Calorimetry
- state of the art -

Erika Garutti
DESY

Thermodynamics:
A calorimeter is a thermally isolated box containing a substance to study

Calorimetry in particle physics

Calorimetry is a widespread technique in particle physics:

- instrumented targets
  - neutrino experiments
  - proton decay / cosmics ray detectors
- shower counters
- 4π detectors for collider experiments

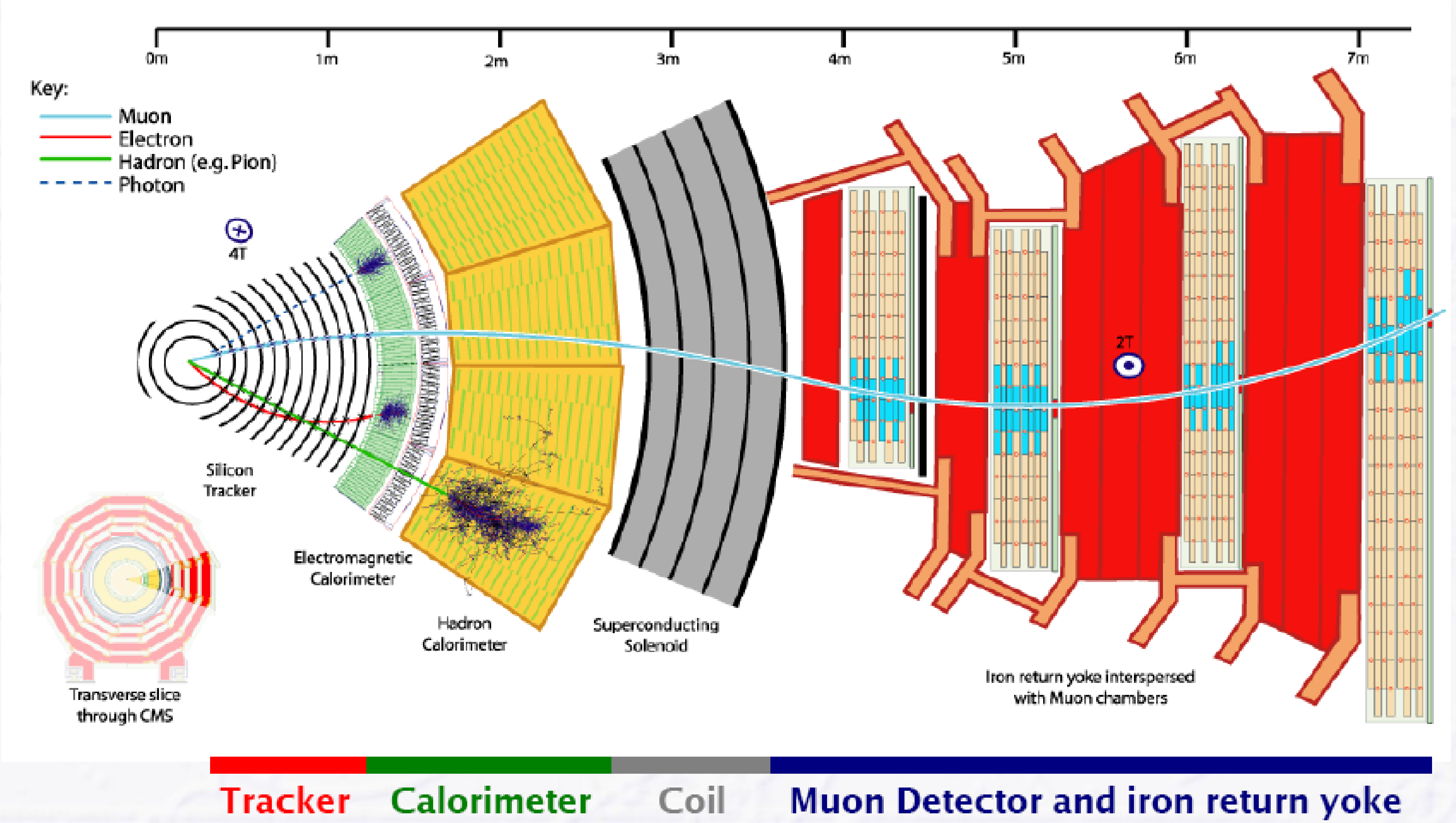
Common feature of all calorimeters is that the measurement process is destructive

• the particles are no longer available for inspection once the calorimeter is done with them.

• only exception: muons

In the absorption, almost all particle's energy is eventually converted to heat, hence the term calorimeter

Detectors for collider experiments



CMS

Typical onion like structure for most of modern collider detectors

Main difference: - what fraction of detector is inside the coil

- calorimeter system (most expensive component)

Why calorimetry?

• Measure *charged + neutral* particles

At high energy calorimetry is a must

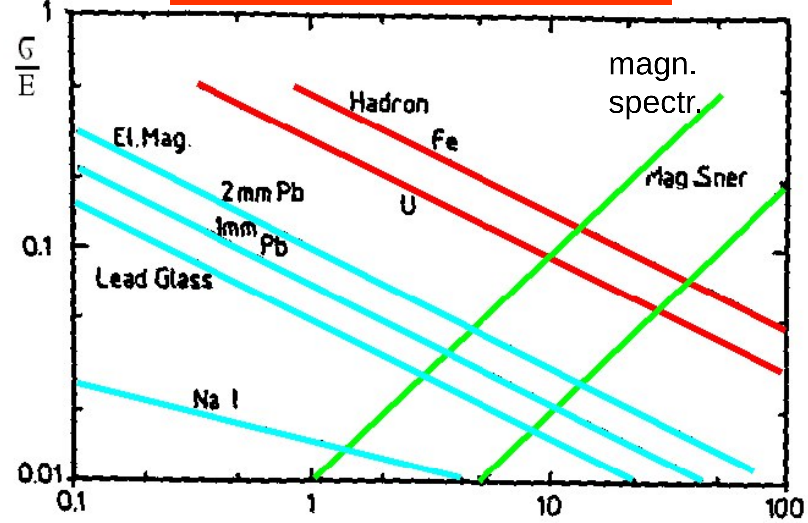
• Performance of calorimeters

improves with energy

ΔE/E ✪ $E^{-1/2}$ + const.

while in a magnetic spectrometer

Δp/p ✪ p

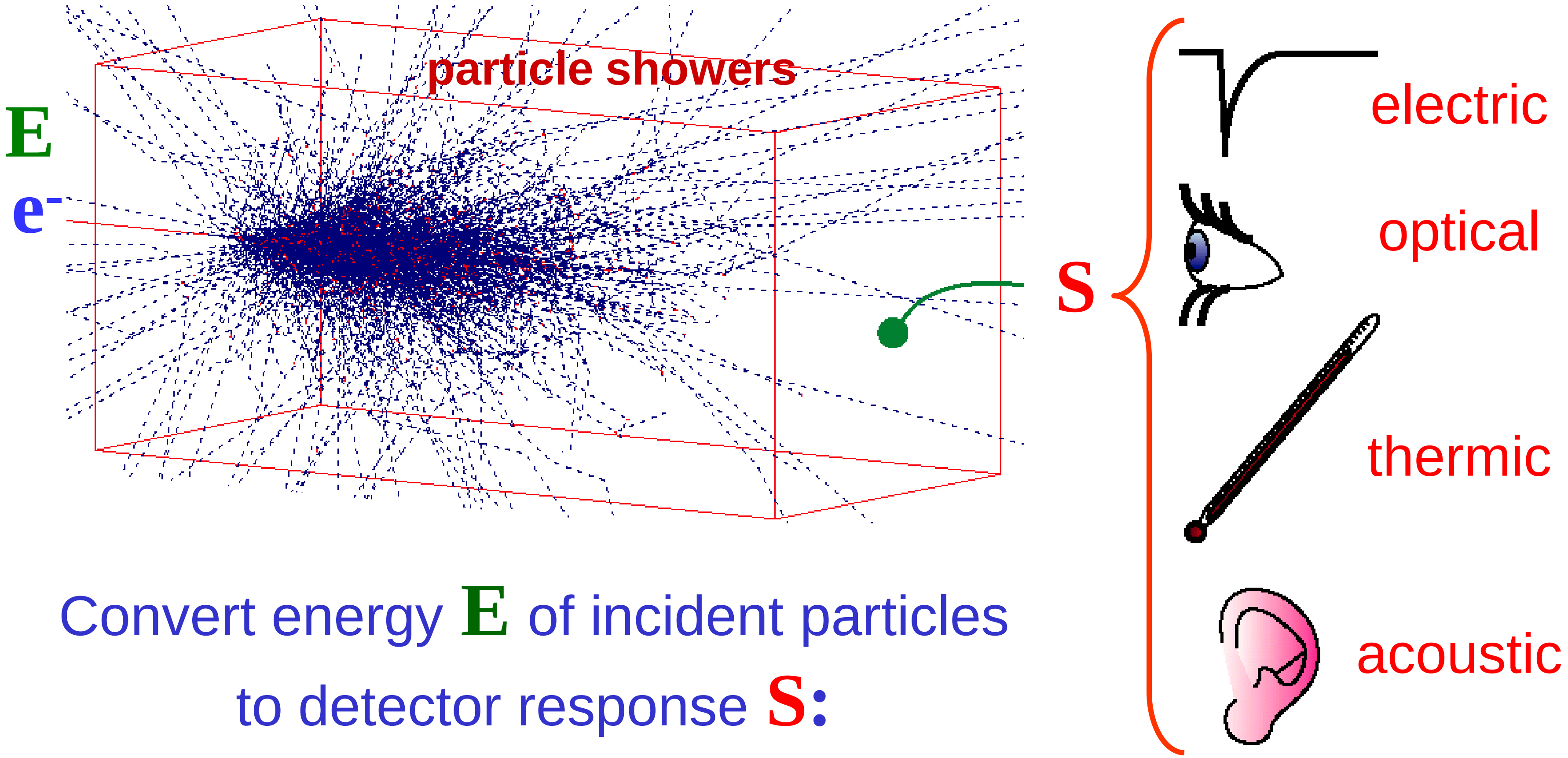


• Obtain information on *energy flow*: total (missing) transverse energy, jets, incoming particle direction (with high segmentation)

• Obtain information *fast* (<100ns feasible)

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

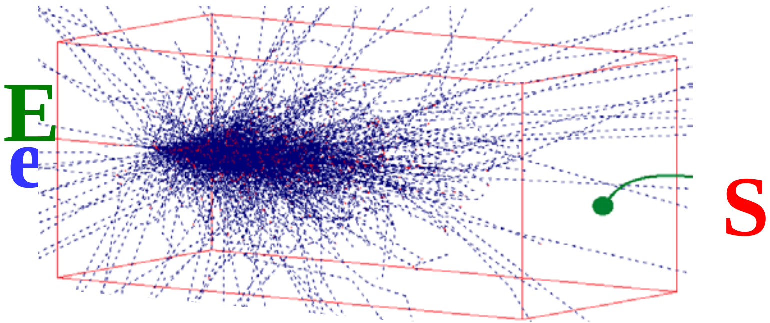
Calorimeters: a simple concept



Convert energy **E** of incident particles to detector response **S**:

$$\mathbf{S} \propto \mathbf{E}$$

Homogeneous vs non-homogeneous



Ideal calorimeter:
Contain all energy of one particle+
Convert all energy into measurable signal
➔Homogeneous (i.e. crystal)

In practice:
Homogeneous calorimeter only possible for electrons (shorter showers)
Sometimes too expensive also for electrons
Lateral segmentation possible but no depth information

Alternative solution ➔ Sampling calorimeter
Contain all energy of one particle+
Sample its energy during shower development ($E_{visible}$ ✪ E_{total})

Many different designs
- calorimeter imbiss: sandwich, shashlik, spaghetti
- liquid versions: LAr
- …

Particle detection

The detector sees only “stable” particles:

- Electrons, muons, photons, pions, kaons, protons and neutrons

In order to detect a particle, it has to interact - and deposit energy

Ultimately, the signals are obtained from the interactions of charged particles

Neutral particles (photons, neutrons) have to transfer their energy to charged particles to be measured

➔ calorimeters

Physics of particle interaction (one slide)

In absorption process, most of the energy is deposited by ***very soft shower particles***

Electromagnetic showers:

- 3/4 of the energy deposited by *e-*, 1/4 by Compton photoelectrons

These are *isotropic,* have forgotten direction of incoming particle

- The typical shower particle is a 1 MeV electron, range < 1 mm

➔ important consequences for *sampling calorimetry*

Hadron showers:

- Typical shower particles are a 50 - 100 MeV proton and a 3 MeV evaporation neutron
- Range of 100 MeV proton is 1 - 2 cm

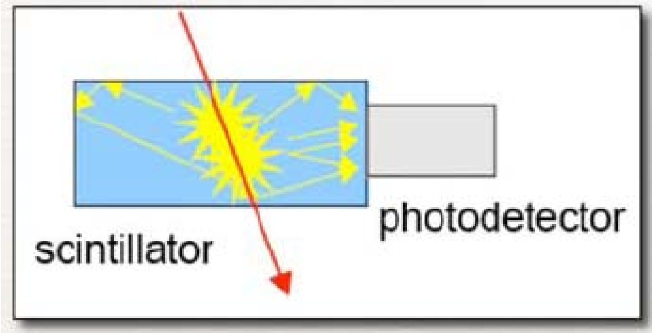
Neutrons travel typically several cm

What they do depends crucially on details of the absorber

How to "look" at the signal

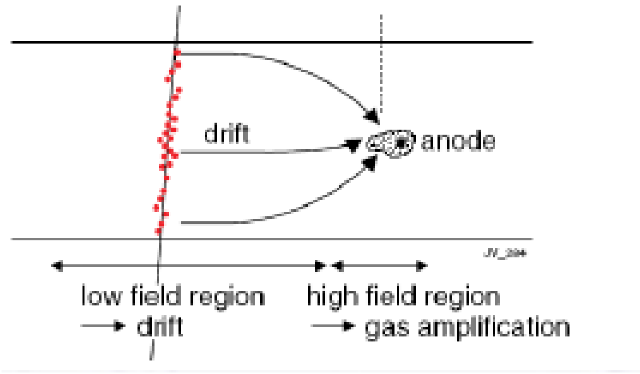
1) Convert particle energy to light:
scintillator (org. / in-org.)

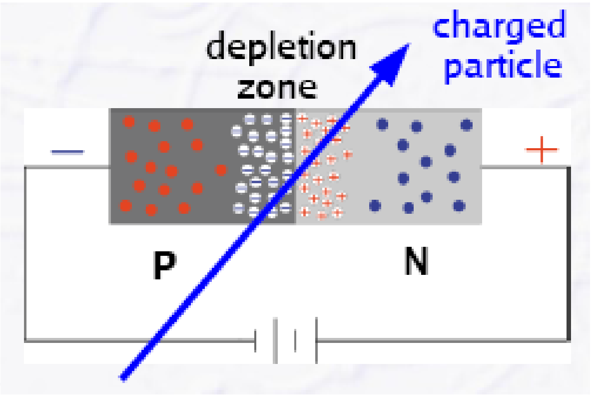
& measure light:
PMT / APD / HPD / SiPM …



2) Measure ionization E:
gas
noble liquids
semiconductors

& measure charge signal





3) Measure temperature:
specialized detectors for: DM, solar νs, magnetic monopoles, double β–decay
very precise measurements of small energy deposits
phenomena that play a role in the 1 Kelvin to few milli-Kelvin range

A quick round of the most modern calorimeters

Cannot show them all ➔ make a selection of one / technology

Homogeneous calorimeter: CMS ECAL ($PbWO_4$ crystals)

➔ Fast, Best resolution relevant for $H \rightarrow \gamma\gamma$

➔ Difficult to calibrate, expensive

Ionization chamber: ATLAS ECAL (LAr)

➔ Stable, Linear, Easy to calibrate (!)

➔ Moderate resolution

Sampling calorimeter: CALICE HCAL (scintillator tiles)

➔ Fast, Cheap, high granularity possible relevant for PFLOW

➔ Moderate resolution, Difficult to calibrate

A look more into the future:
- ultimate granularity: digital HCAL
- silicon micro-pixels r/o: digital ECAL

Calibration and monitoring

Several steps to calibrate calorimeter response:

- Multi-channels calorimeters need to be equalize before summing energy
  ➔ use e, μ or injected charge as reference

- Energy sum in reference units has to be converted to GeV
  ➔ use MC or well known physics (i.e. Z_0)

Once the calorimeter is calibrated the response stability in time needs to be monitored:

- Variety of systems to monitor r/o electronics or whole calo cell

Calibration and monitoring

In calorimeters with optical readout quantities which may vary in time are:

- amount of light generated in the active calorimeter layers
- if using wavelength shifters: the light collection and the conversion eff.
- light attenuation in active layers or WLS materials
- quantum efficiency of light detection
- gain of light detector

Depending on the monitoring method used one or more aspects are monitored but generally not all

- Charge injected in electronics monitors only readout circuit
- Laser light to the PMT monitors photodetector + r/o but not active material
- Movable β or γ sources cannot decouple problems in light generation or light transport

➔ I will mix calorimeter technologies and their calibration & monitoring

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Crystal calorimeters in HEP

Experiment	C. Ball	L3	CLEO II	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	Tevatron	PEP II	KEK	LHC
Date	75–85	80–00	80–00	90–10	94–10	94–10	95–20
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (Tesla)	-	0.5	1.5	-	1.5	1.0	4.0
Inner Radius (m)	0.254	0.55	1.0	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	2	5.9	9.5	11
L. Yield (p.e./MeV)	350	1,400	5,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	PMT	Si PD	Si PD	APD†
Photosensor Gain	Large	1	1	4,000	1	1	50
Noise/Chan. (MeV)	0.05	0.8	0.5	Small	0.15	0.2	30
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^5

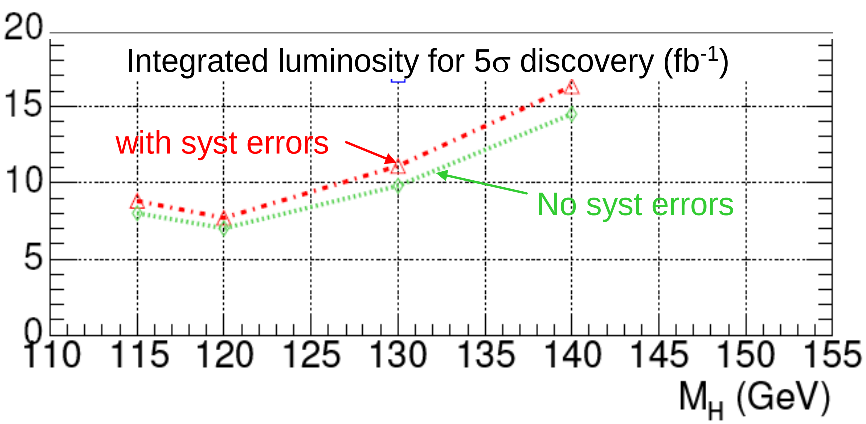
† Avalanche photo-diode.

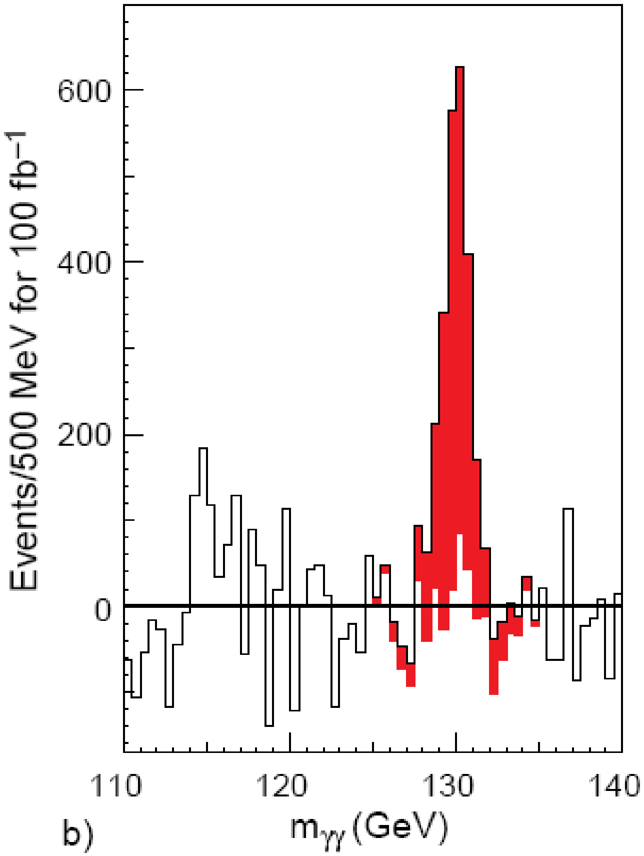
Golden channel for Higgs discovery

CMS ECAL is designed for excellent performance in the golden Higgs decay channel: H → $\gamma\gamma$ (BR~0.002)

<u>Requirements to the ECAL:</u>
Constant term <1% (0.55% design value)
➔ Higgs σ_E ~ 1%

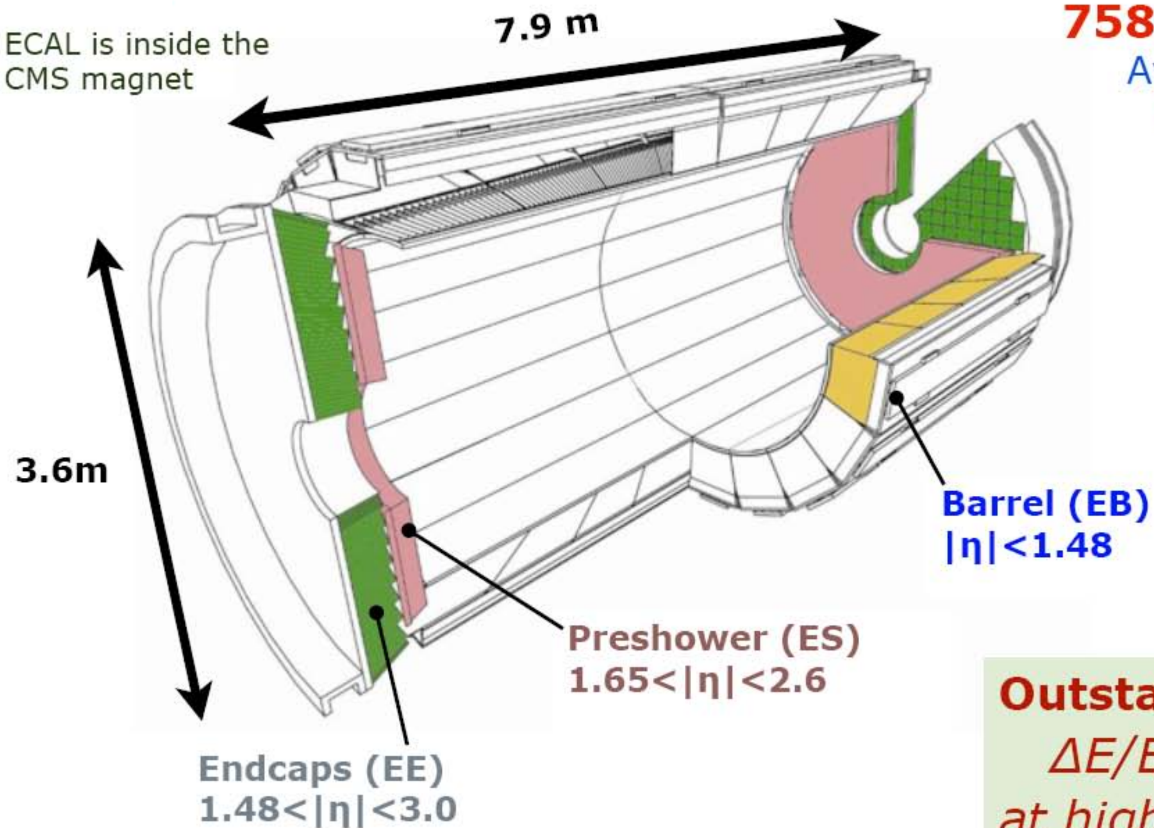
Linearity better than 0.5% [2-180 GeV]



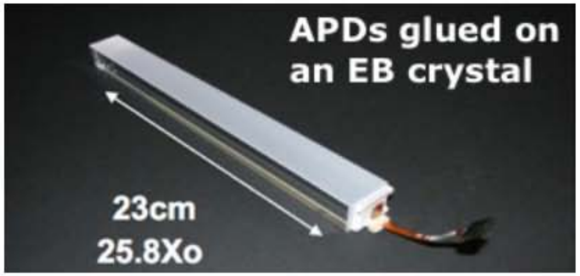


The expected background subtracted Higgs mass peak reconstructed from its two photon decays measured by the CMS PbWO4 crystal calorimeter

CMS EM calorimeter



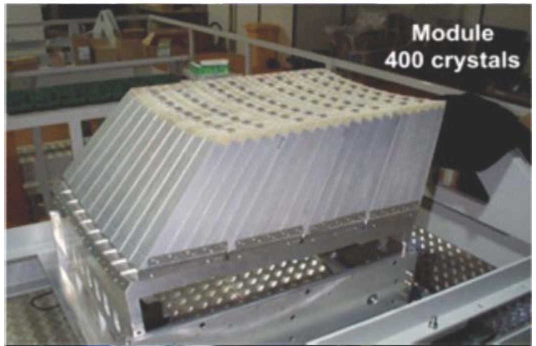
75848 Lead Tungstate crystals
Avalanche Photo Diodes (APDs) in **EB**
Vacuum Photo Triodes (VPTs) in **EE**



Fast light emission:
80% of light collected in the first 25ns

Outstanding energy resolution:
ΔE/E < 0.5 % for unconverted γ at high energies (testbeam result)

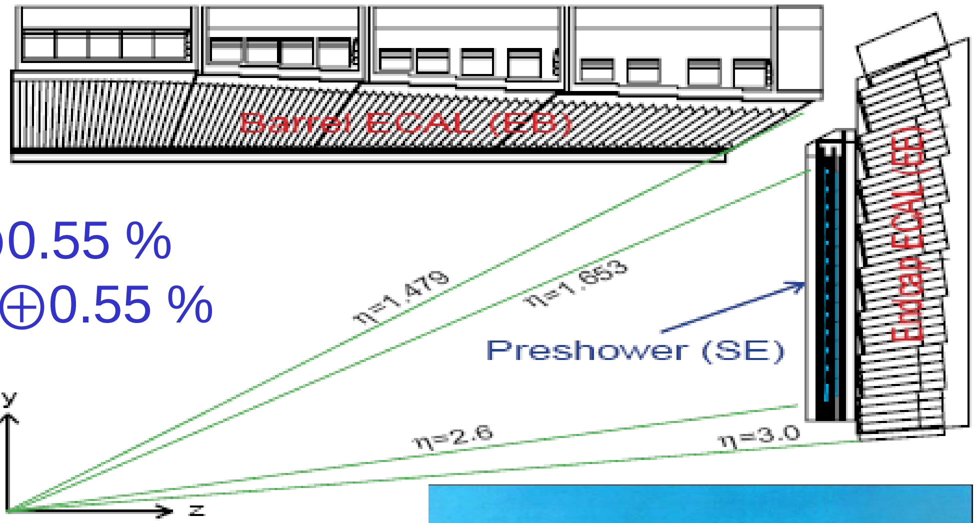
Fine granularity:
$\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175$ (EB)



Crystal length: 23 cm = 25.8X_0
➔ excellent EM containment

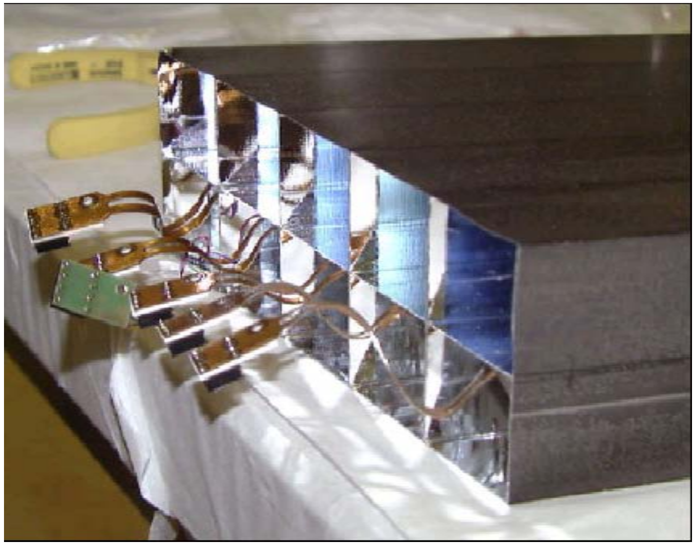
CMS EM calorimeter

Lead-Tungsten crystals
light yield 6 p.e./MeV

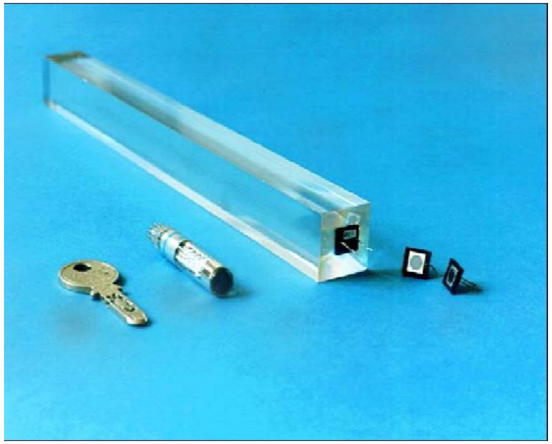


Energy resolution:
Barrel : $\sigma(E)/E = 200\ \mathrm{MeV} \oplus 3\%/\sqrt{E} \oplus 0.55\ \%$
End-cap: $\sigma(E)/E = 200\ \mathrm{MeV} \oplus 6\%/\sqrt{E} \oplus 0.55\ \%$

Dynamic range : 16 bits
50 MeV-3 TeV

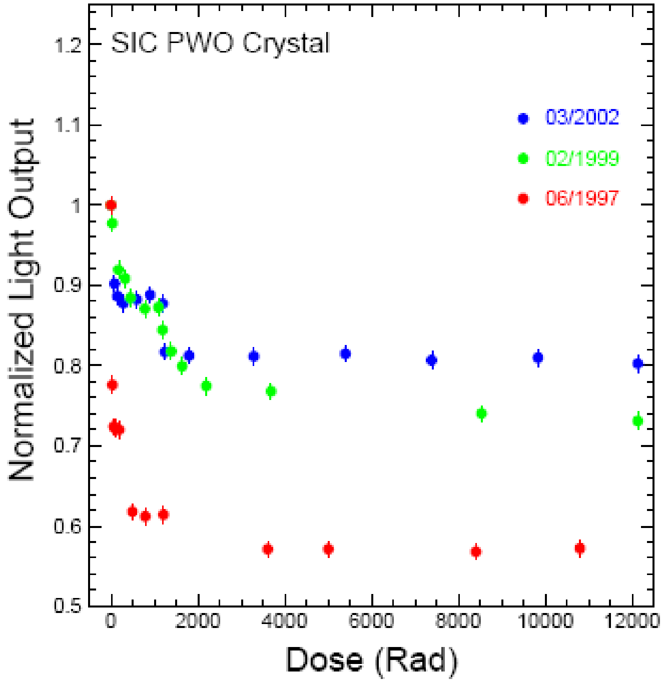


glass fiber + epoxy support structure for crystals (~100um)



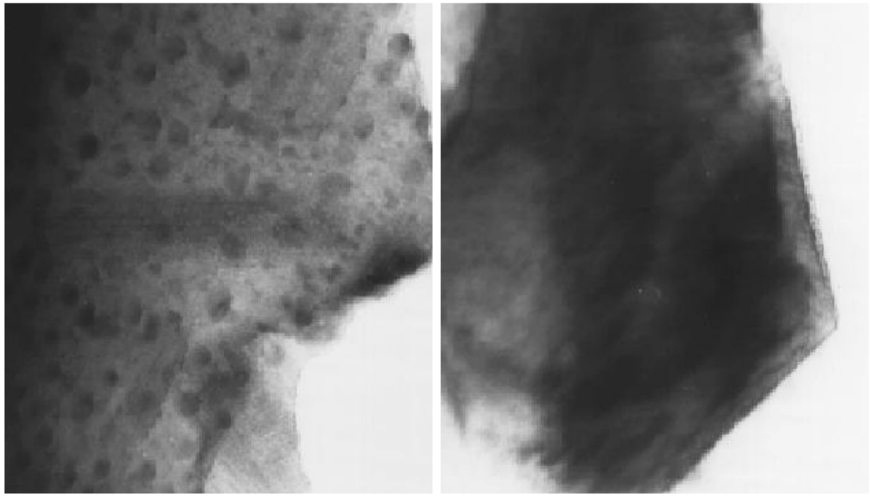
Similar design using LYSO crystals under investigation for forward EMC@SuperB factory

Radiation hardness of $PbWO_4$



The progress of PbWO4 radiation hardness for full size (23 cm) CMS PbWO4 samples

Transmission Electron Microscopy pictures of a PbWO4 crystal of poor (left) radiation hardness, showing clearly the black spots of Ø 5–10 nm related to oxygen vacancies, as compared to that of a good one (right)



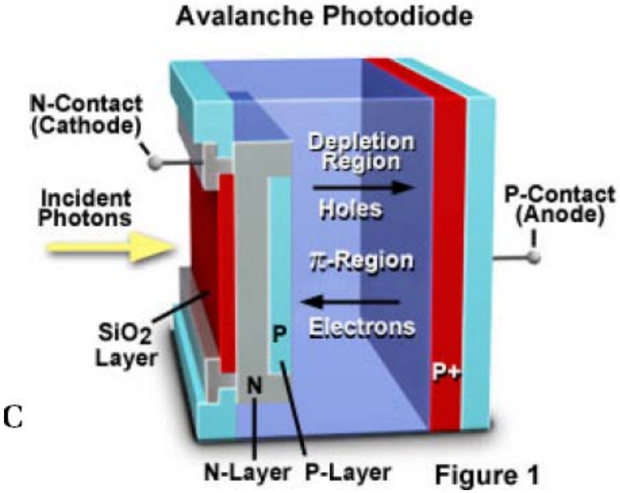
Various approaches were tried to compensate oxygen vacancies by annealing PbWO4 crystals in an oxygen rich atmosphere or by doping.
Significant improvement of radiation hardness was observed in both cases.
A practical solution is to dope PbWO4 crystals with yttrium.

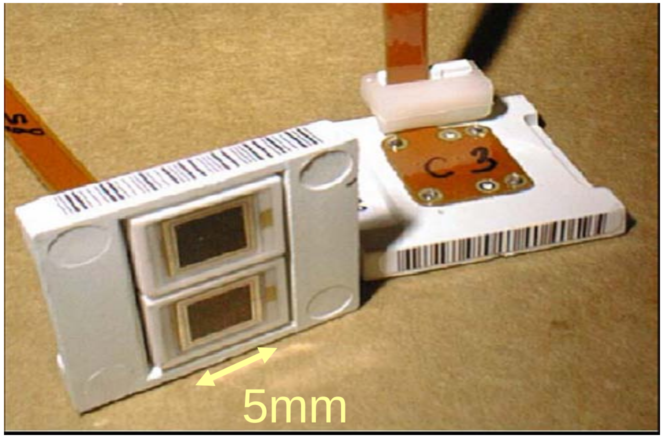
Avalanche Photo-Diode (APD)

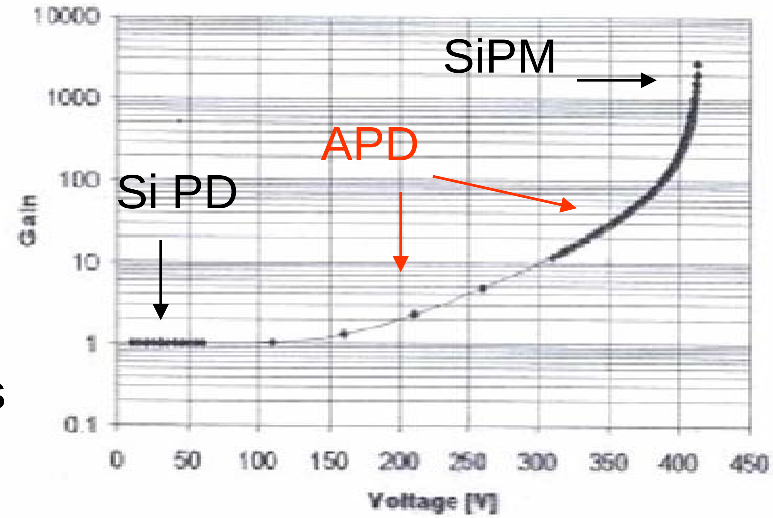
Silicon based photo-detector operated in proportional mode

Area : 25 mm^2 QE = 80%
Gain = 50 Excess noise factor: 2.2
C= 30 pF, Bias~200-300 V

APD gain decreases by 2.3%/^{O}C.
Crystal light yield decreases by 2.2%/^{O}C
Need temperature stabilization within 0.1^{O}C in the ECAL!



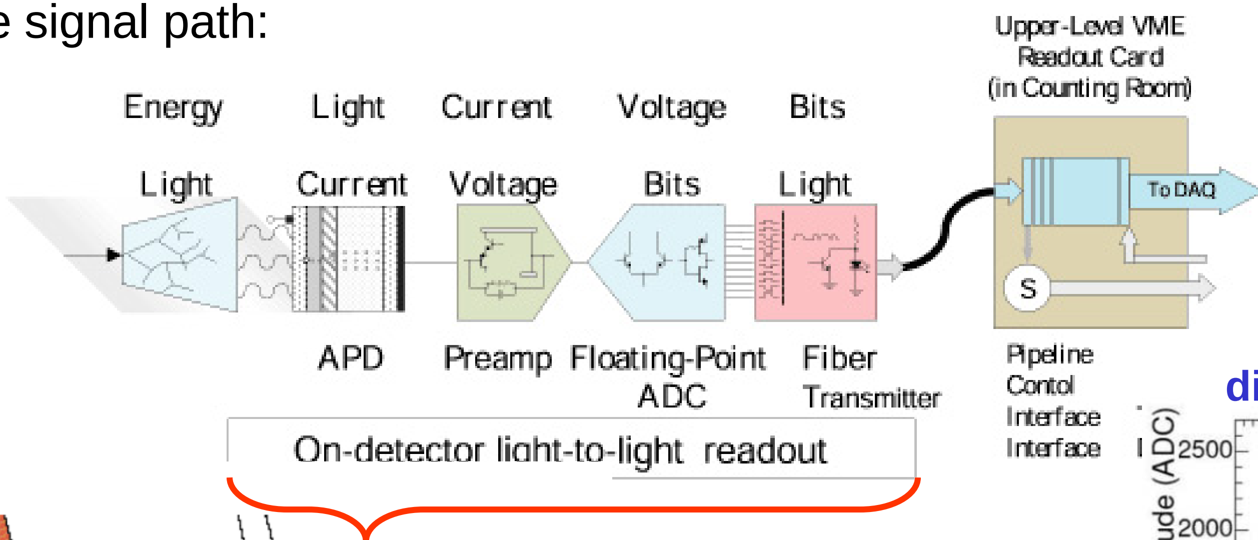


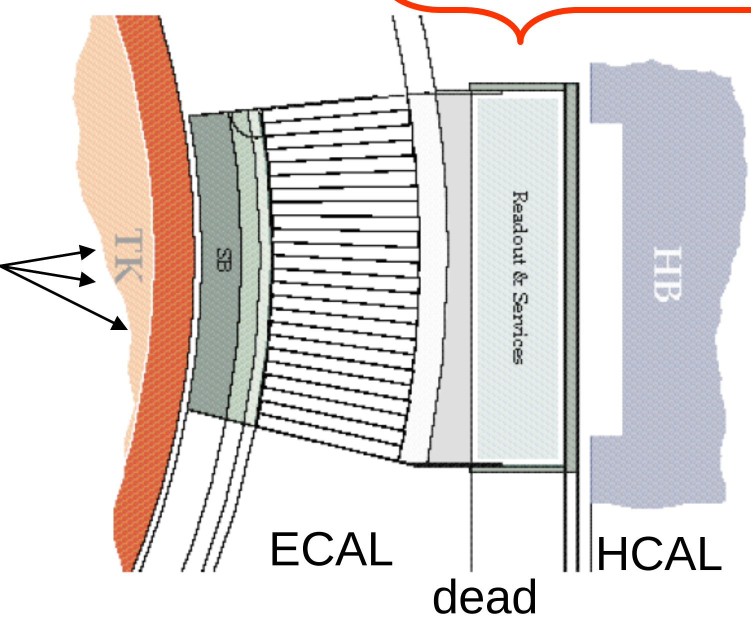


maximum neutron fluence in barrel is estimated to be 2x10^{13} neutrons/cm^2
➔ irradiation tests

CMS ECAL readout

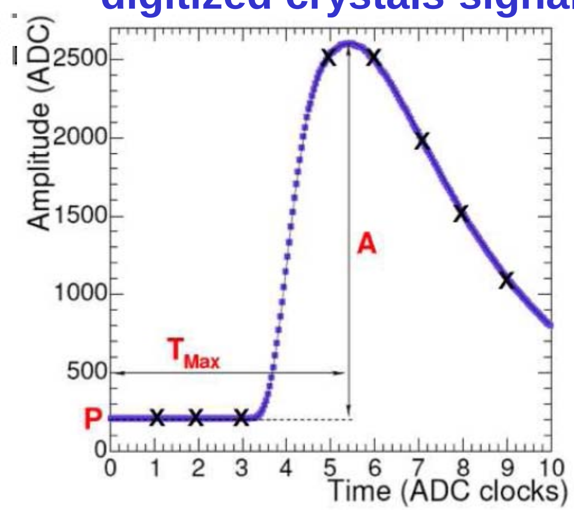
The signal path:





➔ reconstruct amplitude A and peaking time T_{max} with digital filtering technique

digitized crystals signal



ECAL electronics is dead material for the HCAL

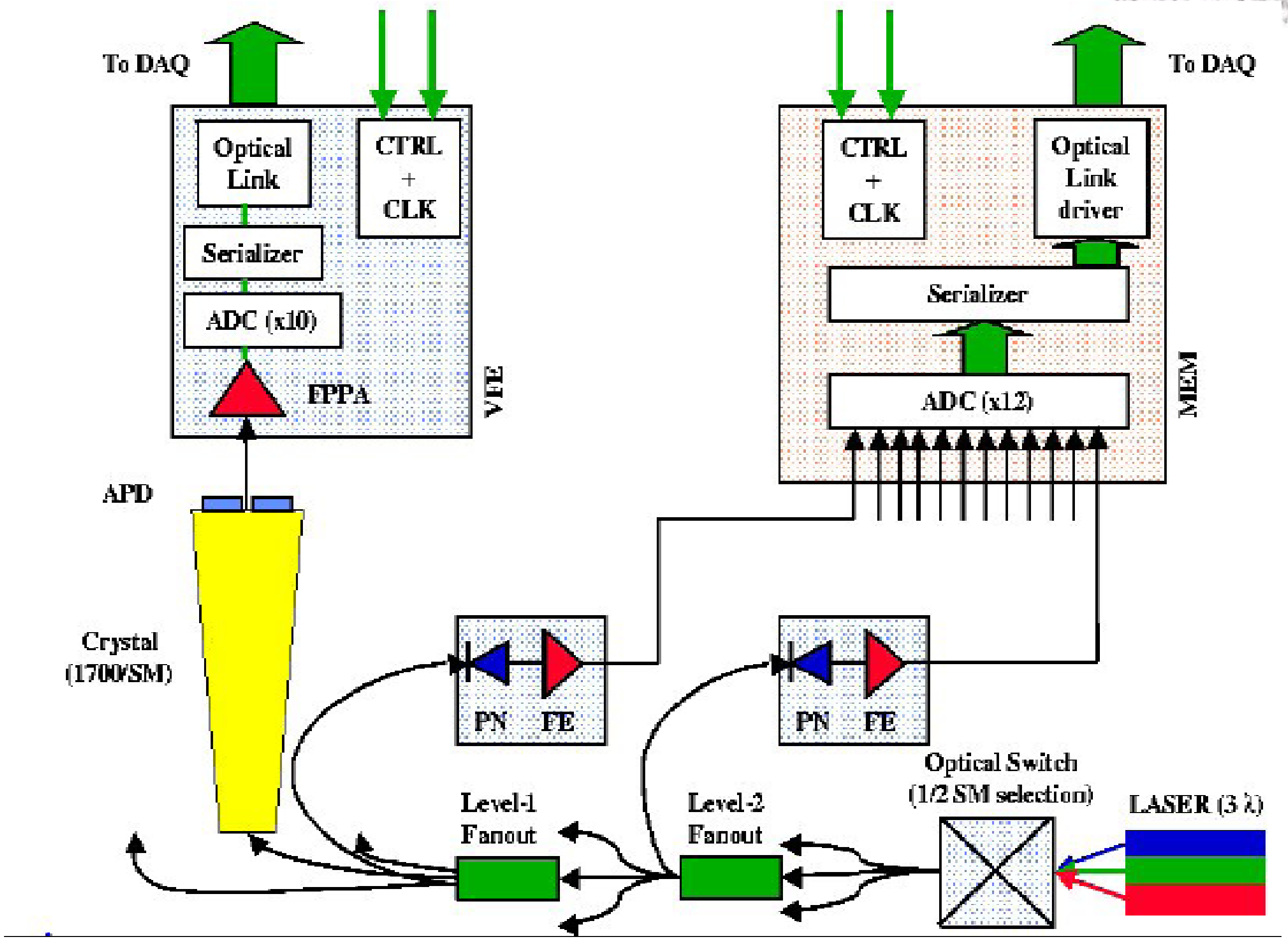
➔ Crucial for jet energy resolution

CMS ECAL Monitoring

Optical system
Mimic physics

➔ monitor changes in crystal transparency with an accuracy of better than 0.2% to maintain ECAL constant term of ~0.55%.

Requirement:
Measurements of each crystal transparency every 30 minutes during LHC operation.



