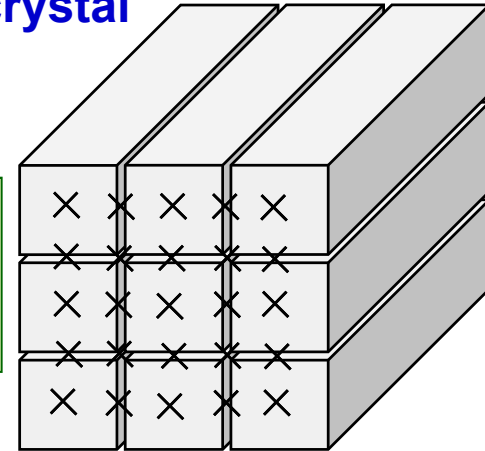
Correct by a function of log ratios of energies in 3x3 matrix
- **universal in η (and ϕ)**
- **energy independent**
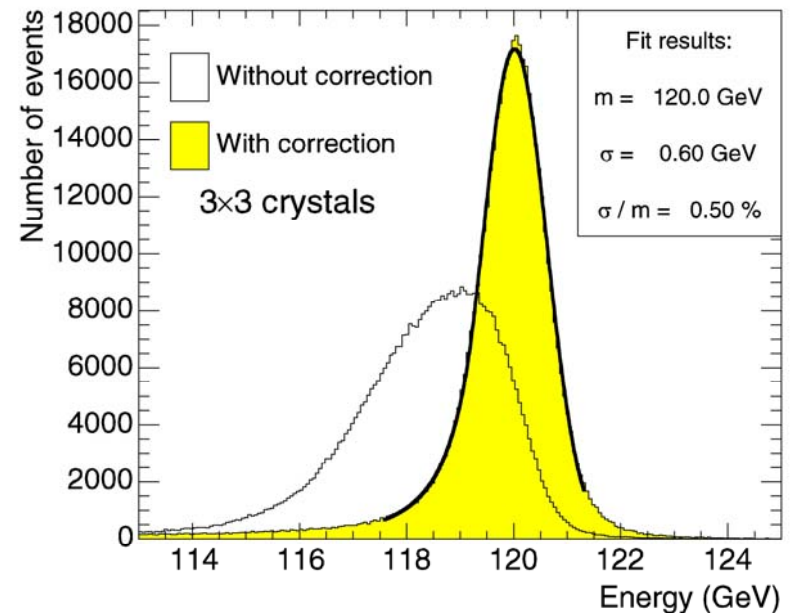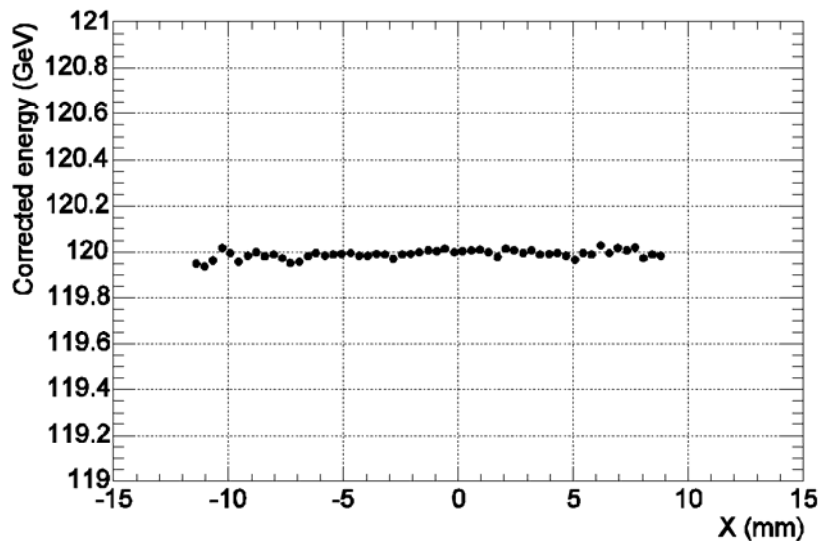
Atlas em calorimeter+preshower:
