Calorimetry
- particle flow -

Erika Garutti

DESY

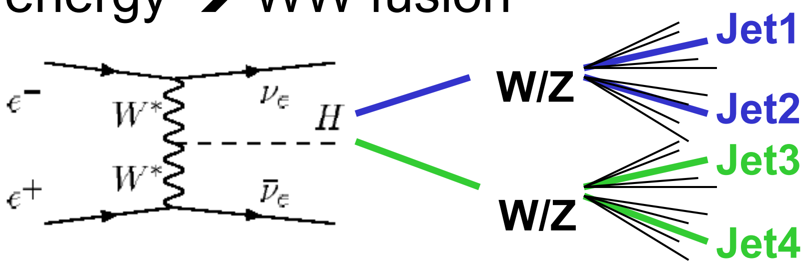
Jet physics

After discoveries (LHC) ➔ precision physics ➔ lepton machine

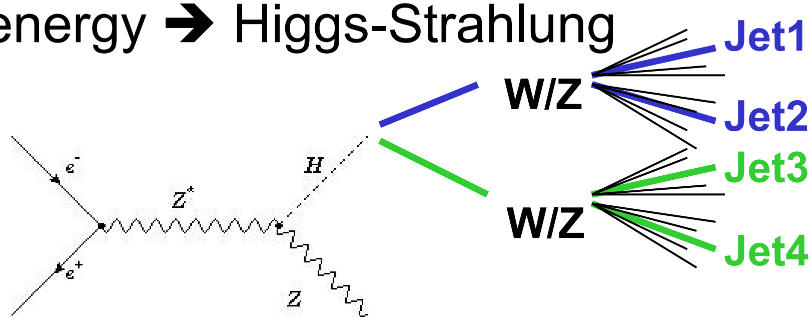
The Higgs scenario:

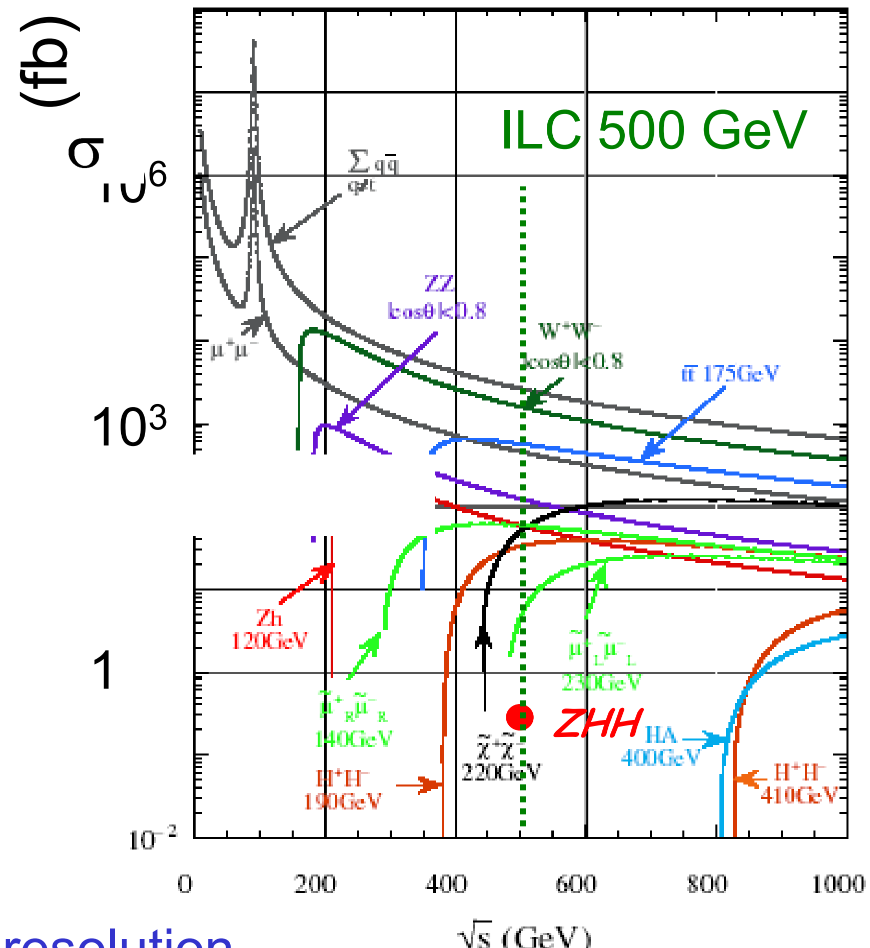
main production mechanisms

High energy ➔ WW fusion



Low energy ➔ Higgs-Strahlung





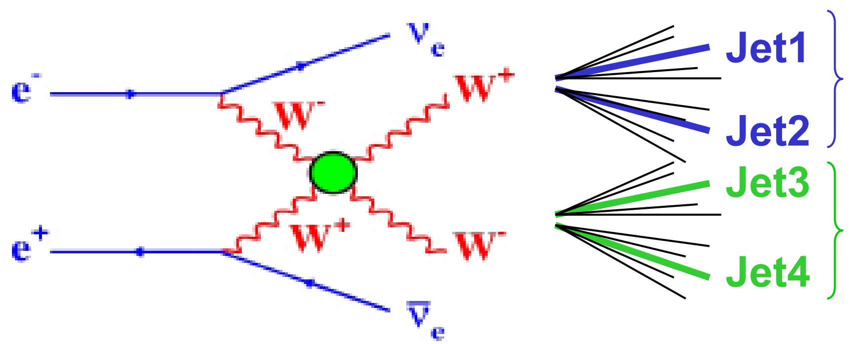
➔Jet physics

Build a detector with excellent jet energy resolution

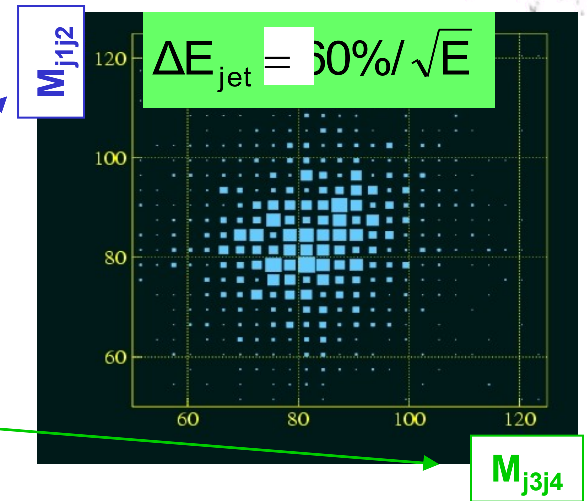
Jet physics (continue)

No Higgs scenario:

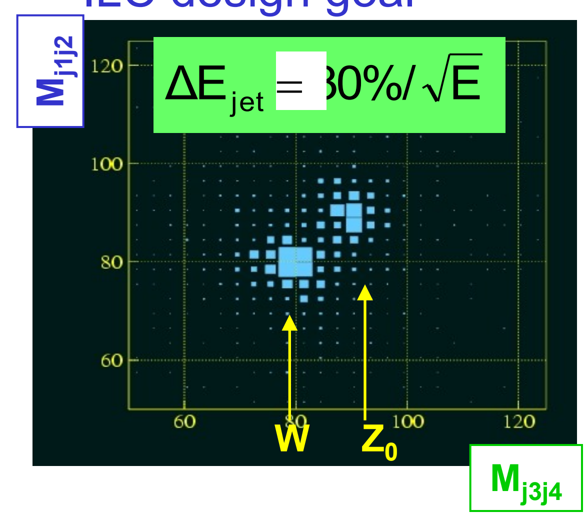
- WW scattering violates unitarity at ~1.2TeV, or new forces show up



LEP-like detector



ILC design goal

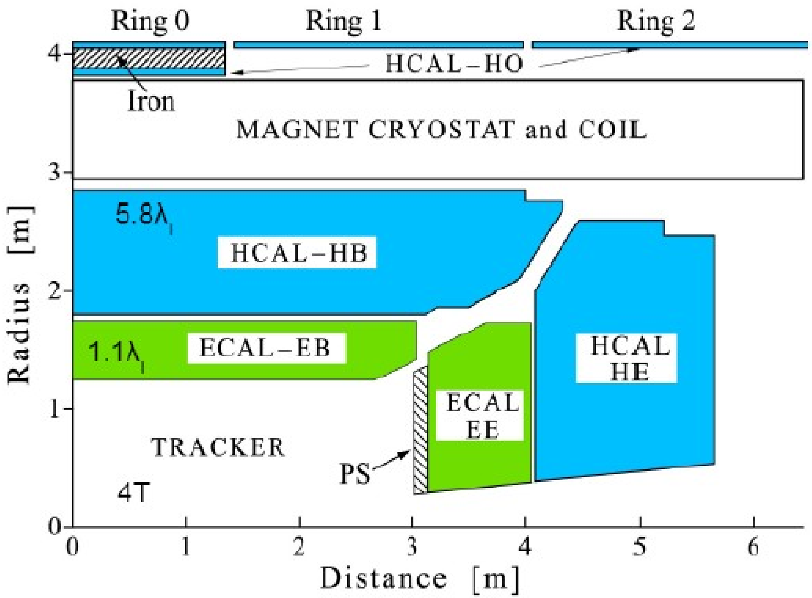


- access EWSB mechanism from WW scattering
- analyze ee→WWνν and ee→ZZνν channels
- no kinematic fit possible due to the neutrinos