Blue laser peaked at the scintillation light wavelength 440 nm

CMS ECAL Calibration

convert individual channel response to particle energy for electrons, photons and hadrons

e.g. CMS ECAL:

to be determined

$$E_{e,\gamma} = G \times \mathcal{F} \times \sum_{i}^{\text{Cluster}} c_i \times A_i,$$

absolute energy scale

digitized signals

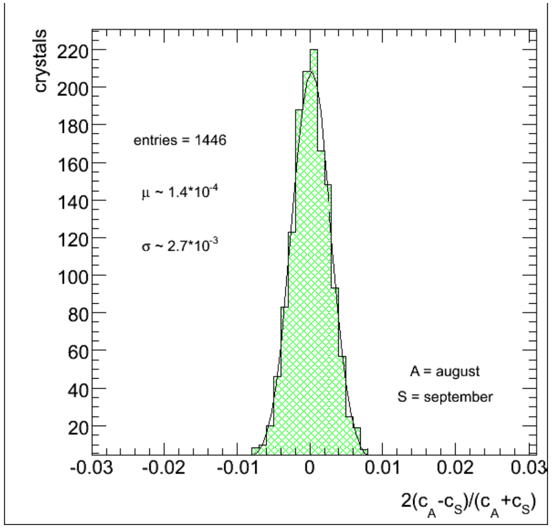
inter-calibration constants

cluster-algorithm dependent factor
(containment, position, particle type, momentum…)

ECAL was pre-calibrated prior to LHC collisions
@0.5%-2% (EB), ~5%(EE)

pre-calibrations: mixture of testbeams, cosmics, beam splashes and lab data

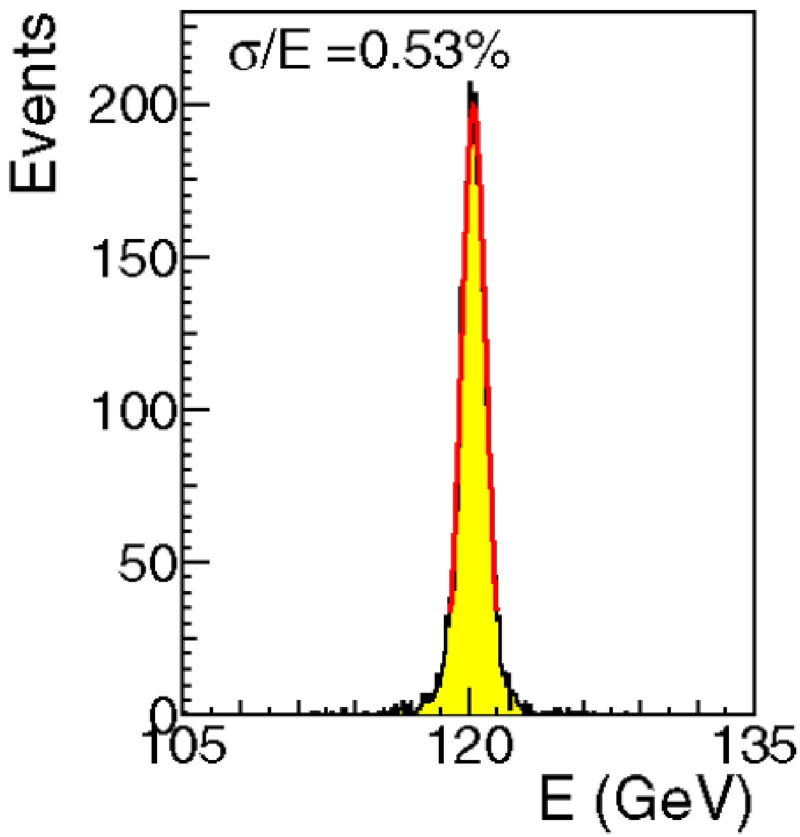
Cell inter-calibration using response to electron beam (120 GeV) as reference



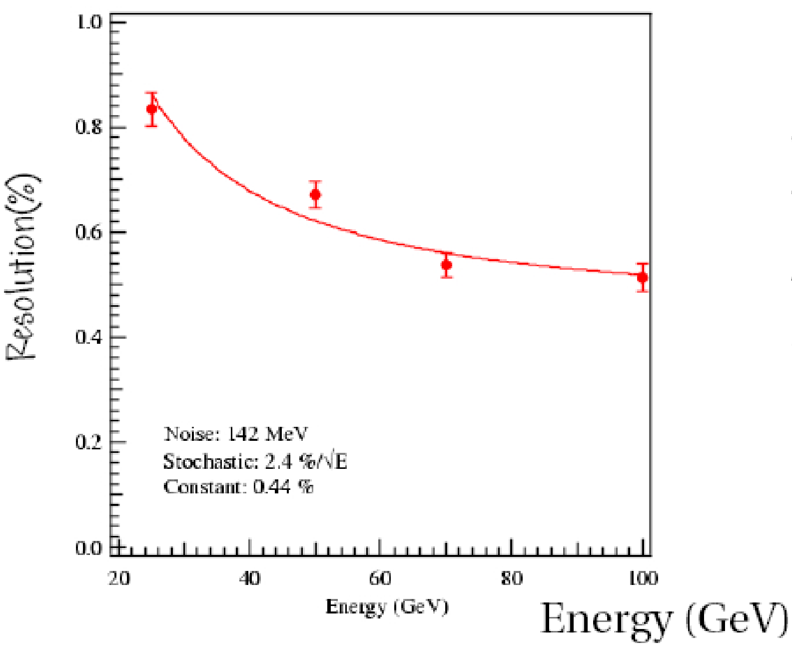
Supermodule22 exposed to e-beam in Aug. and Sept.
➔ precision of inter-calibration coefficients, c_i ~0.3%

CMS ECAL performance

Response of a $PbWO_4$ calo to a 120 GeV e^- test beam:



Energy



$$\frac{\sigma(E)}{E} = \frac{2.4\ \%}{\sqrt{E}} \oplus \frac{142\ \mathrm{MeV}}{E} \oplus 0.44\ \%$$

0.6% at 50 GeV.

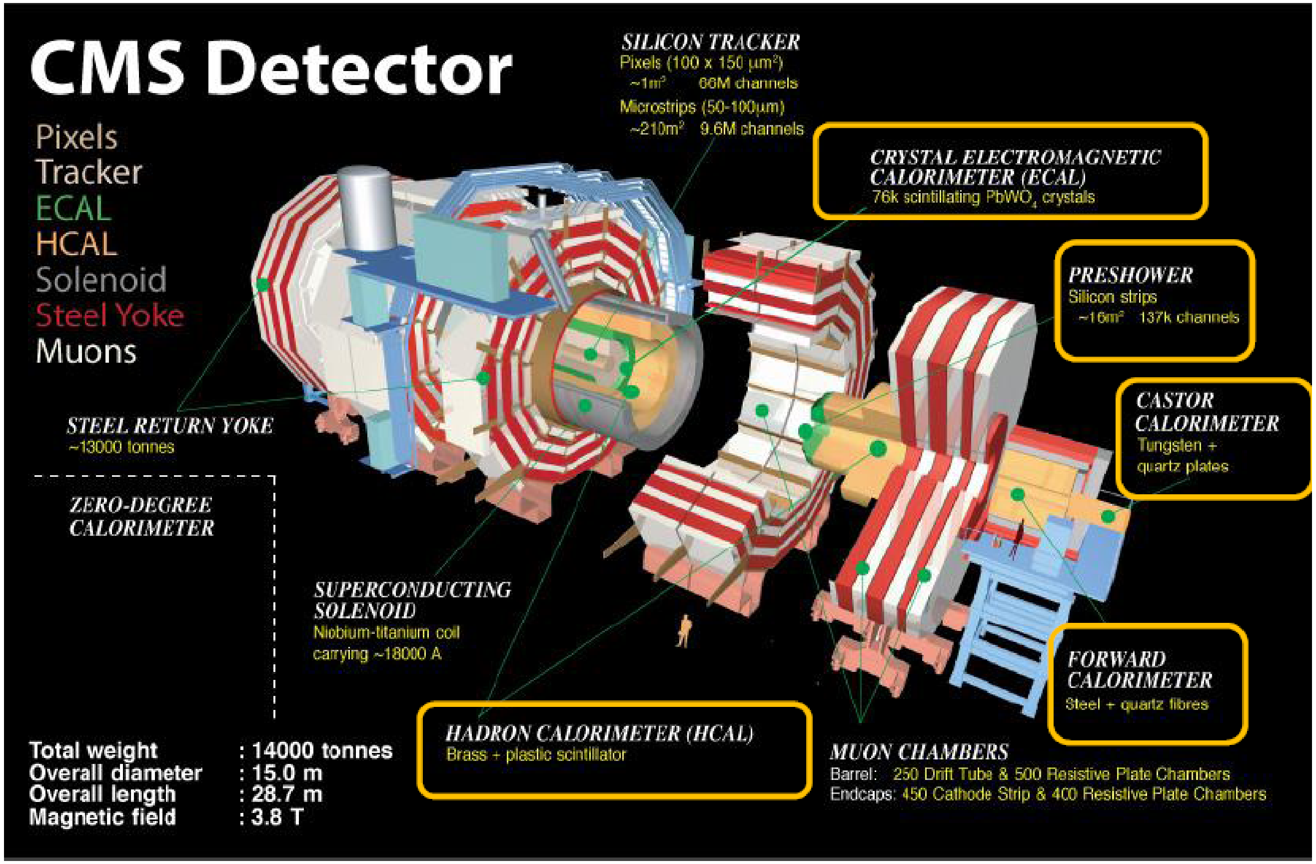
CMS upgrade plans

- phase 0 (2012):
- new SiPM photodetectors for Hadronic Calorimeters in the outer barrel region (HO)
- new PMT's for SPACAL / CASTOR Calorimeter

- phase 1 (2016):
- replacement of HPD photodetectors for Hadronic Calorimeters (HB, HE)
- new PMT's and fibers for forward Hadronic Calorimeter (HF)

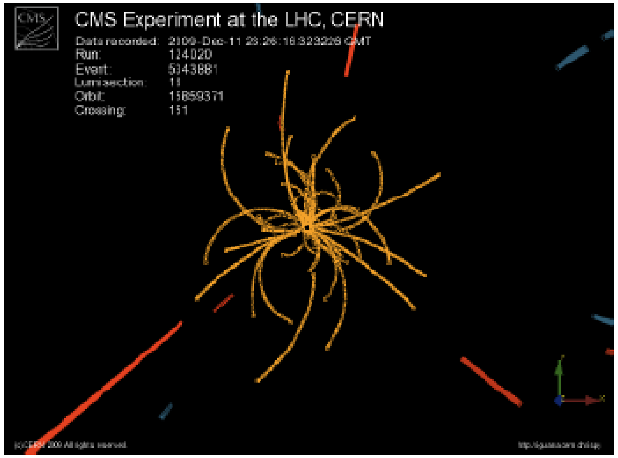
- phase 2 (2020):
- possible modification of APD readout of ECAL barrel
- possibly replacement of ECAL $PbWO_4$ endcaps

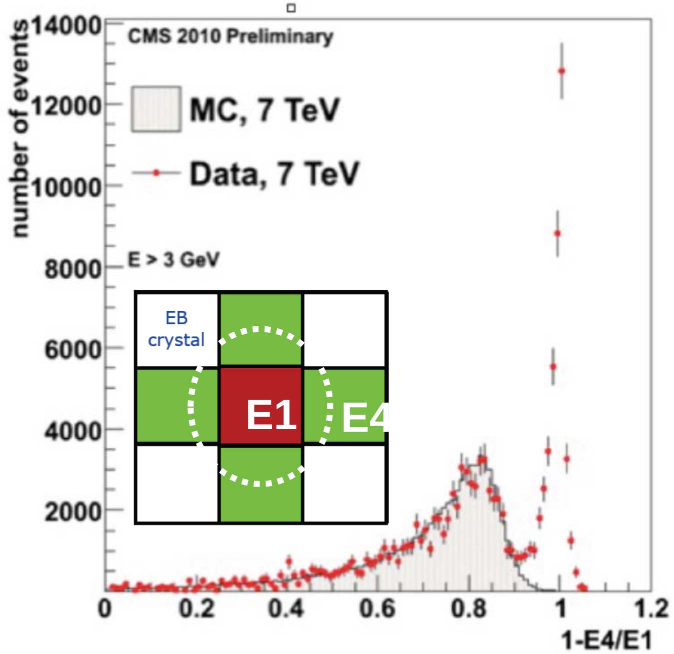
- trigger/DAQ system upgrade



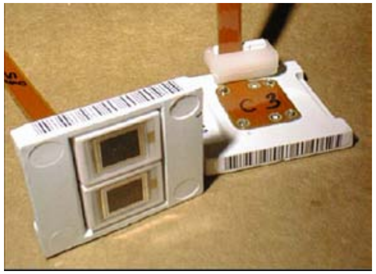
Anomalous signals in CMS-ECAL

ECAL





Rate:~ 1 / 10^3 minimum-bias events on 900 GeV collision data



- Appear mostly in a single crystal
- In time with collisions but with wider time-spread (also occur in cosmics at a much lower rate)
- Caused mostly by deposits in APDs by highly ionising secondary particles.

G. Tonelli, CERN/INFN/UNIPI

2 APD photodetectors / crystal

Current readout electronics is a sum of APD1+APD2

Using a logic OR would avoid the problem of huge APD signals

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Homogeneous calorimeter: CMS ECAL ($PbWO_4$ crystals)

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➔ Difficult to calibrate, expensive

Ionization chamber: ATLAS ECAL (LAr)

➔ Stable, Linear, Easy to calibrate (!)

➔ Moderate resolution

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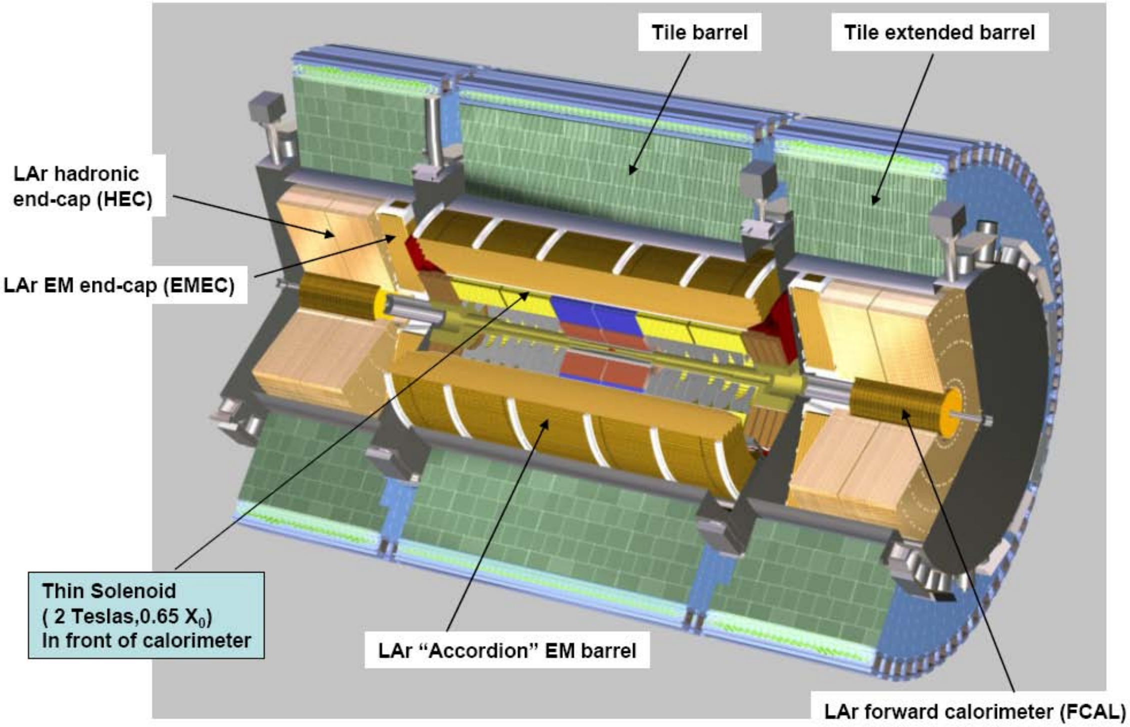
ATLAS LAr EM calorimeter

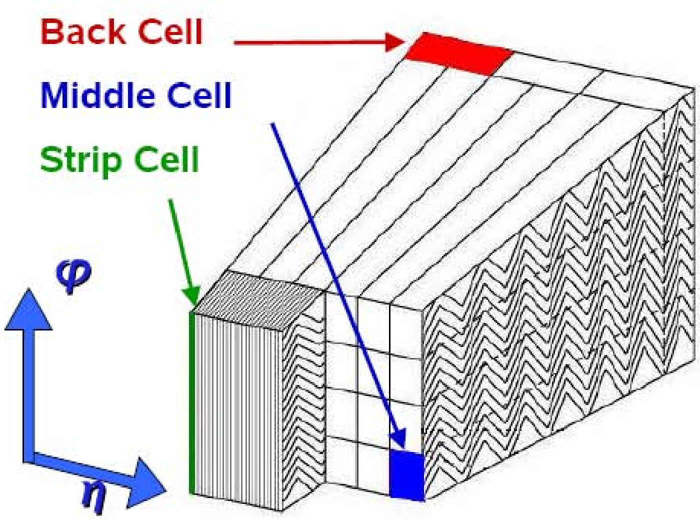


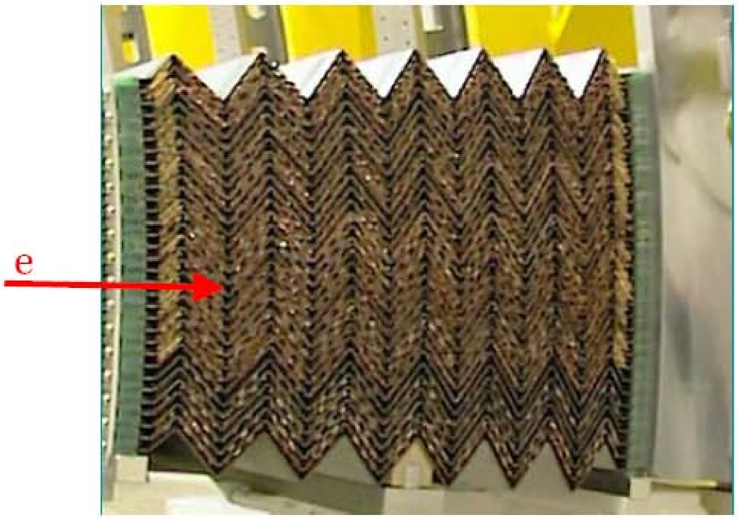
Why LAr? Stability and uniformity of the ionisation signal

Physics requirements:

- Excellent energy resolution: to reconstruct energy of e-, γ and jets
- Large dynamic range: from 50 MeV to 3 TeV
- Charge not totally integrated: fast response (< 50 ns)
- Good radiation tolerance: high fluences during 10 years

ATLAS LAr EM calorimeter



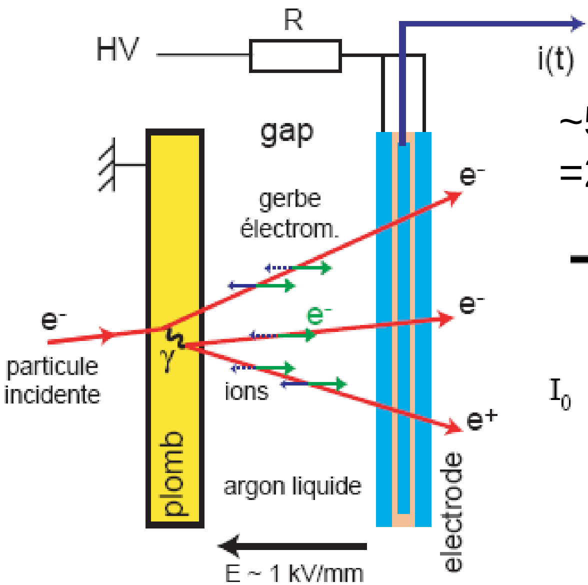


3 sections:
- strips for position res. and γ/π separation
- middle for energy measurement
- back for leakage control and h/e separation

Sampling calorimeter:
Pb accordion + Liquid Ar
contained in a cryostat (T = 87 K)

pointing "tower" geometry:
- granularity 0.03 x 0.03 $\Delta\eta$ x $\Delta\phi$
- no cracks in azimuth ➔ Accordion geometry for routing of signals to the back
- presampler to correct for energy losses in the material in front of ECAL

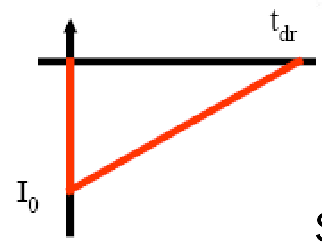
Principle of operation and readout



Drift region:
2.1 mm ~ 450 ns

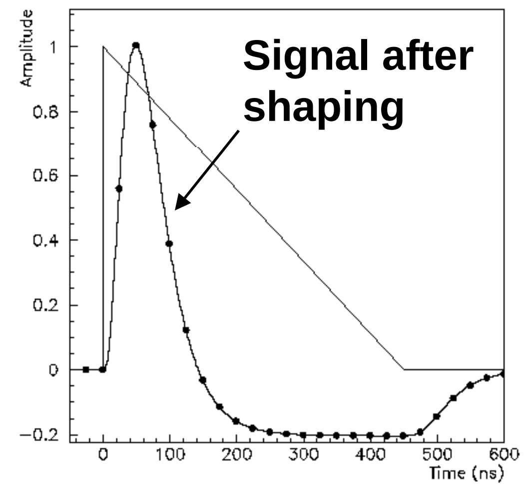
Ionization signal

~500ns long
=20 bunch xings

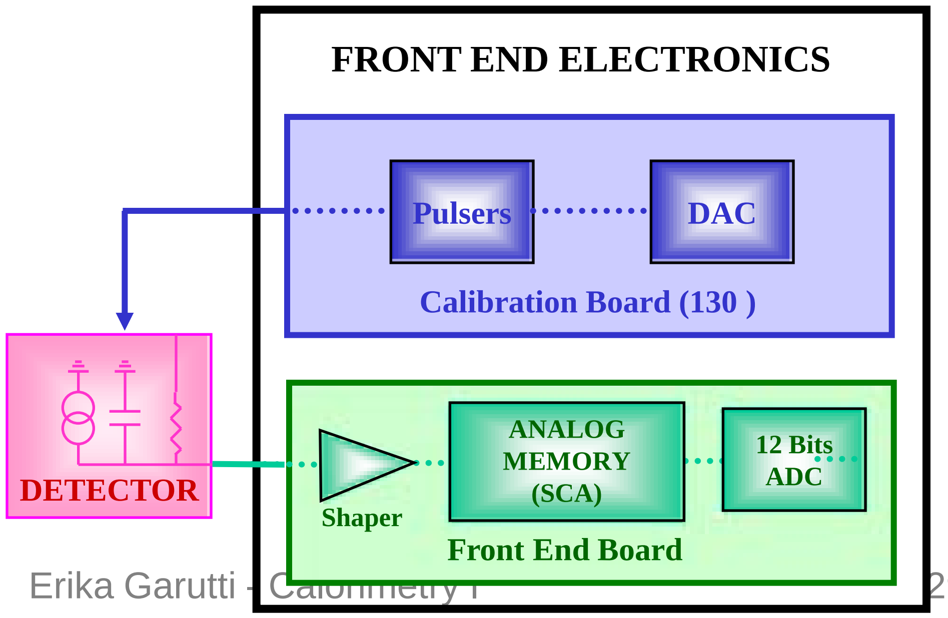


➔ reduced to 45ns peaking time by shaping

Shaped signal sampled every 25 ns ➔



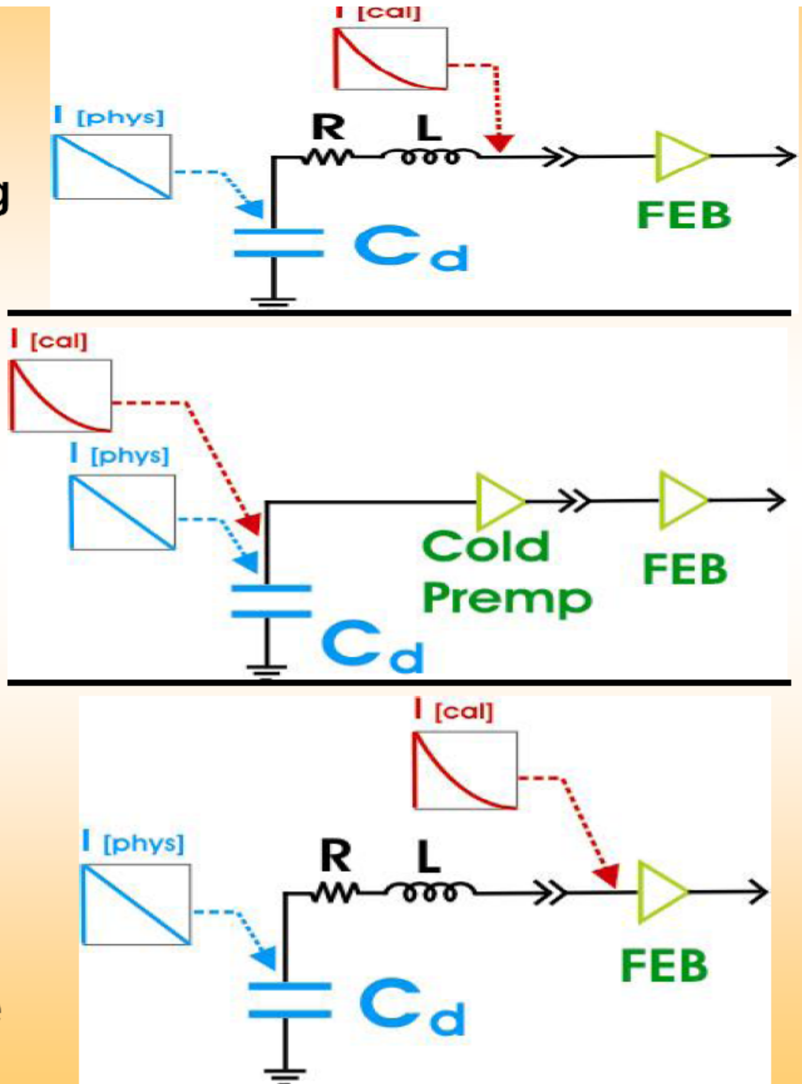
Accordion material:
Pb (1.5 mm in the barrel)
+ two stainless-steel sheets
(0.2mm thick)

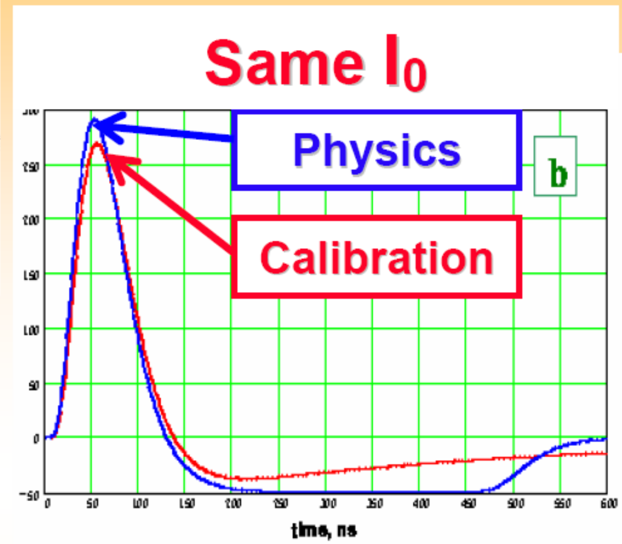


LAr detectors: calibration pulser system

Very stable design: Accuracy / channel uniformity: O(0.5%)

- **EM**
  - Inject on summing boards
- **HEC**
  - Inject at calo pads
- **FCAL**
  - Inject on FEB backplane





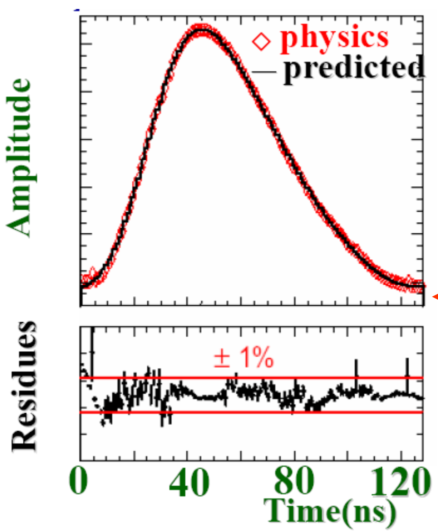
- **To use calibration system:**
  - Understanding ADC[phys]/ADC[cal] for fixed I_0 is key

Cell reconstruction step

Convert measured current [μA] to ADC amplitude

use channel-to-channel calibration pulser system

➔Correct for calibration ↔ physics pulse height differences for same injection I



Intended LAr electronics calibration chain:

- ADC[Phys] → ADC[Cal] → Current in μA (calib board)

Deliver uniform, stable and linear signal with a shape similar to that of the calorimeter ionization current

Note: T dependence on signal generation 2%/K ➔ not relevant since T stability expected ~0.3K

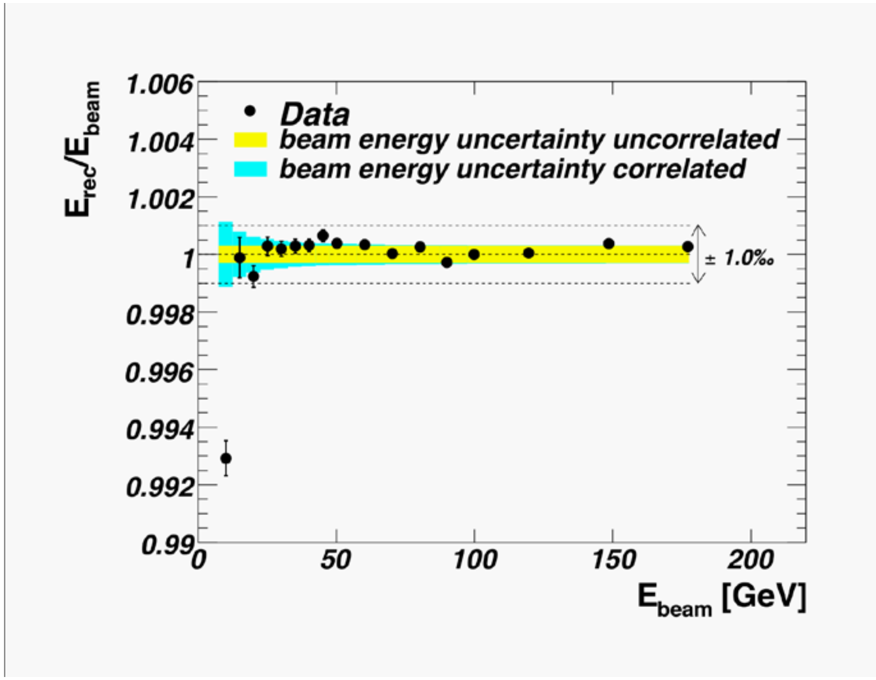
Still need: μA →MeV (from testbeam, MC, ...)

Alternative, if channel response uniform enough, can convert directly

ADC[Phys] →MeV (from testbeam)

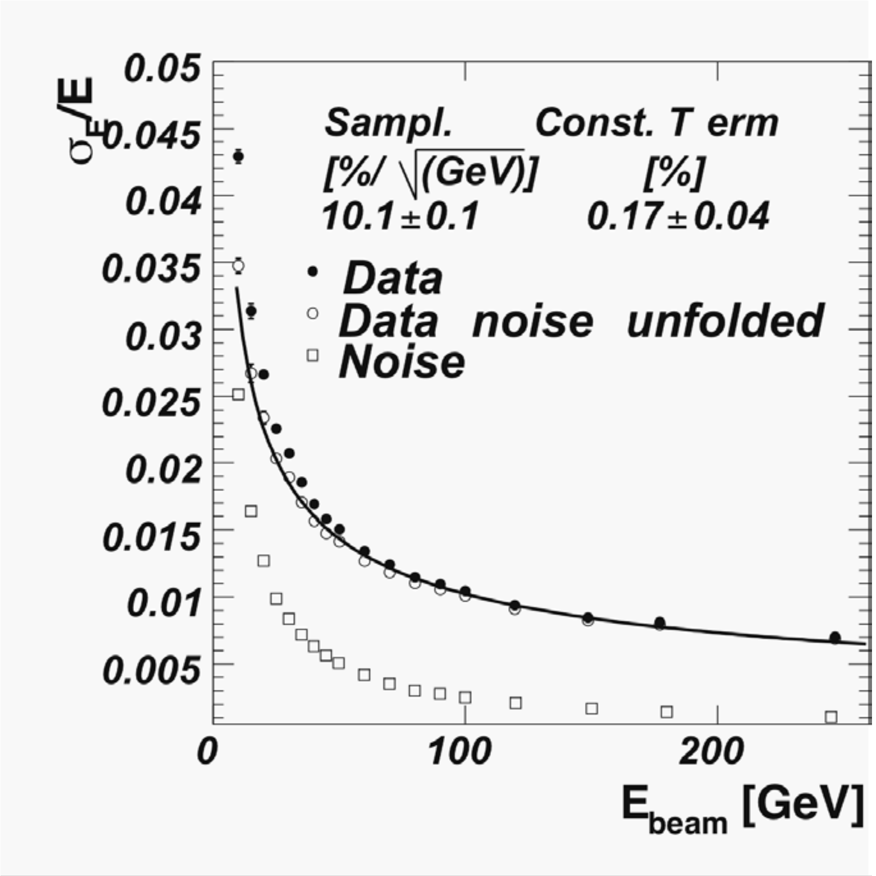
ATLAS LAr performance

Linearity better than 0.1%



within 0.1% for 15-180 GeV,
E=10 GeV is 0.4% too low
➔ reason unclear

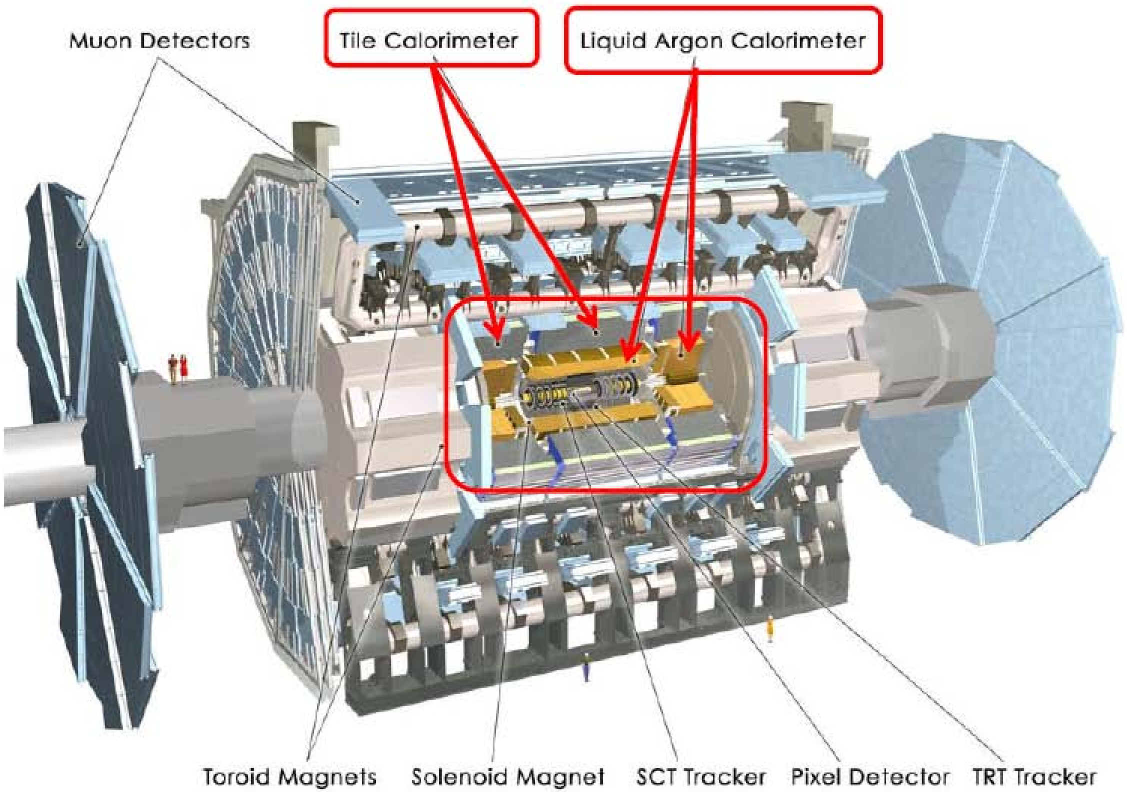
Energy resolution



ATLAS upgrade plans

- consolidation phase (2011-2012):
  - replacement of non-reliable electronics on the detector (low-voltage power supplies, optical transceivers, slow-control boards)
  - improve accessibility of electronics (hadronic endcap)

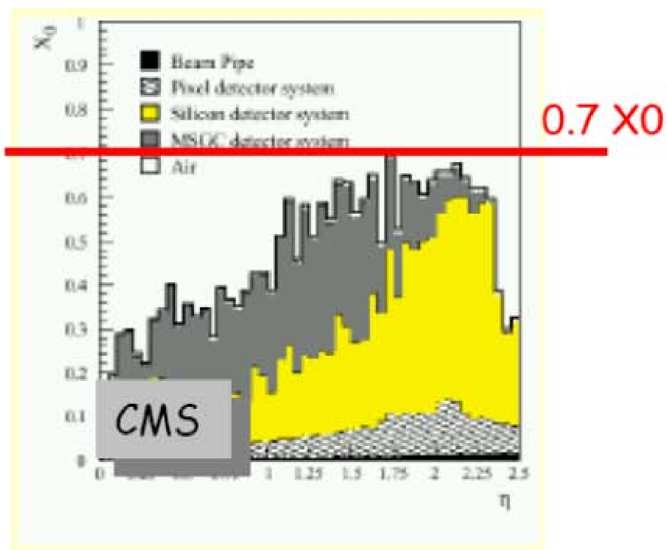
- 1st upgrade phase (2016) / 2nd upgrade phase (2020):
- free-running readout electronics for LAr and Tile calorimeters
- new digital L1 Calorimeter trigger electronics
- possible replacement of HCAL cold electronics
- possibly new diamond-Cu sampling forward calorimeter (MiniFCal) or
- new forward LAr-Cu calorimeter (sFCal1)



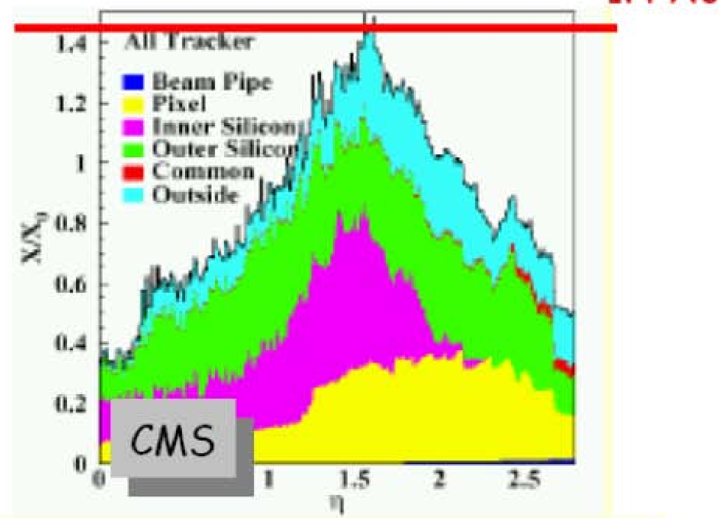
LHC tracker material budget

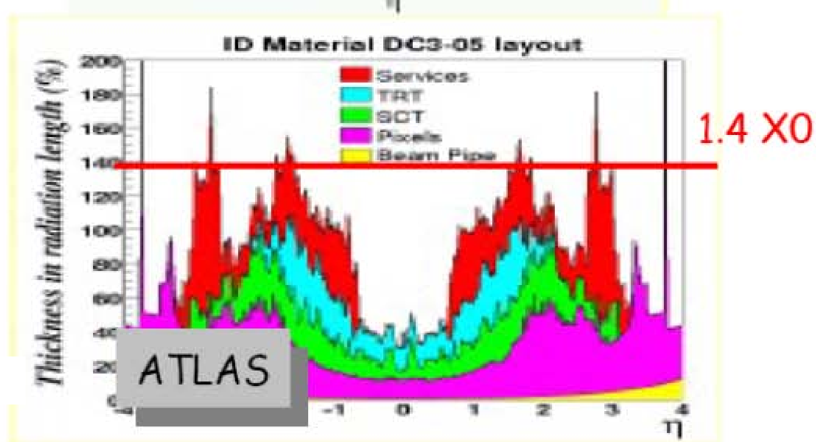
Watch out !
A calorimeter often
does not live alone!

The detector TDR 1996



... and the reality 10 years later





Interactions before the calorimeter
spoil energy resolution !!

Cannot show them all ➔ make a selection of one / technology

Homogeneous calorimeter: CMS ECAL ($PbWO_4$ crystals)

➔ Fast, Best resolution relevant for H➔$\gamma\gamma$

➔ Difficult to calibrate, expensive

Ionization chamber: ATLAS ECAL (LAr)

➔ Stable, Linear, Easy to calibrate (!)

➔ Moderate resolution

Sampling calorimeter: CALICE HCAL (scintillator tiles)

➔ Fast, Cheap, high granularity possible relevant for PFLOW

➔ Moderate resolution, Difficult to calibrate

A look more into the future:- ultimate granularity: digital HCAL

- silicon micro-pixels r/o: digital ECAL

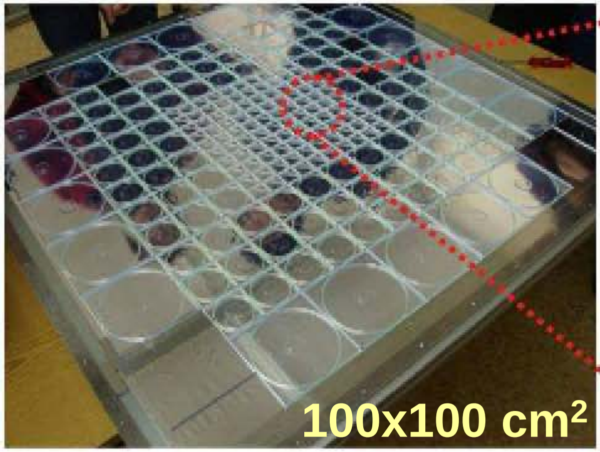
ILC: hadronic calorimeter

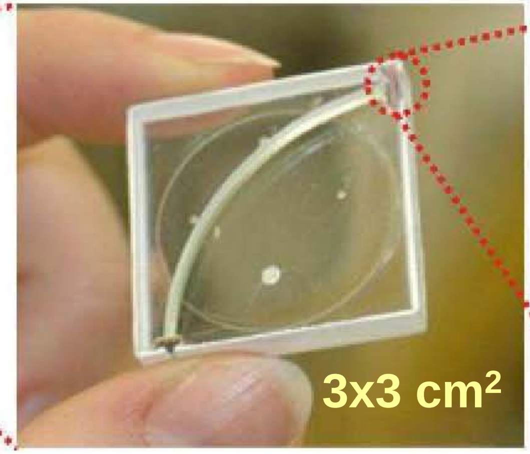
A crucial technology improvement to calorimetry

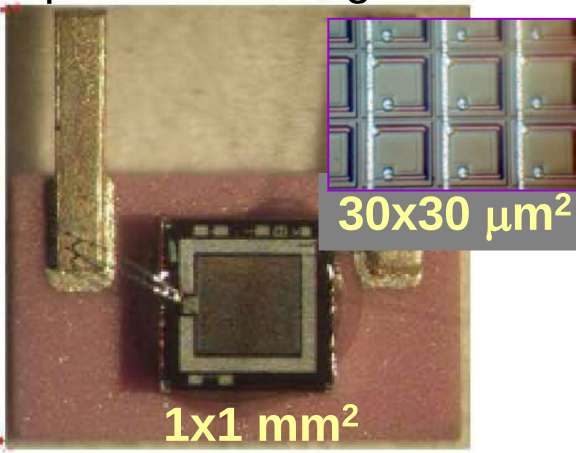
One calorimeter active layer

Scint. tile readout
with SiPM

pixel photo-detector
operated in Geiger mode







Read out 216 tiles/module
38 sampling layers
~8000 channels = ~8000 SiPMs

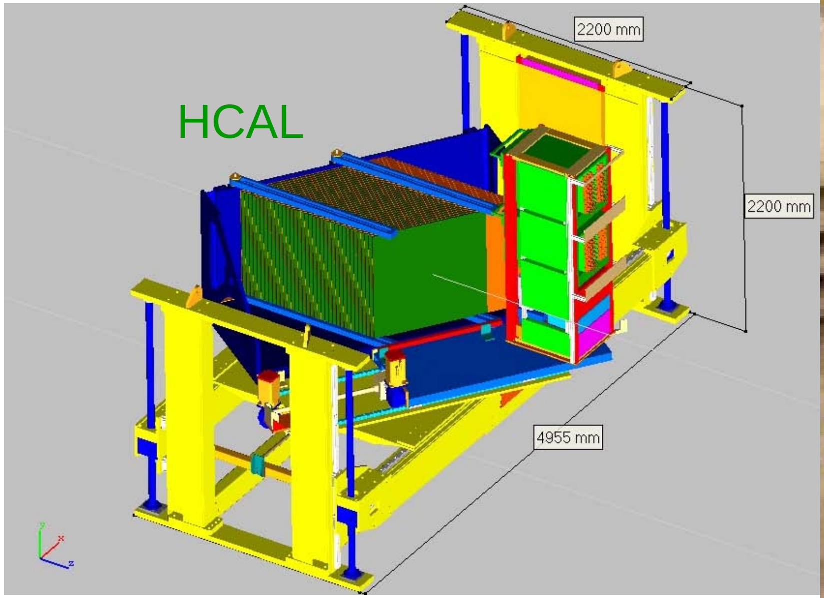
VFE: control board for 12 ASICs / layer
connect to SiPMs

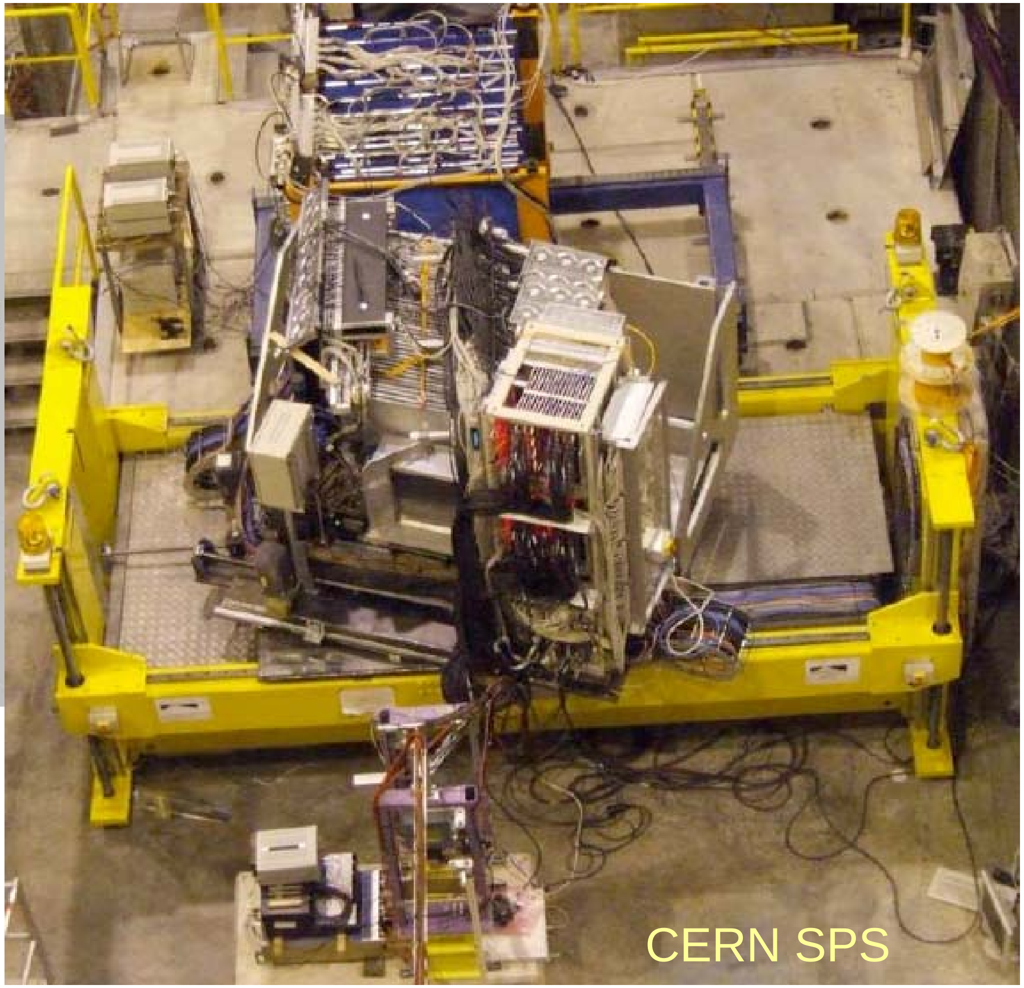
ASIC: amplification + shaping +
multiplexing (18 ch.)