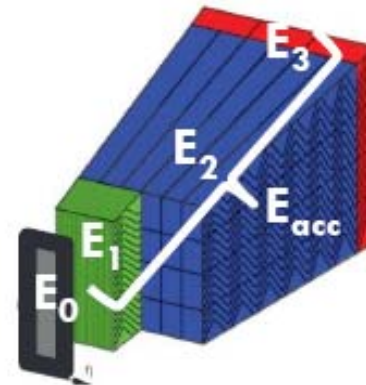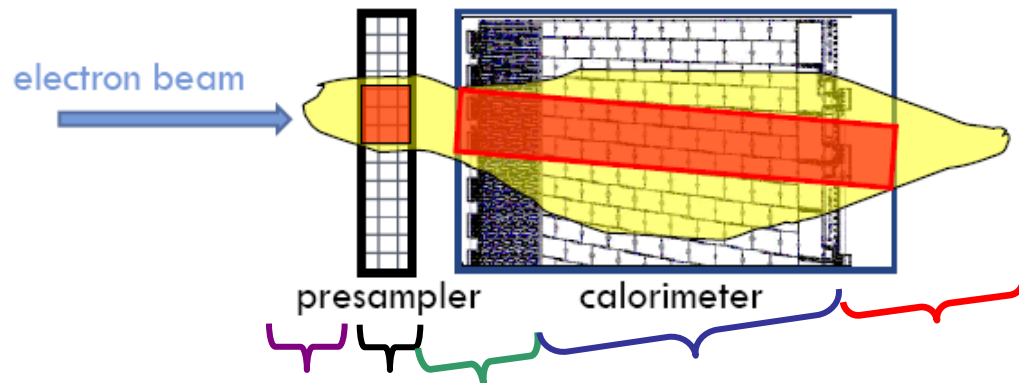
$$E_{electron} = \textbf{offset} + \textbf{W}_0\textbf{E}_0 + \textbf{W}_{01}\sqrt{\textbf{E}_0\textbf{E}_1} + \lambda\textbf{E}_{acc} + \textbf{W}_3\textbf{E}_3$$

Offset: energy lost in front of the calorimeter

W_0: energy deposited in preshower

W_{01}: correction for energy between pressampler and calorimeter

Λ: energy deposited in calorimeter

W_3: correction for energy leakage

Study effects of dead material:

Introduce 25, 50 and 75mm of Al in front of the calorimater
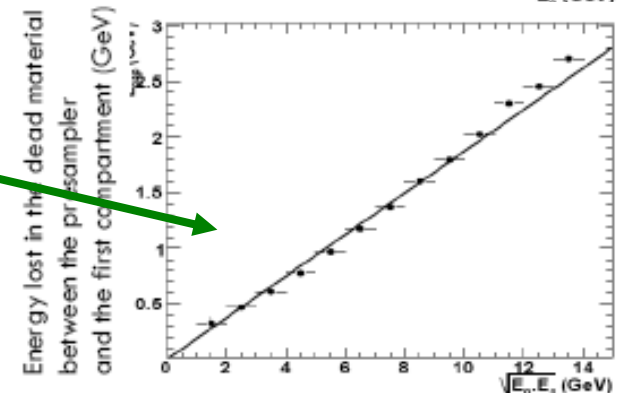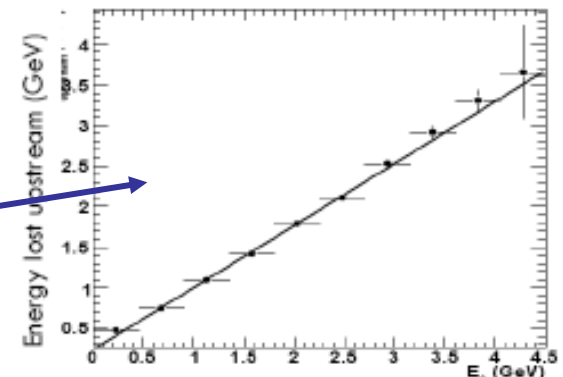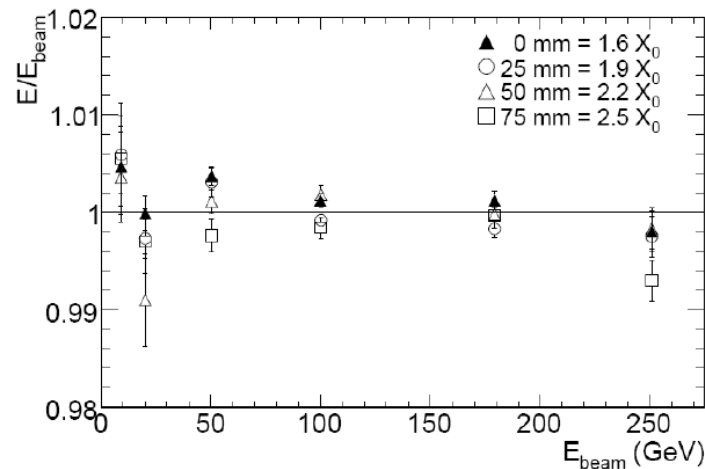
linearity:
0.5% effect observed
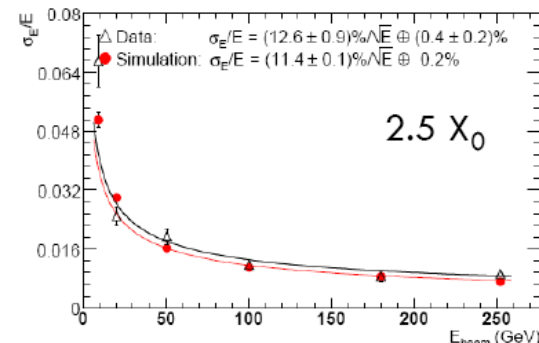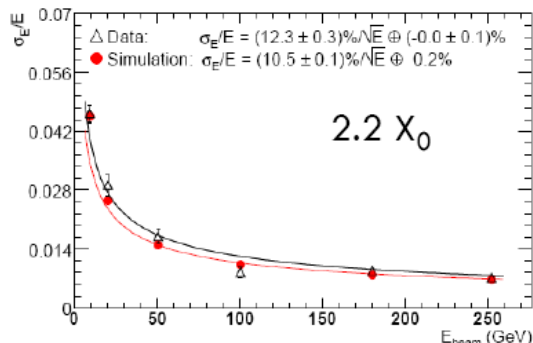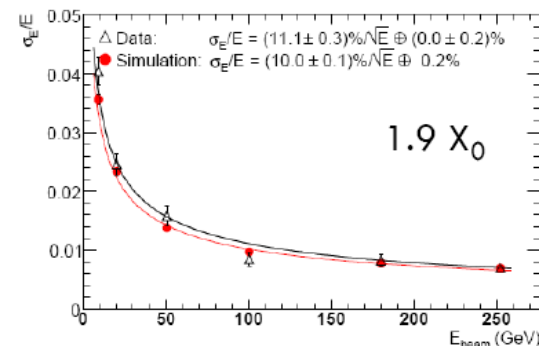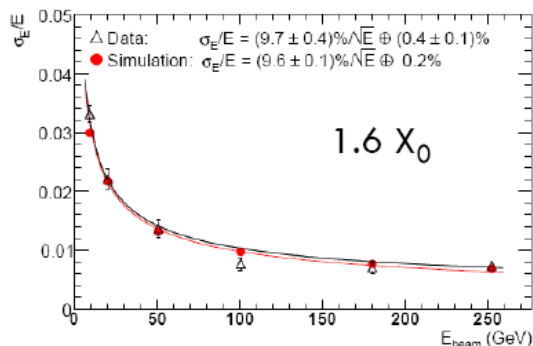
energy resolution:
degradation of
0.5%/√E per 30% X_0

Installation

It's a lot of work!