A calorimeter for test beam experiments

38 layers Fe/scint. sampling structure

High longitudinal and lateral segmentation





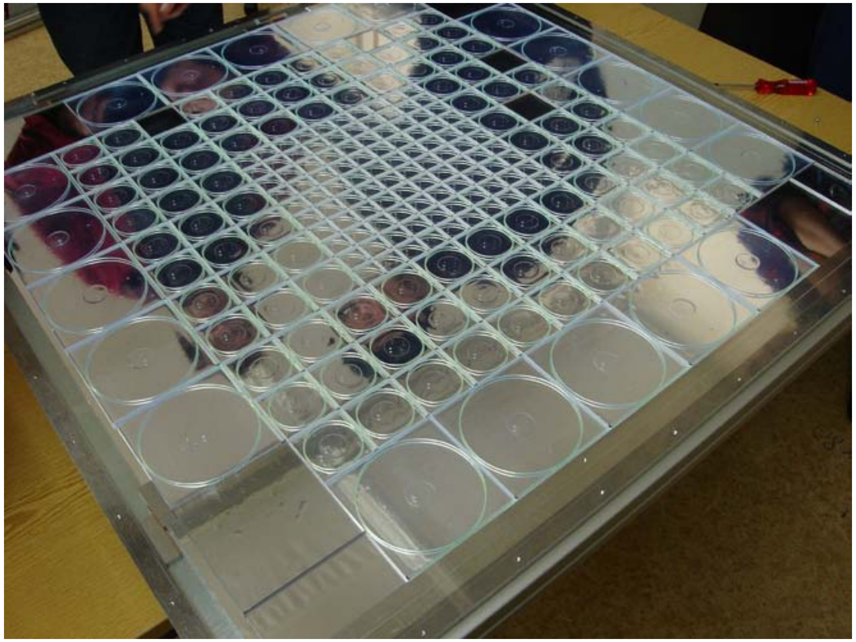
Mounted on a movable stage for flexible scans in the beam

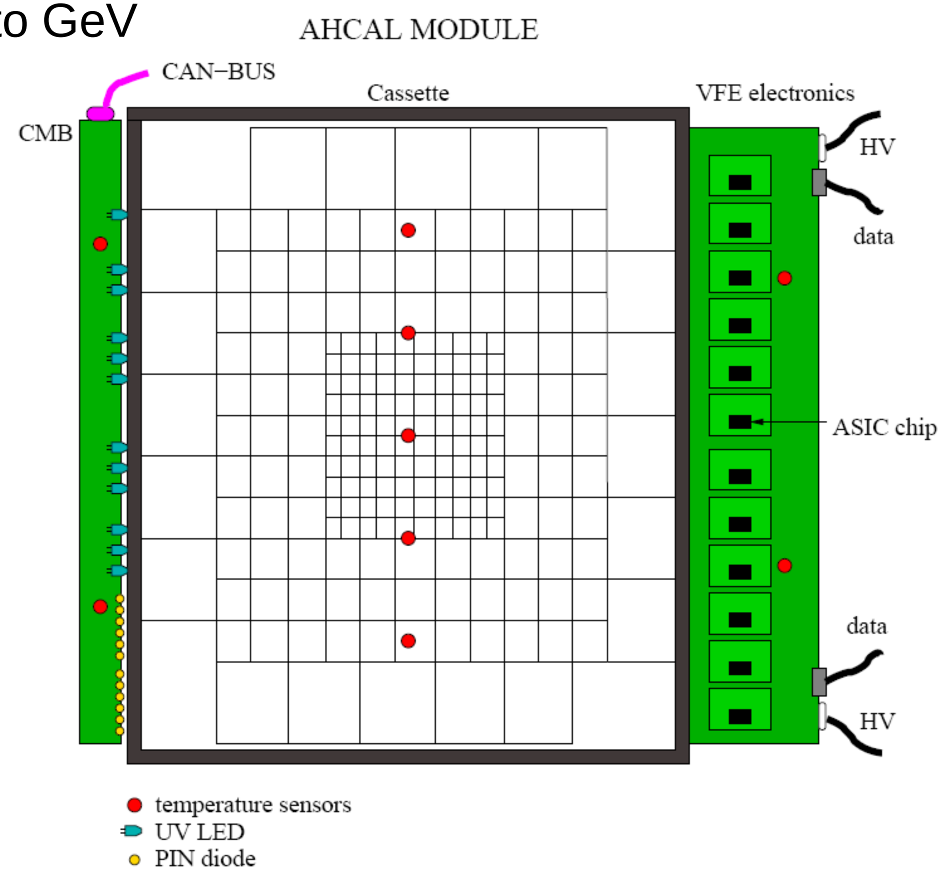
Calibration strategy

Non trivial equalization of scintillator tiles response based on:

- Detection of mip from μ or π stabs
- Redundant monitoring system combining low/high intensity UV LED light on each tile + temperature readout of each layer

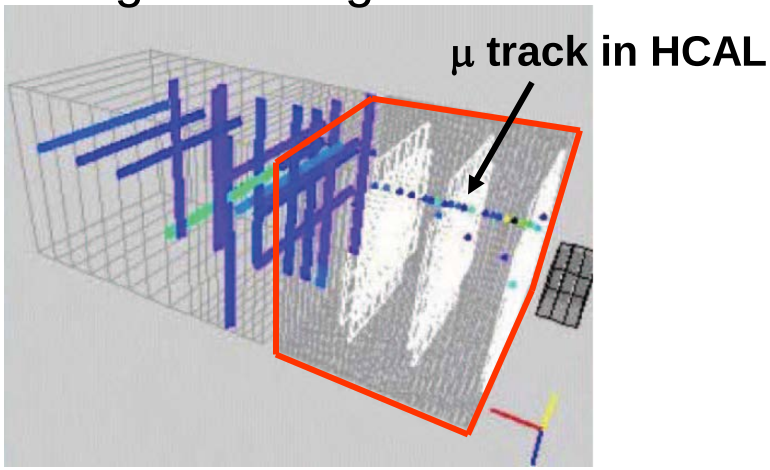
Use EM scale to convert response in MIP to GeV



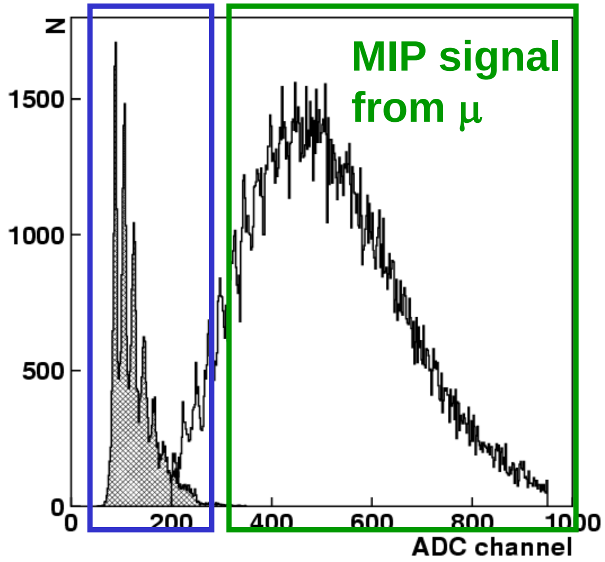


Tile response equalization with MIP

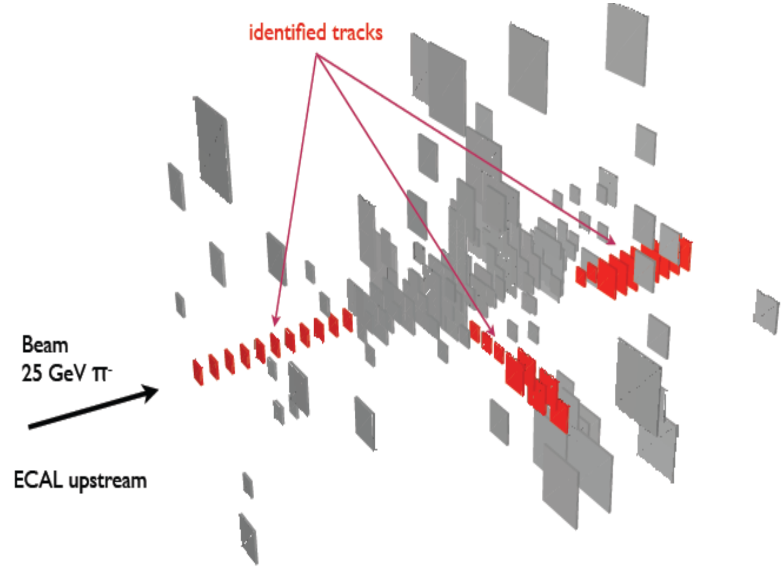
Using muon signal



Single pixel signal from SiPM



Using pion shower
select MIP stabs using the high granularity of the HCAL



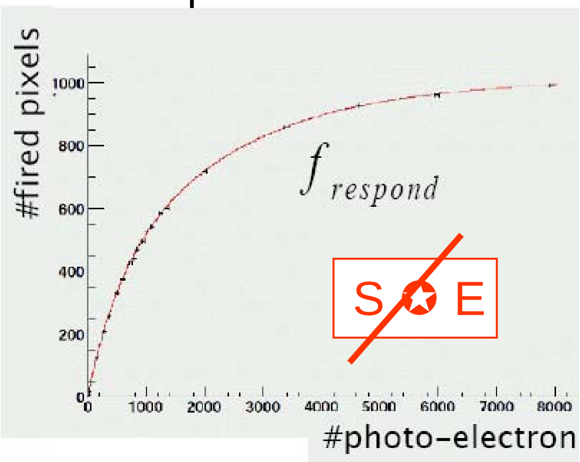
Luminosity requirement for in-situ calibration with MIP stabs from jets (ILC detector)

	Luminosity at 91 GeV	Luminosity at 500 GeV
layer-module to 3% to layer 20	1 pb^{-1}	1.8 fb^{-1}
layer-module to 3% to layer 48	10 pb^{-1}	20 fb^{-1}
HBU to 3% to layer 20	20 pb^{-1}	36 fb^{-1}

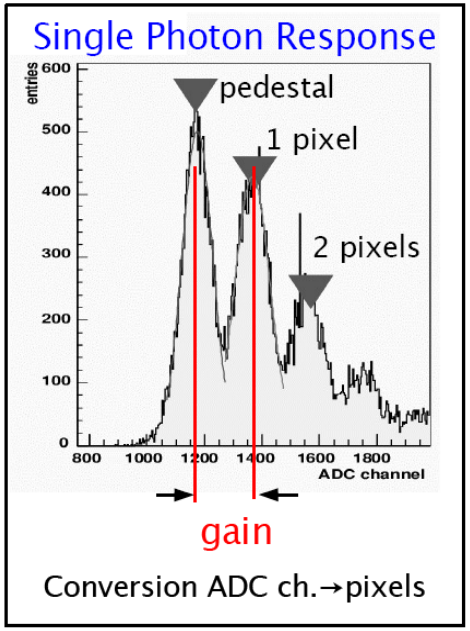
more statistics obtained from $Z_0 \rightarrow \mu\mu$ events

Importance of monitoring/calibration system in a SiPM based calorimeter

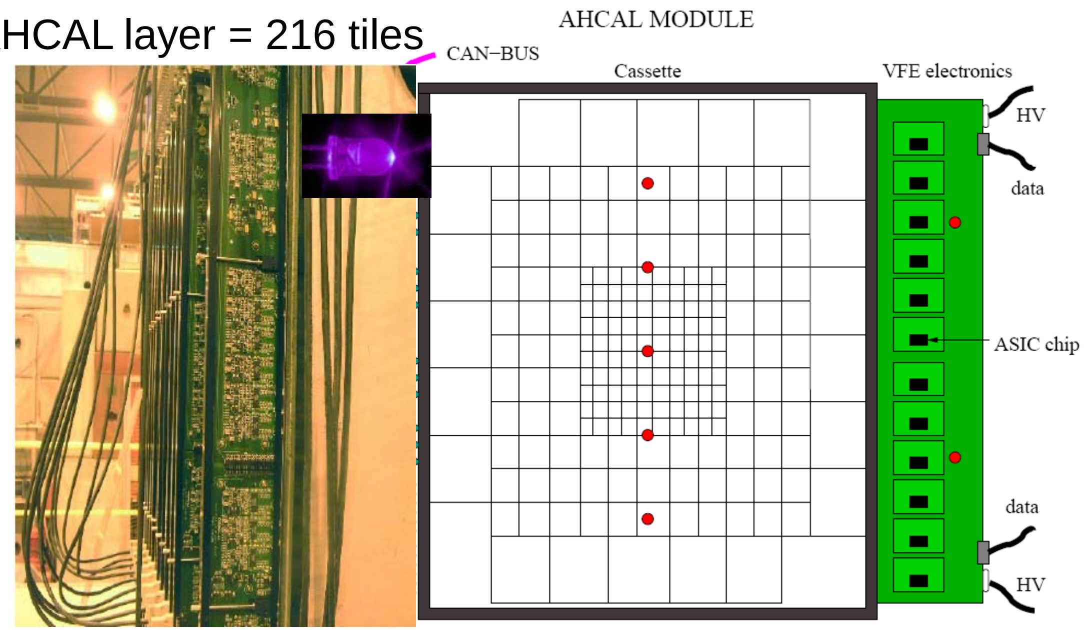
SiPM response is non-linear



Calibration system should deliver:
-Low intensity light for SiPM Gain calibration
-High intensity of light for saturation monitoring
-Medium intensity light for monitoring T,V variations



AHCAL layer = 216 tiles

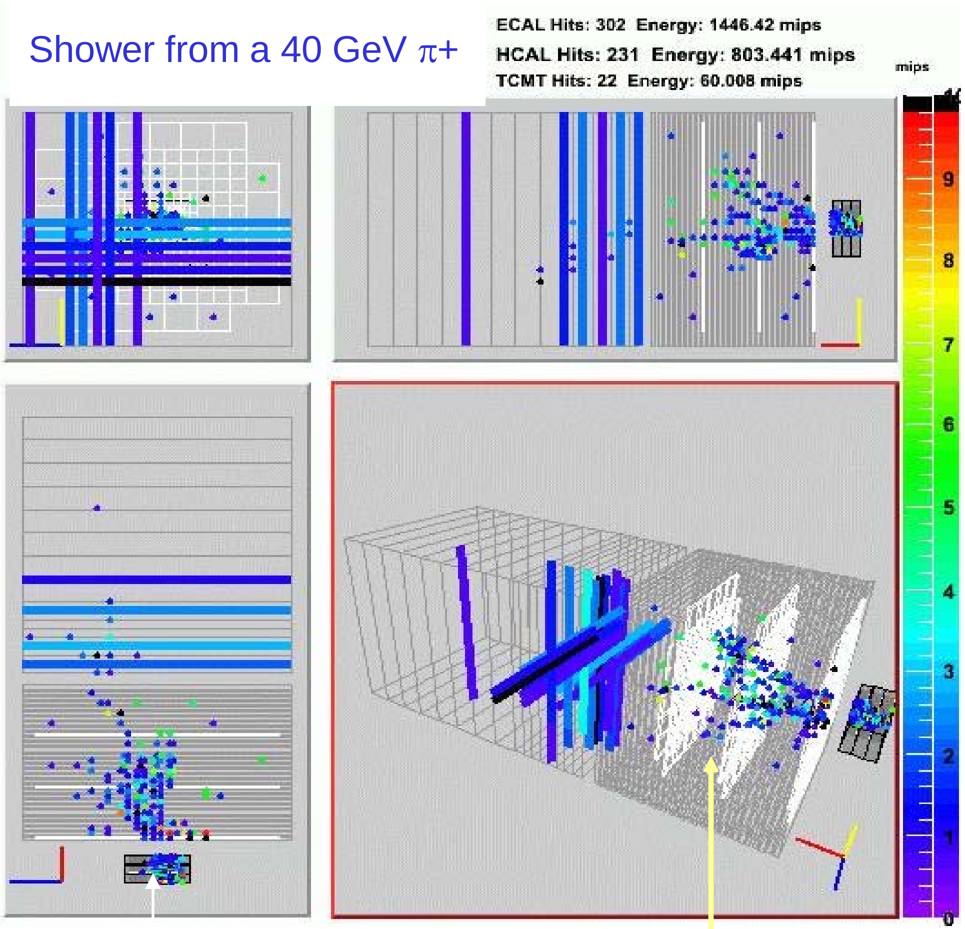


Light intensity for 8000 channels within factor 2
>94% calibration efficiency on full calorimeter

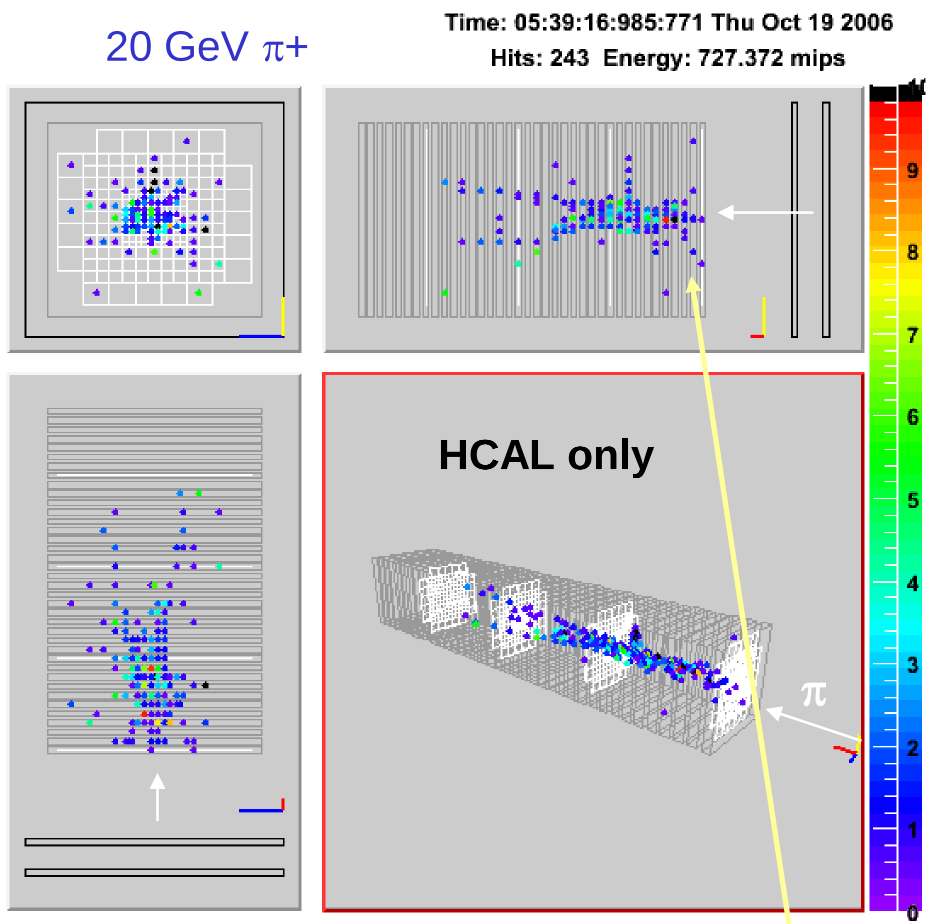
The power of high granularity

REAL DATA!

Shower from a 40 GeV π+



20 GeV π+



Clear structure visible in hadronic shower

Back-scattered particle

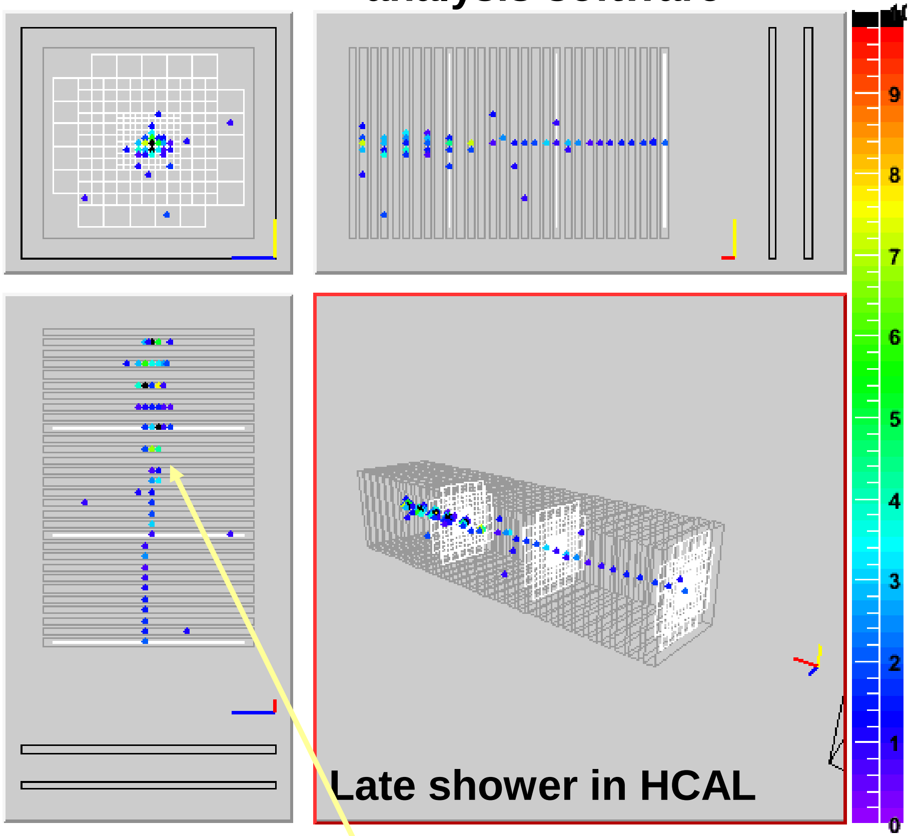
The power of high granularity

REAL DATA!

HCAL

40GeV/c pion with CALICE online analysis software

Imaging calorimetry

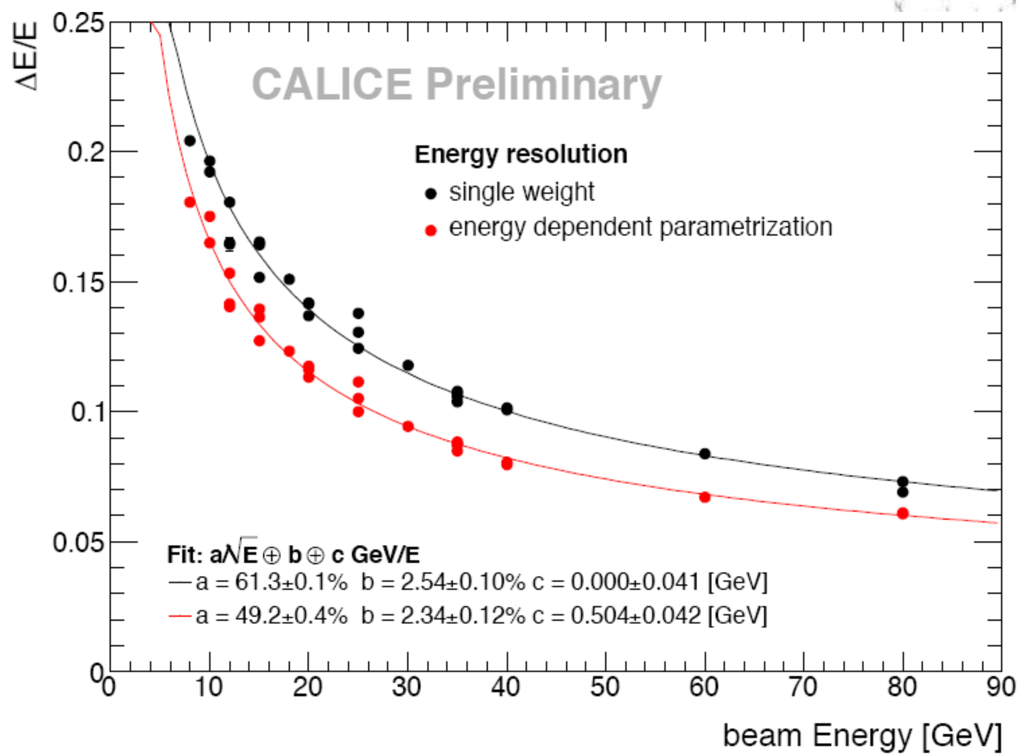


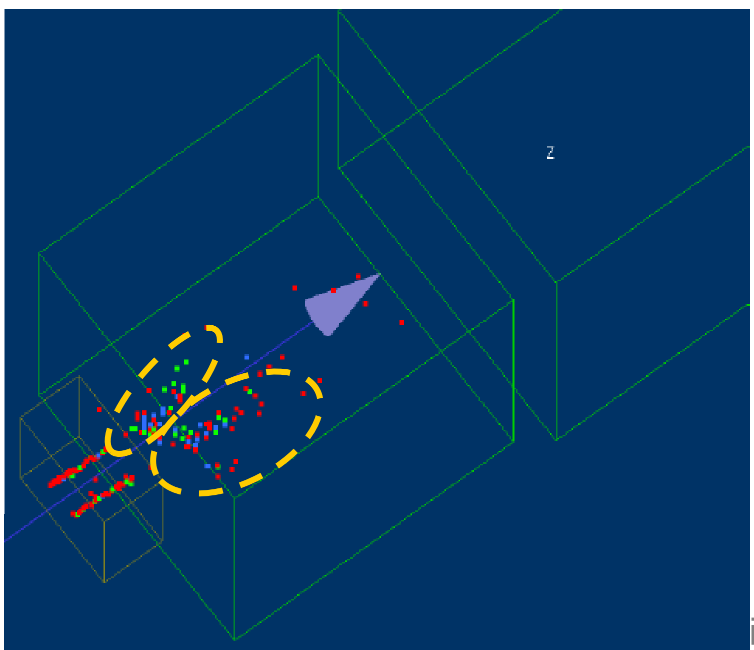
Clear determination of the first interaction

A calorimeter for particle flow

High granularity allows precise weighting techniques for E in each ch.

➔ Single hadron energy resolution using energy density weights $\sim 50\%/\sqrt{E}$





Particle flow ➔ tomorrow lecture

Key requirement is showers separation and NOT single hadron resolution!

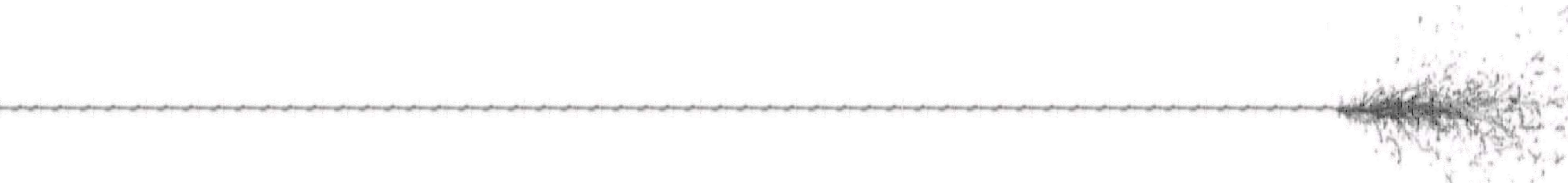
Summary

We have seen a selection of existing / working calorimeters based on various technologies:

- Homogeneous calorimeter
- Ionization sampling chamber
- Scintillator sampling calorimeter

We have compared pro/cons and discussed results from various calo.

Lecture of tomorrow : Particle flow calorimetry
i.e. highly granular calorimeters
- ultimate granularity: digital HCAL
- silicon micro-pixels r/o: digital ECAL



Calorimetry
- particle flow -

Erika Garutti
DESY

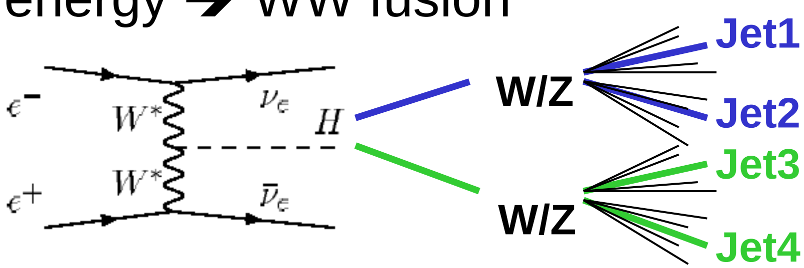
Jet physics

After discoveries (LHC) ➔ precision physics ➔ lepton machine

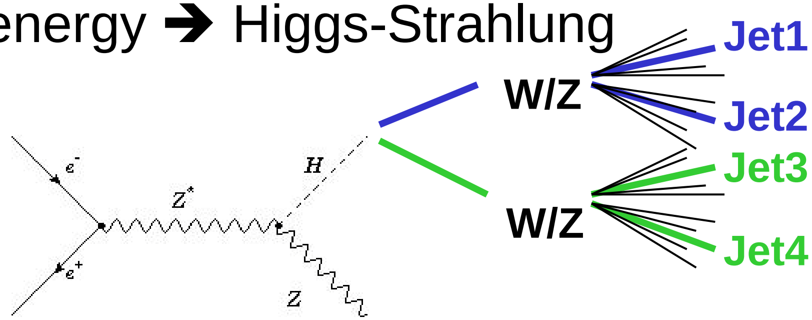
The Higgs scenario:

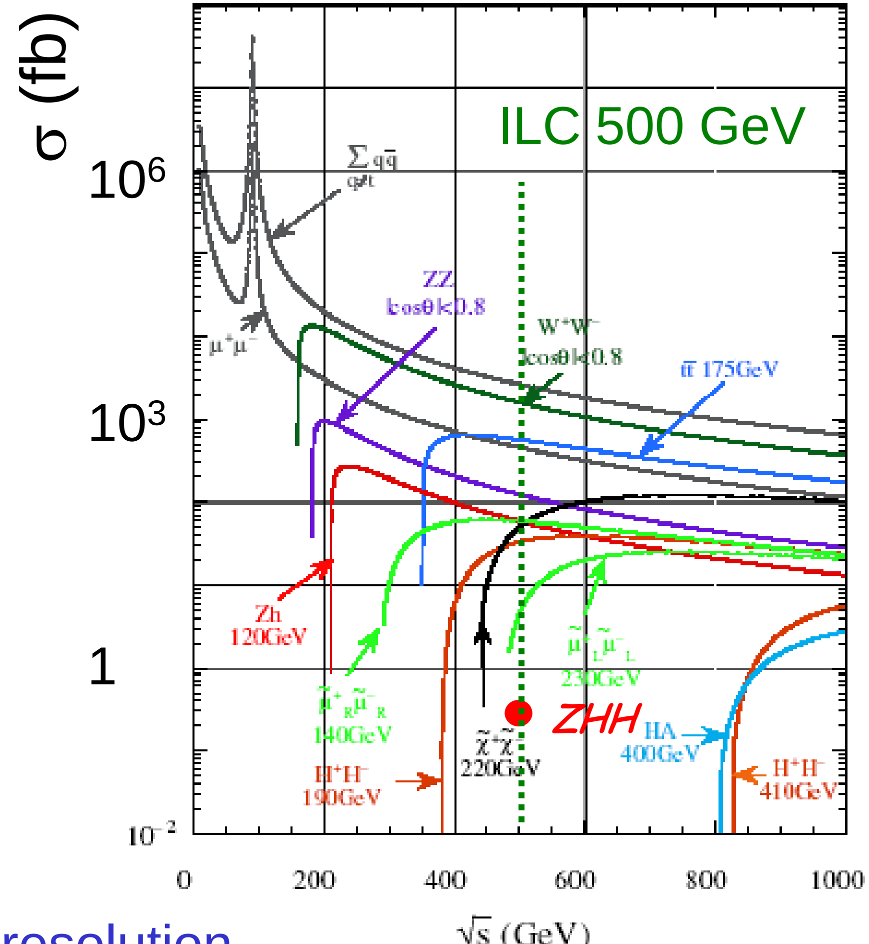
main production mechanisms

High energy ➔ WW fusion



Low energy ➔ Higgs-Strahlung





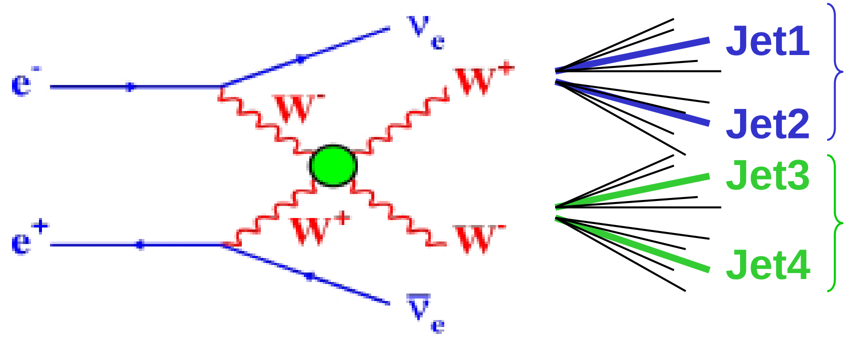
➔Jet physics

Build a detector with excellent jet energy resolution

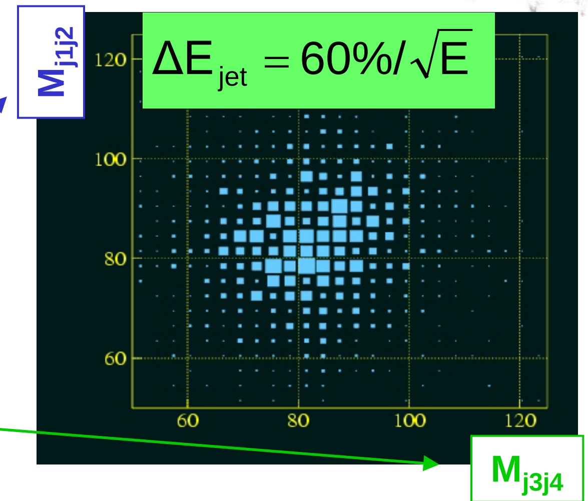
Jet physics (continue)

No Higgs scenario:

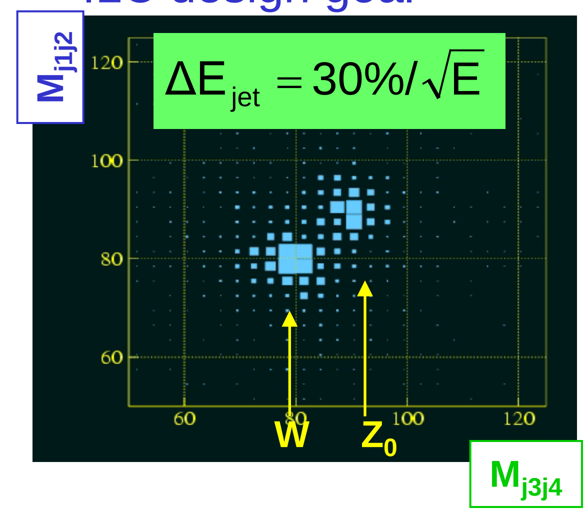
•WW scattering violates unitarity at ~1.2TeV, or new forces show up



LEP-like detector



ILC design goal



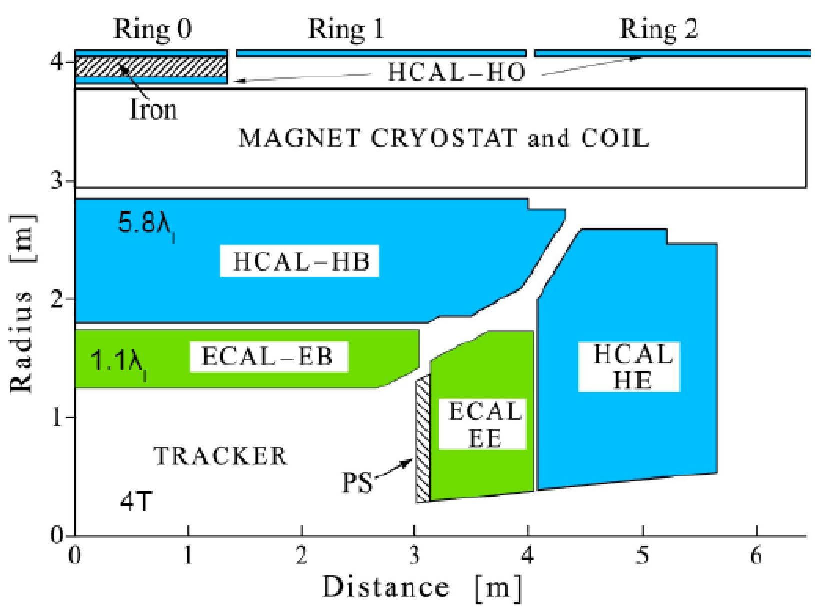
•access EWSB mechanism from WW scattering

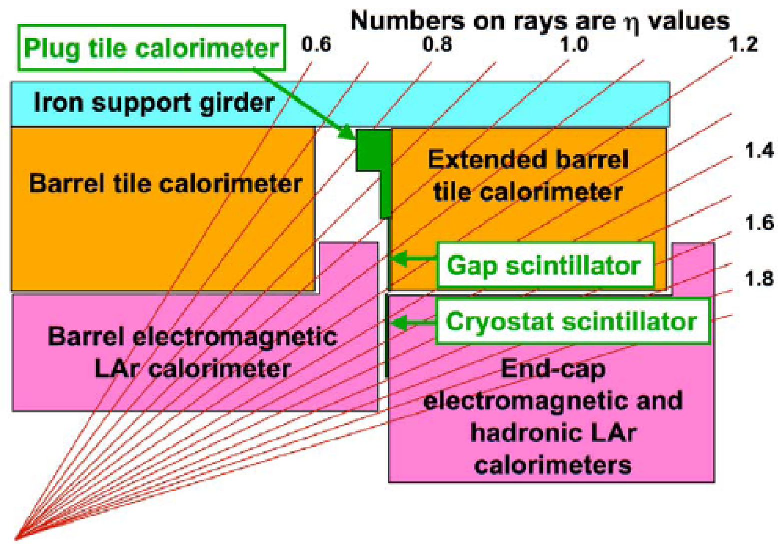
•analyze ee→WWνν and ee→ZZνν channels

•no kinematic fit possible due to the neutrinos

➔Worse jet energy resolution (60%/√E) is equivalent to a loss of ~40% luminosity

Jet energy resolution at LHC





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

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

Expected jet resolution:

$$\frac{\sigma}{E} = \frac{125\%}{\sqrt{E}} \oplus \frac{5.6\ \text{GeV}}{E} \oplus 3.3\%$$

Jet resolution with weighting:

$$\frac{\sigma}{E} = \frac{60\%}{\sqrt{E}} \oplus 3\%$$

Stochastic term for hadrons only: ~93% and 42% respectively

Calorimeter for Particle Flow

jet energy resolution is worse than or at most as good as hadron resolution
➔for the precision physics planned for the next machines we need more

Next ➔ how to improve jet energy resolution to match the requirement of the new physics expected in the next 30-50 years

➔ Need to “get rid of” fluctuations

Two approaches:

- minimize the influence of the calorimeter
  ➔ use combination of all detectors

- measure the shower components in each event
  ➔ access the source of fluctuations

The first idea: Energy flow

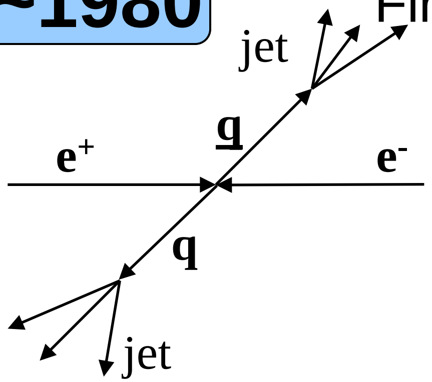
Idea (early 90ies):

- Combine energy measurement from the calorimeter with the momentum measurement from the tracking
- To not double count the energy: energy deposited in the calorimeter by the tracks has to be masked

- First algorithms developed by Aleph: clean e+/e- environment
- Algorithms also developed by H1 for inclusive measurements, successfully adapted by CDF:
  - extrapolate track to the inner surface of the calorimeter and apply a cone or a cylindrical mask to the calorimeter cells behind the track
  - maximize between the energy in the mask and the track momentum

Energy flow history

~1980

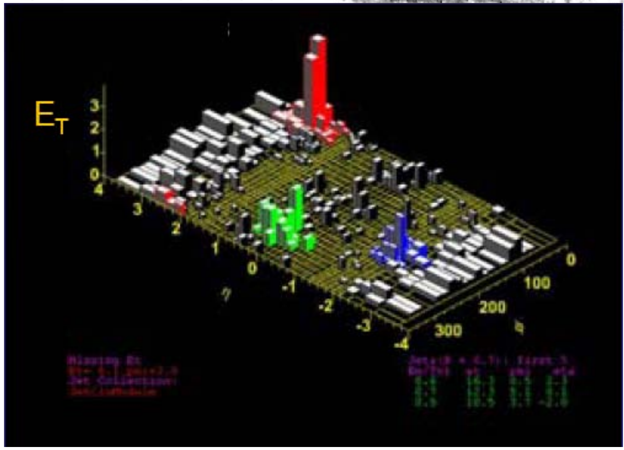


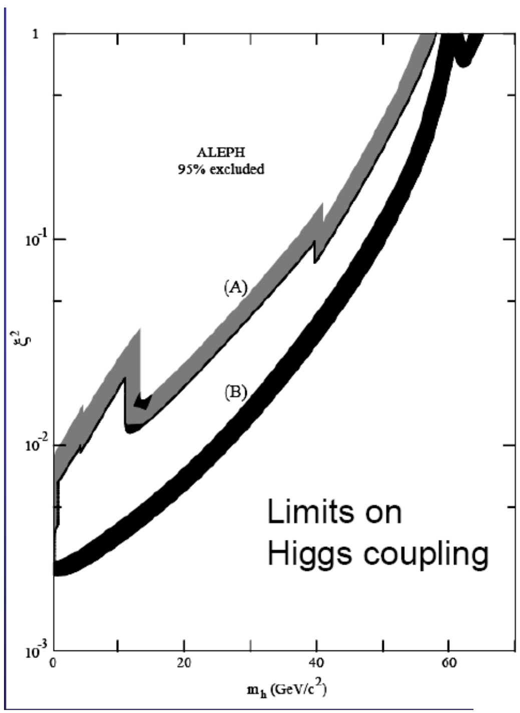
First observation of quark Jets

UA1, UA2 @ SppS, CERN
JADE @ PETRA collider, DESY

Traditional Jet measurement:
use the calorimeter alone

→ example of CDF life event





Discovery of new physics requires higher resolution

First application of Energy Flow Algorithm

ALEPH detector searching for Higgs

1990

Use tracker information to improve jet energy resolution

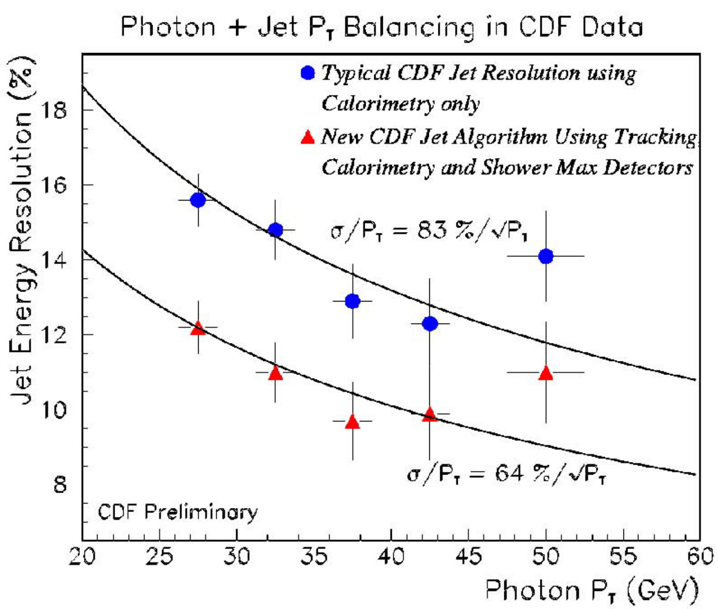
Particle Flow Algorithms

Does the method work ?

Test on existing detectors

ALEPH, CDF, ZEUS, …

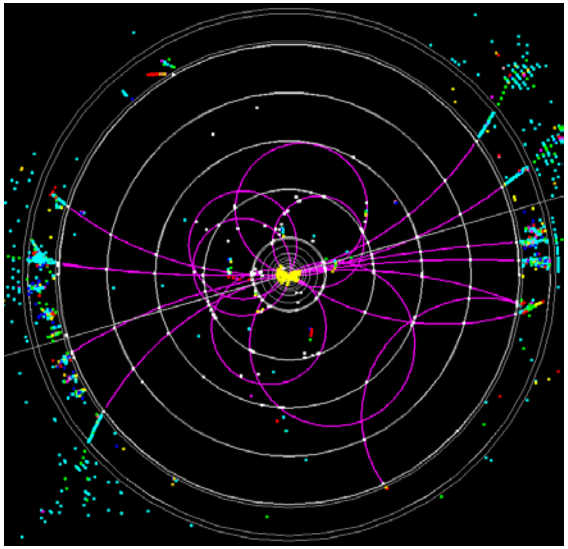
→Significantly improved resolution



YES ! But that is not enough …

Goal of the Linear Collider

Design a detector optimized for Particle Flow application



Particle Flow paradigm

➔ reconstruct every particle in the event

up to ~100 GeV **Tracker** is superior to calorimeter →

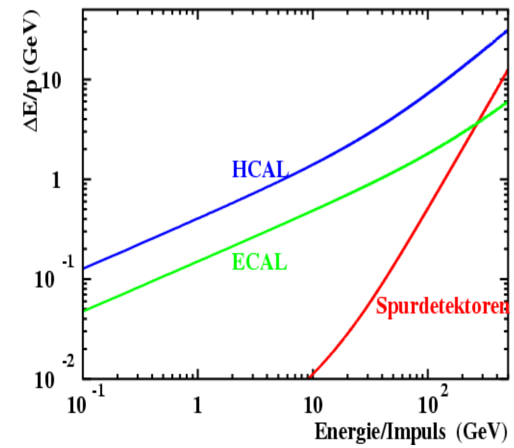
use tracker to reconstruct **e ,μ ,h** (<65%> of E_{jet})

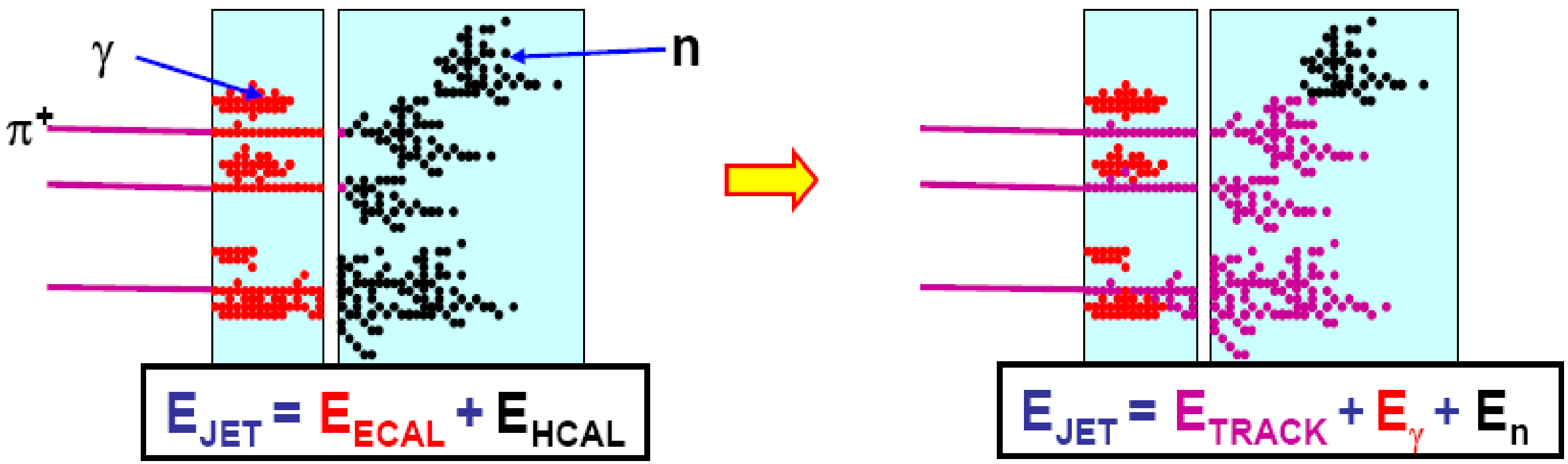
use **ECAL** for γ reconstruction (<25%>)

(ECAL+) HCAL for $\mathbf{h^0}$ reconstruction (<10%>)

HCAL E resolution still dominates E_{jet} resolution

But much improved resolution (only 10% of E_{jet} in HCAL)





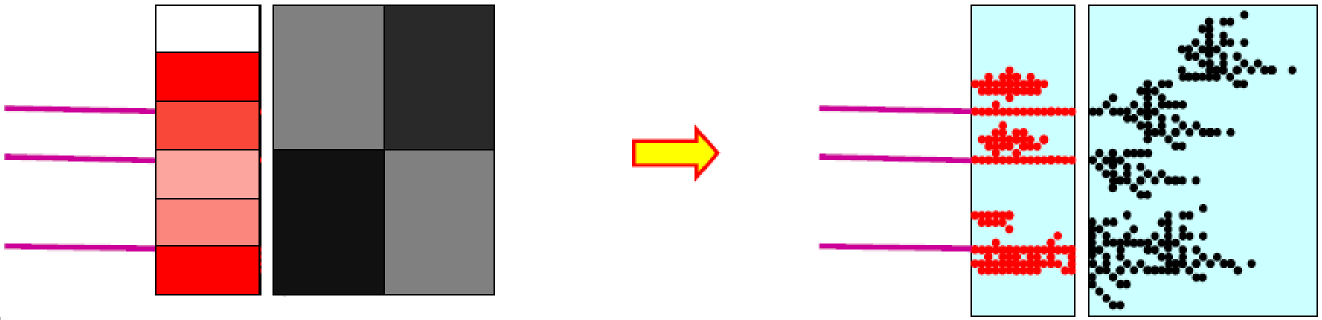
PFLOW calorimetry = Highly granular detectors
+ Sophisticated reconstruction software

Particle flow calorimetry

Hardware:

★Need to be able to resolve energy deposits from different particles

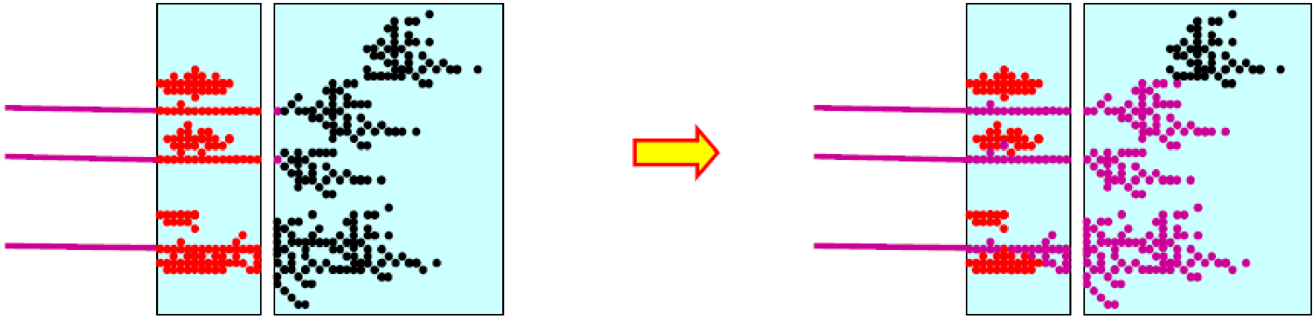
➡ Highly granular detectors (as studied in CALICE)



Software:

★Need to be able to identify energy deposits from each individual particle !