Commissioning

Verifying each an every component if it is working properly!
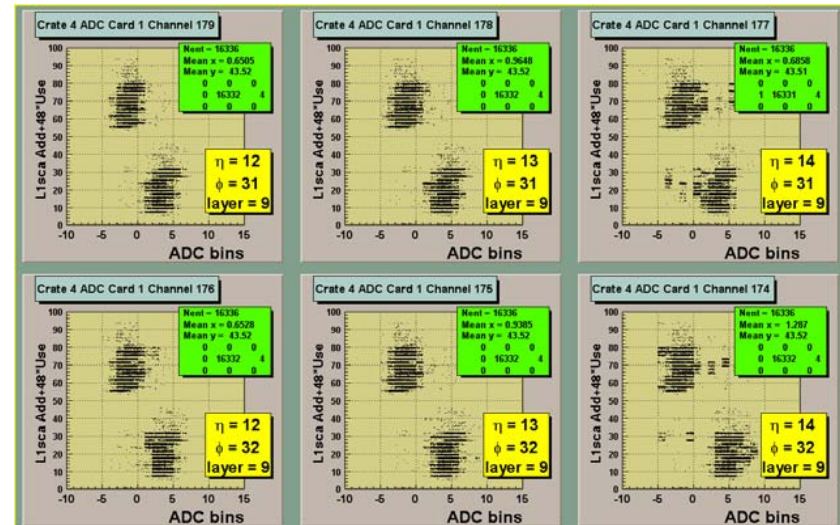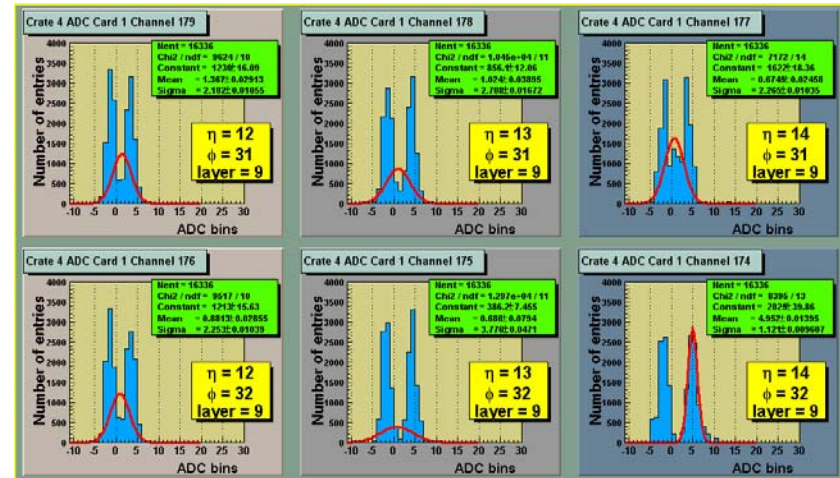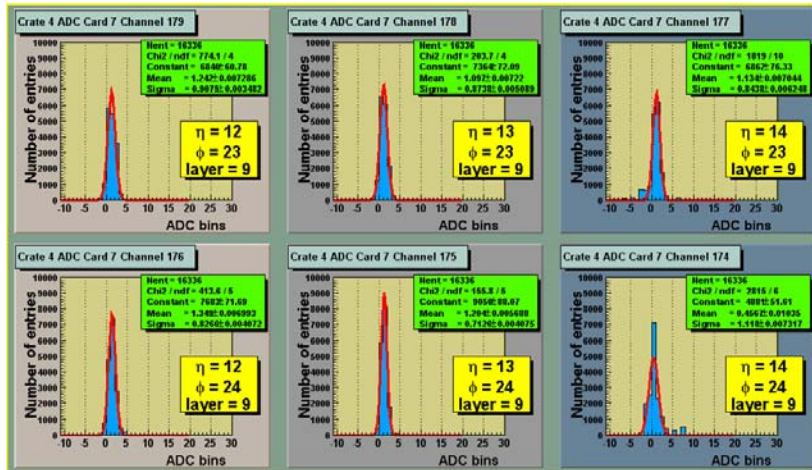
Aim:

Reducing the number of bad channels

Understanding the behavior of the apparatus:

- **Noise measurements**
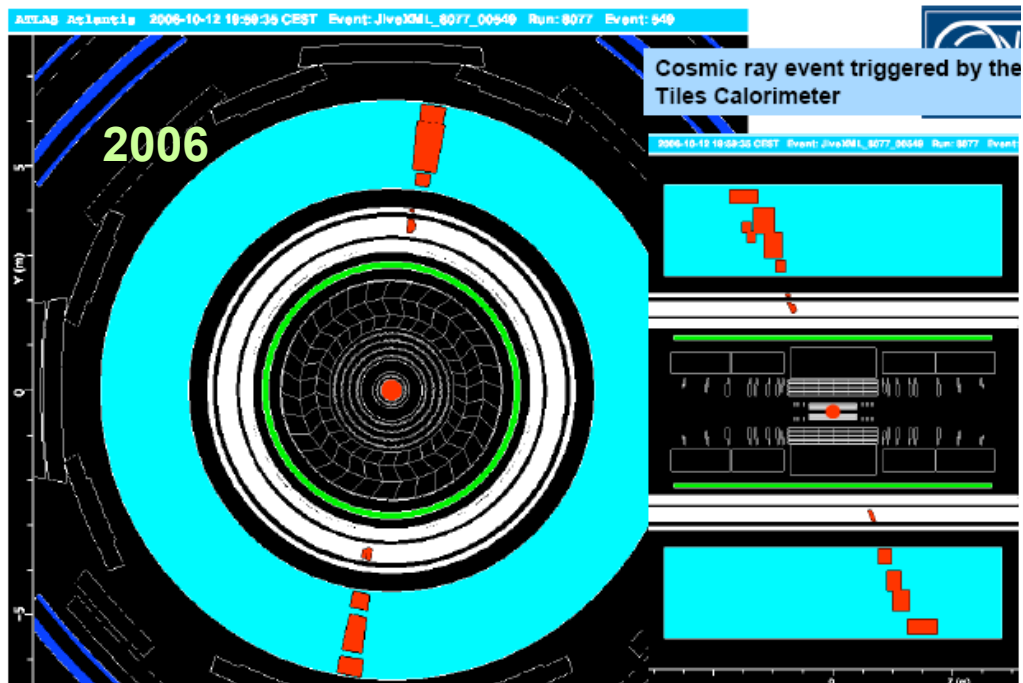- **Cosmic muons**
- **Timing measurements**
- **Cross talk studies**

Timing
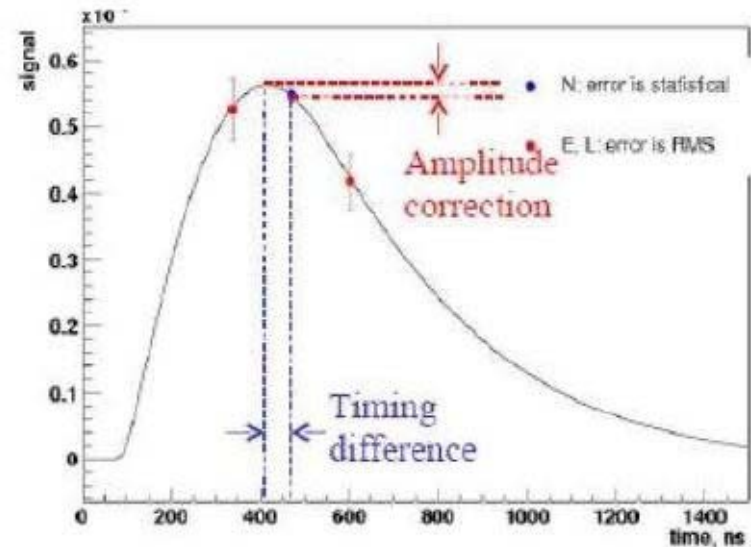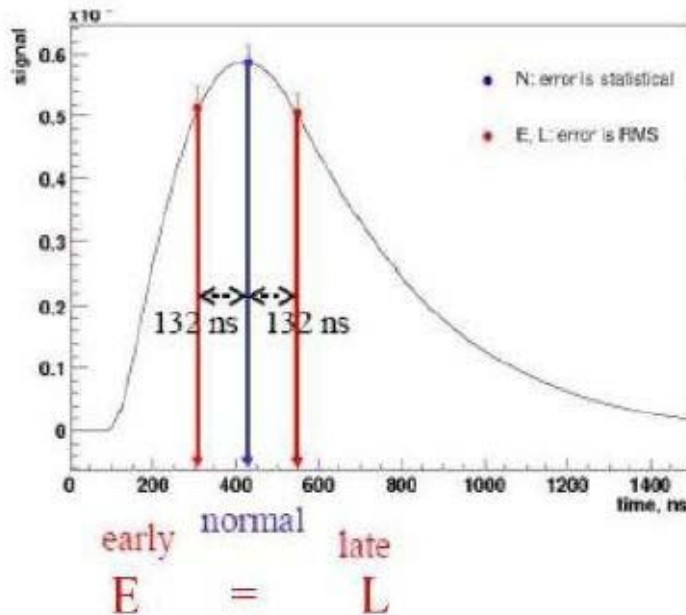
The correct cell energy depends on *timing*