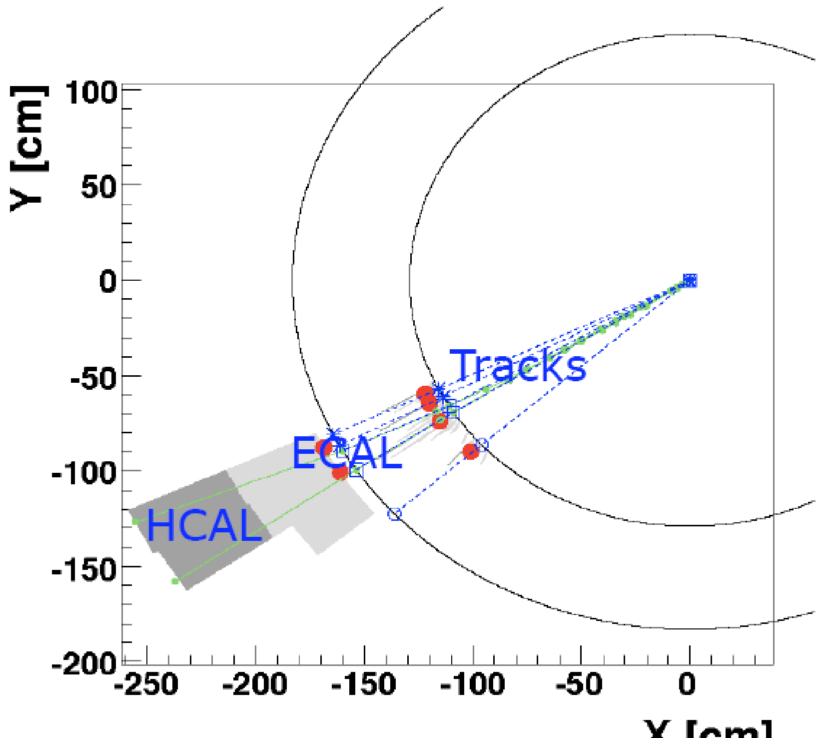
➡ Sophisticated reconstruction software



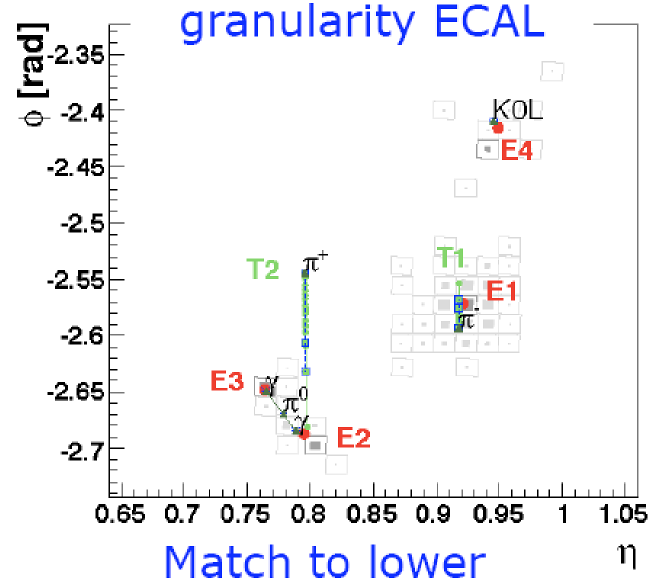
★Particle Flow Calorimetry = HARDWARE + SOFTWARE

Particle Flow @ LHC

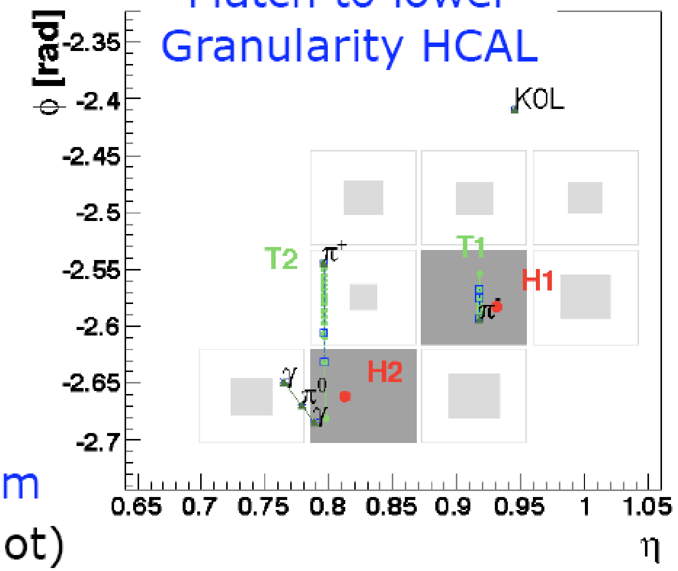
CMS



Match track to high granularity ECAL



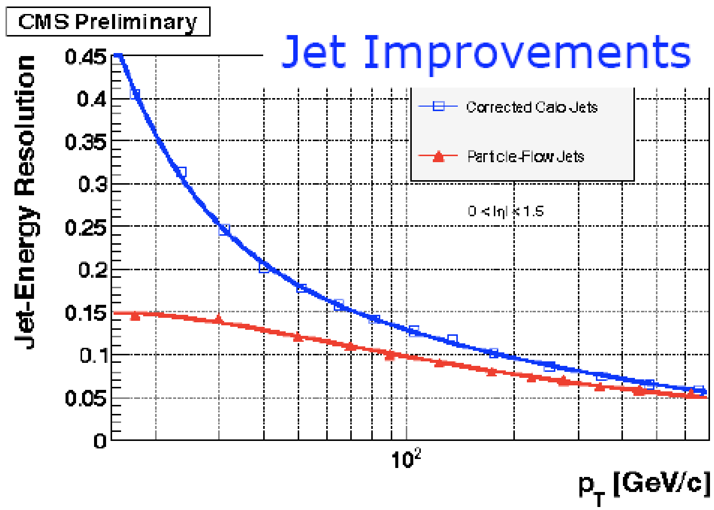
Match to lower Granularity HCAL

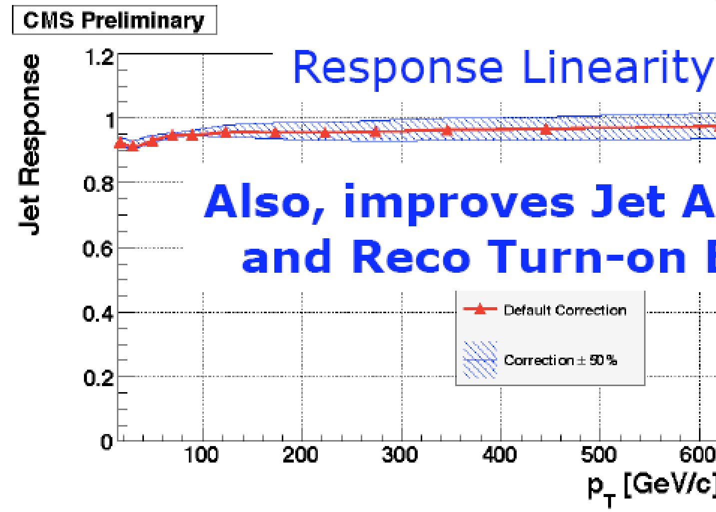


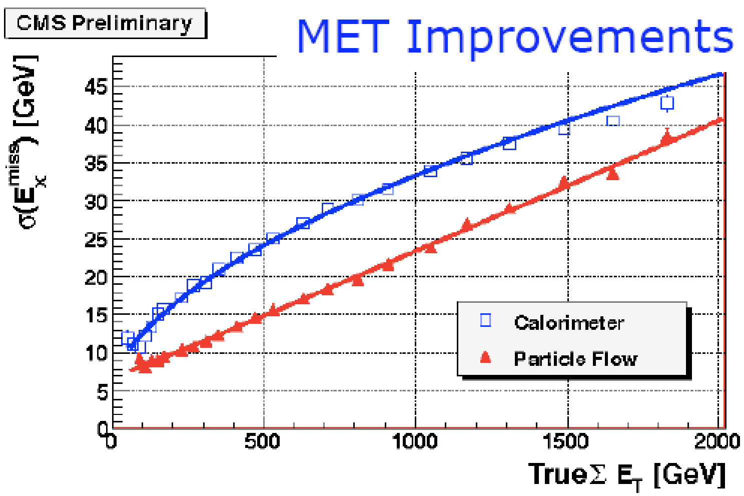
1) Leverage High Precision Tracking
2) And High Resolution ECAL EM-Showers
3) Match and Discard Charged Hadron Showers Replacing with Track Momentum

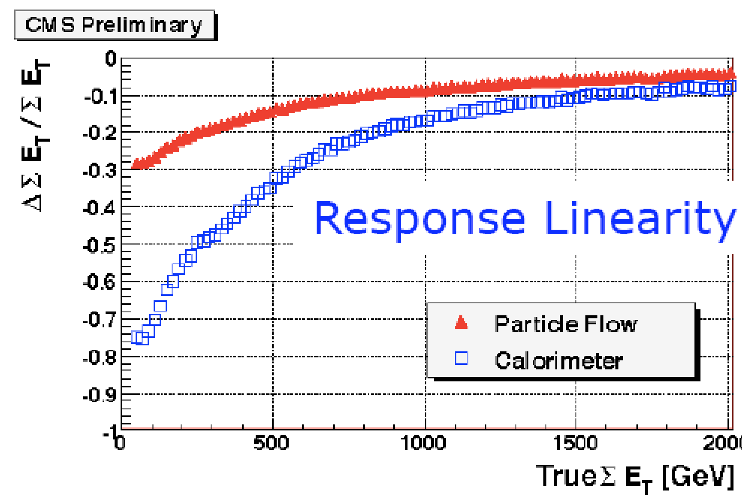
(Courtesy of P. Janot)

PFlow improvements at CMS









10

Summary of PFlow concept

Particle flow is a concept to improve the jet energy resolution of a HEP detector

It is based on:

proper detector design (high granular calorimeter!!!)

+ sophisticated reconstruction software

PFlow techniques have been shown to improve jet E resolution in existing detectors, but the full benefit can only be seen on the future generation of PFlow designed detectors

➔ push to ultimately small single calorimeter cells:

~ 5x5 mm^2 – 50x50 um^2 for ECAL

~ 1cm^2 for HCAL

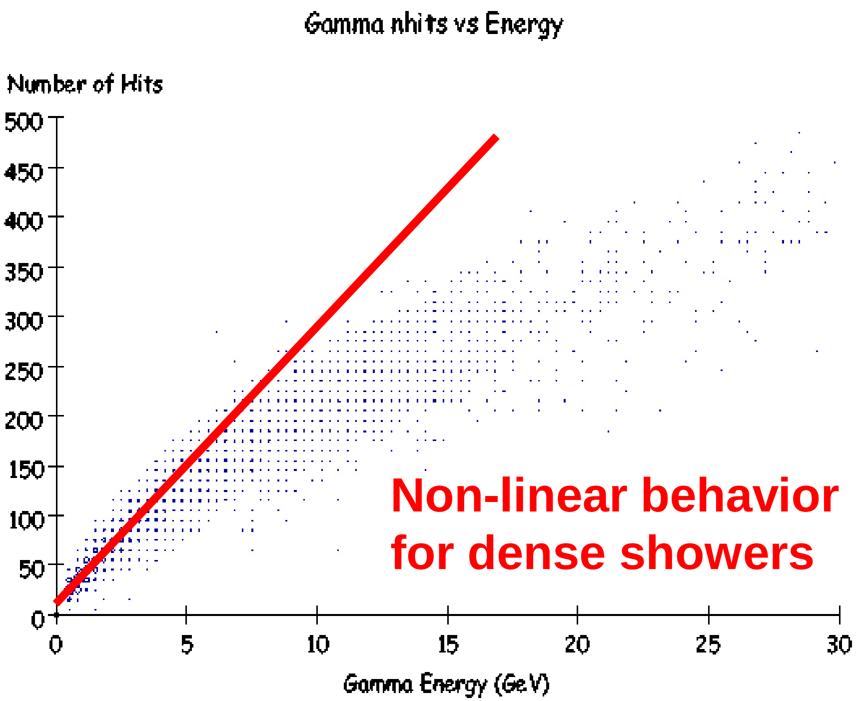
➔ Develop new techniques

Analog .vs. Digital

photon analysis

$$E_\gamma \neq \sum N_i$$

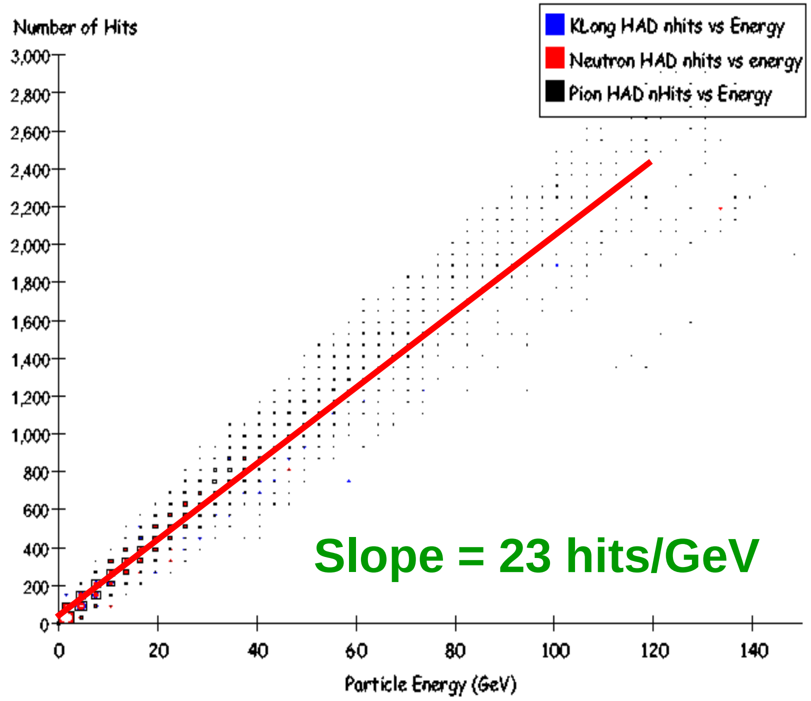
ECAL: Analog readout required



hadron analysis

$$E_h \propto \sum N_i$$

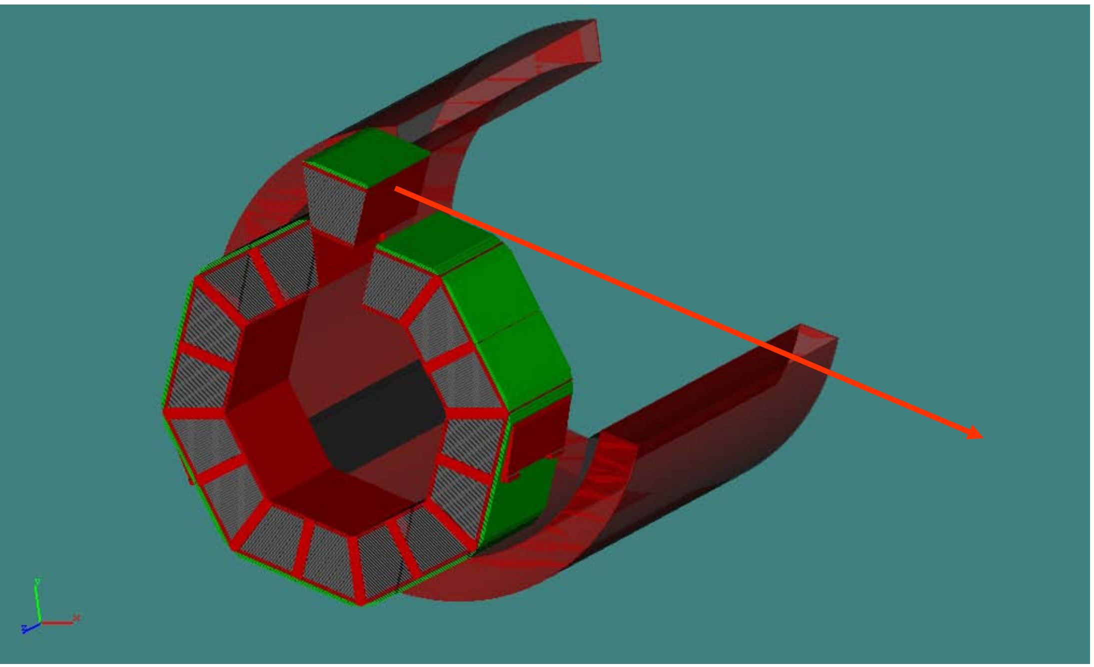
HCAL: either Analog or Digital readout



Calorimeter cell size 1x1cm^2

Analog HCAL with high granularity

A calorimeter for the ILC detector ➔ ILD one of the two proposed concepts

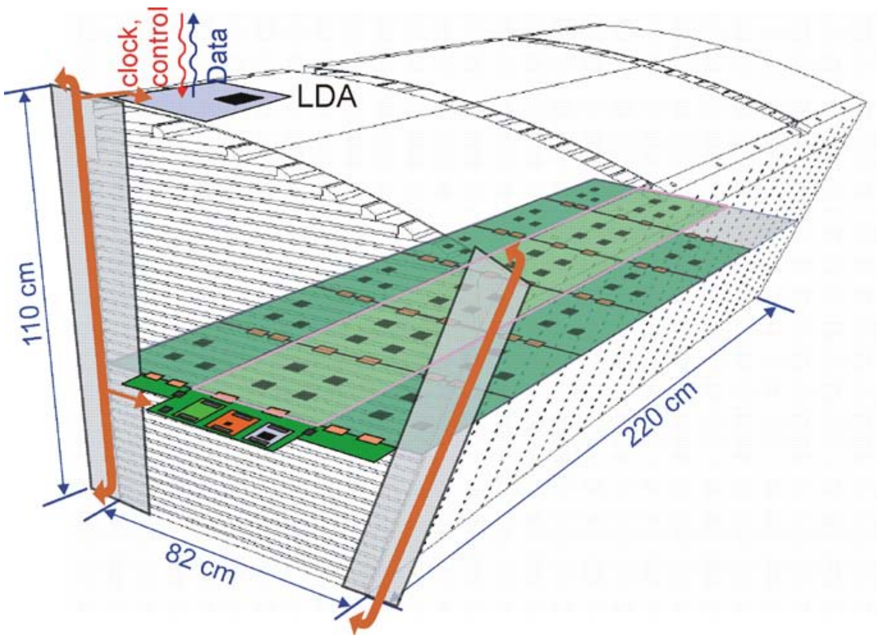


Mechanics:
challenging design with no spacers
➔ validated
plates flatness below 1mm
➔ solved at low cost with roller leveling technique

- no spacer between layers in the wedge
- minimize dead material between wedges
- minimize gap between barrel and end-cap

➔ integrated readout electronics

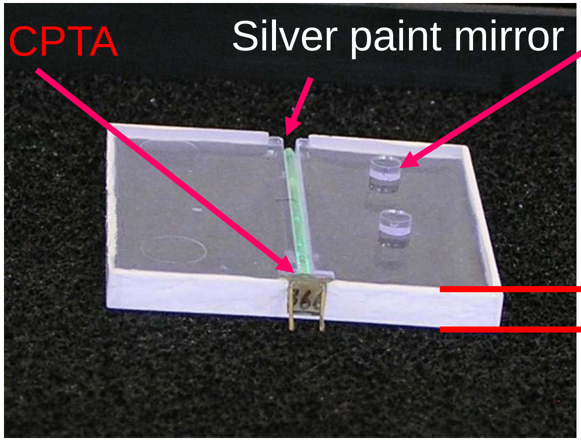
Analog HCAL with high granularity



Sandwich structure of steel/scint.
Compact design with minimum dead material + integrated electronics

- “no” gap in z in the barrel
- 10cm gap between barrel and endcap

Engineering prototype



Alignment pin

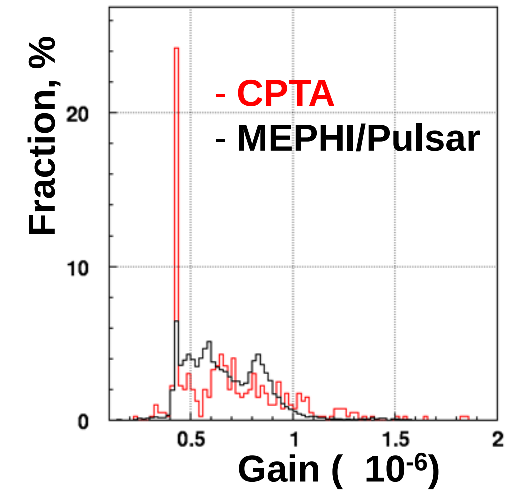
3mm

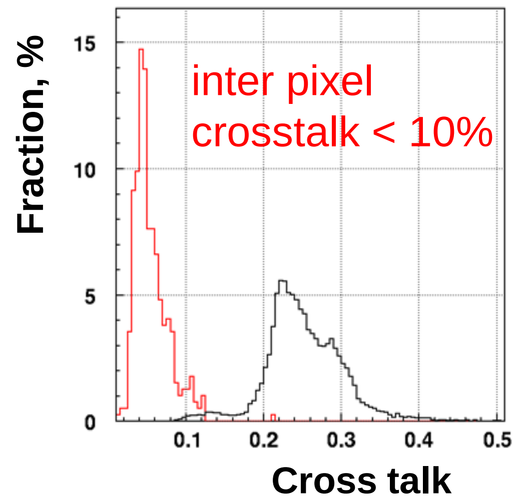
Tile size optimized with Particle Flow
➔ 3x3 cm^2

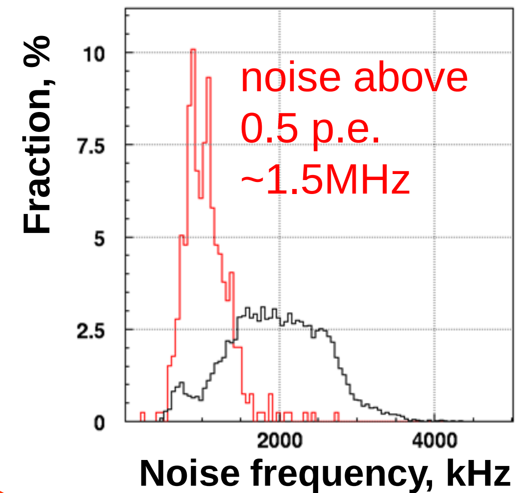
Tile thickness 3mm for ILD design

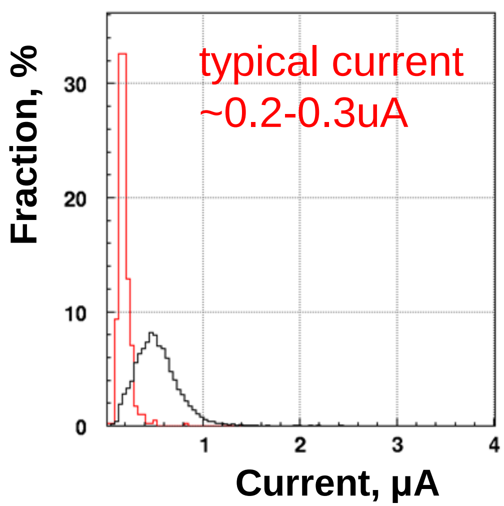
Light yield ~ 10 – 11 p.e. / MIP

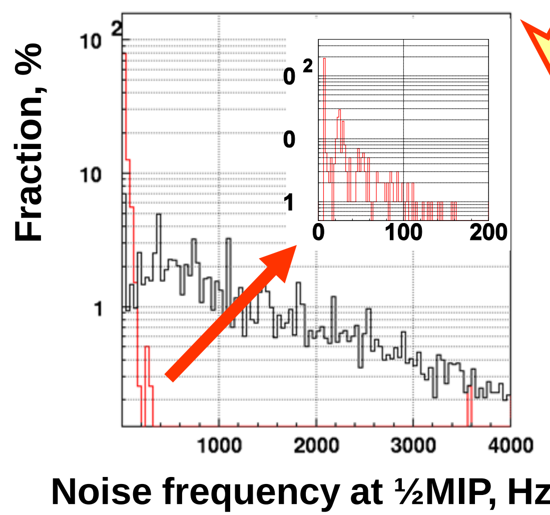
SiPM parameters



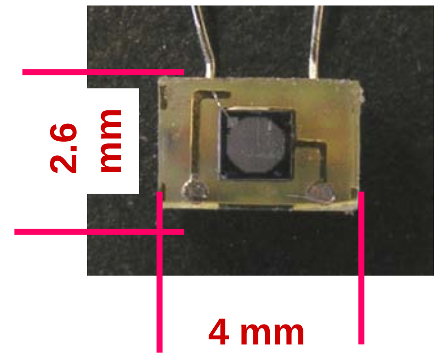




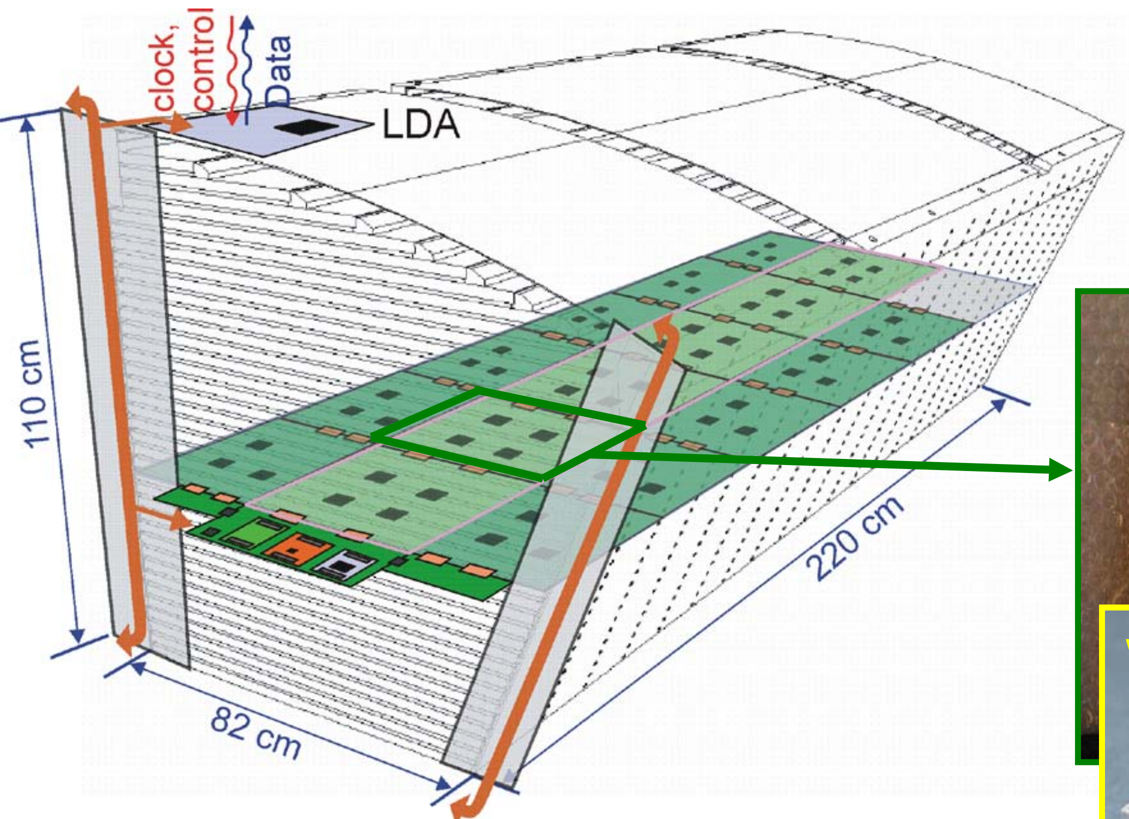




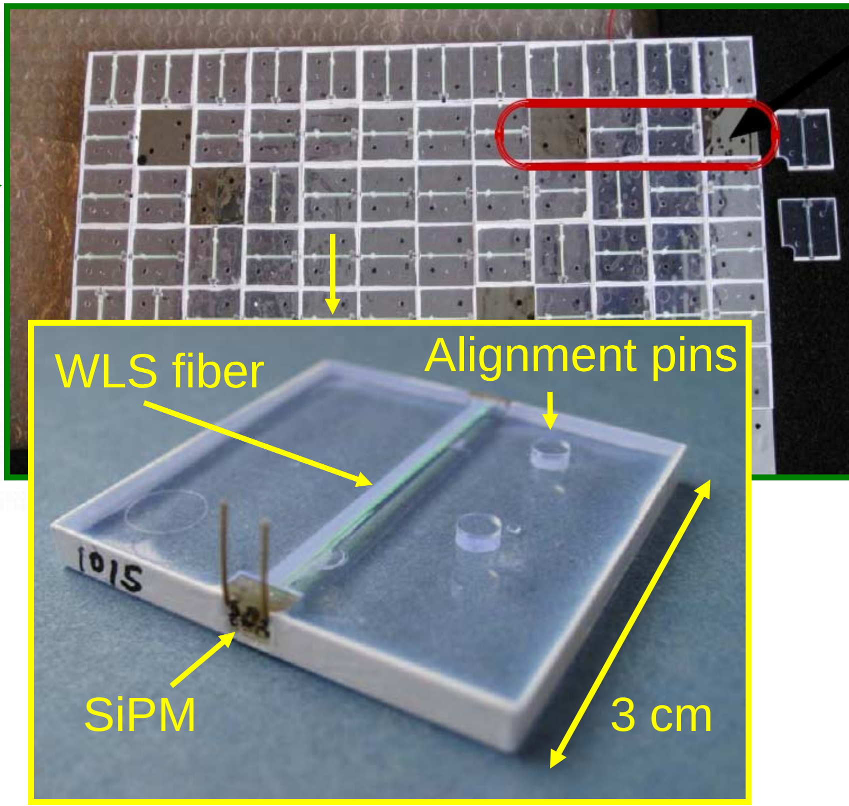
CPTA SiPM



Architecture design (I)

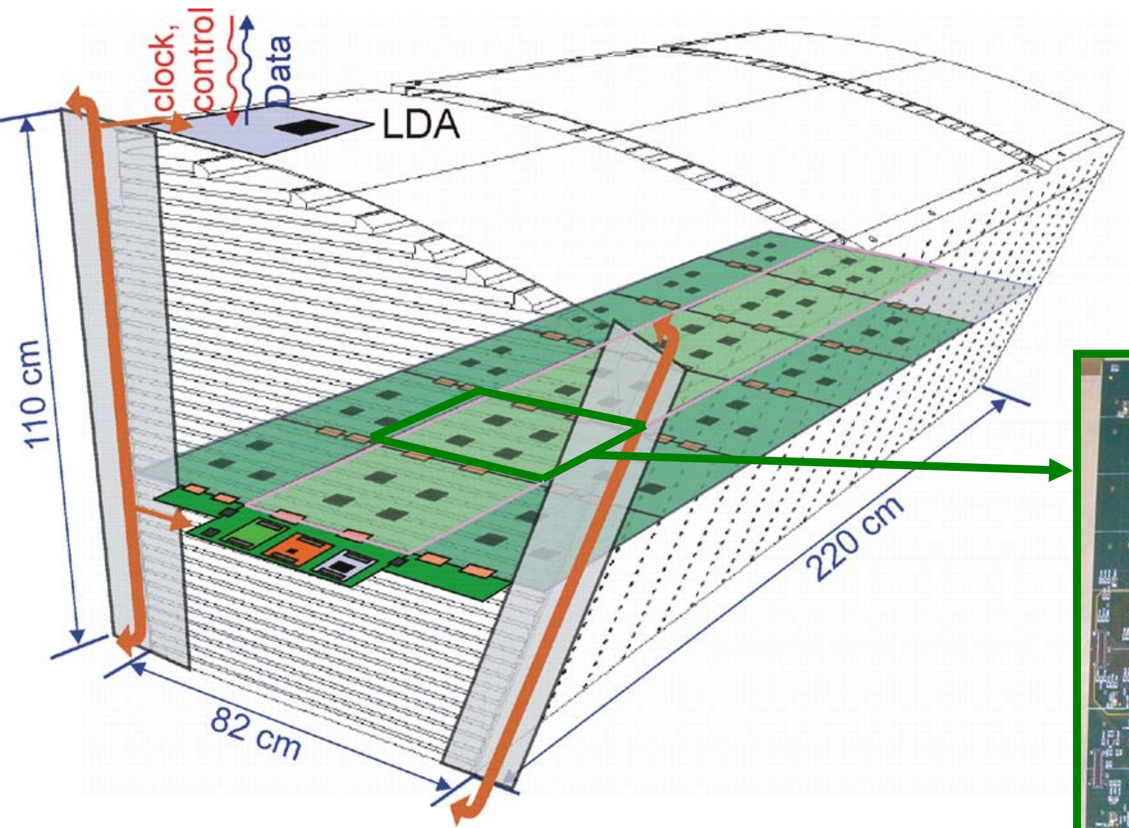


PCB board back side:
- reflector foil layer
- scintillator tiles fixed by alignment pins

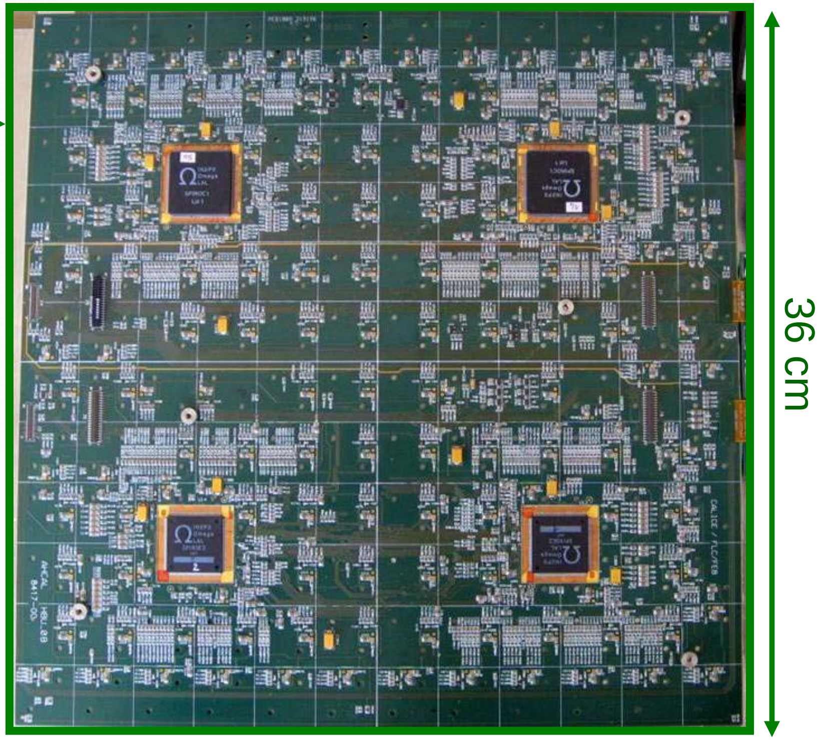


- Front End electronics integrated in active layer
- made of interconnected cassettes (36x36 cm)
- power and calibration modules at barrel edge
- 2.2m long communication lines in the layer

Architecture design (II)



PCB board with 4 SPIROC chips connected to 144 scintillator tiles with SiPM readout

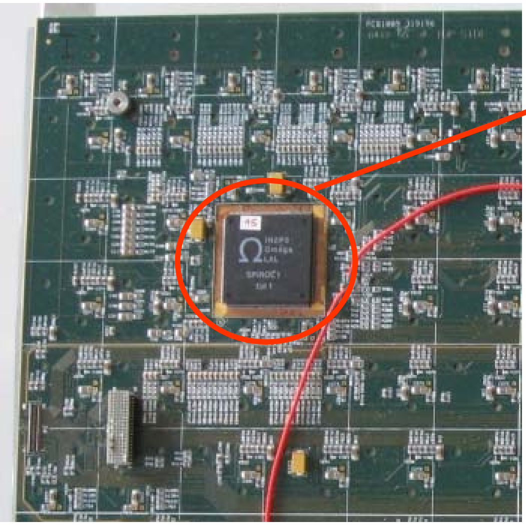


- Front End electronics integrated in active layer
- made of interconnected cassettes (36x36 cm)
- power and calibration modules at barrel edge
- 2.2m long communication lines in the layer

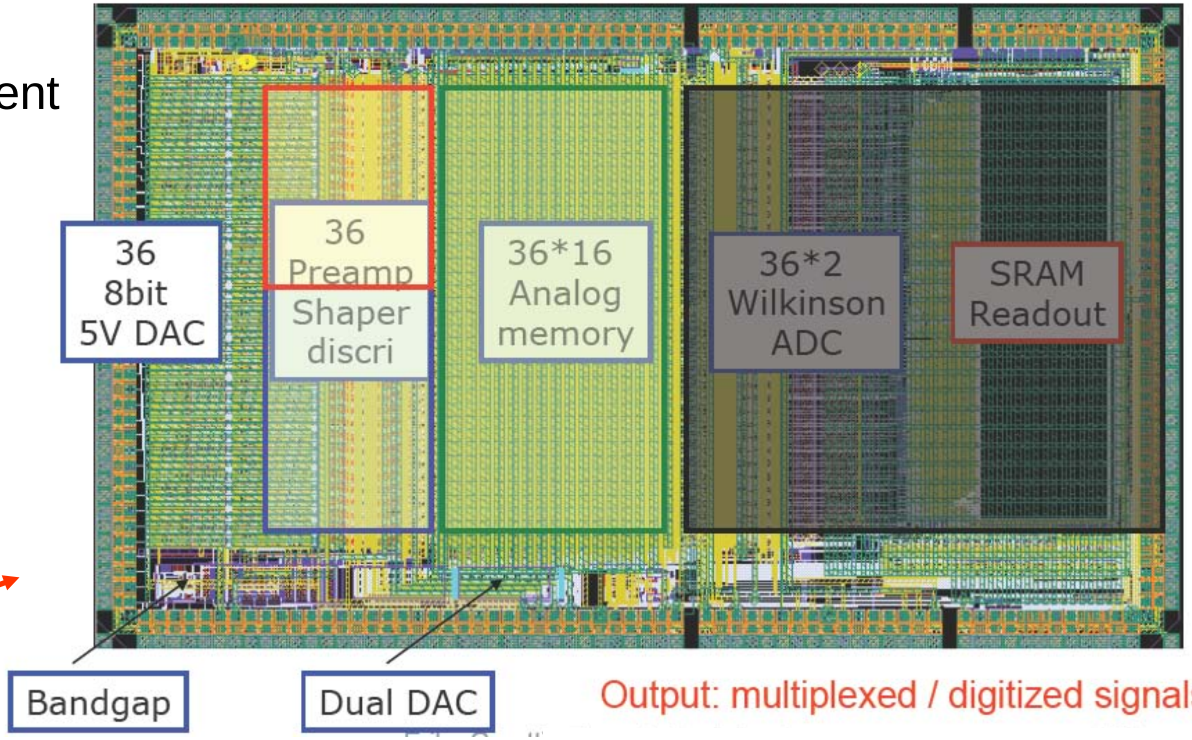
The SPIROC chip

Specific chip for SiPM:
- input DAC for bias adjustment

Designed to work at ILC:
- power pulsing mode
- 25 μW /ch
- internal ADC / TDC
- auto-trigger mode
- time stamp (~1ns)



SPIROC layout (CALICE chip for Analog HCAL readout)



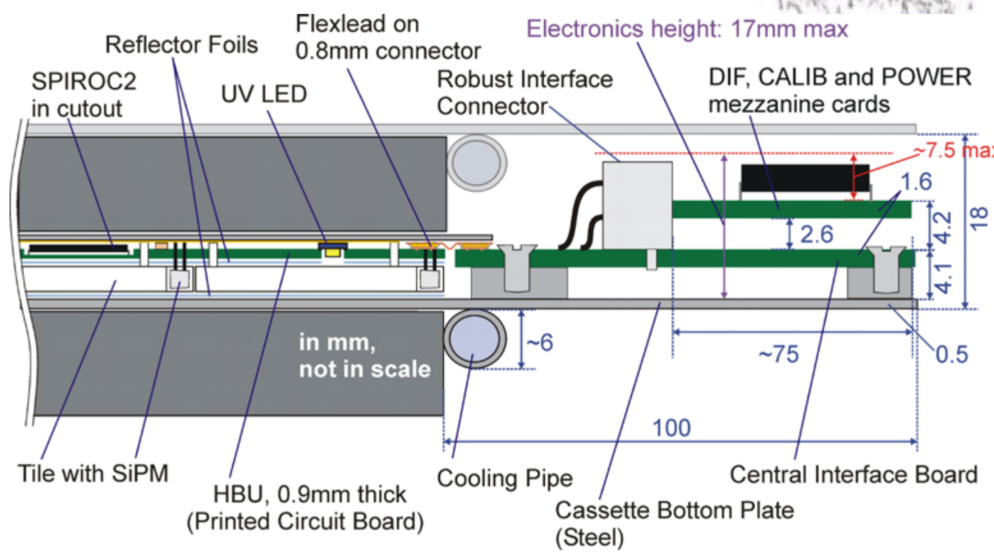
Output: multiplexed / digitized signals

designed by Omega group LAL (Orsay)

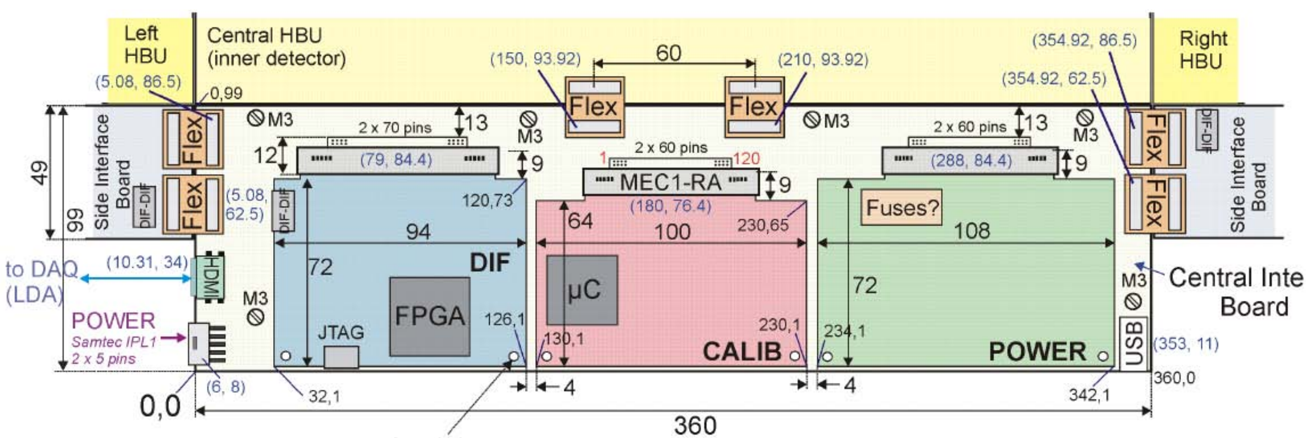
Layer design

Cassette cross-section:

- each calo layer 18 mm including Fe
- 3 mm scintillator tiles
- one SMD-LED mounted on each tile
- flex-lead connection between boards



Connection to the detector interface electronics at the end of the HCAL barrel



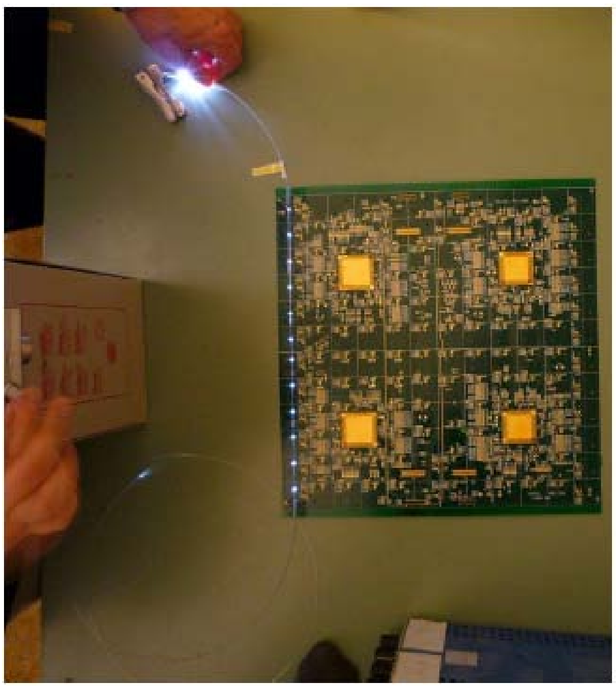
Ultra-thin
Low power consumption
High concentration/data reduction

LED monitoring system(s)

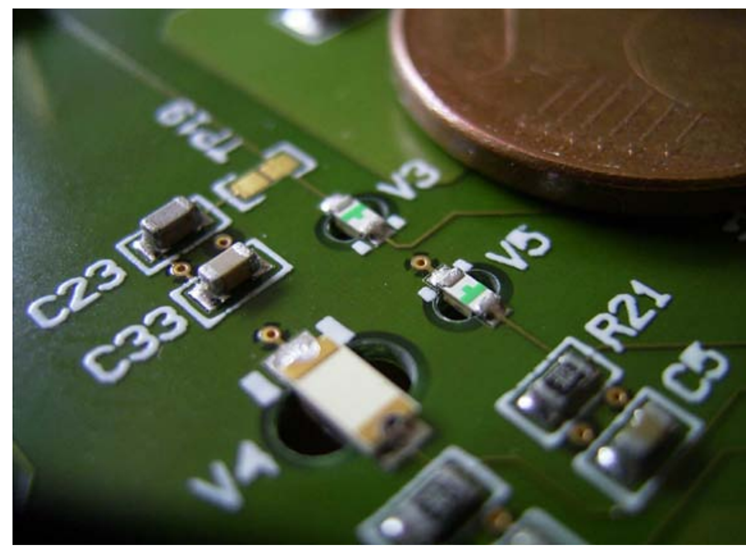
System task: SiPM gain calibration via single photoelectron peak spectra (~1-2 p.e.)
long term stability via response @ medium light (~20-100 p.e.)
measure SiPM saturation level (~2000 p.e.)