– Timing can be adjusted by "jumpers" or adding "cable"

-- Verification on real data: Sample amplitude 3 times:

      before, at and after signal peak

– Performed channel by channel

● **90% of all channels see a 0.5% difference or less**

● **Performed every 6 months**

– **Overall results very stable with time**

Cosmics

The first particles seen in the "real" detector!

2006

Cosmic ray event triggered by the Tiles Calorimeter

Run 43566, Event 37324 :
Triggered by DT: Clear association w/ DT
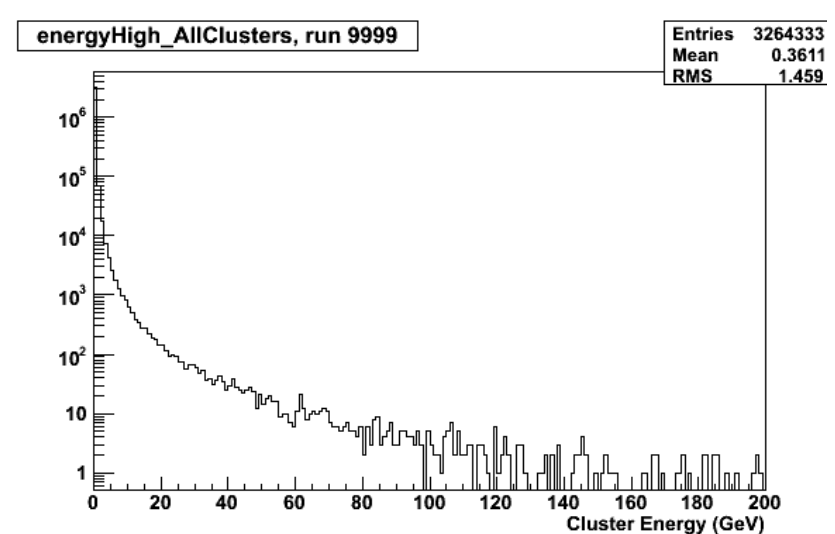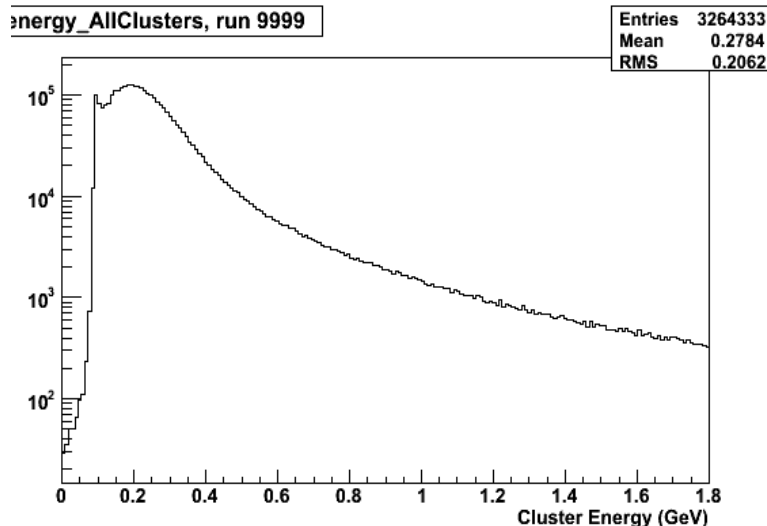High Energy Event: 288 GeV, 25 crystals
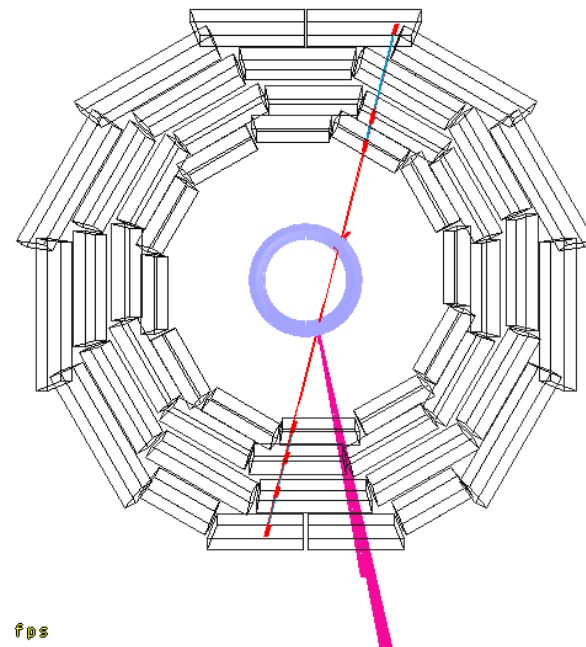
Cosmics