Two technological solutions:

Light distributed by notched fibres



Light directly on tile by SMD-LED
- distributed LED



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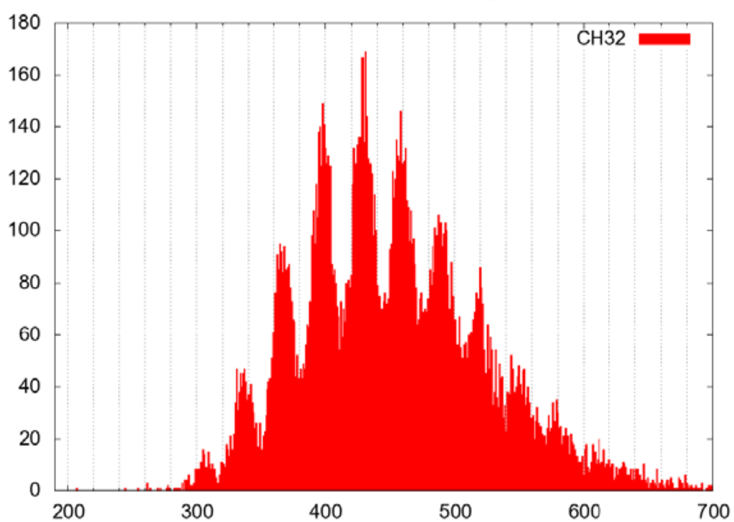
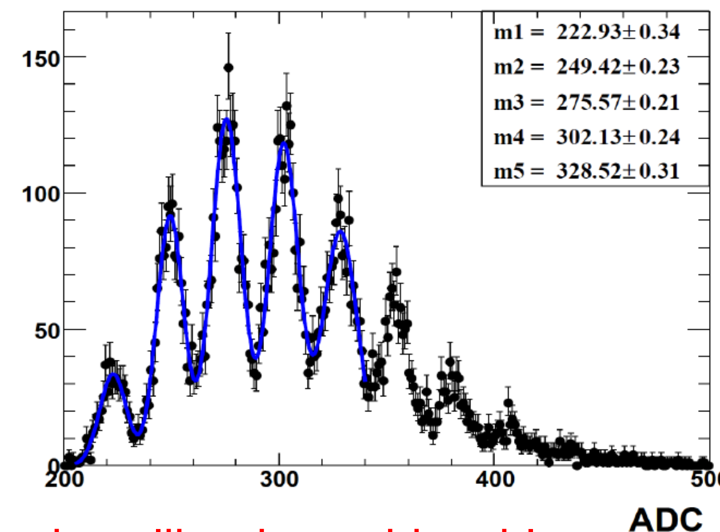


Light directly on tile by SMD-LED - distributed LED



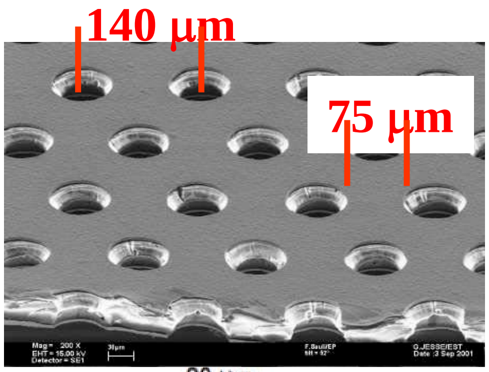
Both systems commissioned ➔ SiPM gain calibration achievable
Next step ➔ reduce spread in light intensity between channels

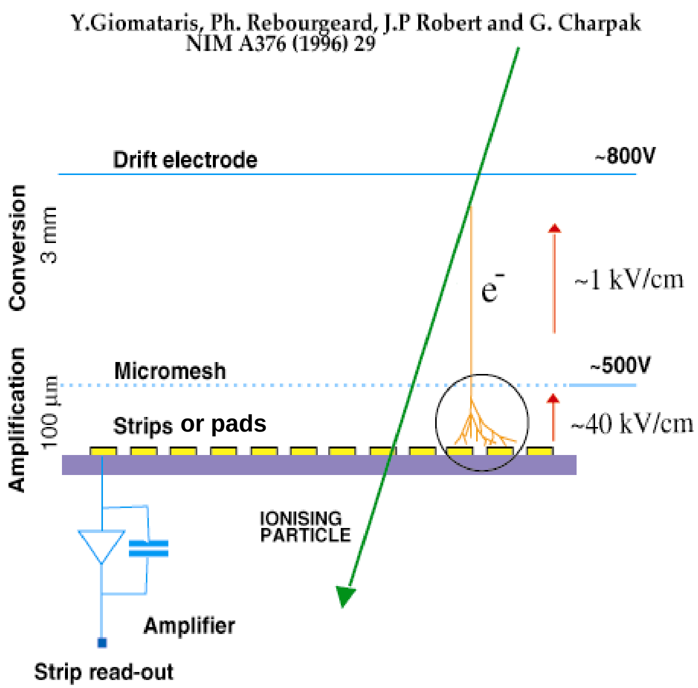
The Digital HCAL: super-high granularity

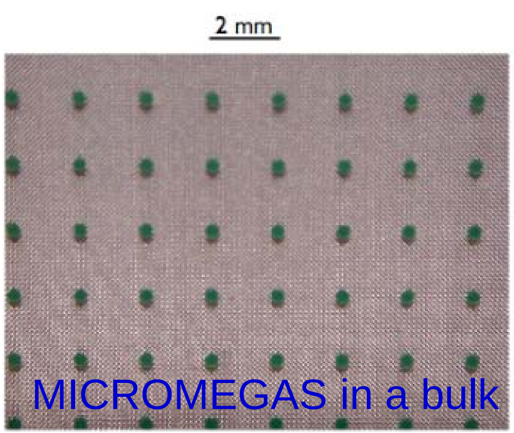
Basic technique for the active media:

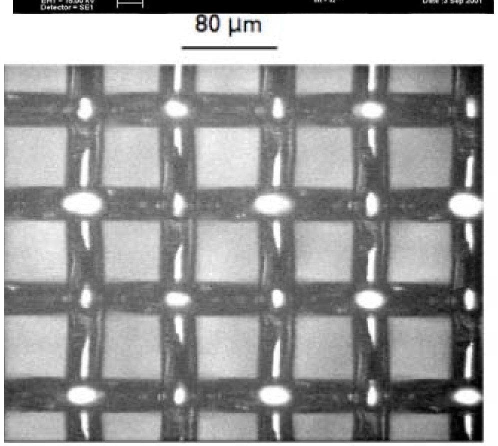
- Ionization-gas chambers with charge amplification (RPC, GEM, MicroMegas)
- digital readout on pads 1x1cm^2
- integrated electronics inside active layer
- high level of data concentration (~0.5 M channels / m^3)

Gas Electron Multiplier foil





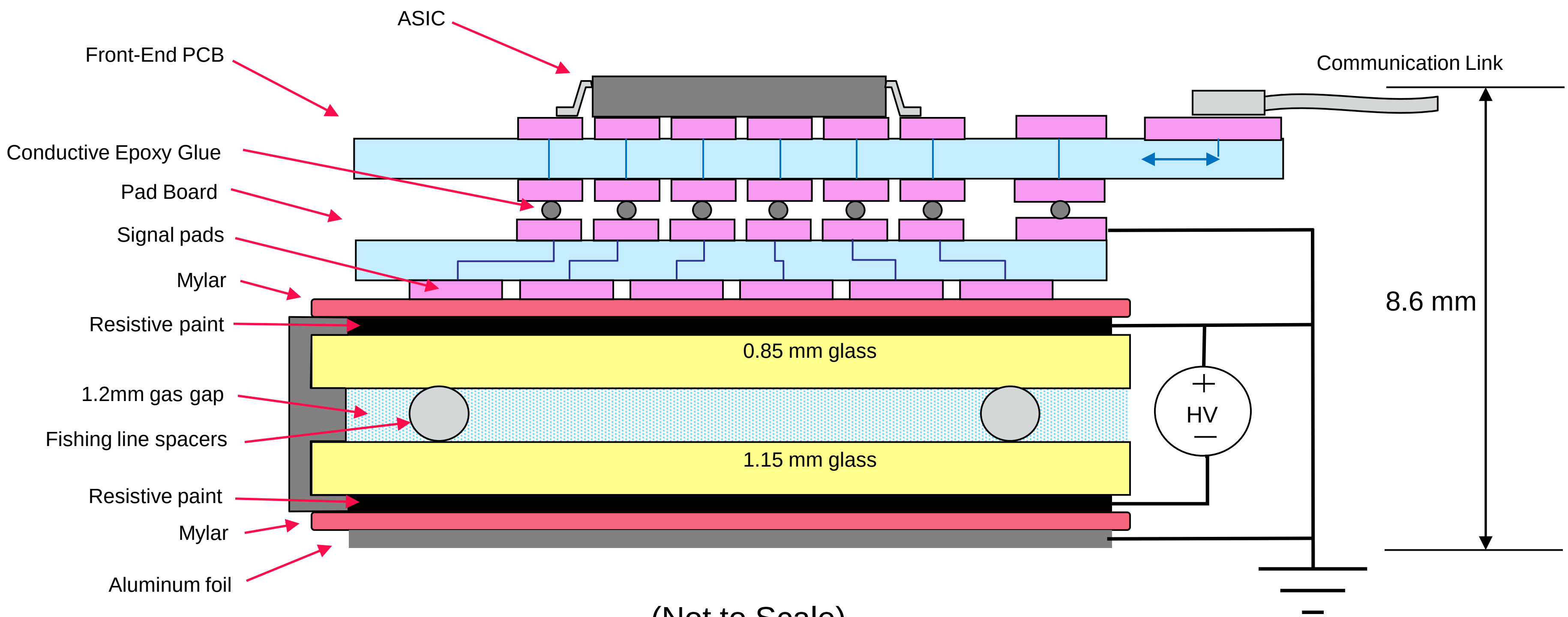




Pillars: 400u Ø, 100u height
Ampl. gap 25-150µm → narrow avalanches
excellent spatial and time resolution

Resistive Plate Chamber readout

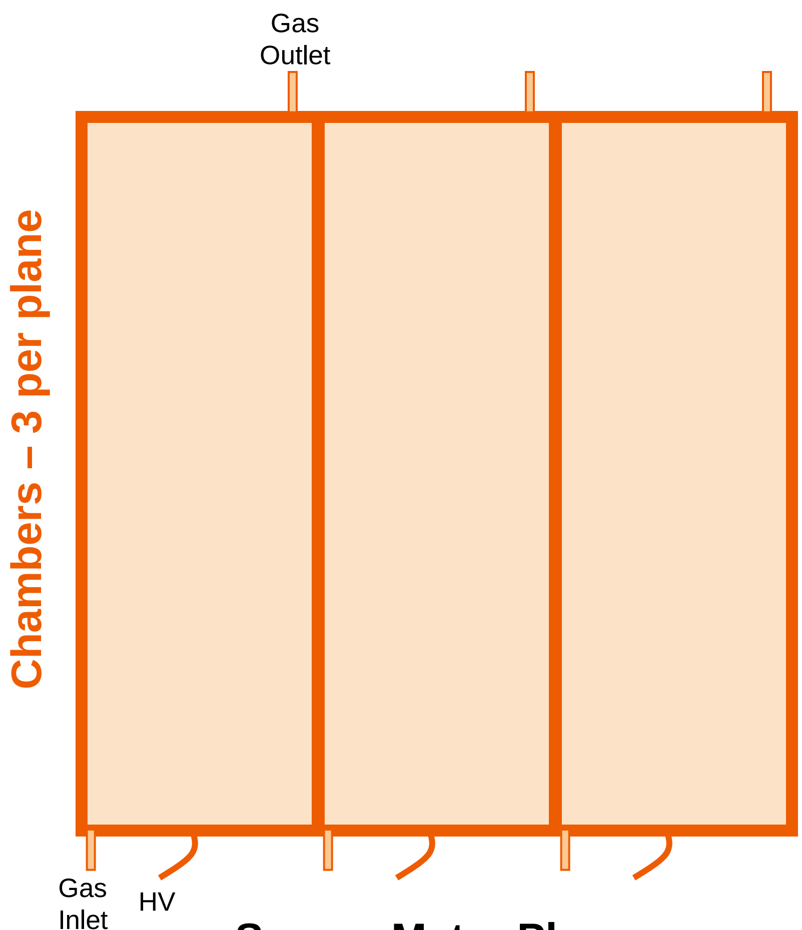
Chamber Construction:



(Not to Scale)

Avalanche mode:
Typical induced charge of
0.1—10 pC/mip with rising time ~10 ns

Digital HCAL with RPC readout

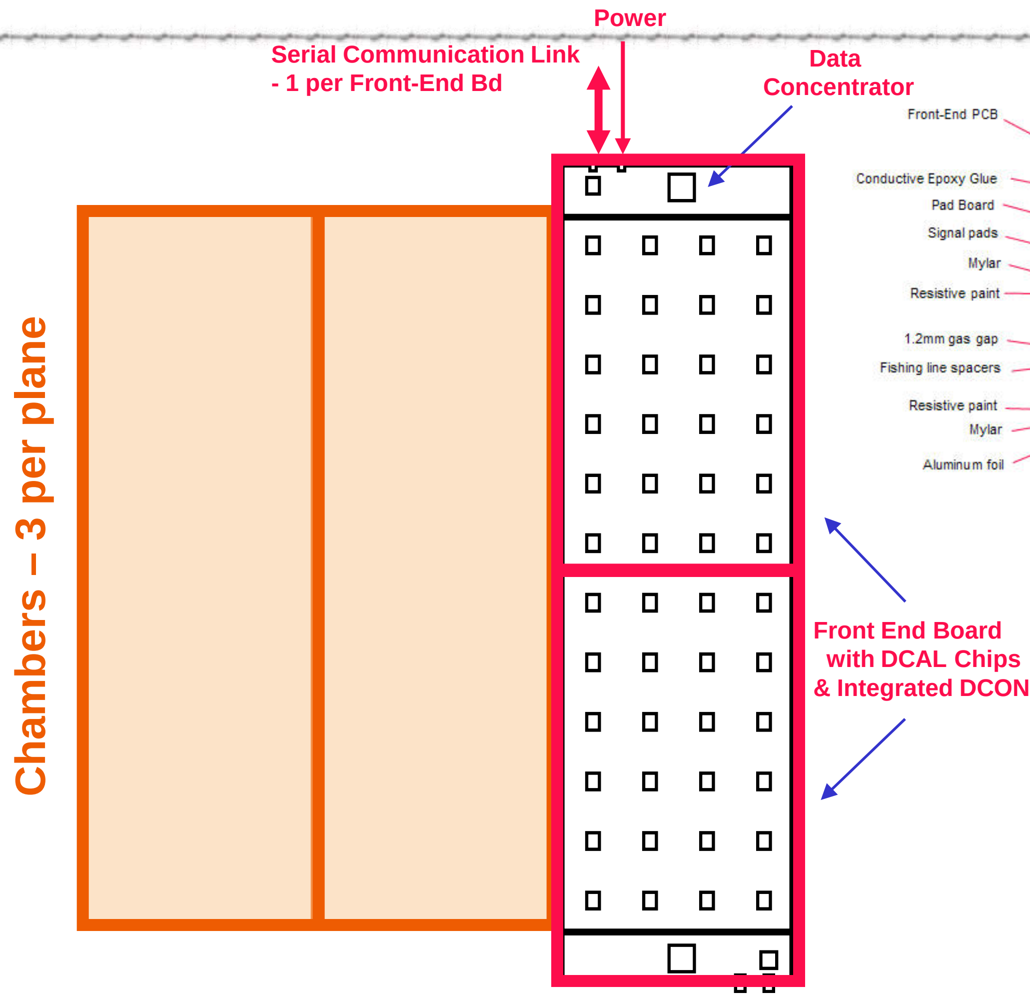


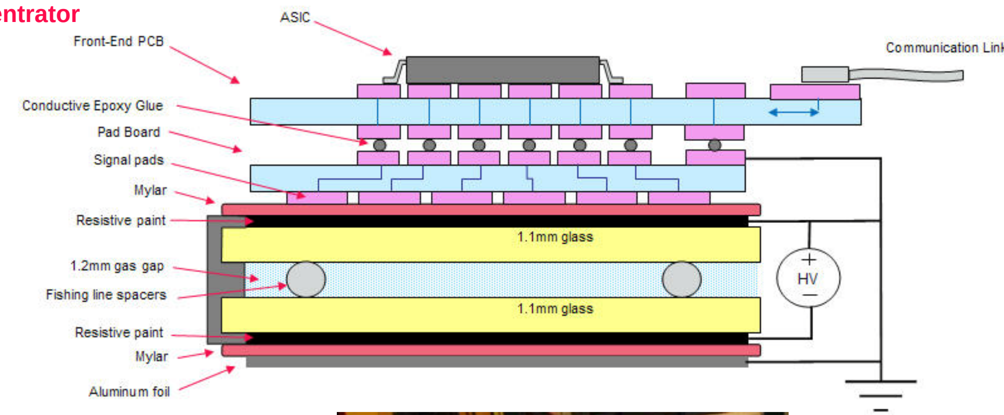
Square Meter Plane
(3) 32 cm X 96 cm chambers

Plane Construction

- A plane consists of 3 independent chambers

Digital HCAL with RPC readout





Square Meter Plane

(2) 32 cm X 48 cm Front End Boards per Chamber

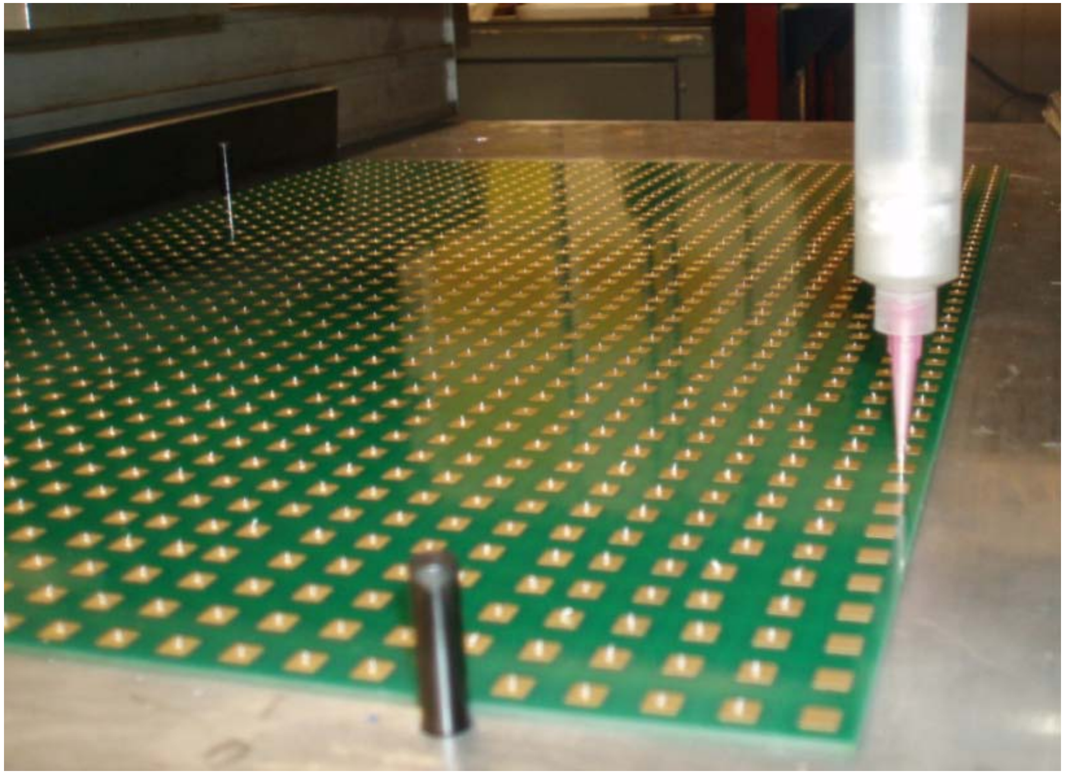
Front End Board

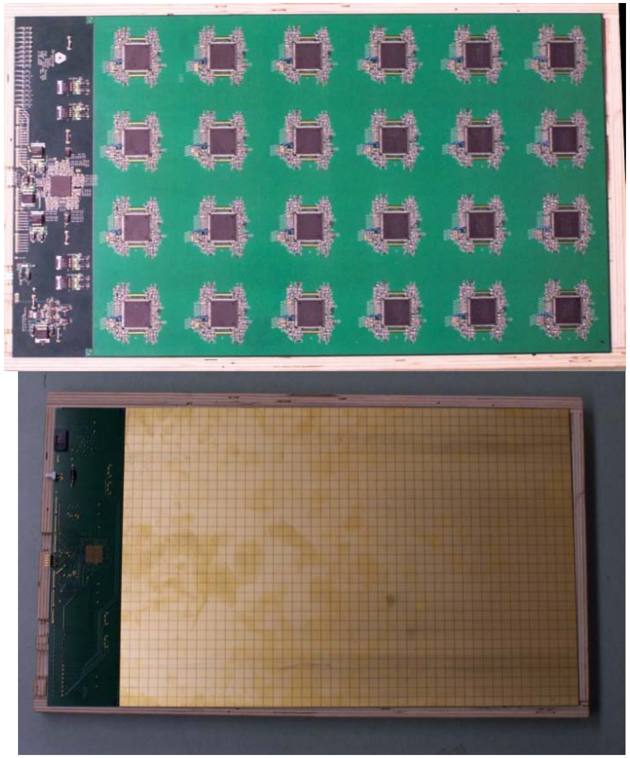
- (24) 64-Ch Chips / Bd
- 1536 Channels / Bd

Digital HCAL with RPC readout

Pad Boards

- Glued to Front End Board using Conductive Epoxy
- Gluing done after Front End Board assembly and check out

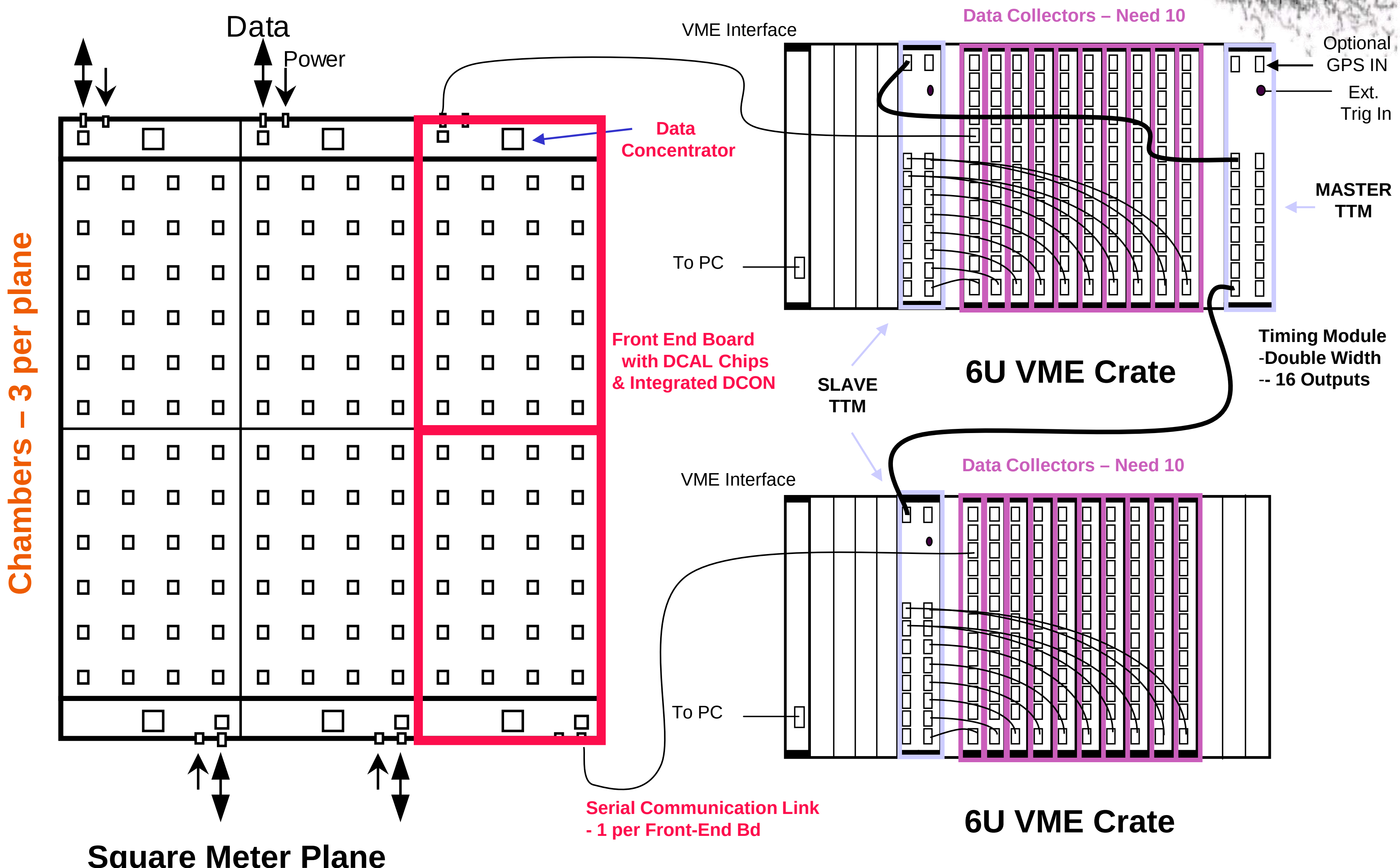




Digital HCAL with RPC readout

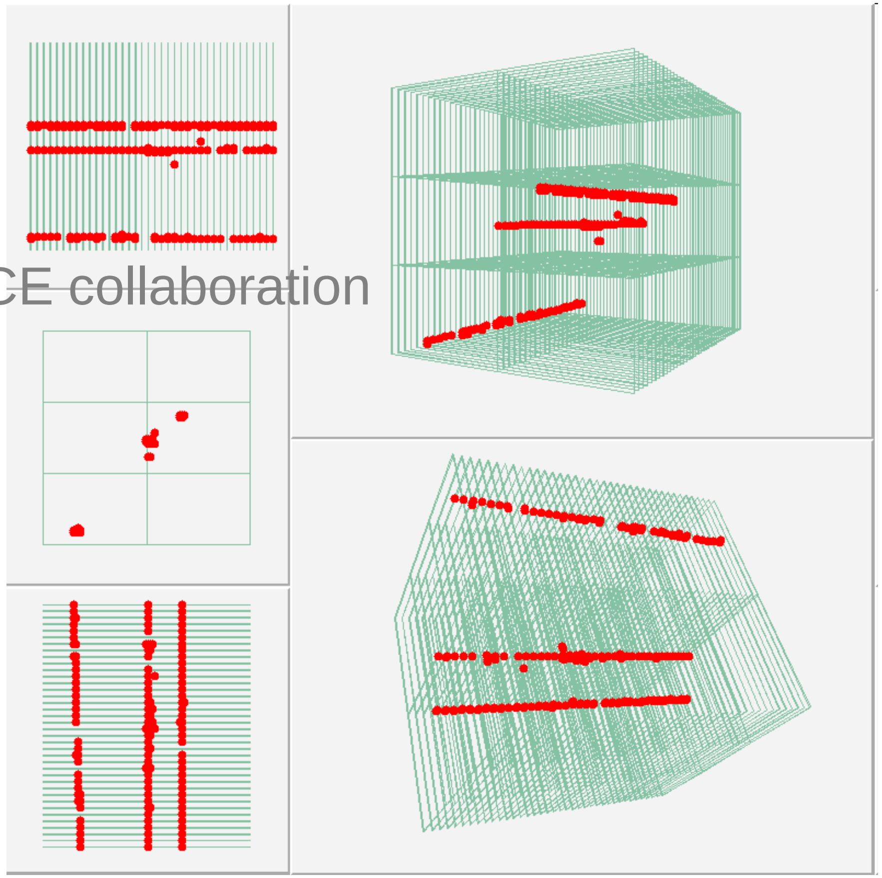
Square meter plane mounted on cassette
using prototype Front End Boards

Digital HCAL with RPC readout



Digital HCAL first data: 16/10/10

first ever realized 1m^3 prototype of Digital HCAL with Resistive Plate Chamber readout operational at Fermilab MTBF since this weekend!!



CALICE collaboration

The first multi tracks from muons recorded

Different readout approach: semi-digital

Semidigital RPCs

Biggest challenge: integrate electronics in 6mm PCB ➔ special chip design

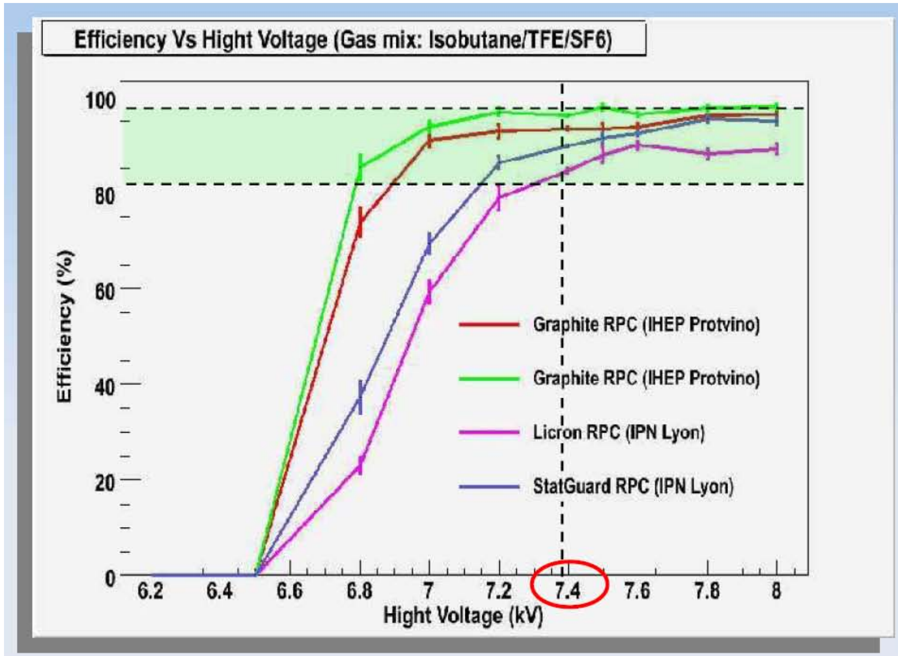
ASIC - HARDROC (Ω LAL)

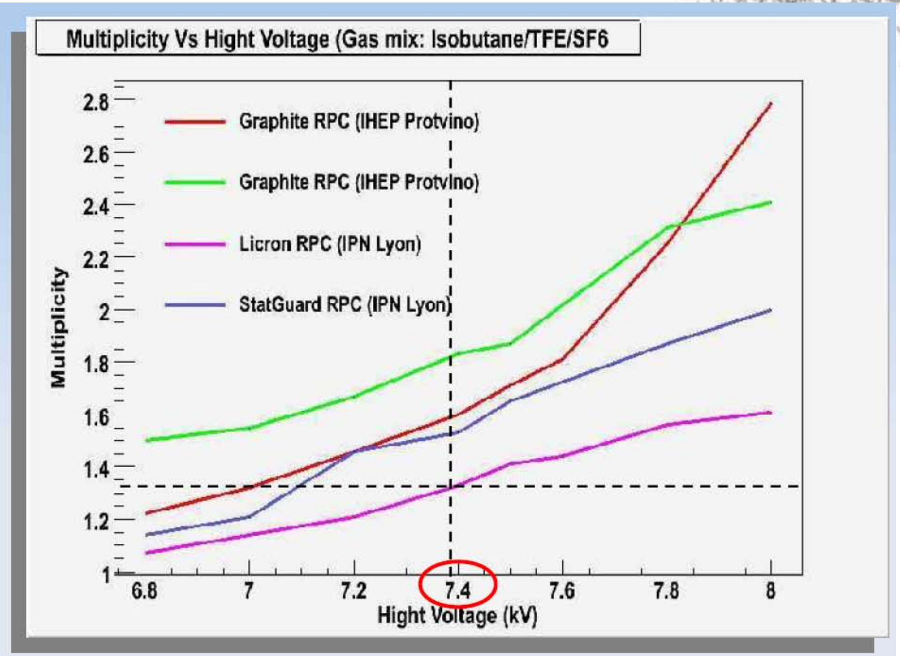
- 3 thresholds, masks, optimized power pulsing
- controlled in a fully automatic way using a robotic system used for CMS trackers

- 1 cm^2 readout pads
- 3 mm of Ar/iC_4H_{10} : 95/5
- Analog readout prototypes for characterization (GASSIPLEX chips), 6x16, 12x32 cm^2
- Digital readout prototypes with embedded electronics (HARDROC/DIRAC chips), 8x32, 32x48 cm^2

2 x 48 ASICs = 3072 channels = 1/3 m^2

Efficiency and hit multiplicity



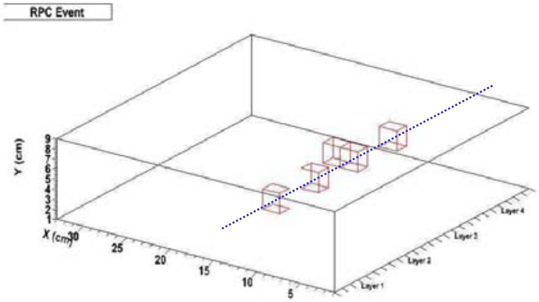


Using muon signal as MIP + tracking

Plateau: 7.2 — 8 kV → Efficiency between 80 and 98%

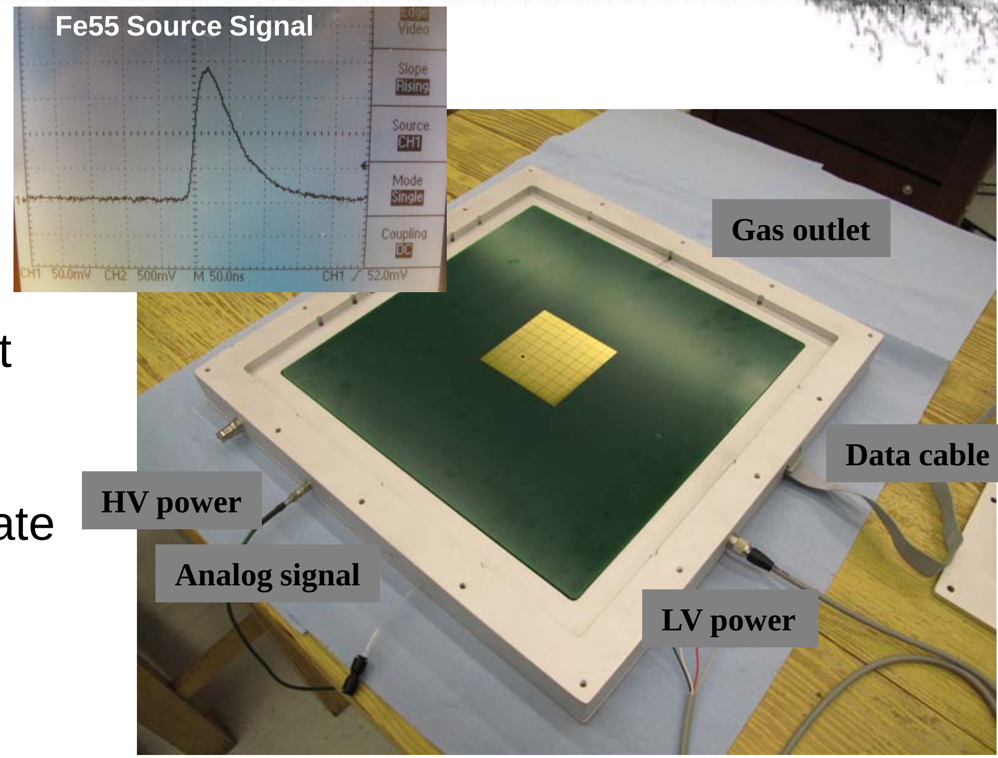
➔ Lower multiplicity is preferred

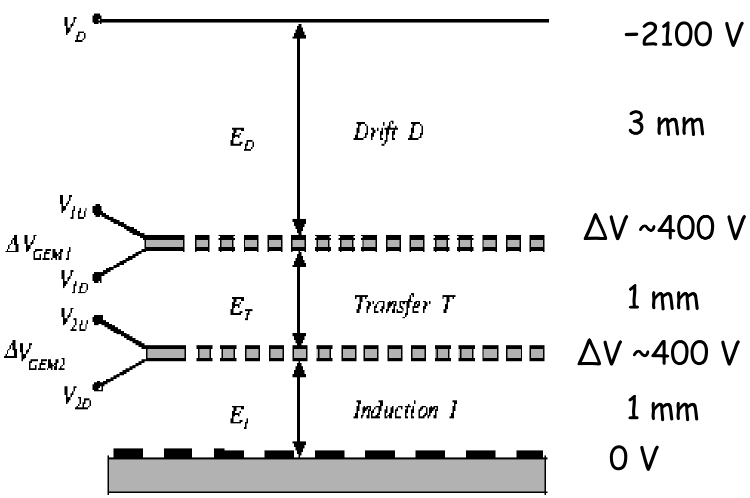
➔ Best ratio multiplicity/efficiency: around 7.4 kV

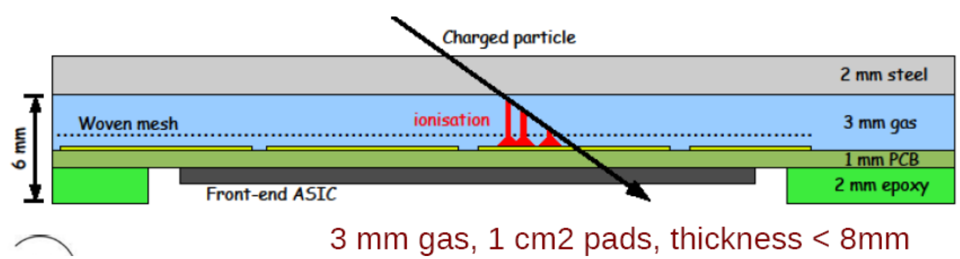


Different gas amplification method:
GEMs or Micromegas

Advantages:
- Low working voltage (~400V)
- Proportional mode operation
- Standard gas mixtures (Ar+CO_2, 80%+20%)
- Robust (up to 10^{12} part/mm^2 without performance degradation)
- High rate capability
- modified chip design to accommodate for smaller signals (> ~20 fC)







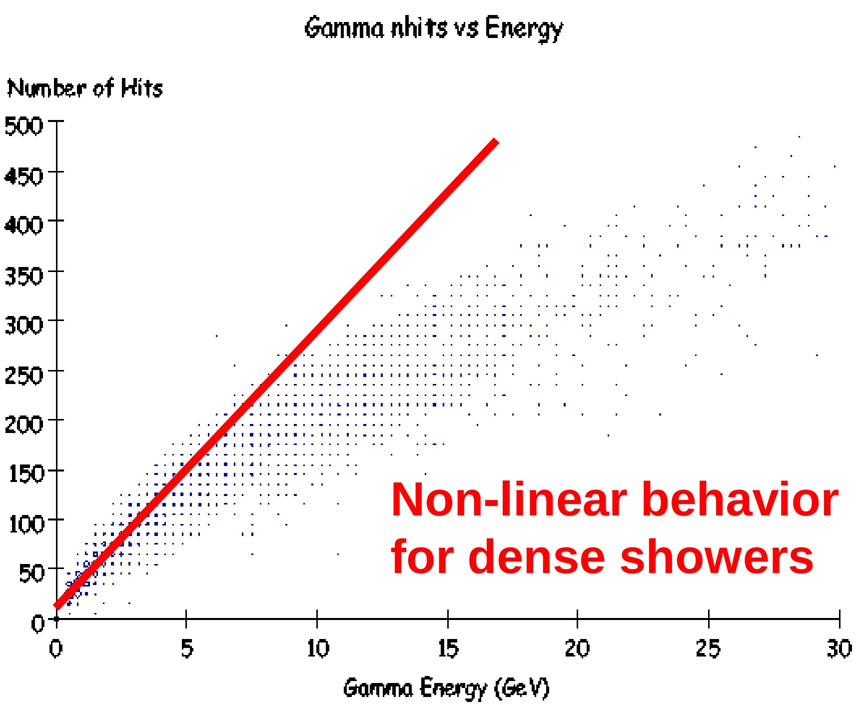
3 mm gas, 1 cm2 pads, thickness < 8mm

Analog .vs. Digital

photon analysis

$$E_\gamma \neq \sum N_i$$

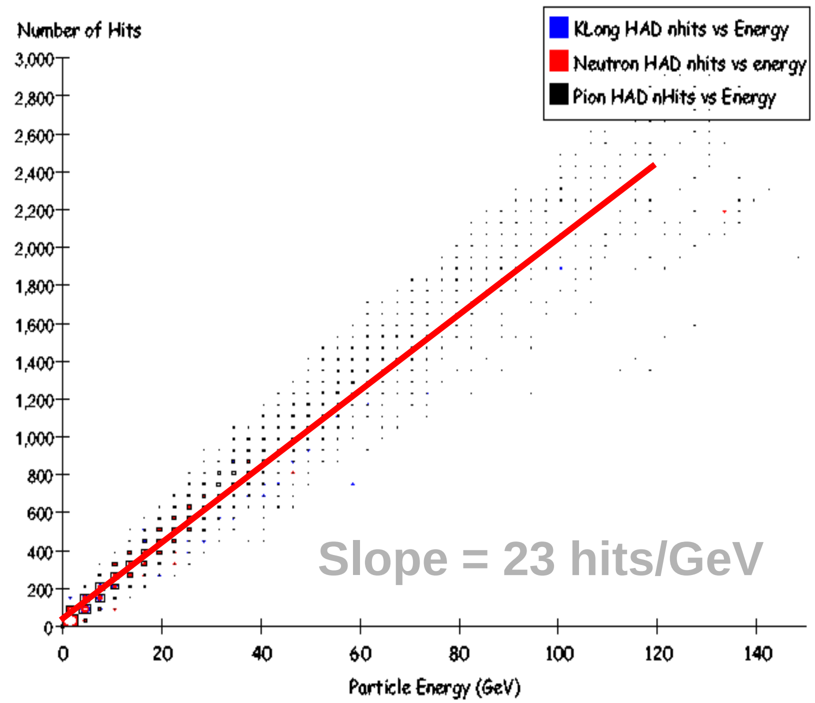
ECAL: Analog readout required



hadron analysis

$$E_h \propto \sum N_i$$

HCAL: either Analog or Digital readout



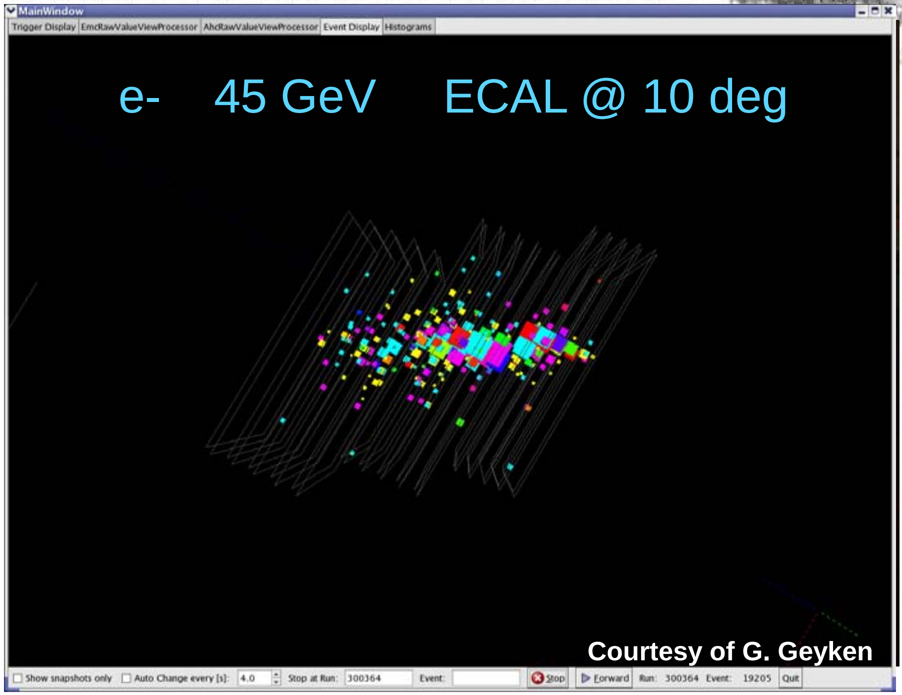
Calorimeter cell size 1x1cm^2

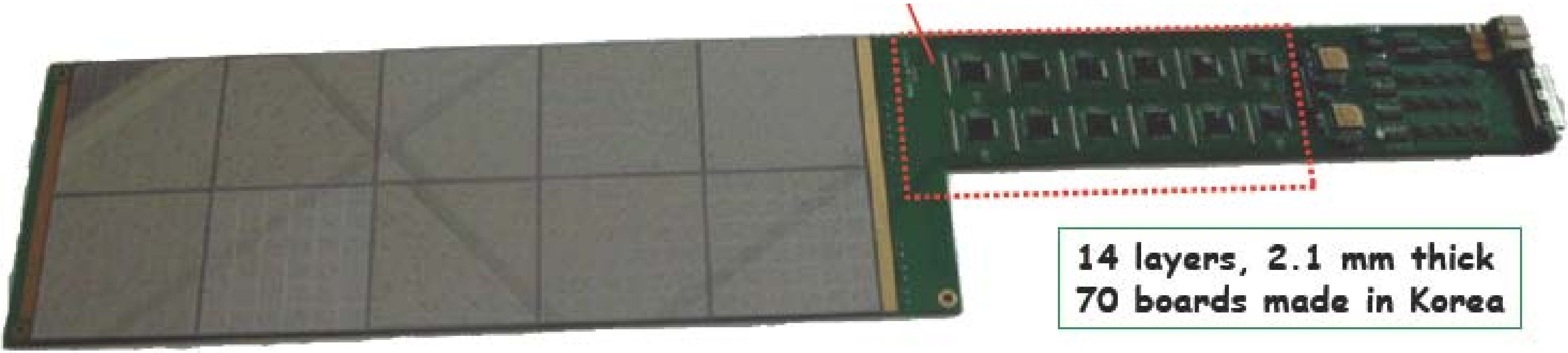
Highest granularity ECAL

CALICE:
Si-W with analog readout

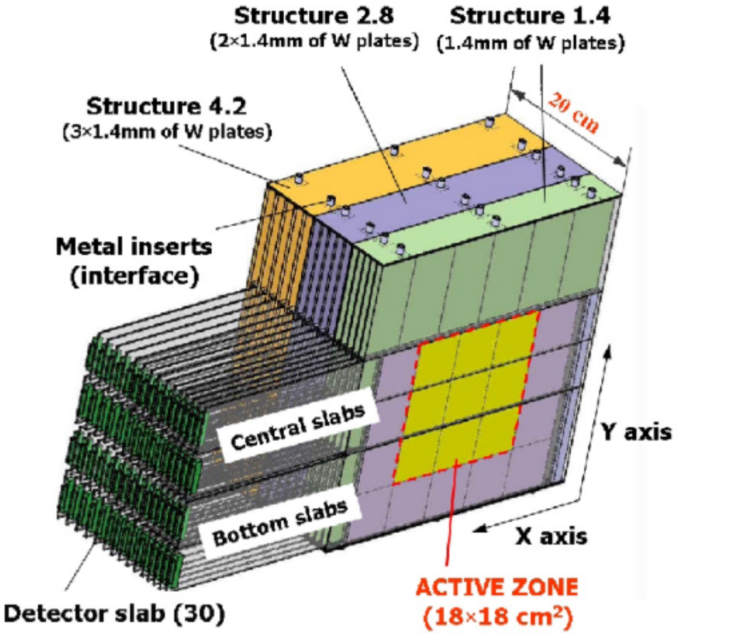
30 layers W-Si
1 cm^2 Si-PADs (next version with 0.5x0.5 cm^2 Si-PADs)
~10000 channels

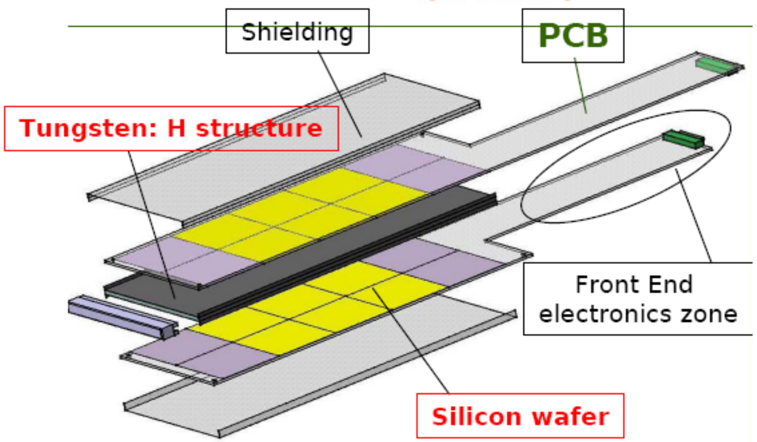
➔ Imaging calorimeter!!





Si-W ECAL





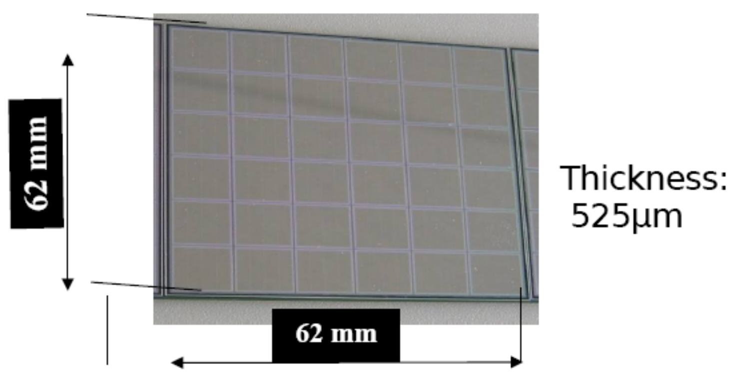
30 layers of Tungsten:

- 10 x 1.4 mm (0.4 X_0)
- 10 x 2.8 mm (0.8 X_0)
- 10 x 4.2 mm (1.2 X_0)
- 24 X_0 total, 1 λ_I

½ integrated in detector housing
⇒ Compact and self-supporting detector design

6x6 PIN Diode Matrix

Resistivity: 5kΩcm - 80 (e/hole pairs)/μm



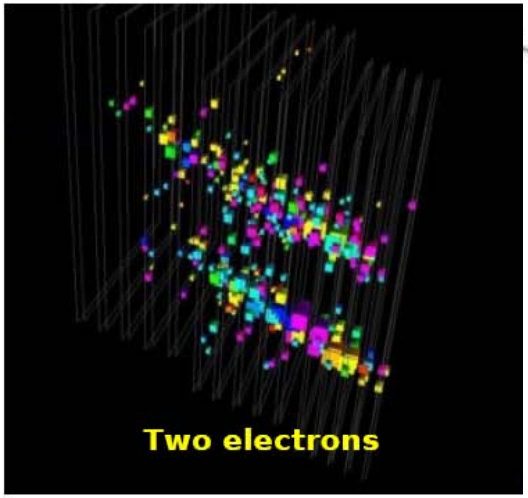
Total: 9720 Pixels/Channels

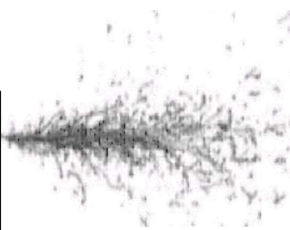
8

Experimental Setup

Zoom into Ecal

Particle Distance~ 5 cm
→ No Confusion !!!



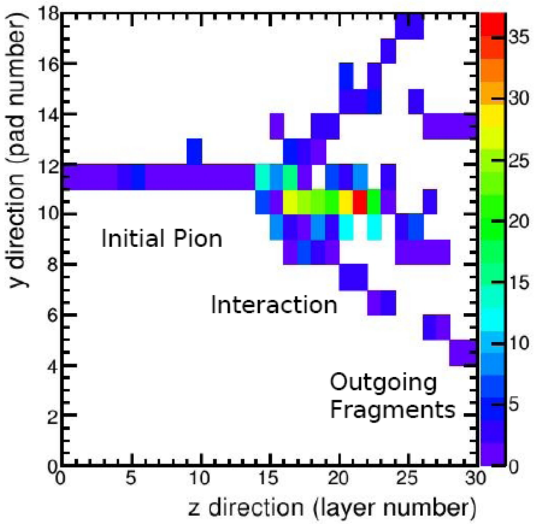


(Start of) Hadronic Showers in the SiW Ecal

Imaging calorimeter

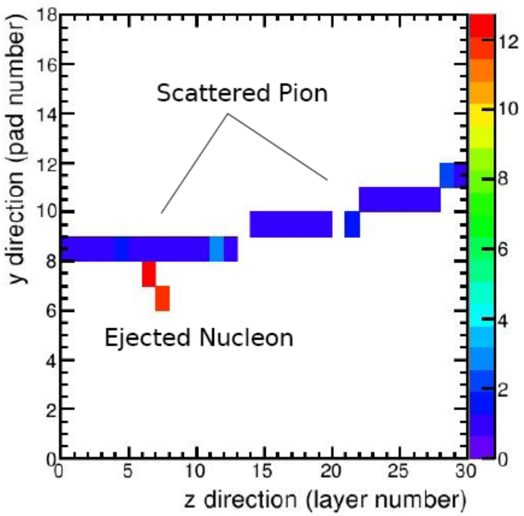
CALICE Si-W ECAL data

Complex and Impressive



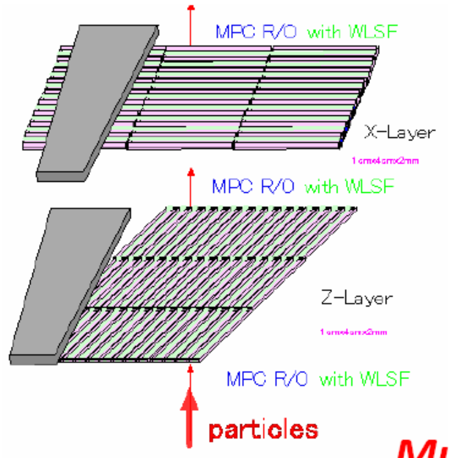
Inelastic Reaction in SiW Ecal

Simple but Nice



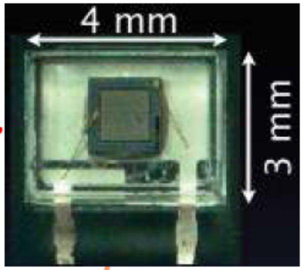
Nucleon Ejection in SiW Ecal

High granularity scintillator ECAL



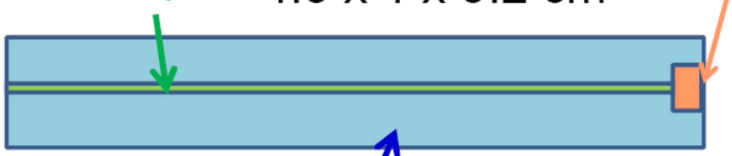
Elementary Components
(Scintillator-Strip & Photo-Sensor)

Multi-Pixel Photon Counter (MPPC)

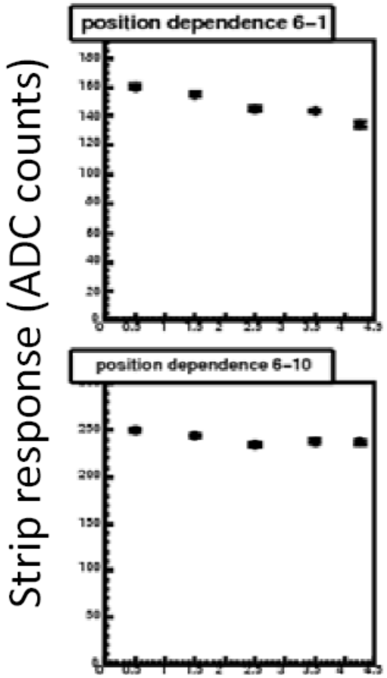


Wavelength Shifting Fiber (Y11 1mmϕ)

4.5 x 1 x 0.2 cm

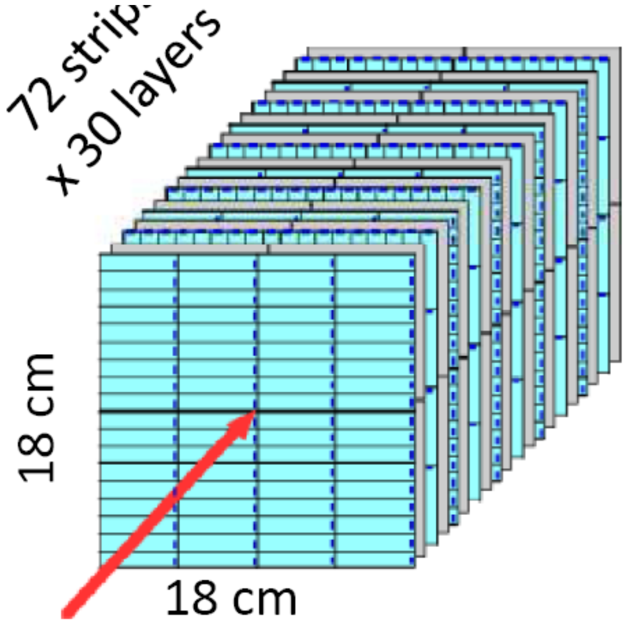


Plastic scintillator strip by extrusion technique

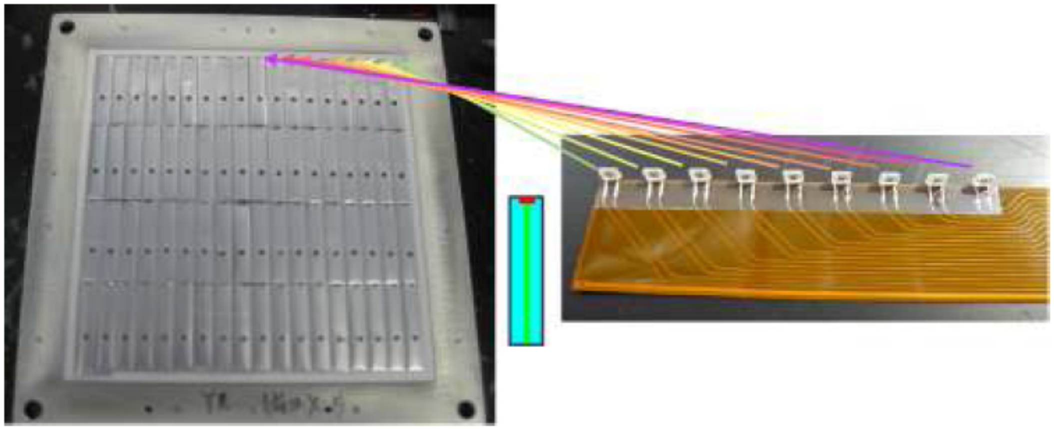


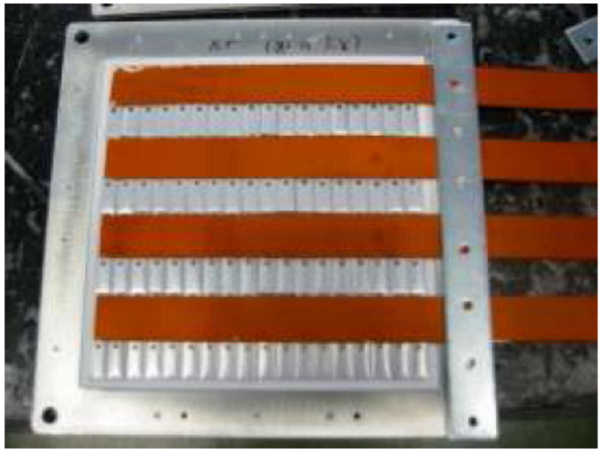
Position along the strip (cm)

High granularity scintillator ECAL

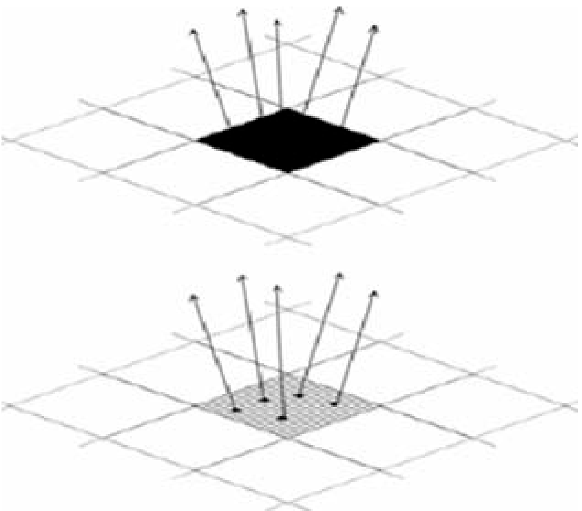


- The technical prototype to establish the ScECAL feasibility.
- Sandwich structure with scintillator-strips (3 mm) and tungsten layers (3.5 mm).
- Extruded scintillator and the MPPC are fully adopted.
- Strips are orthogonal in alternate layers.
- 72 strips x 30 layers = 2160 channels.



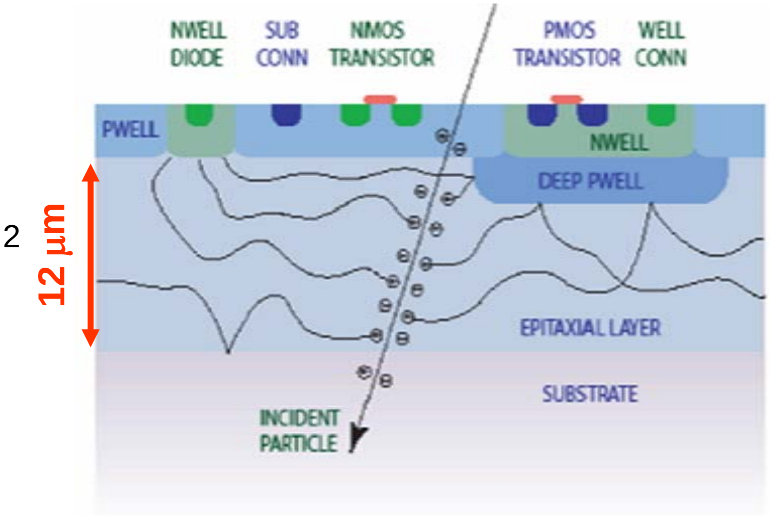


Digital ECAL



Next R&D steps:

- Swap ~0.5x0.5 cm^2 analog readout Si pads with smaller pixels readout digitally
- "Small" = at most one particle/pixel
- 1-bit ADC/pixel, i.e. Digital !



Monolithic Active Pixel Sensors

How small should a pixel be?

- EM shower core density at 500GeV is ~100/mm^2
- Pixels must be<100×100μm^2
- Baseline: 50×50μm^2
- Gives ~10^{12} pixels for ECAL

a "Tera-pixel calorimeter"

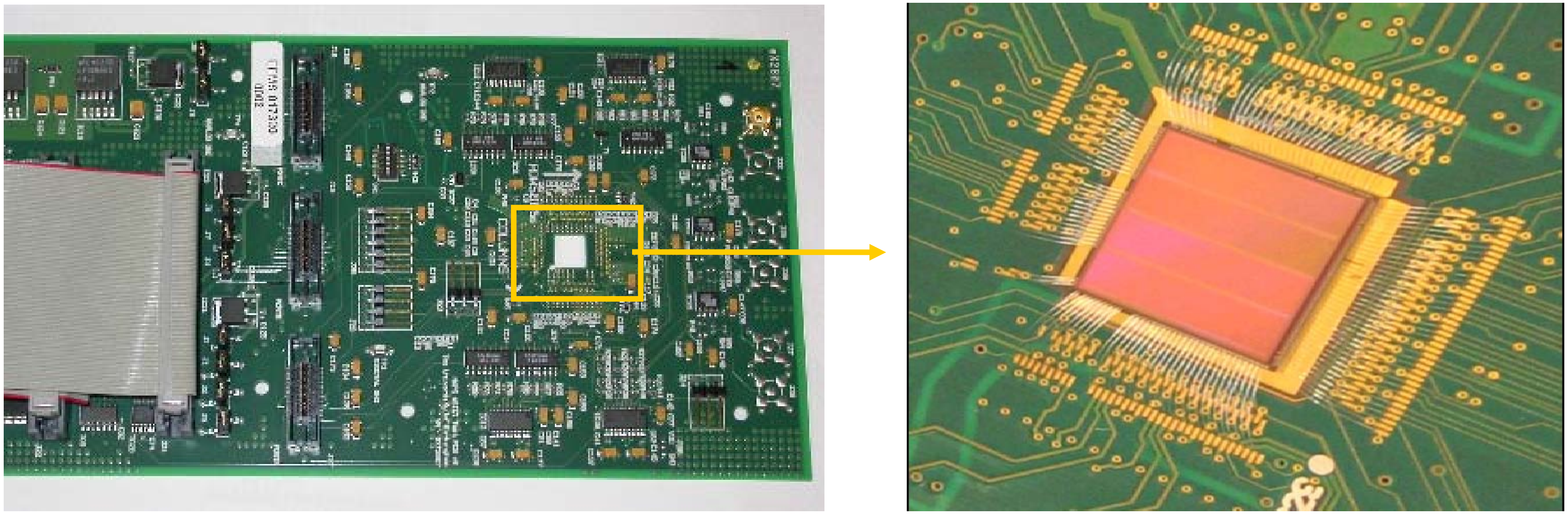
- Mandatory to integrate electronics on sensor

➔MAPS (Monolithic Active Pixel Sensors)
- developed for vertex detectors

Digital ECAL technology

The technology: MAPS (Monolithic Active Pixel Sensors)
- A standard CMOS product developed for vertex detectors

• Potentially significant price advantage over high resistivity Si diodes
• Tests of sensor prototypes at CERN in ‘09: 8.4 x 8.4 mm^2 sensitive area



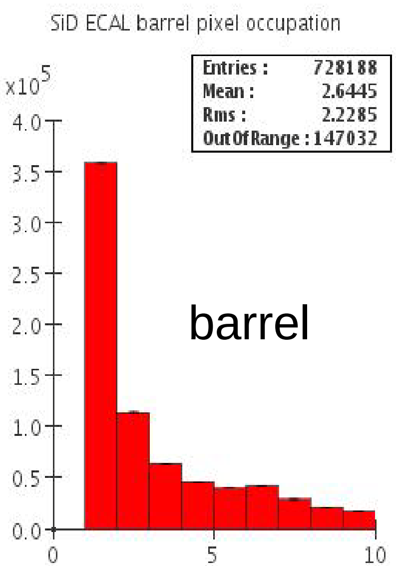
8.2 million transistors
□ 28224 pixels; 50x50 μm^2

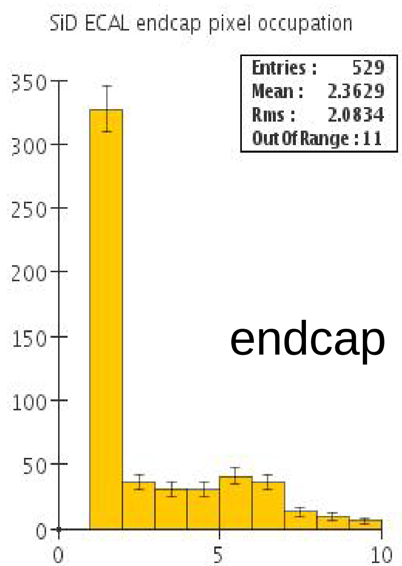
Pixel Occupancy

MAPS concept requires binary readout...

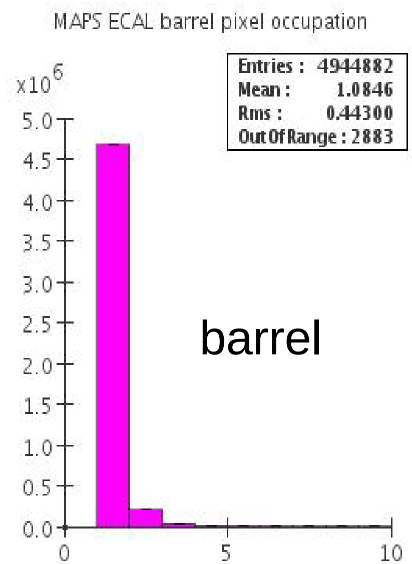
➔ need at most 1 hit per pixel or else lose information

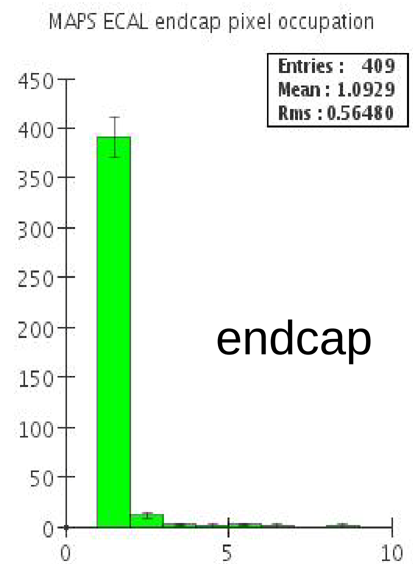
Si-W ECAL, 100GeV electrons





MAPS ECAL, 100GeV electrons

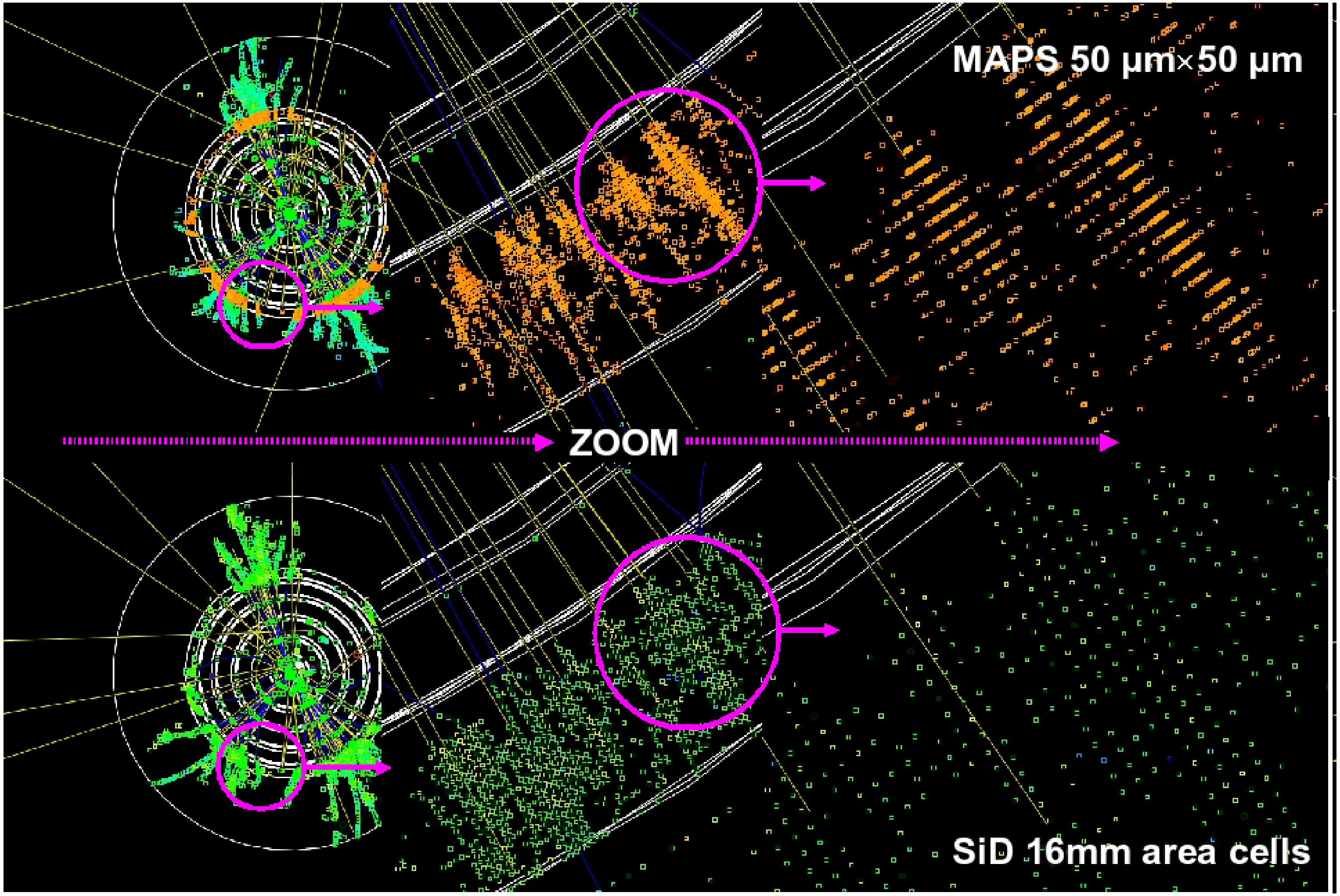




Select optimal pixel pitch from simulation studies

Analog vs digital ECAL

great improvement in imaging capability



Summary on Particle Flow

PFLOW is a proposed technique to improve jet energy resolution at collider experiments

➔It is based on extremely high granularity calorimeters to allow single shower separation in a dense jet environment

➔It requires development of new technologies

➔ push to ultimately small single calorimeter cells:

~ 5x5 mm^2 – 50x50 um^2 for ECAL

~ 1cm^2 for HCAL

- Analog and digital readout solution discussed
- all based on sampling calorimeters

➔ not optimized for ultimate energy resolution performance !

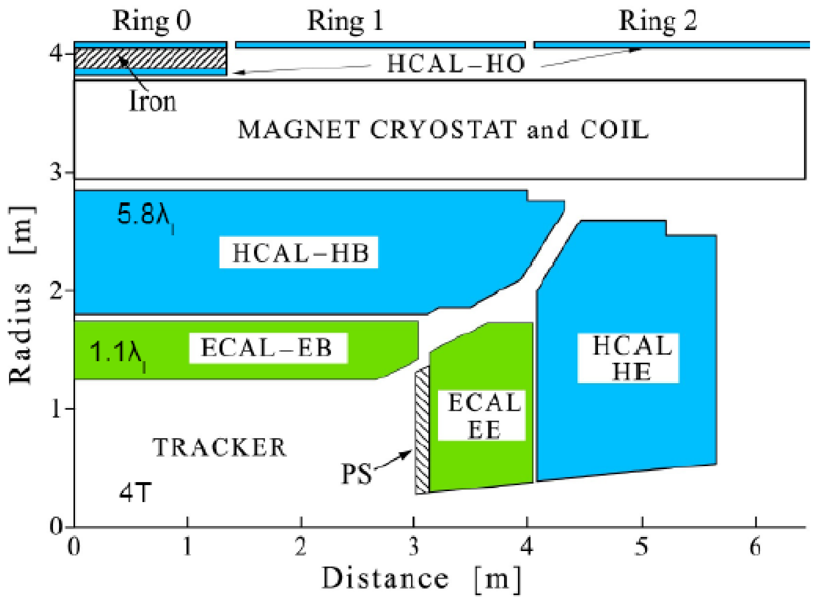
Tomorrow lecture: the ultimate hadronic energy resolution
the fight against fluctuations
& calorimeters without colliders

Calorimetry
- emerging technologies -

Erika Garutti
DESY

Jet energy resolution at LHC

CMS

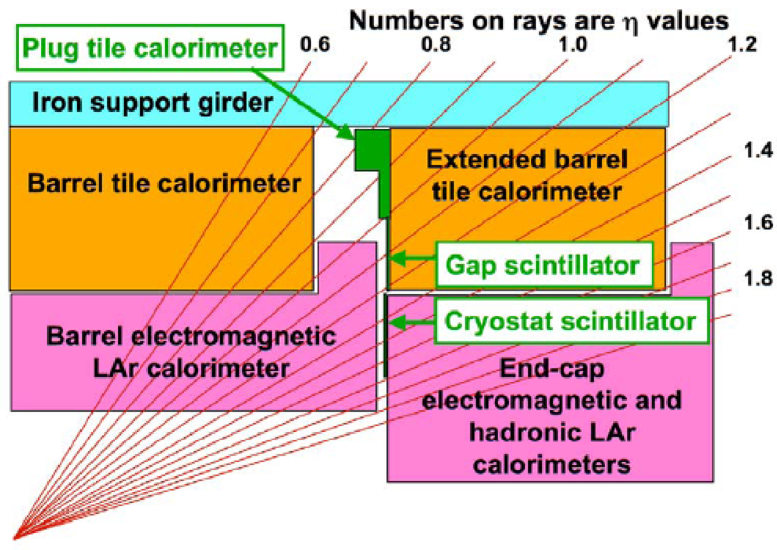


5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

Expected jet resolution:

$$\frac{\sigma}{E} = \frac{125\%}{\sqrt{E}} \oplus \frac{5.6\ \text{GeV}}{E} \oplus 3.3\%$$

ATLAS



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

Jet resolution with weighting:

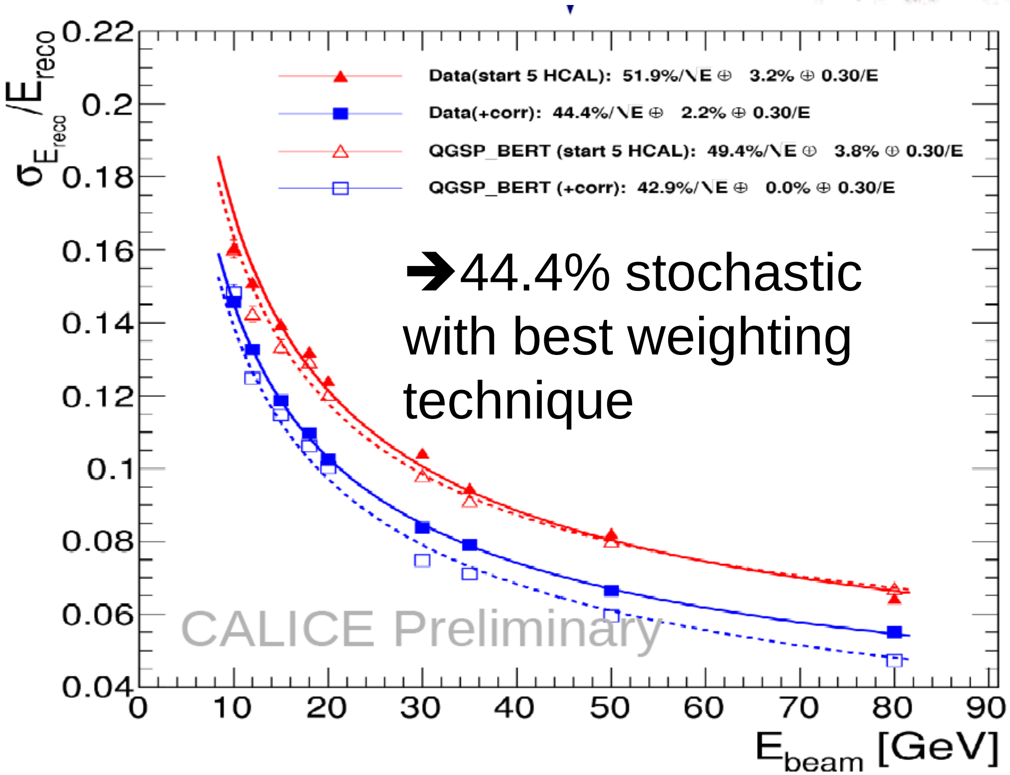
$$\frac{\sigma}{E} = \frac{60\%}{\sqrt{E}} \oplus 3\%$$

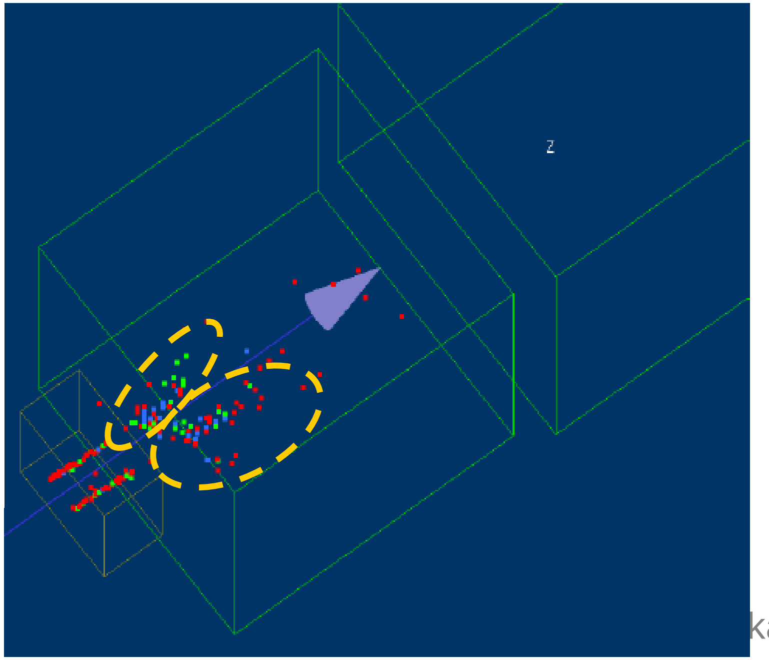
Stochastic term for hadrons was ~93% and 42% respectively

AHCAL: a calorimeter for particle flow

High granularity allows precise weighting techniques for E in each ch.

➔ Single hadron energy resolution using energy density weights <50%/⌧E



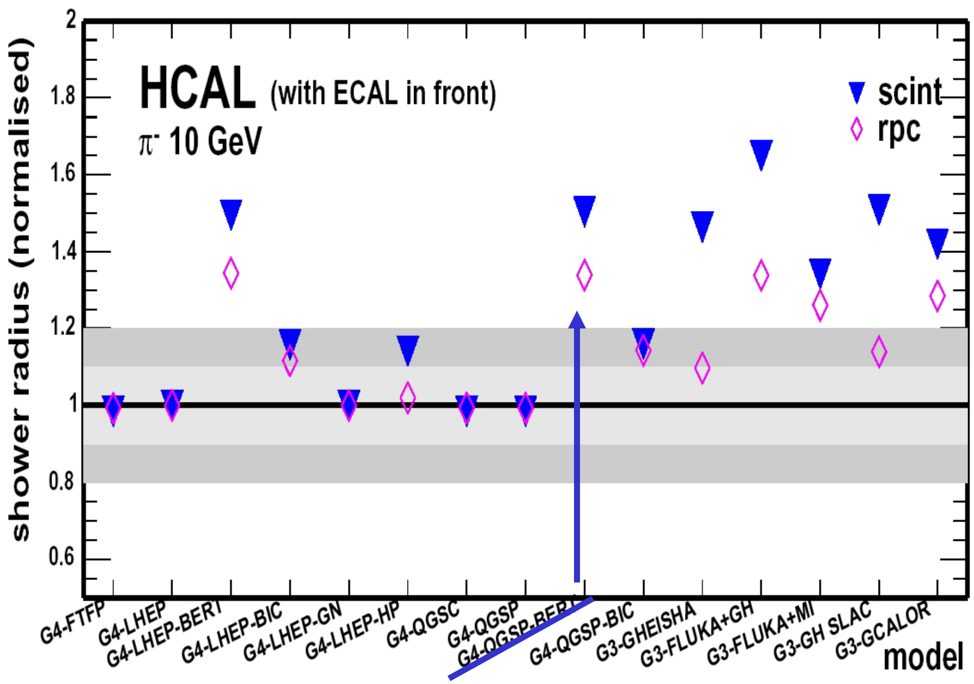


Particle flow ➔ tomorrow lecture

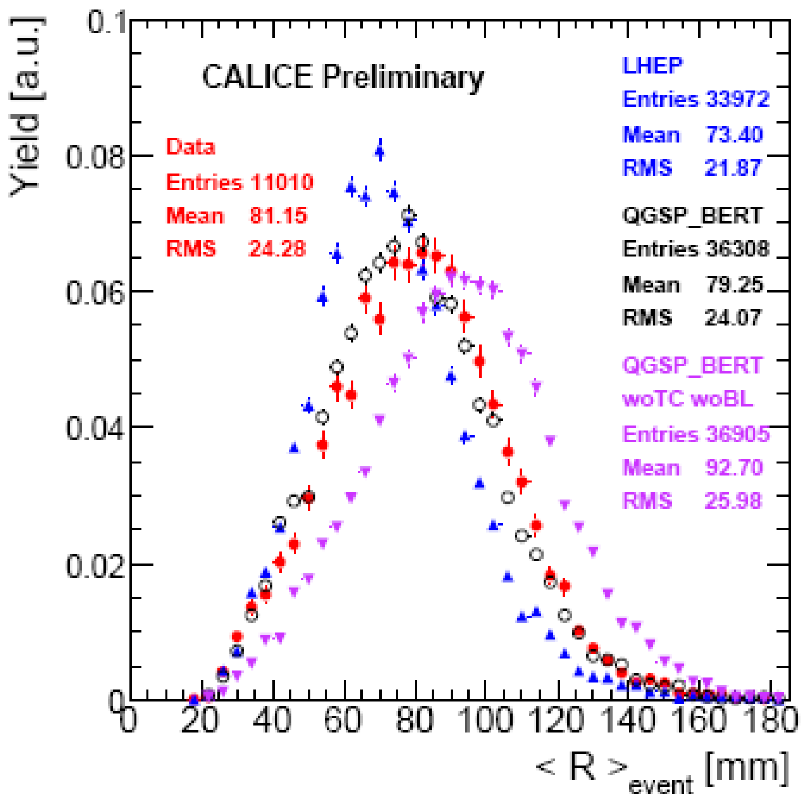
Key requirement is showers separation and NOT single hadron resolution!

Models comparison

Comparison of MC models predictions of mean shower radius <R>



PRELIMINARY CALICE measurement of <R>



The HCAL high granularity offers the possibility to investigate longitudinal and lateral shower shapes with unprecedented precision

Dual readout calorimetry

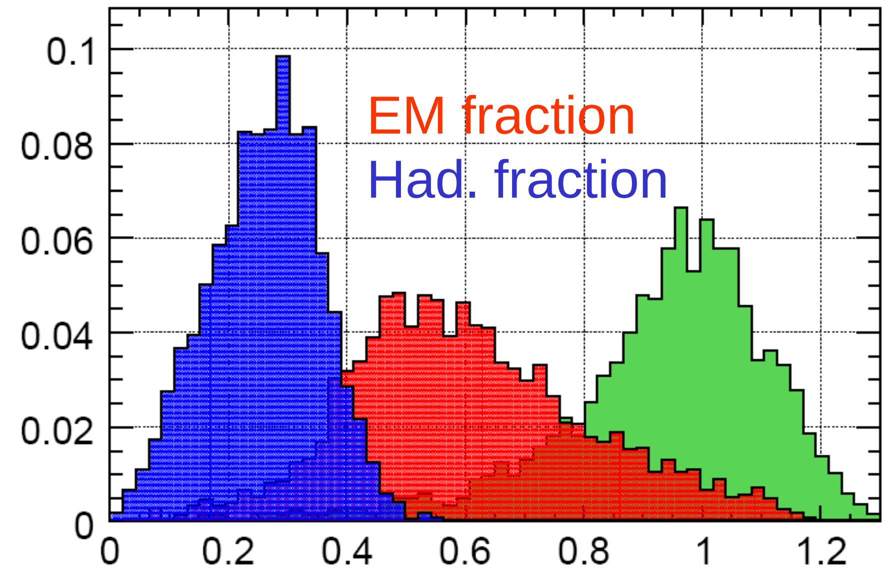
Alternative approach to the problem of improving hadronic / jet energy resolution:

- measure the shower components in each event

➔ access the source of fluctuations:

- measuring f_{em} in each event removes the EM fluctuations

- ideally one wants to measure also f_n which is proportional to the binding energy to remove fluctuations in the invisible energy



Norm. 10 GeV pion

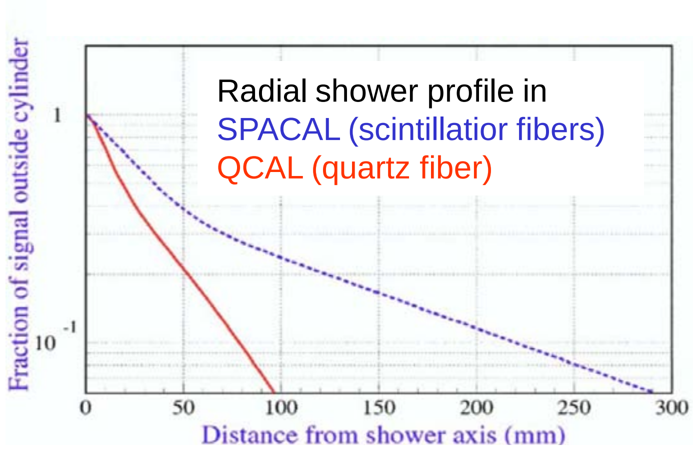
-Example: The DREAM calorimeter as a test of this approach

The Dual REAdout Method principle

Use Cerenkov light !!!

Quartz fibers (cherenkov emitter) are only sensitive to em shower component !

- ~80% of non-em energy deposited by non-relativistic particles
  - ⇒ e/h=5 (CMS-HF)
  - ⇒ radial profile of hadronic showers
- Hadronic component mainly spallation protons
  E_k ~ few hundred MeV ⇒ non-relativistic
  ⇒ no Cherenkov light
- Electron and positrons emit Cherenkov light
  up to a portion of MeV



Use dual-readout system:

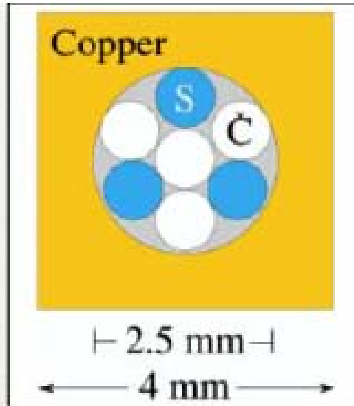
- Regular readout (scintillator) measures visible energy
- Quartz fibers measure em shower component E_{em}

➔ Combining both results makes it possible to determine f_{em} and the energy E of the showering hadron

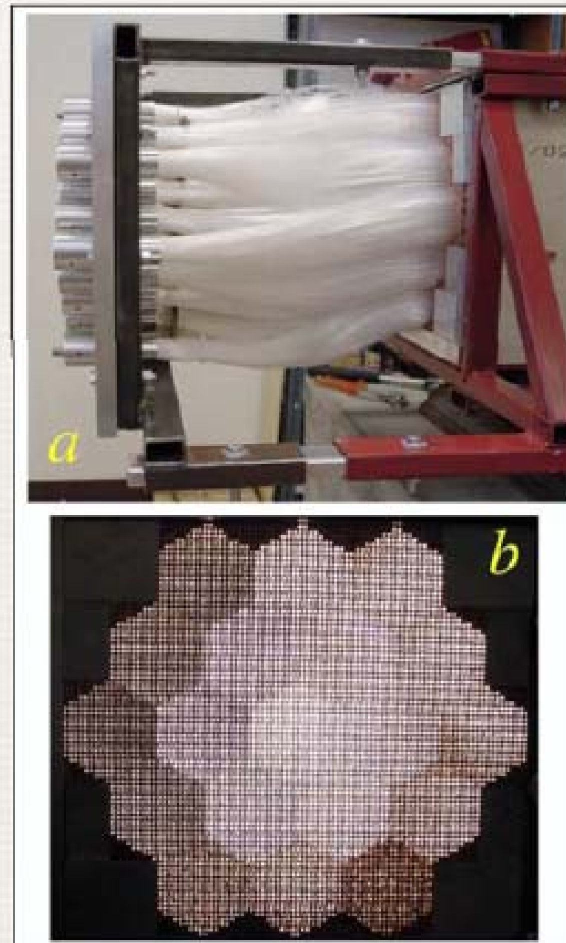
➔ Eliminates dominant source of fluctuations

The DREAM prototype

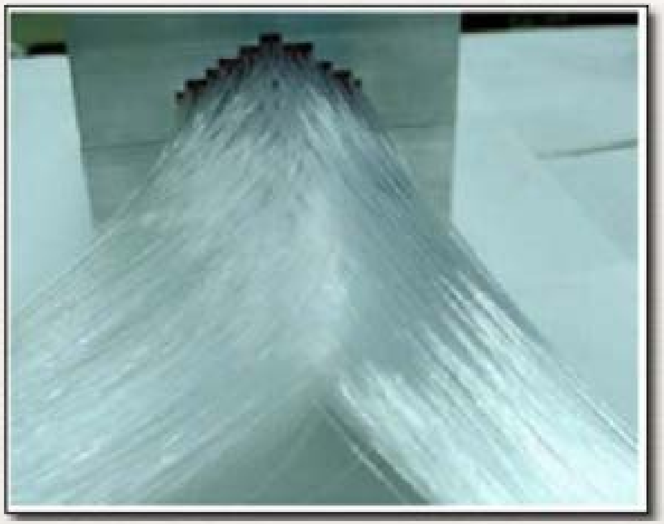
Basic structure:
4×4 mm^2 Cu rods
2.5 mm radius hole
7 fibers
3 scintillating
4 Čerenkov



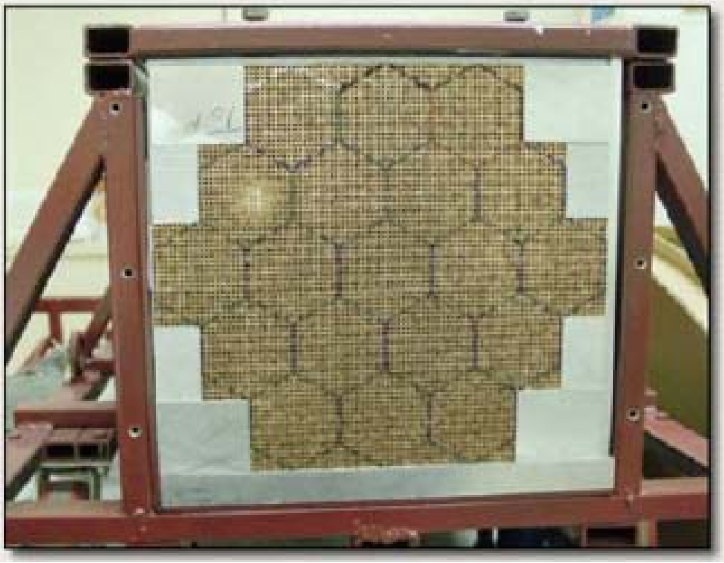
DREAM prototype:
5580 rods, 35910 fibers, 2 m long (10 λ_{int})
16.2 cm effective radius (0.81 λ_{int}, 8.0 ρ_M)
1030 Kg
X_0 = 20.10 mm, ρ_M =20.35 mm
19 towers, 270 rods each
hexagonal shape, 80 mm apex to apex
Tower radius 37.10 mm (1.82 ρ_M)
Each tower read-out by 2 PMs (1 for Q and 1 for S fibers)
1 central tower + two rings



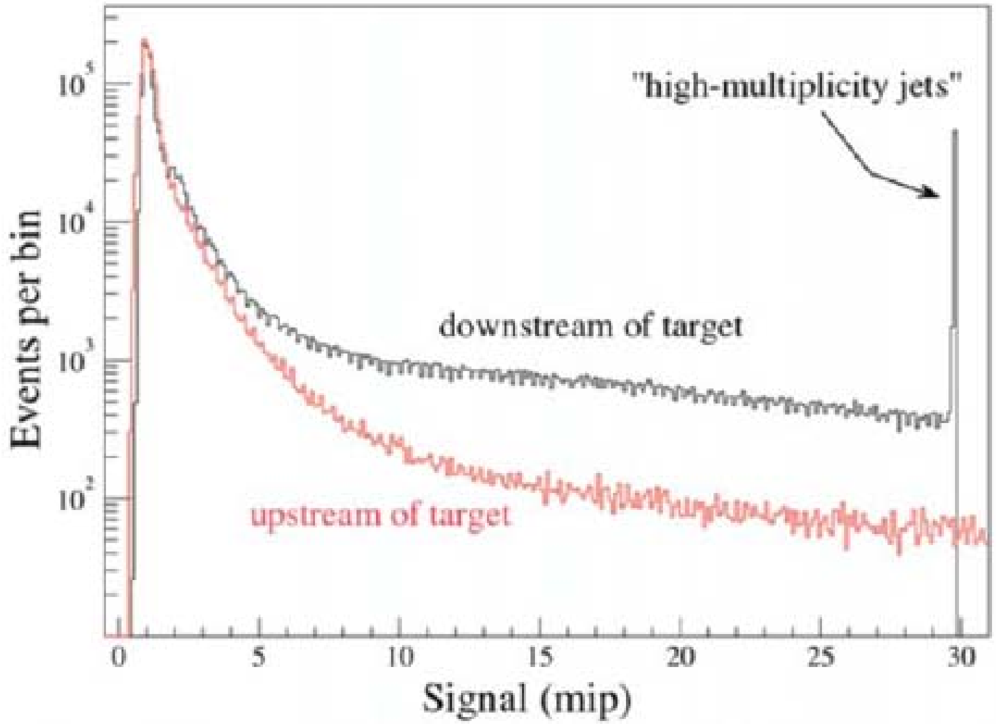
The DREAM prototype



DREAM prototype:
tested at the CERN H4 beam line
Data samples:
π from 20 to 300 GeV
"Jets" from 50 to 330 GeV
"Jets" mimicked by π interaction on 10 cm polyethylene target in front of the detector