2 types of cosmic muons:

• **Minimum Ionizing particles**

➔ **Tests during construction and installation**

    ➔ **Very low Signal/Noise ratio, easier to spot in hadronic calorimeters**

• **High energy muons E>500 MeV (~1%)**

    ➔**Bremsstrahlung and EM shower**

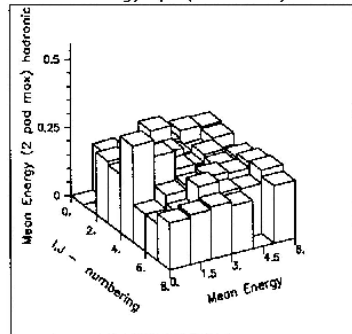**Difficulty: cosmics are generally not projective ➔ different software**
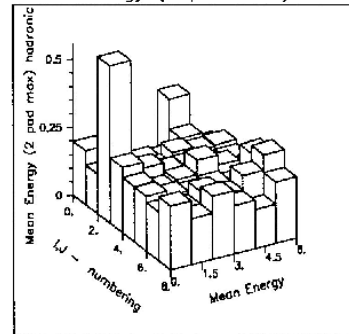
Muons as MIP particles
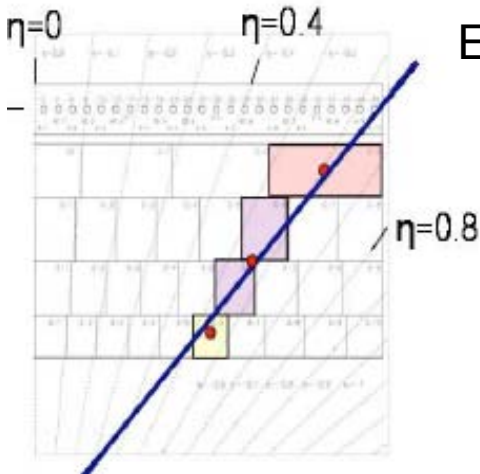
Energy deposit proportional to the path length in the active material