Making “jets” at test beams



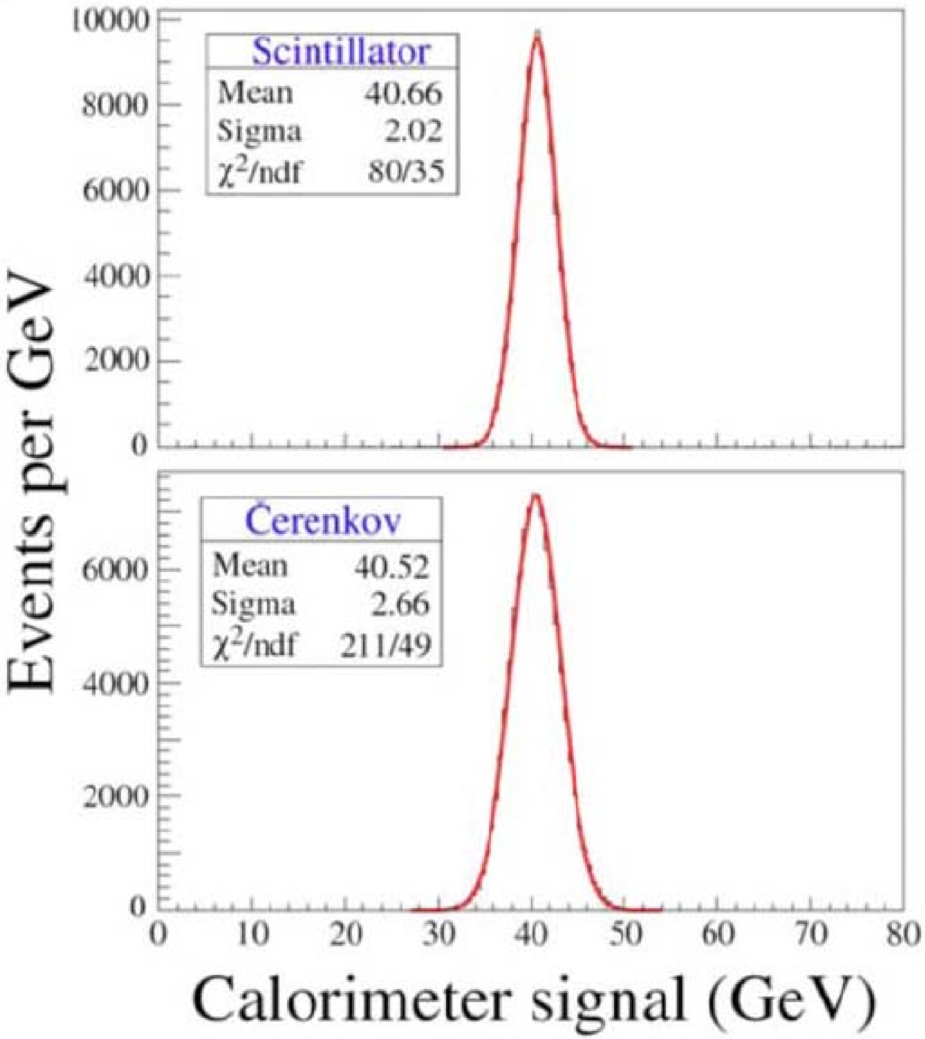
"JET" Measurements

Calibration with 40 GeV electrons

- Tilt 2° respect to the beam direction to avoid channelling effects

- Modest energy resolution for electrons (scintillator signal):

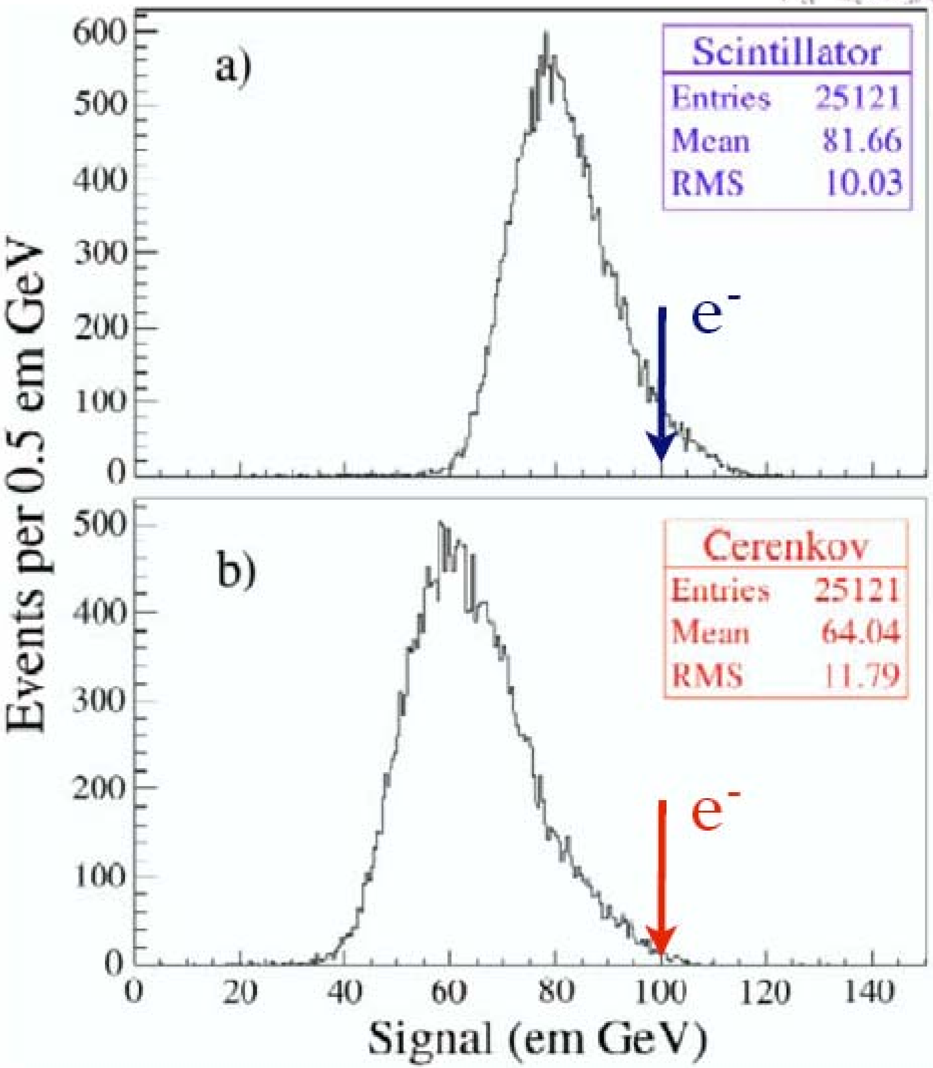
$\sigma/E = 20.5\%/\sqrt{E} + 1.5\%$



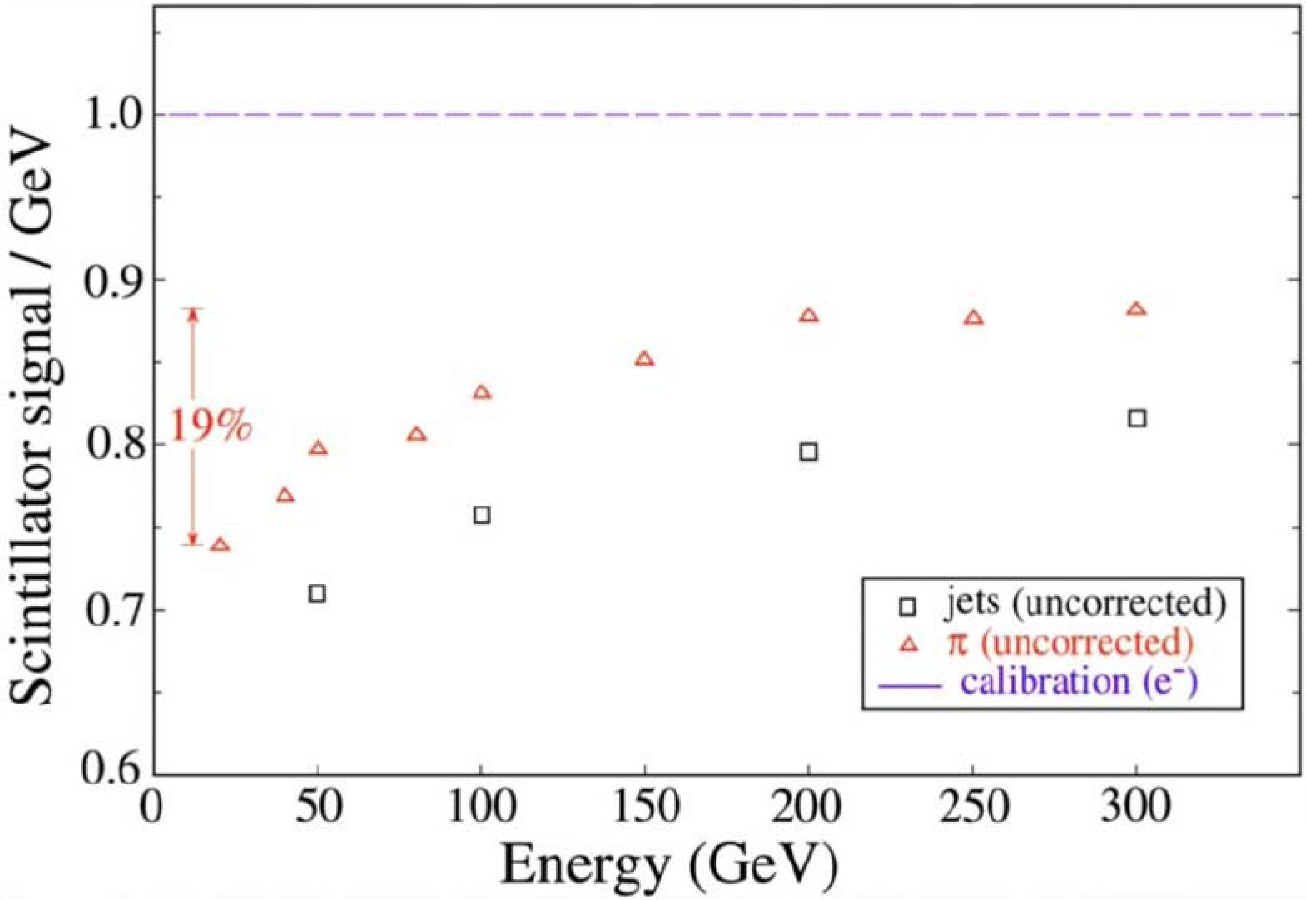
100 GeV single pions (raw signal)

Signal distribution:

- Asymmetric, broad, smaller signal than for e-
- Typical tails feature of a non-compensating calorimeter



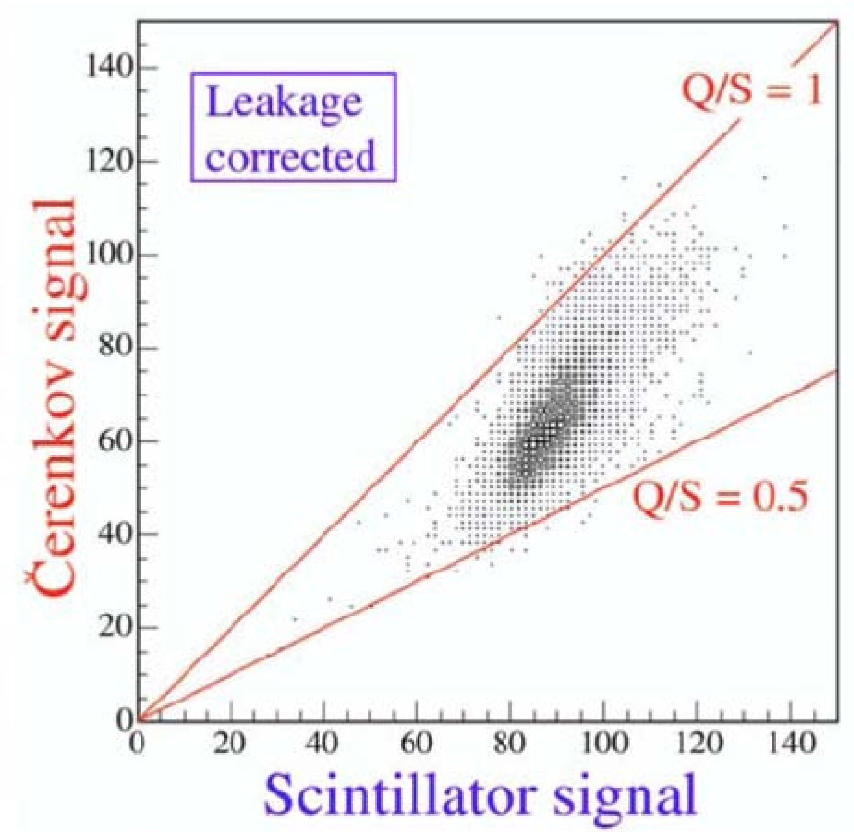
Hadronic response non-linearity



Hadron response is < 1 and ~20% non-linear

Similar non-linearity for jets

How to determine f_{em} and E



Q/S<1 ➔ ~25% of the scintillator signal from pion showers is caused by non-relativistic particles, typically protons from spallation or elastic neutron scattering

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

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

e.g. If $e/h = 1.3\ (S),\ 4.7\ (Q)$

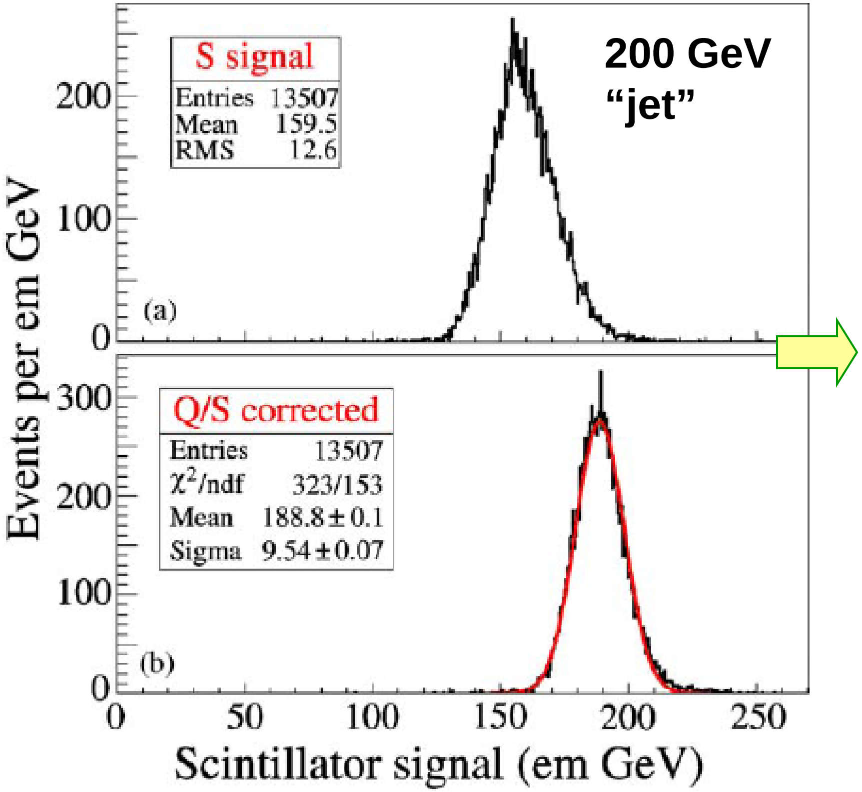
$$\boxed{\frac{Q}{S} = \frac{f_{\mathrm{em}} + 0.21\,(1-f_{\mathrm{em}})}{f_{\mathrm{em}} + 0.77\,(1-f_{\mathrm{em}})}}$$

$$\boxed{E = \frac{S - \chi Q}{1 - \chi}}$$

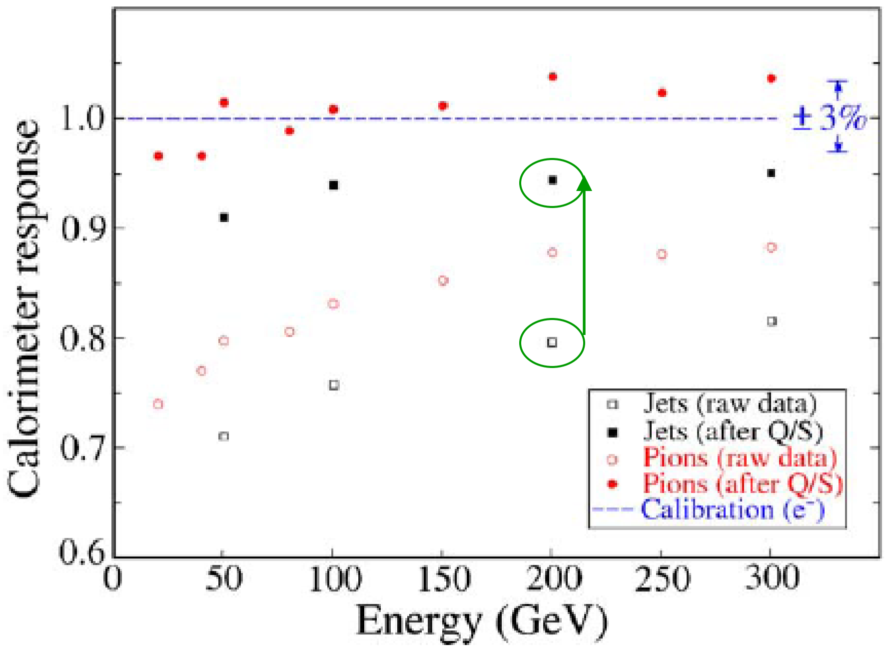
with $\chi = \dfrac{1-(h/e)_S}{1-(h/e)_Q} \sim 0.3$

Reconstructed hadron energy

Scintillator signal before correction ➔ asymmetry due to non-compensation

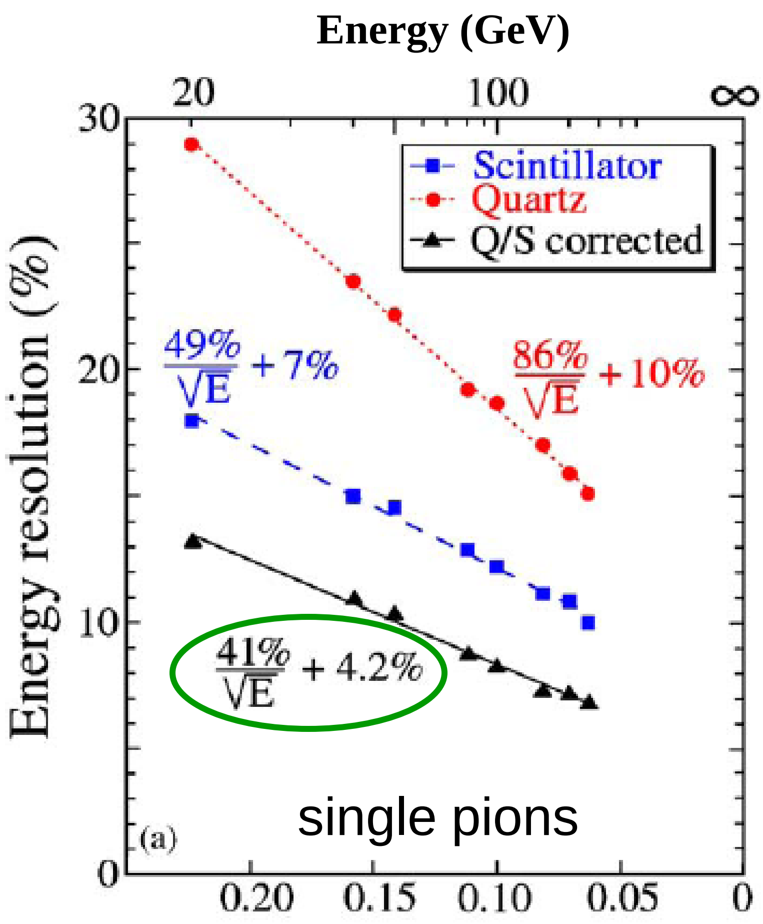


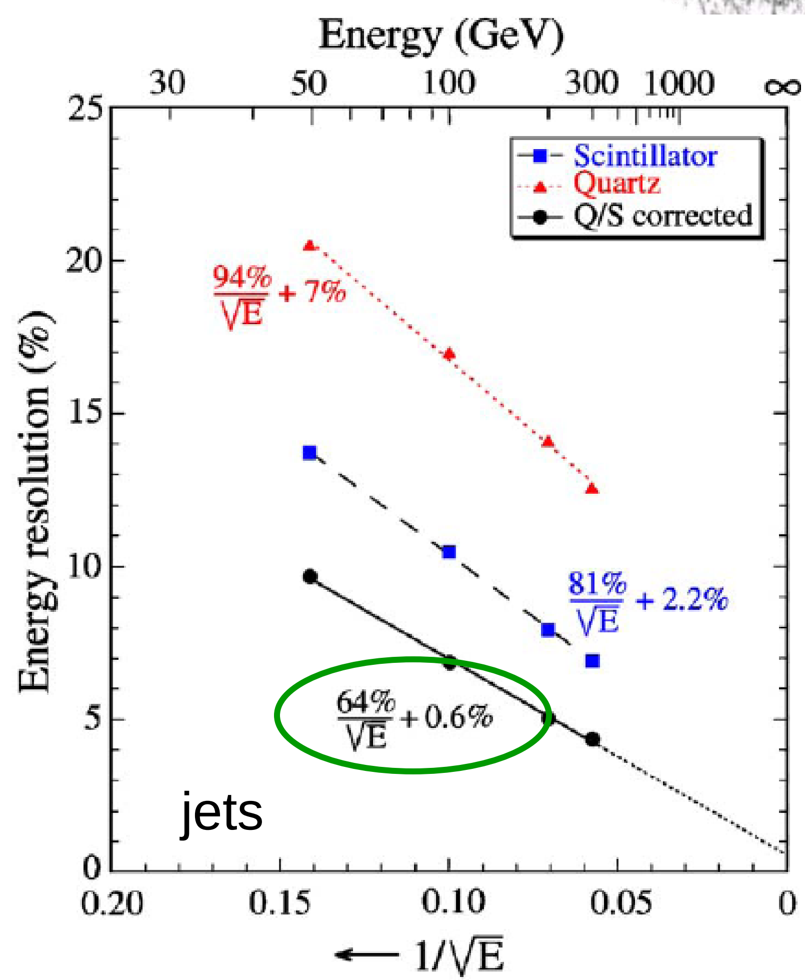
After Q/S method correction
➔ good Gaussian signal



Recovered linearity of response to pions and "jets"

Energy resolution





Significant improvement in energy resolution especially for jets

DREAM conclusions and beyond

DREAM technique powerful to improve hadronic resolution:

- Correct hadronic energy reco. in an instrument calibrated with electrons
- Linearity for hadrons and jets
- Gaussian response functions
- Energy resolution scales with sqrt(E)
- $\sigma/E < 5\%$ for high-energy “jets”, in a detector with a mass of only 1 ton !
  (dominated by fluctuations in shower leakage)

How to further improve:

- Increase Cherenkov light yield
  - DREAM: 8 p.e./GeV ➔ fluctuations contribute 35%/⌦E
- No reason why DREAM principle is limited to fiber calorimeters
  - Homogeneous detector ?!

  ⇒ Need to separate the light into its Č, S components
  - Sampling structure with alternating tiles of Č, S materials

Dual Readout with homogeneous material

Separation of Scintillation & Cherenkov light can be based on:

- Time structure of the signal
- Spectral difference
- Directionality of Cherenkov component

	Cherenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos\theta_c=1/\beta n$	Isotropic

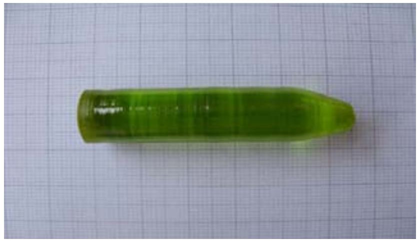
Tests performed at the SPS (CERN) by the DREAM collaboration with 2 kinds of crystals: **$PbW0_4$**, **BGO**

Crystal	LightYield % NaI(Tl)	Decay Time (ns)	Peak wavel.(nm)	Cutoff wavel.(nm)	Refr. Index	Density (g/cm³)
BGO	20	300	480	320	2.15	7.13
PWO	0.3	10	420	350	2.30	8.28

Disadvantages: BGO much brighter → C/S factor 100 smaller

Advantages: Scintillation spectrum peak at 480 nm → use filters Yellow for S, UV for C
Scint Decay time 300 ns (very different from prompt Cherenkov signal)

New crystals $PbWO4$ doped with different concentrations of
→ Praesodymium (peak 630 nm, τ~µs)
→ Molybdenum (500 nm, τ~30 ns) → seems to me more promising



Cherenkov light in PbWo4 crystals

- Light yield typically 10 p.e./MeV (dependent on T, readout)
- Lead glass 0.5 - 1 p.e./MeV from Cherenkov effect (3 - 5%/⌦E)

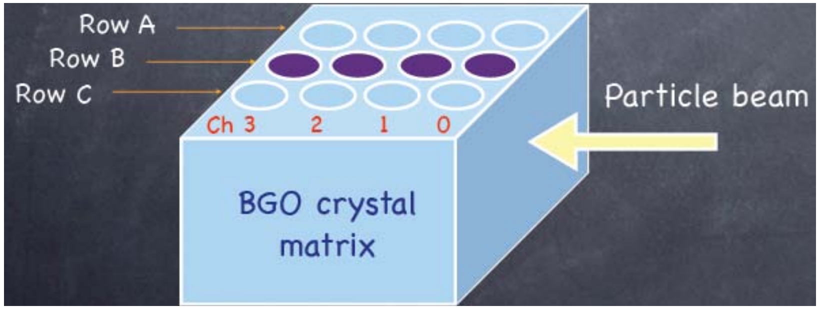
  ➔ Expect substantial Č component in PbWO4 signals

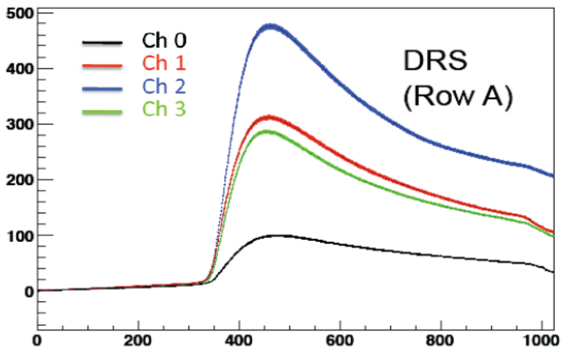
- How to detect/isolate Cherenkov component ?
  - Directionality of Cherenkov component
  - Time structure of signals
  - Spectral differences
  - Test doped Pb-glass with red / green scintillator

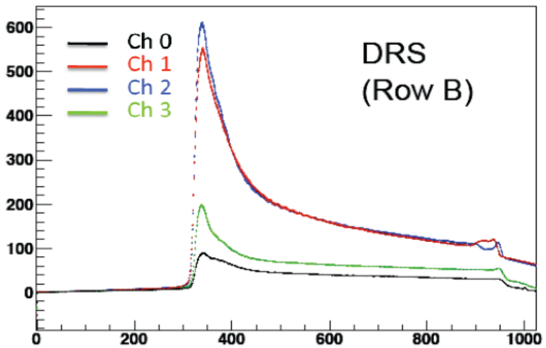
Dual readout with BGO crystals

100 crystal BGO matrix was placed upstream of DREAM as the electromagnetic section

➔need longitudinal segmentation to resolve γ from π in jet





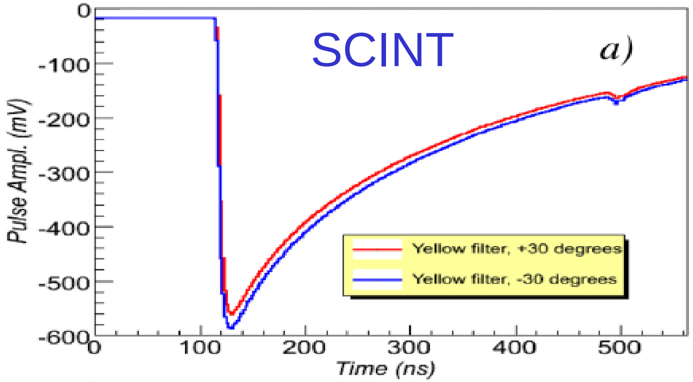


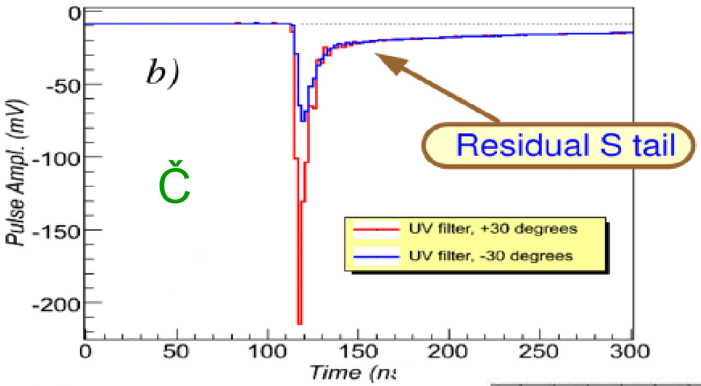
Use UV filters upstream of 4 PMTs to suppress the scintillation component

➔ PMTs with UV filter have an enhanced prompt peak due to the Cherenkov light

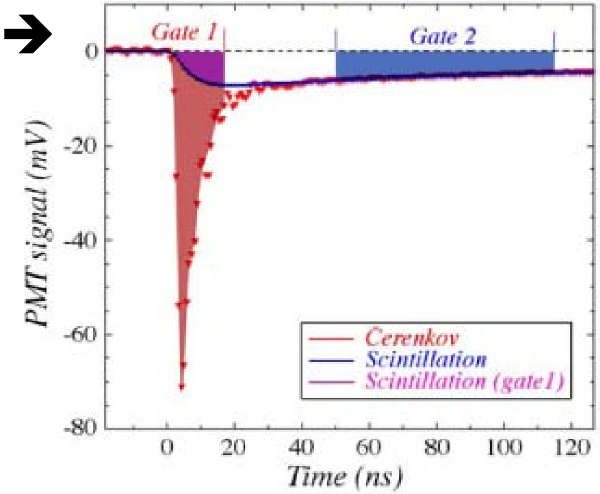
Cherenkov light measurements

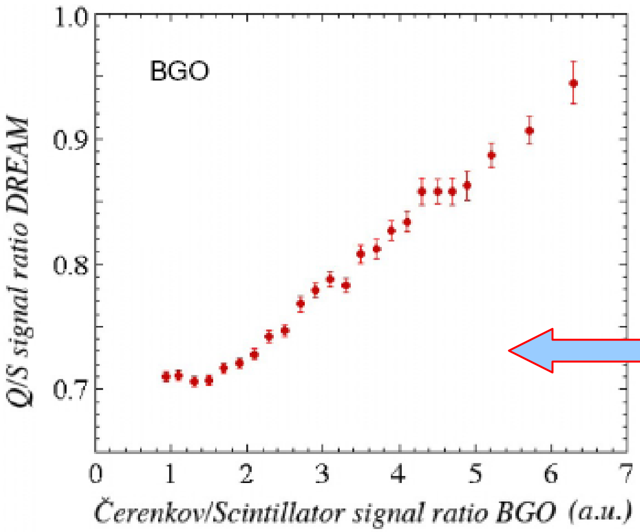
Average Time structure for 50 GeV electrons





C/S ratio event by event: integrate charge Q1 collected in the Gate1, and Q2 collected in Gate2 ➔



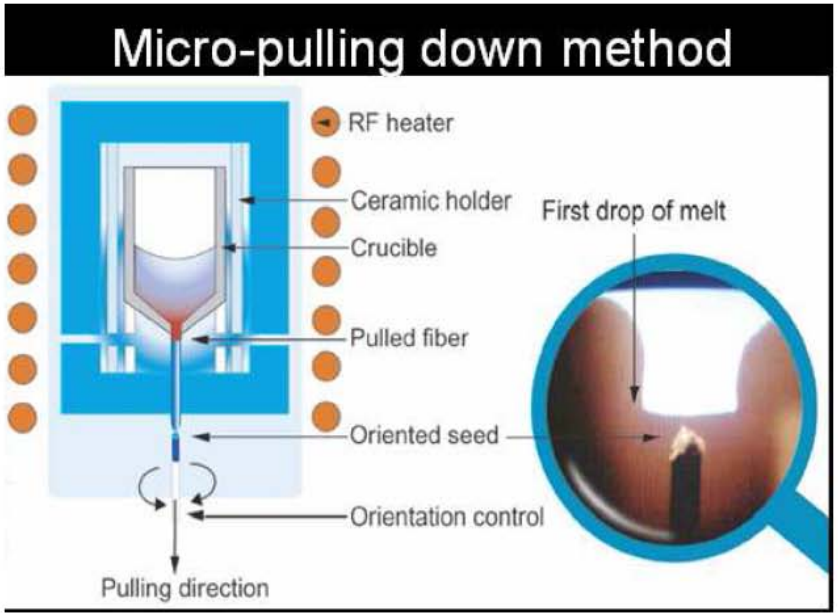


The variable C/S on BGO is able to measure the em component of the shower on the Calorimeter

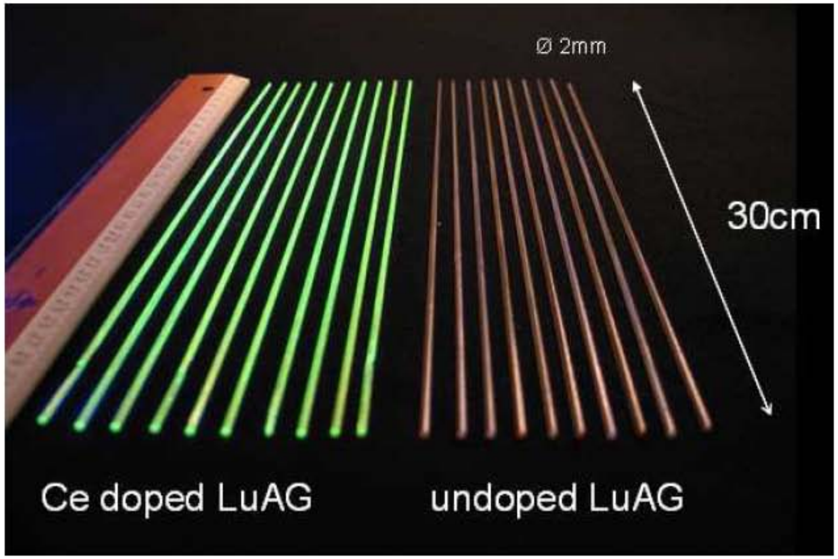
meta-materials, crystal fibers

Meta-material consisting of **undoped** and ***Ce doped*** heavy crystal bars of identical material. The undoped crystals behave as **Cherenkov radiators** while the doped crystals behave as ***scintillators***

➔ a candidate material is the Lutetium Aluminium Garnet (LuAG) crystal



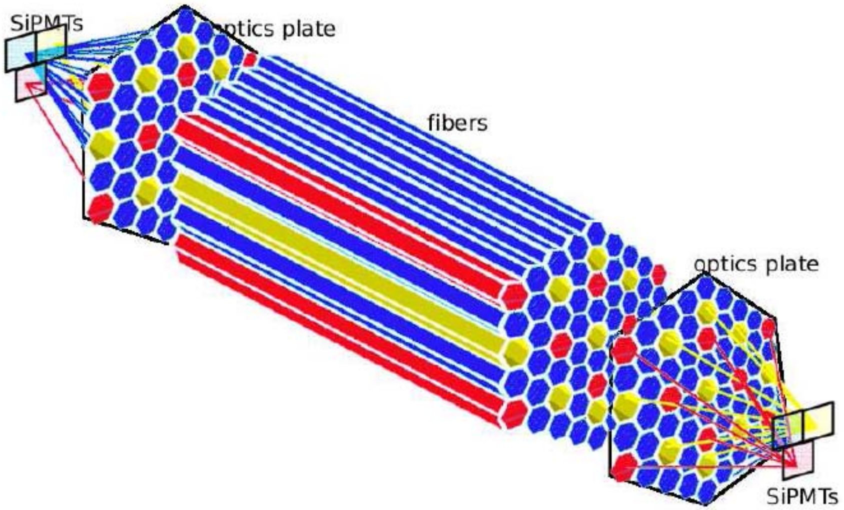
(courtesy of Fibercryst-Lyon, Cyberstar-Grenoble)



(20 fibers of diameter=2 mm, length=30 cm)

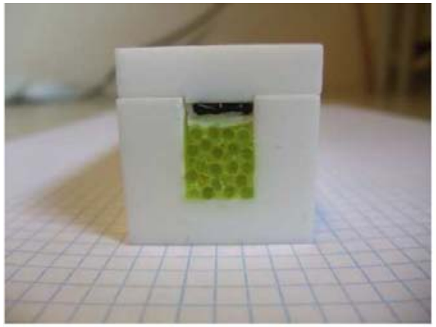
- fiber diameter between 0.3-3 mm, length up to 2 m
- pulling rate ranging from 0.1 to 0.5 mm/min
- capillary die can be non-cylindrical (e.g. square, hexagonal etc)

Design of a calorimeter readout unit

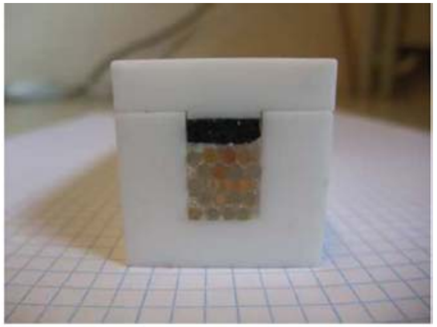


- a unit consists of a structured distribution of different types of fibers
- typical dimensions of a unit :
  d = 1-1.5 R_M; L = 20-25 X_0
- light from different types of fibers is directed to different SiPMTs by using diffractive optics light concentrators (micro-lenses) diffractive optics plate

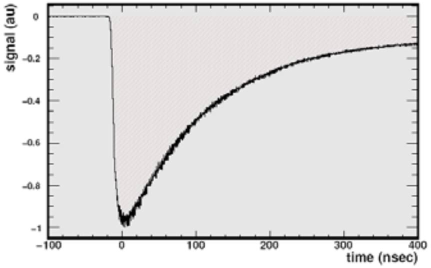
Fiber bundles exposed to beam



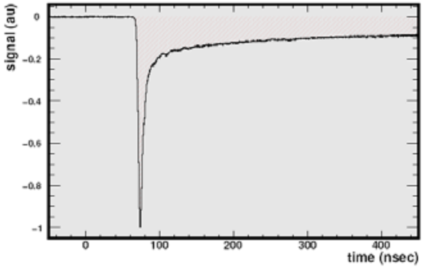
(20 fibers of diameter=2 mm, length=80 mm)



(20 fibers of diameter=2 mm, length=80 mm)



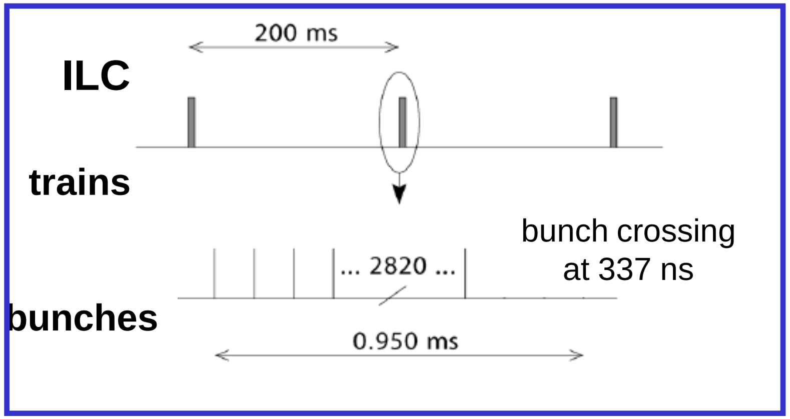
(scintillator)
Ce doped LuAG

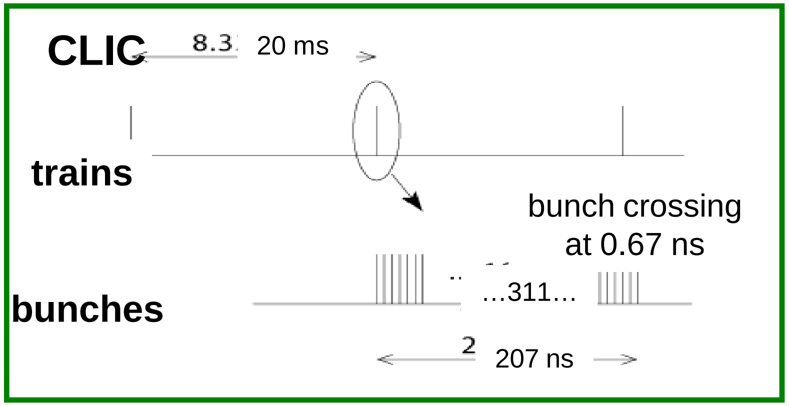


(Cherenkov radiator)
undoped LuAG

expected difference in signal shape

Time resolution





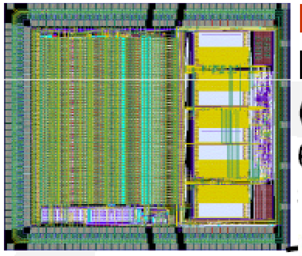
Time res. also relevant to study neutron component of hadronic showers

Beyond ILC ➔ CLIC
Higher gradient: 100 MV/m vs 35MV/m
Higher cms energy: 3 TeV vs 500 GeV

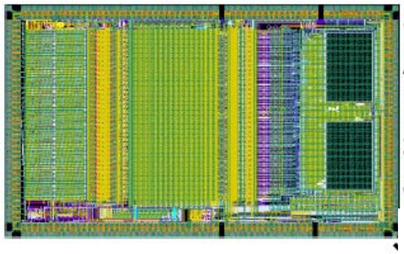
➔ Price to pay: 0.5 ns bunch crossing

Time stamp O(10ns) mandatory

TDC integrated in the "ROC" family of chips for future calorimeters
~ 1ns time resolution

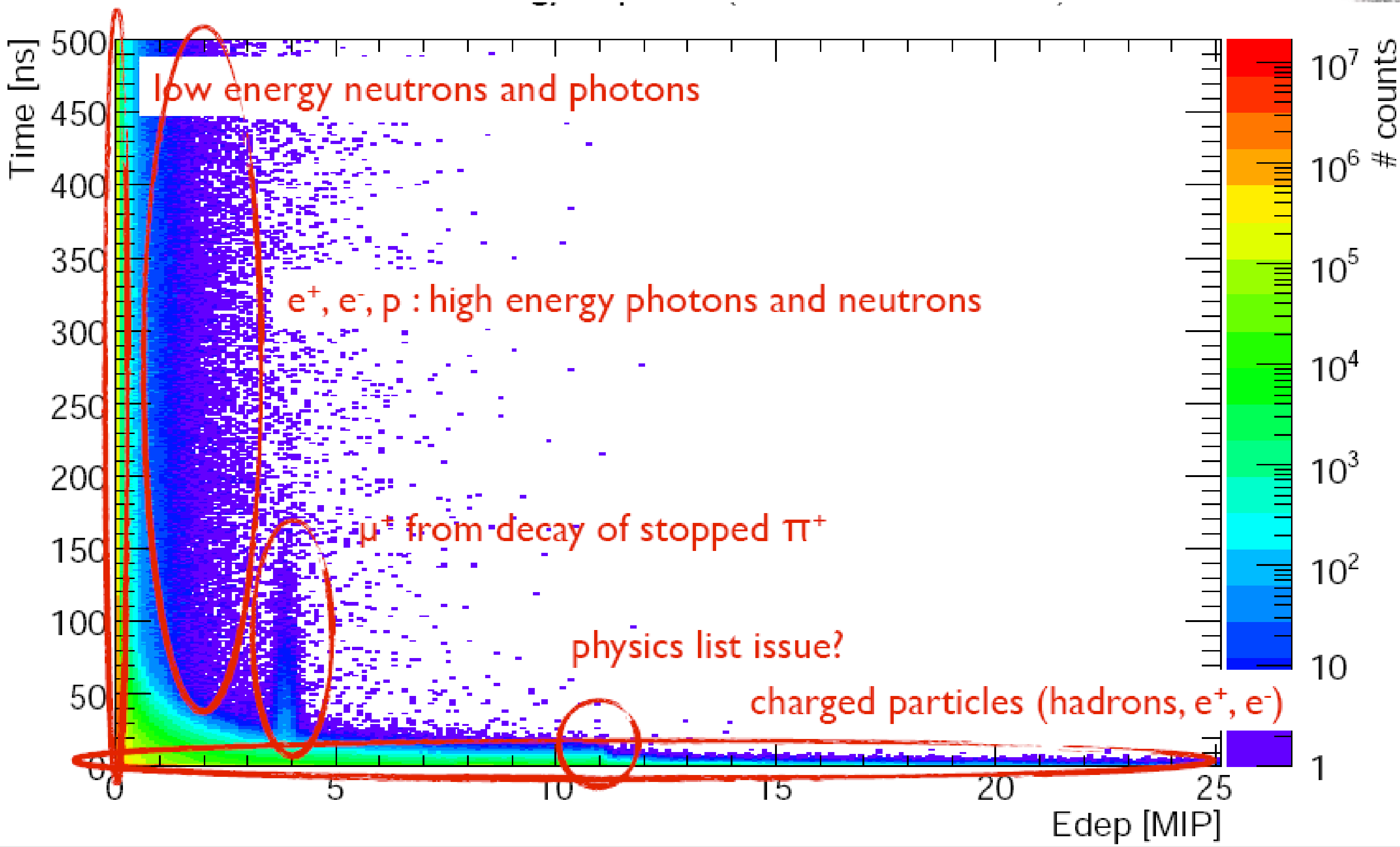


HARDROC
Digital HCAL
(RPC or µmegas)
64 ch. 16mm²



SPIROC
Analog HCAL
(SiPM)
36 ch. 32mm²
June 07

Time resolution



Time res. also relevant to study neutron component of hadronic showers

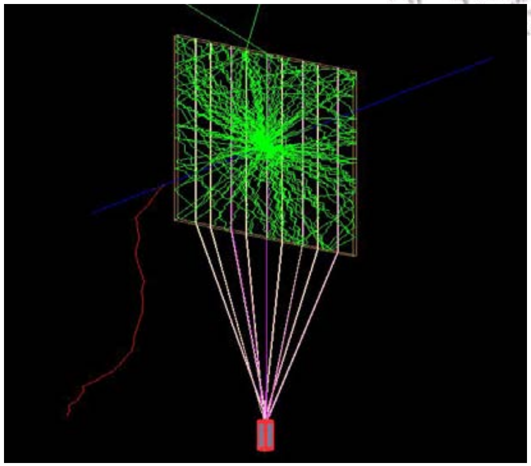
Next generation of calorimeters will be "4D imaging" calorimeters !!

sLHC & CLIC R&D

Calorimetry at sLHC ➔ radiation hard material

Exchange scintillator with quartz

Test of different quartz + WLS fiber geometries



Advantages of WLS fiber:

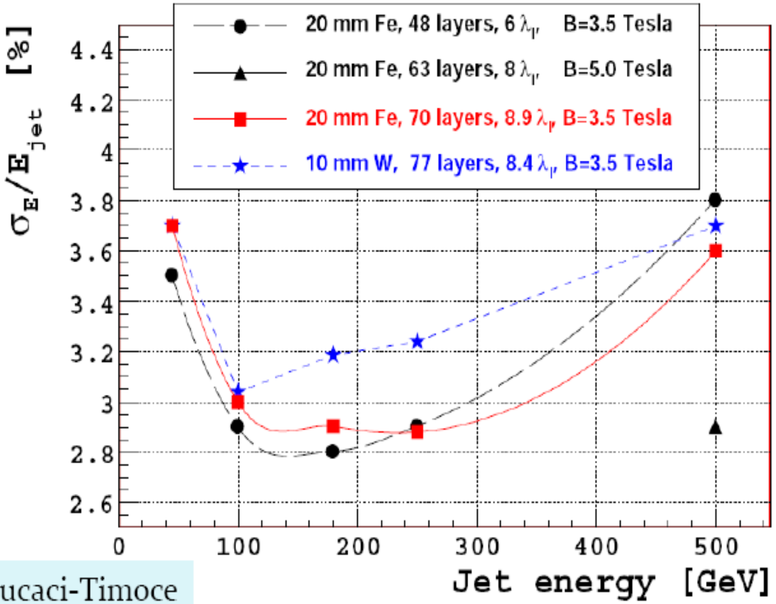
collect light to photo-detector

Improves homogeneity of tile

Disadvantages of WLS fiber:

Degradation of fast Cherenkov signal (<1ns)

due to WLS fiber emission



Lucaci-Timoce

Outlook on future R&D:

- Exploit fast Cherenkov signal + time resolution
- High granularity helps to reduce multiplicity/cell

CLIC: move to Tungsten absorber

Behond DREAM

For ultimate hadron calorimetry ($15\%/\sqrt{E}$)

➔ Measure E_{kin} (neutrons)

- correlated to nuclear binding energy loss (invisible energy)
- can be measured with third type of active material TREAM

➔ hydrogen enriched materials (not yet tested)