Verification of the response uniformity in the H1 hadronic calorimeter :
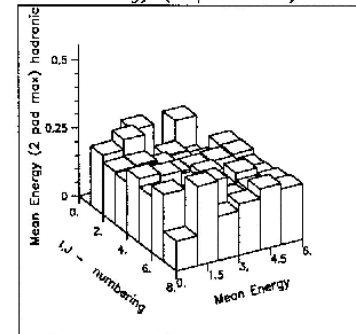

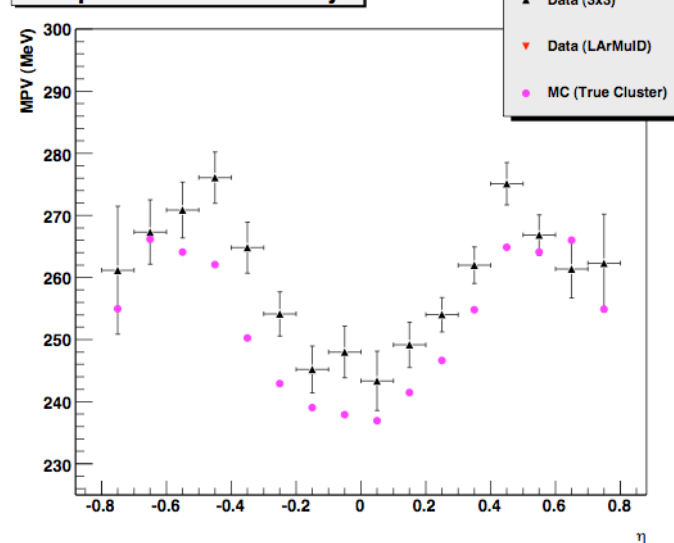**Verification of the response uniformity of muons selected to be "projective" in Atlas**

Cluster Energy (0.3 < |η| < 0.4)

3x3	
Entries	2295
χ² / ndf	35.5 / 37
Prob	0.5395
Width	11.77 ± 1.10
MPV	260.9 ± 2.3
Area	4.529e+04 ± 974
σ_G	60.78 ± 2.35
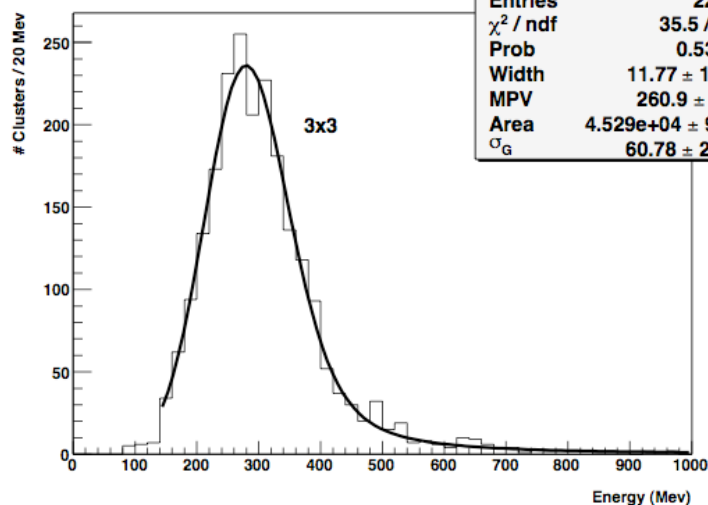
Response Non-Uniformity

- ▲ Data (3x3)
- ▼ Data (LArMuID)
- ● MC (True Cluster)

Signals & commissioning

- **Testbeams are a very important tool:**
  - Validate R&D of new detectors
  - To determine response of the detector to different particle types
  - To test and calibrate modules of the final detector

- **Online calibration allows to characterize the electonics:**
  - Noise suppresion
  - Linearity and Uniformity
  - Powerful tool for commissioning

- **Cosmic muons are often the first particles seen by the full detector!**
  - Allow to debug the interplay between different subdetecors
  - Give a first "in situ" calibration