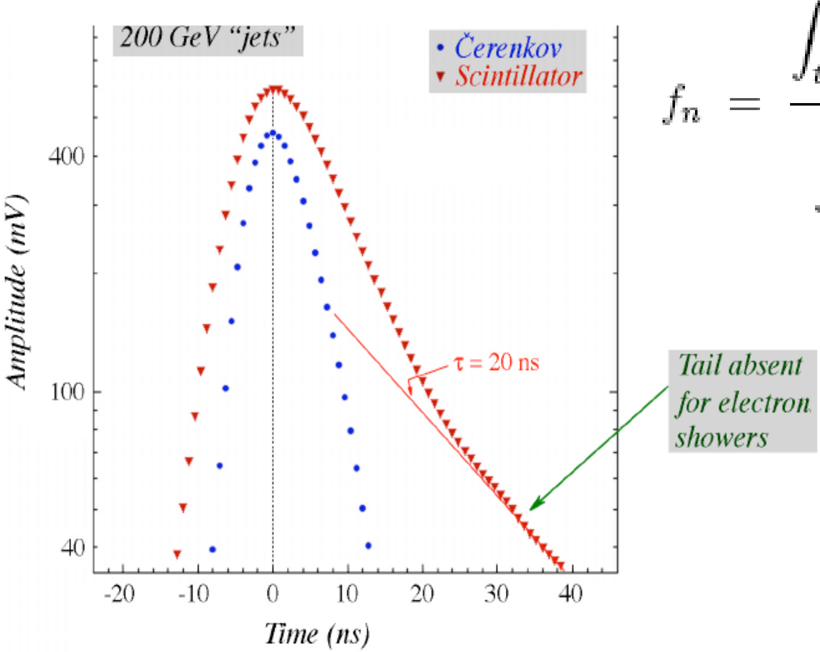
Measure Neutron Fraction

from the time structure of the signal

The neutron fraction is correlated to nuclear binding energy (invisible energy) ➔ next large source of fluctuations to attack

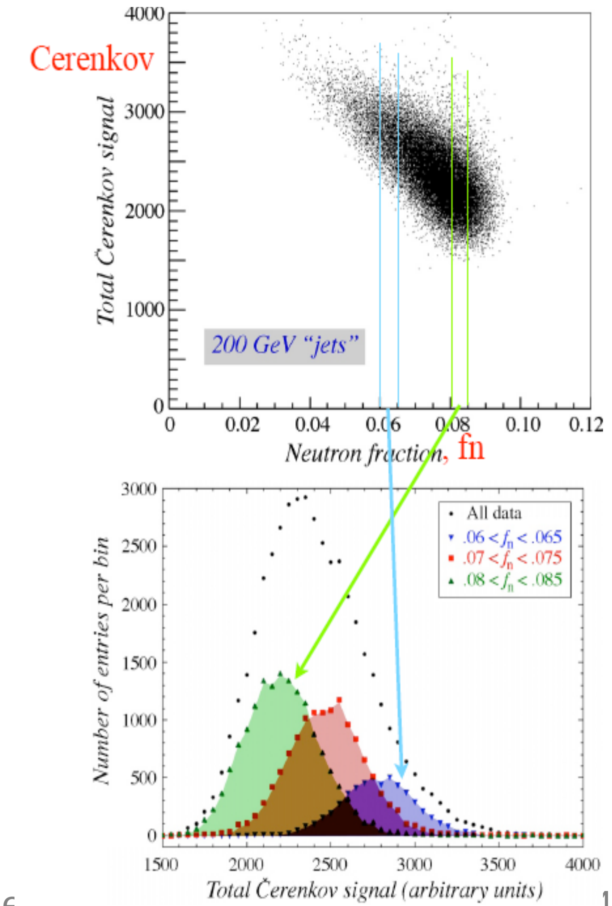
<u>Neutron signal</u> (f_n)= integral of scint signal over 20-40 ns

$$f_n = \frac{\int_{t=20\mathrm{ns}}^{40\mathrm{ns}} \sum_{i=2}^{19} S_i}{\int_{t=0}^{\infty} \sum_{i=1}^{19} S_i}$$



The total C distribution can be decomposed into its constituent parts as a function of f_n

f_n anticorrelated with C as aspected



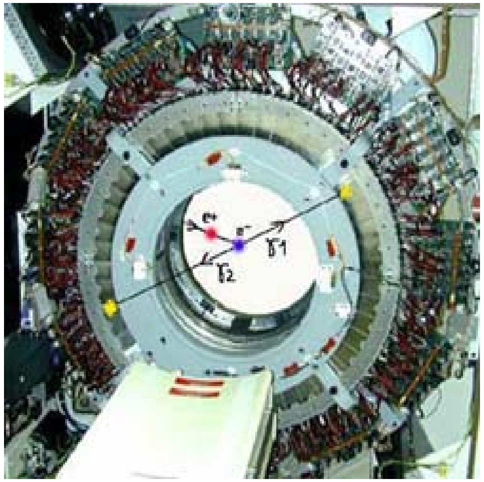
Calorimeters behind HEP

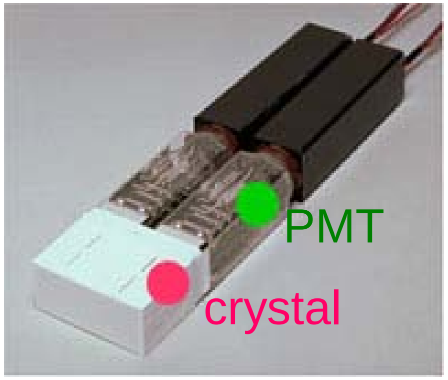
Positron Emission Tomography

How can a calorimeter save your life? ➔ PET

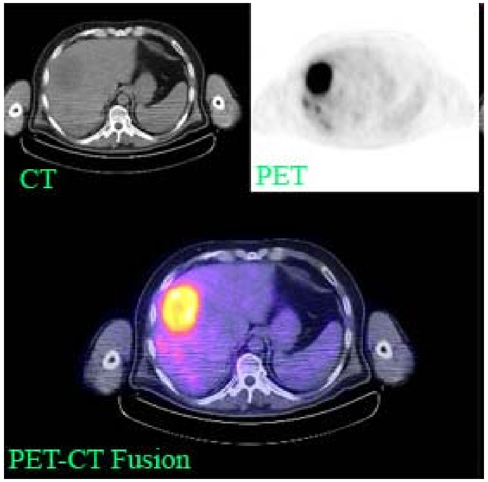
a commercial PET system
for hospital treatment

the same system without cover





basic unit of a PET:
crystal (LSO, BGO) + PMT



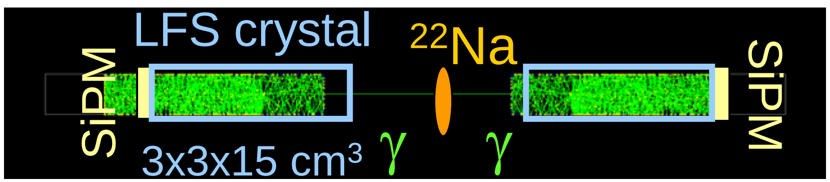
➔ Functional (metabolich) pictures of living organs in addition to Computer Tomography improves high resolution visualization of anatomic parts

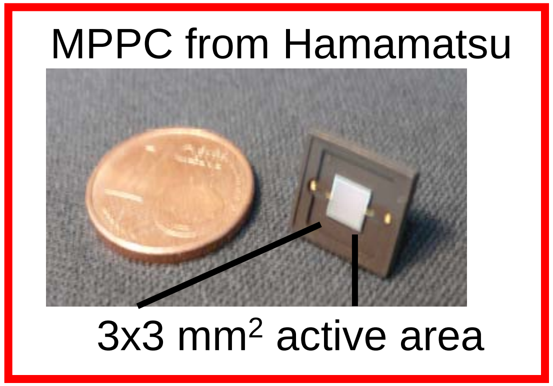
Task: reconstruct 2 γ (511 keV) from annihilation of positron from a β-emitting tracer
➔ calorimeter

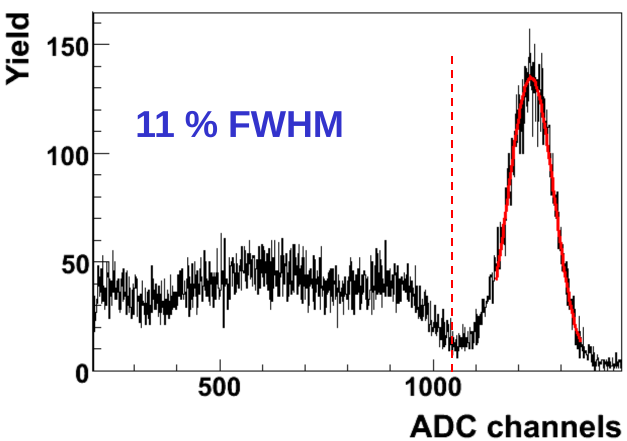
New trends in PET calorimeters

High granularity and small calorimeter cells improve space resolution

➔ Silicon Photomultiplier replace PMT
•compact system
•low HV & cost







•Good E res. ➔ reduce Compton bg.
•Good t res. ➔ reduce combinatorial bg.

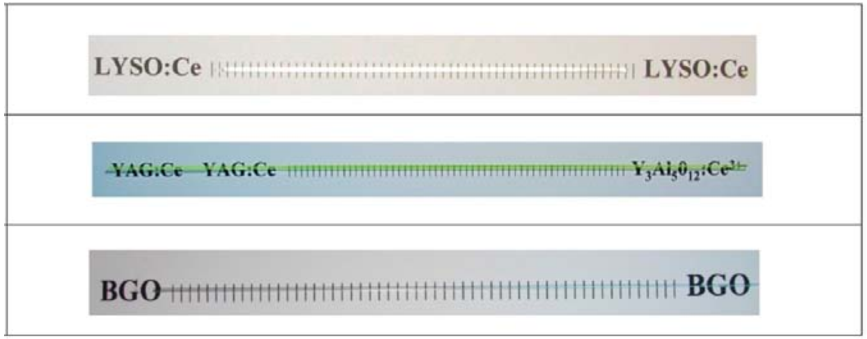
time resolution for coincidence of two channels ~250ps using SiPM readout and dedicated electronics possible

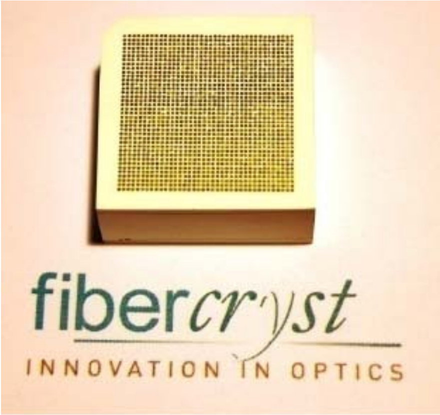
Technology frontier

new products

Extreme granularity

Fiber crystals: ⌀ 350um – 3mm



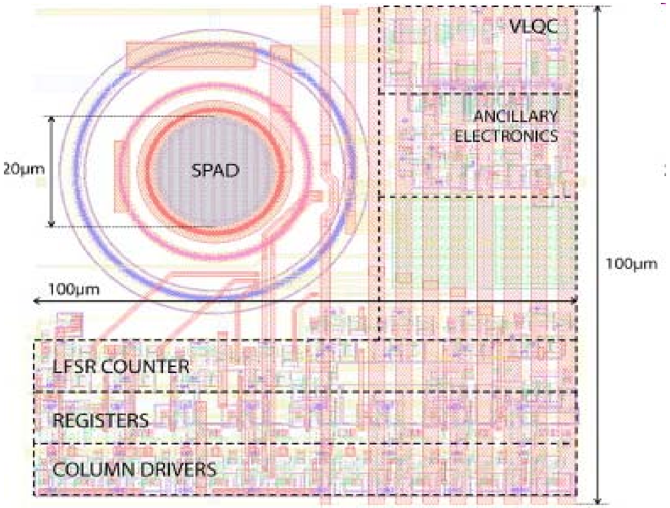


LuAG:Ce Array

Improve space resolution using smallest crystals individually read out

Extreme integration

new generation of Geiger-mode avalanche photo-detector: integrates SPAD on CMOS

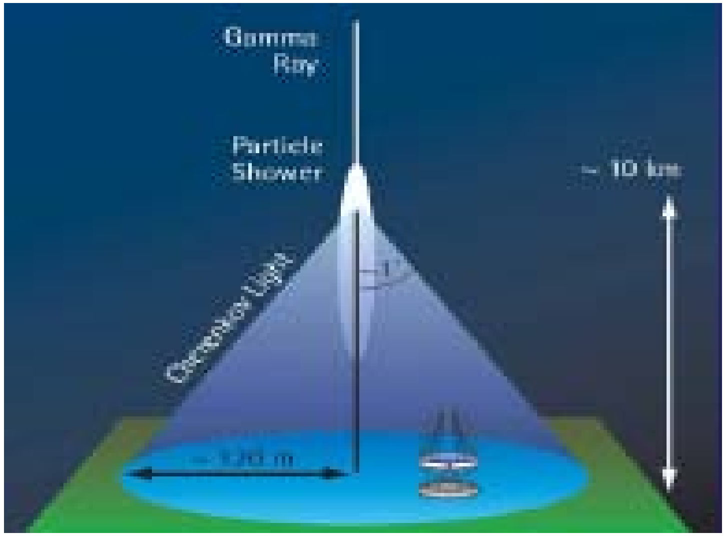


~50 um pixel SPADs arranged in arrays with individual pixel readout
- O(100ps) time resolution on single photon

E. Charbon et al., IEEE (ESSCIRC), Sep. 2009

http://www.everyphotoncounts.com/arrays-linarray.php

Ground based Gamma Ray Astronomy

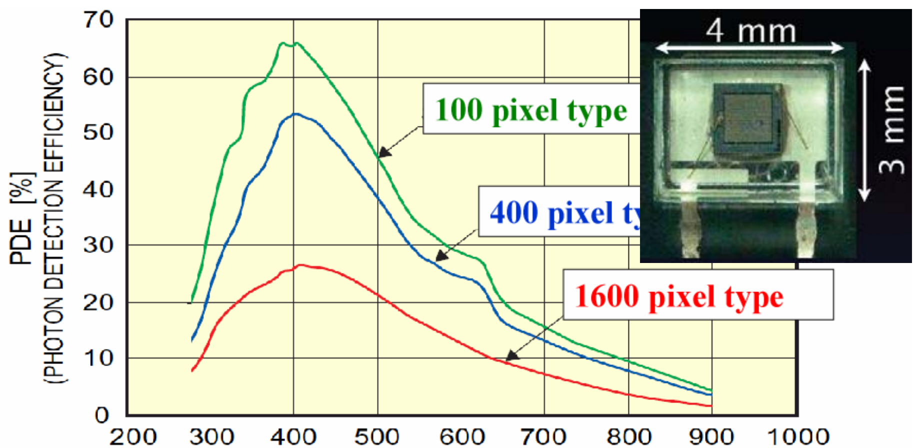


Gamma Ray induces electromagnetic cascade
➔ Relativistic particle shower in atmosphere
➔ Cherenkov light
fast light flash (~ns)
100 γ / m^2 (1 TeV Gamma Ray)

Next generation: **Cherenkov Array Telescope (CTA)**

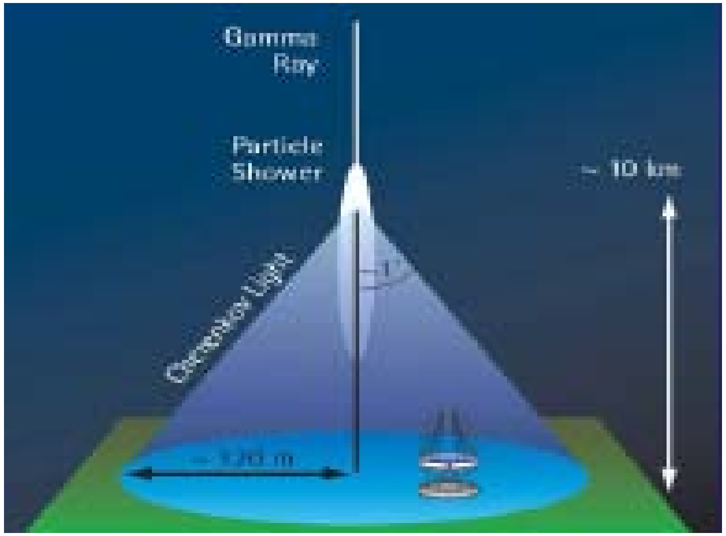
CAMERA

- Expensive
- Camera composed of 1000 pixels ➔ use PMT for baseline (40% PDE)
- Fast timing response (~1ns) to cope with EAS Cherenkov flashes
- Electronics inside the camera
- Keep low weight



SiPM offer 60% PDE at 400nm
+ improvements with lower fill factor

Ground based Gamma Ray Astronomy



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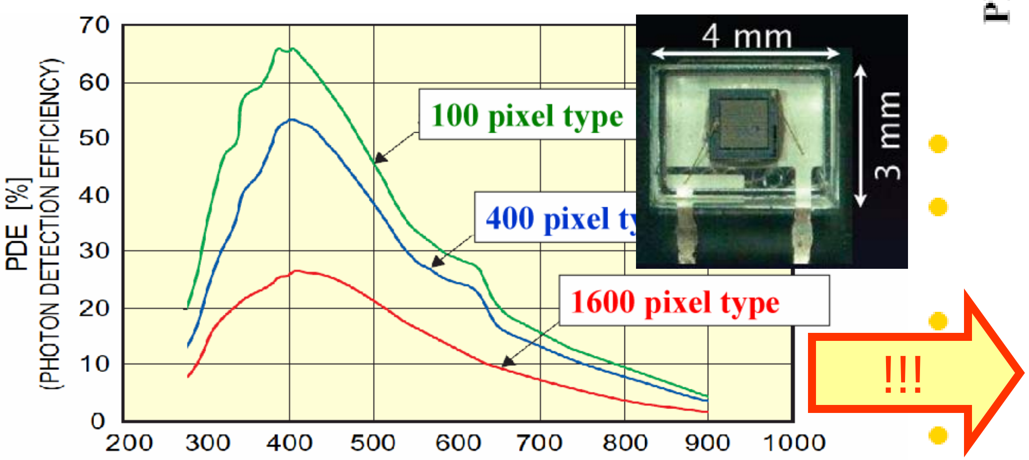
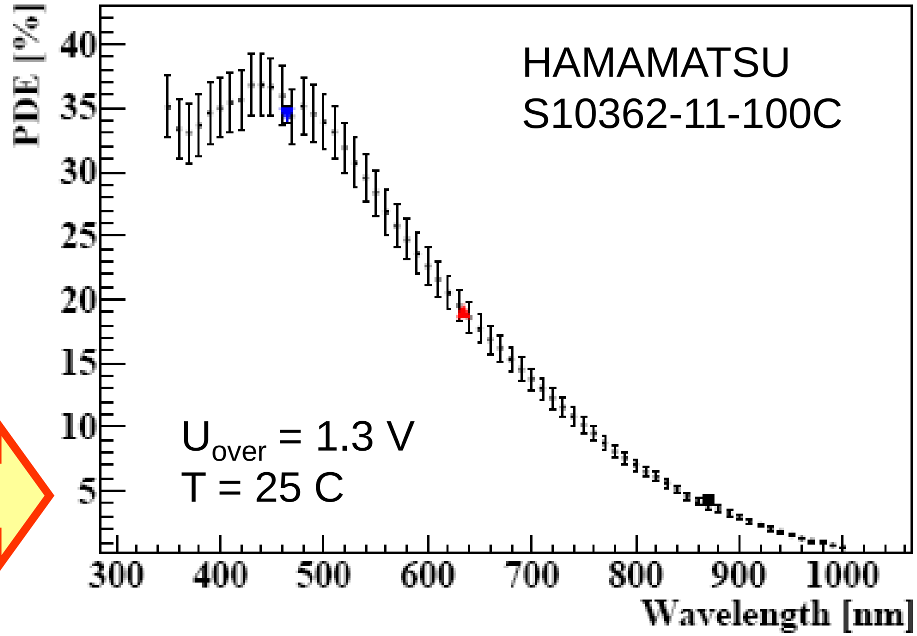




SiPM offer 60% PDE at 400nm
+ improvements with lower fill factor

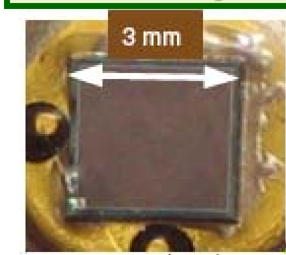
P. Eckert et al, Nucl.Instrum.Meth.A620:217,2010

Positron Electron Balloon Spectrometer

Goal: Measure the cosmic ray positron fraction with a balloon borne spectrometer

Motivation: Indirect search for dark matter

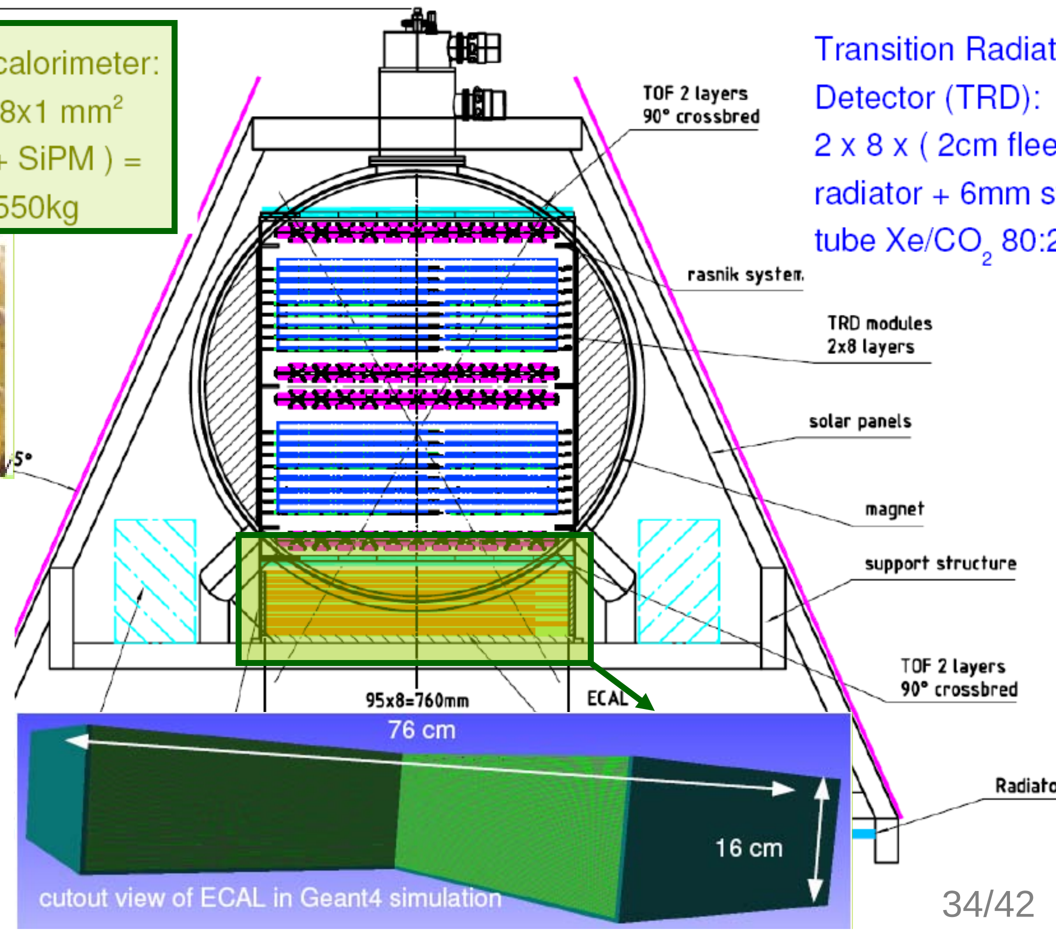
Electromagnetic calorimeter: 80 x (1mm Pb + 8x1 mm^2 scintillating fibre + SiPM) = 14.3 X0, weight: 550kg



Requirements (calorimeter):
- Excellent proton suppression of $O(10^6)$
- Total payload weight < 2t
- Total power consumption < 1000W

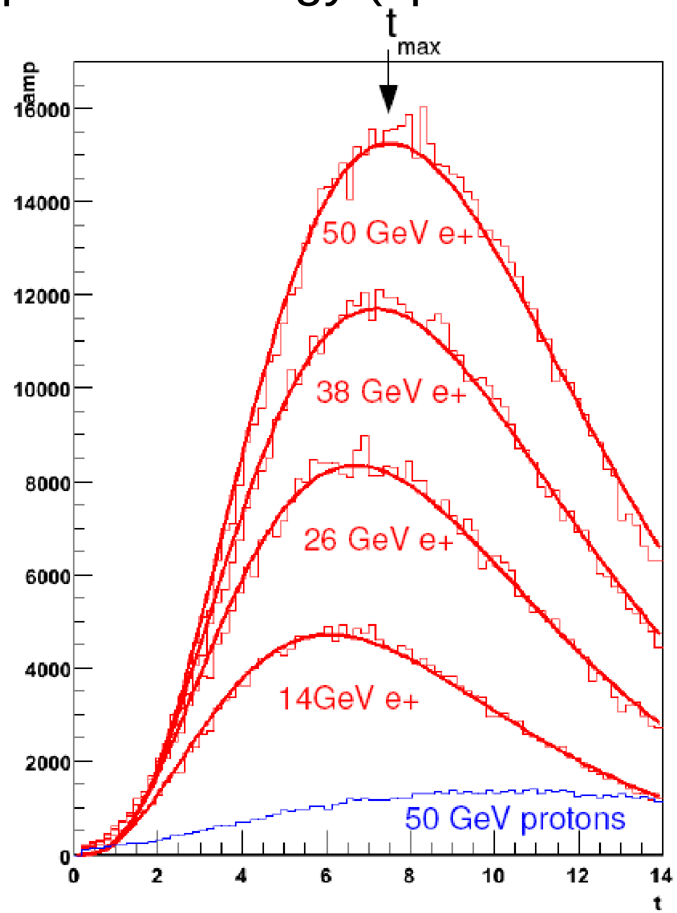
Time-of-Flight system (TOF): 2 x 2 x 5 mm^3 scintillator, SiPM readout; trigger system!

Transition Radiation Detector (TRD): 2 x 8 x (2cm fleece radiator + 6mm straw tube Xe/CO_2 80:20)



Proton rejection

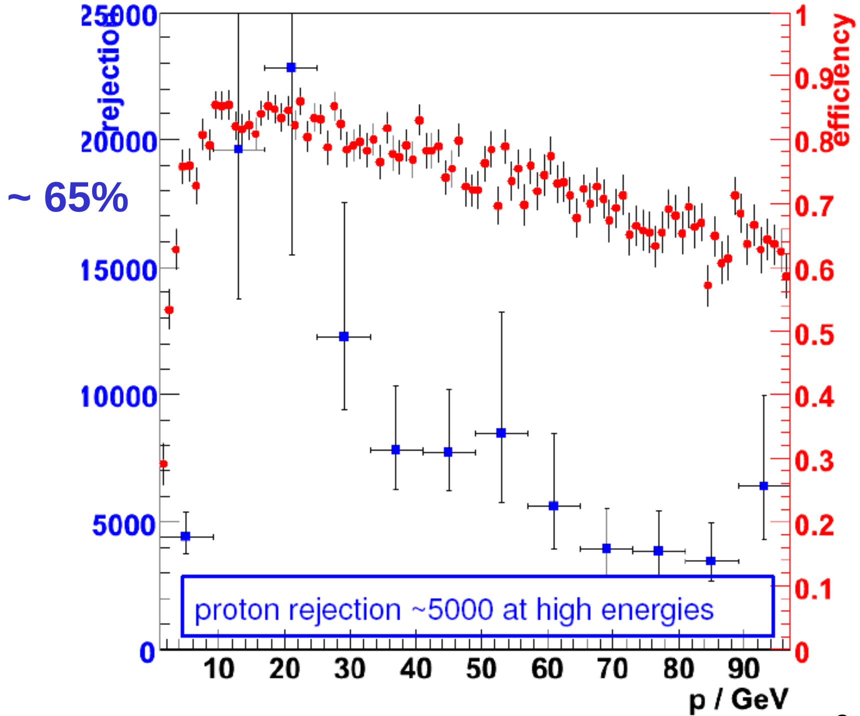
e/p separation based on different longitudinal shower shape at a given particle energy (spectrometer) ➔ extremely high granularity



$$\frac{dE}{dt} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} e^{-bt} \qquad t = x/X_0$$

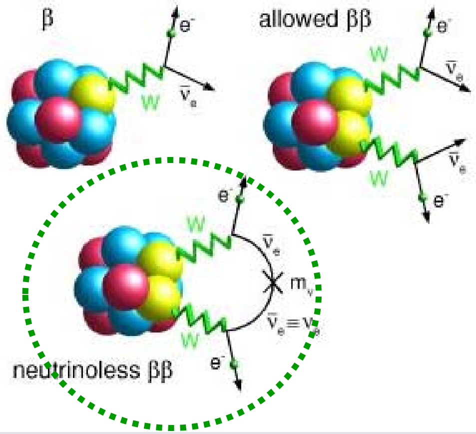
longitudinal shower profiles

Simulated 40k positrons and 1700k protons



intrinsic resolution limited by high energy π^0 production ($p \rightarrow p\pi^0X$) in front of or in first layers of ECAL

Calorimeter for ββ0ν search: The Bolometer

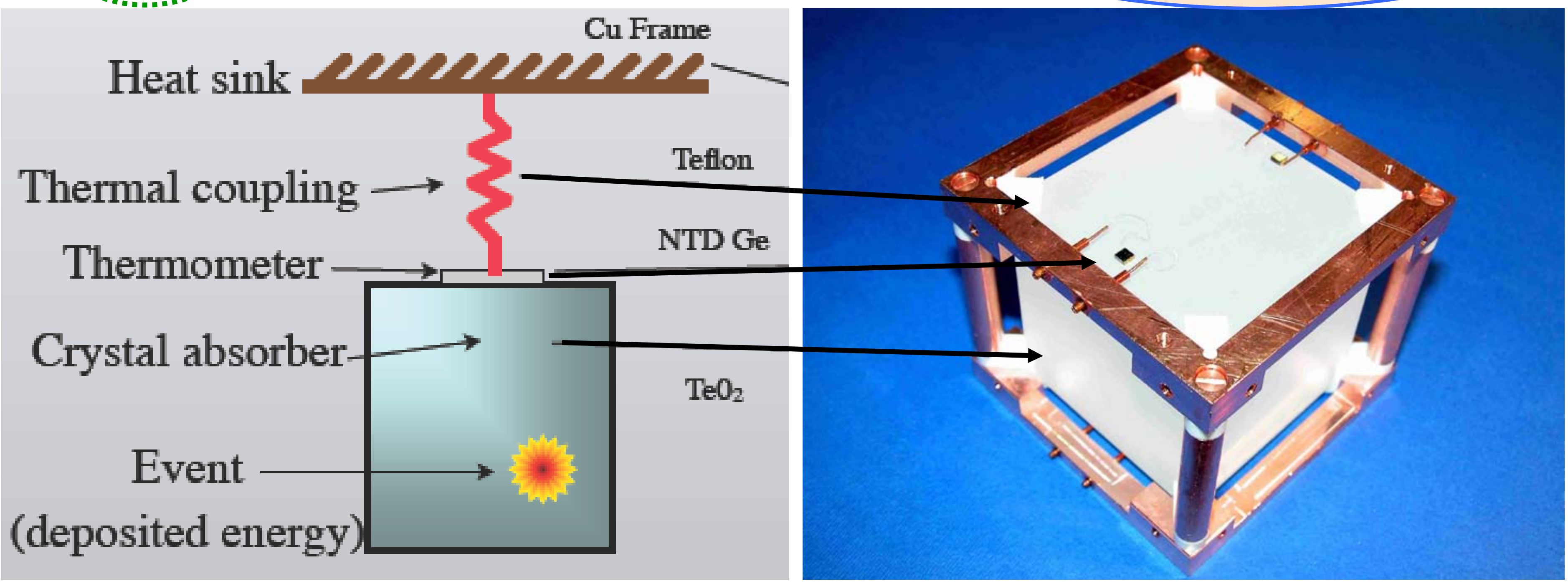


Bolometer operating principles:

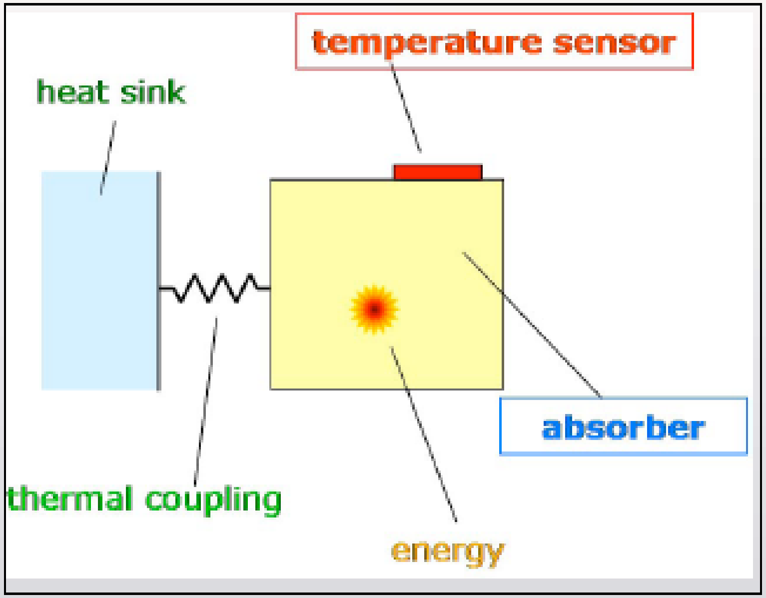
$\Delta T = E/C \approx 0.1$ mK

Low Temperature

Absorber material TeO_2 low heat capacity large crystals available radiopure



Cryogenic bolometer



Heat sink: 8-10 mK

Weak thermal coupling (teflon holders):
$G = 4$ pW/mK

Thermister: NTD Ge-thermistor
$R \cong 100$ MΩ, $dR/dT \cong 100$ kΩ/μK

Crystal absorber: TeO_2 crystal
$C \cong 2$ nJ/K $\cong 1$ MeV / 0.1 mK

Temperature signal for E=1 MeV: $\longrightarrow$ **$\Delta T = E/C \cong 0.1$ mK**

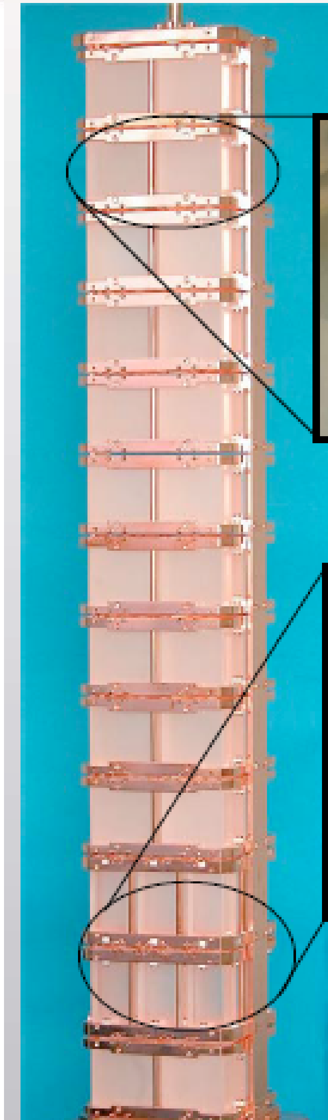
Signal size: $\Delta V = I \times dR/dT \times \Delta T$ $\longrightarrow$ **1 mV/1 MeV**

Signal recovery time: $\tau = C/G$ $\longrightarrow$ **0.5 s**

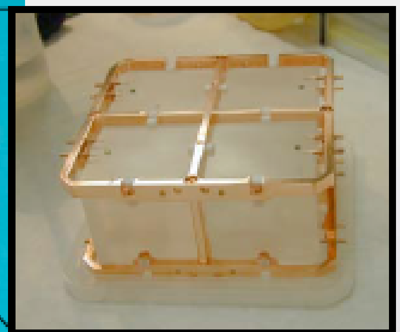
Noise over signal bandwidth (few Hz): $\longrightarrow$ **$V_{rms} = 0.2\ \mu V$**

Energy resolution (FWHM): $\cong$ 1 keV (in theory)

Cuoricino experiment @ Gran Sasso

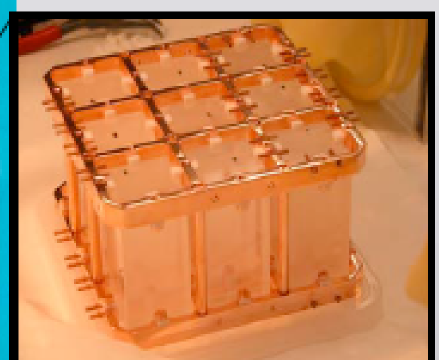


Currently the largest bolometer in the world



11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 750 g
44 x 0.79 = 34.76 kg of TeO_2

Encased in a lead shield, nitrogen box, neutron shield, and Faraday cage



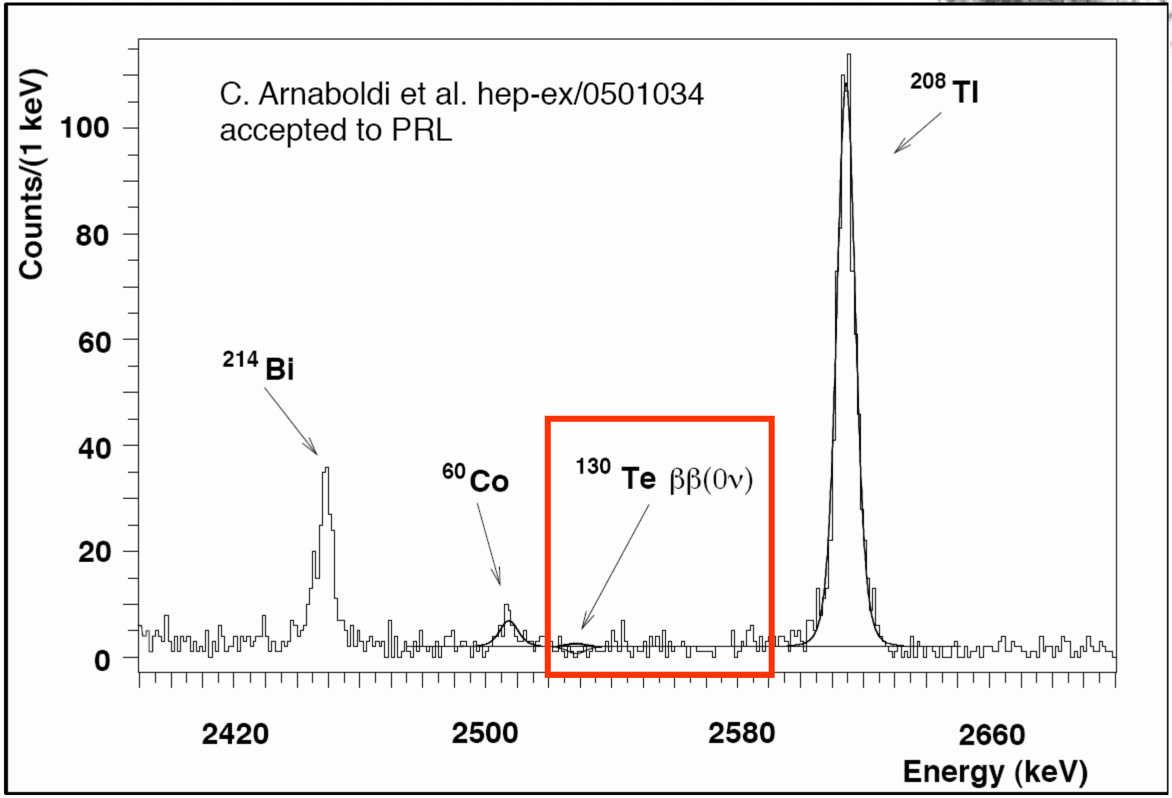
2 modules x 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
18 x 0.33 = 5.94 kg of TeO_2

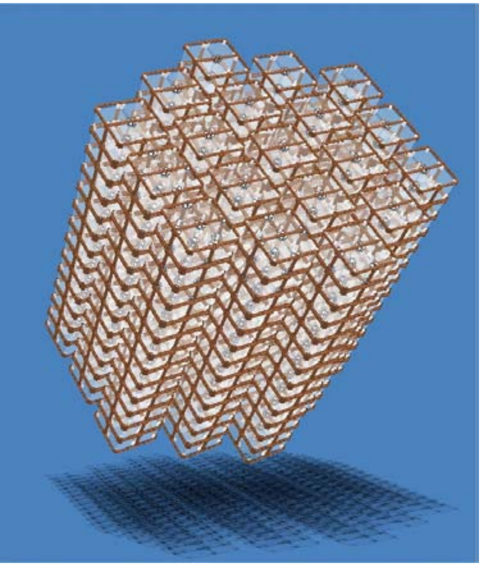
Total detector mass: 40.7 kg TeO_2 $\Rightarrow$ **11.64 kg ^{130}Te**

Cuoricino limit on ββ0ν

Resolution:
FWHM at 2615 keV
= 9.2 ± 0.5 keV

Background:
In the ββ0ν region
= 0.18 ± 0.01 counts/(keV kg y)





Results: no peak found

➔ $\tau^{0\nu}_{1/2} > 3.0 \times 10^{24}$ (at 90% C.L.)

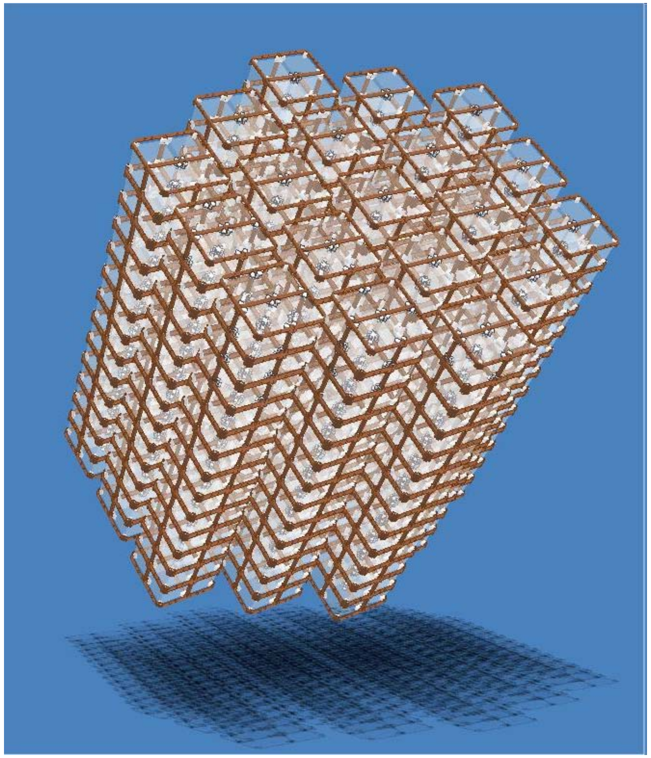
$m_\nu < 0.2 - 0.98$ eV

CUORE will follow with: 988 TeO_2 bolometers cubes 5 cm^3 with a mass of 750 g each.

Next step: Cuore

Cryogenic Underground Observatory for Rare Events:

- Array of 988 TeO_2 crystals
- 19 Cuoricino-like towers suspended in a cylindrical structure
- 13 levels of 4 5x5x5 cm^3 crystals (750g each)
- ^{130}Te: 33.8% isotope abundance
- Time of construction: 4 years
- expected by 2010



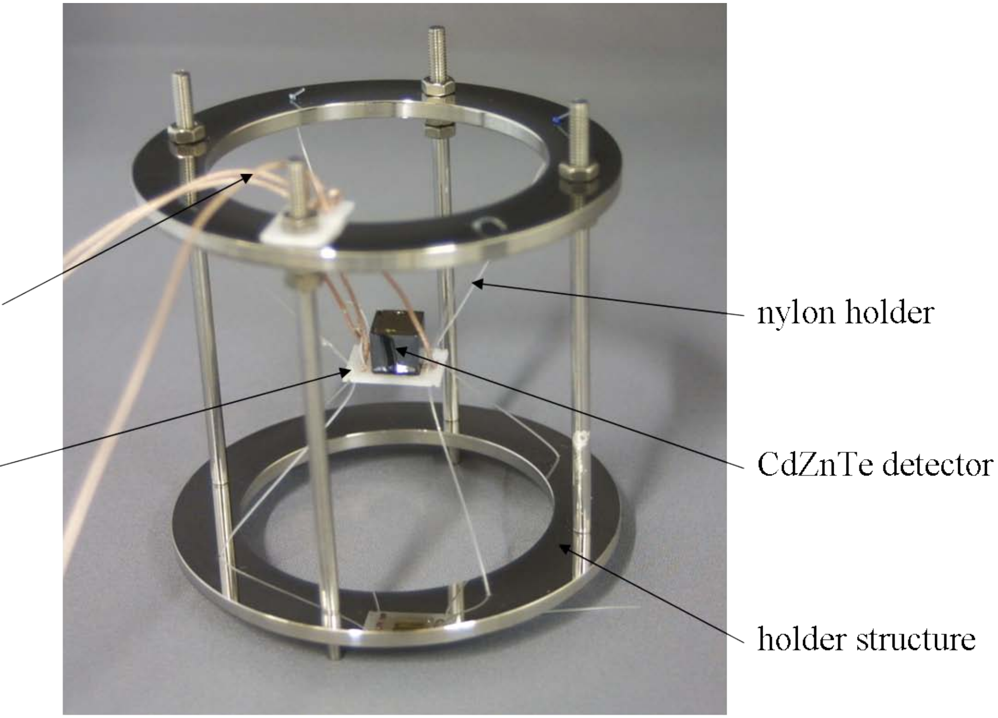
750 kg TeO_2 => 200 kg ^{130}Te

With bolometry we are back to the original meaning of calorimetry !

New sensor materials: CdZnTe

New trends in $0\nu\beta\beta$ decay detectors

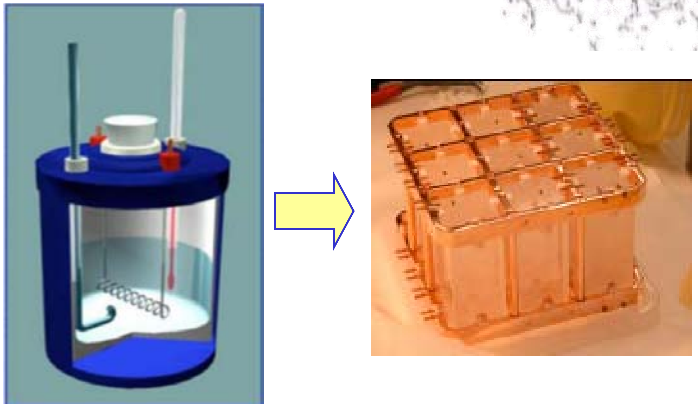
➔ The COBRA experiment



- detector based on CdZnTe semiconductor
- operated at room temperature
- high density of the crystal provides excellent stopping power
- detector array under design:

  ~6400 crystals
  of 1 cm^3 size (~6.5g)
  for a total of 400 kg

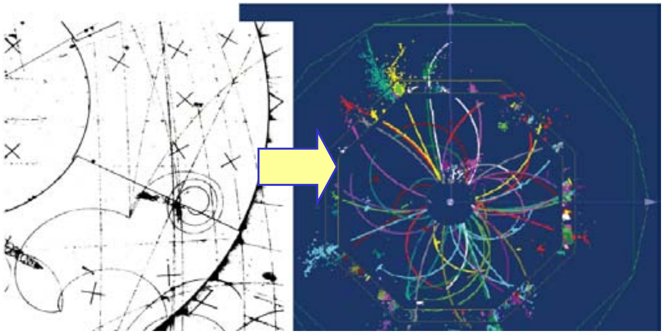
Conclusions



Calorimetry is a field developed over
more than a century,
still vital and in continuous evolution

Calorimetry at the technology frontier drives the development of

new materials, new photo-detectors, new electronics, …, new analysis techniques, new ideas



Present key issues for calorimetry:

- Extreme segmentation (Imaging calorimeters)
- Extreme integration (maximum hermeticity)
- Compensation in limited volume (Pflow/ dual-readout)

Thank you all for your attention and participation during these lectures!

Acknowledgments

These slides are largely based on the work of:

The ATLAS collaboration	http://atlas.ch/
The CALICE collaboration	https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome
The CMS collaboration	http://cms.ch/cms/index.html
The DREAM collaboration	