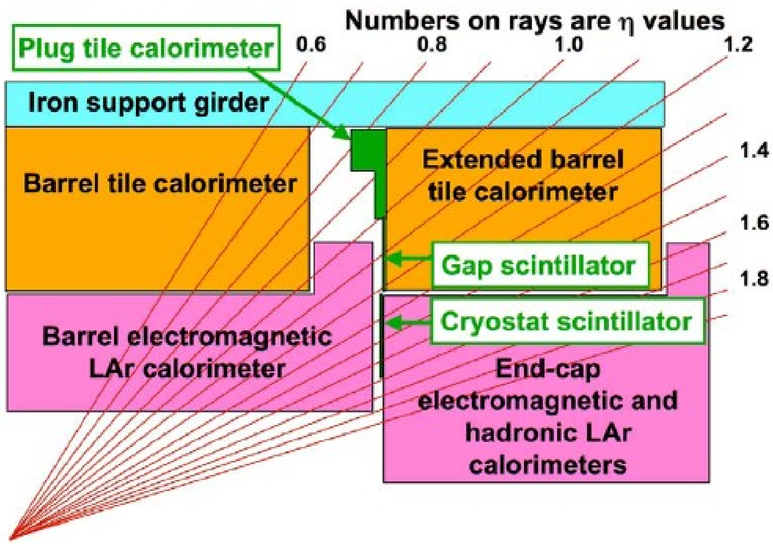
➔Worse jet energy resolution (60%/√E) is equivalent to a loss of ~40% luminosity

Jet energy resolution at LHC

CMS



ATLAS



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

Expected jet resolution:

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

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 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

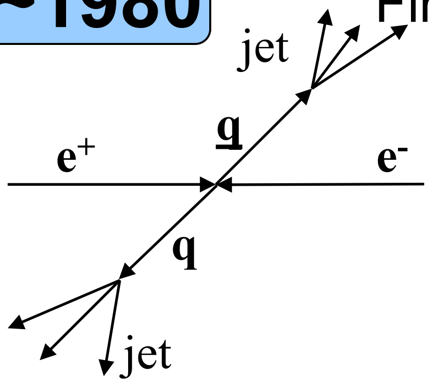
Idea (early 90ies):

- 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

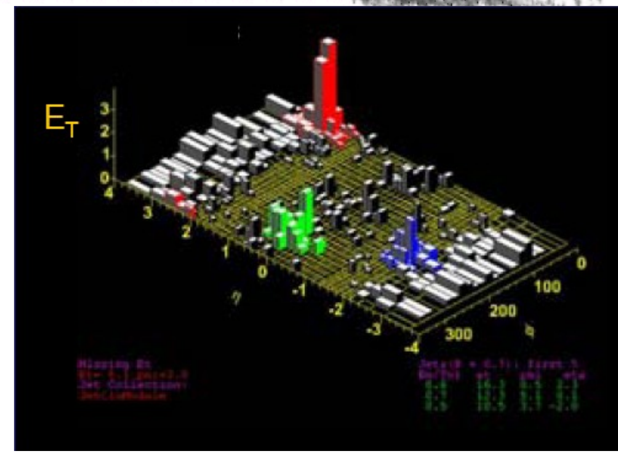


First observation of quark Jets

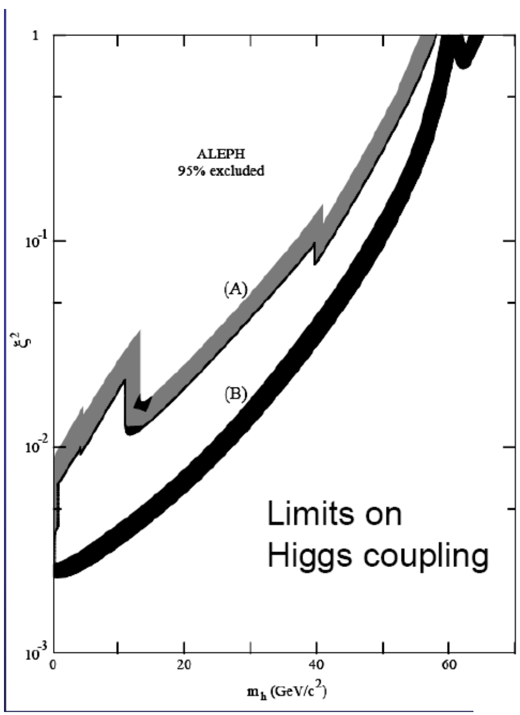
UA1, UA2 @ SppS, CERN
JADE @ PETRA collider, DESY

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

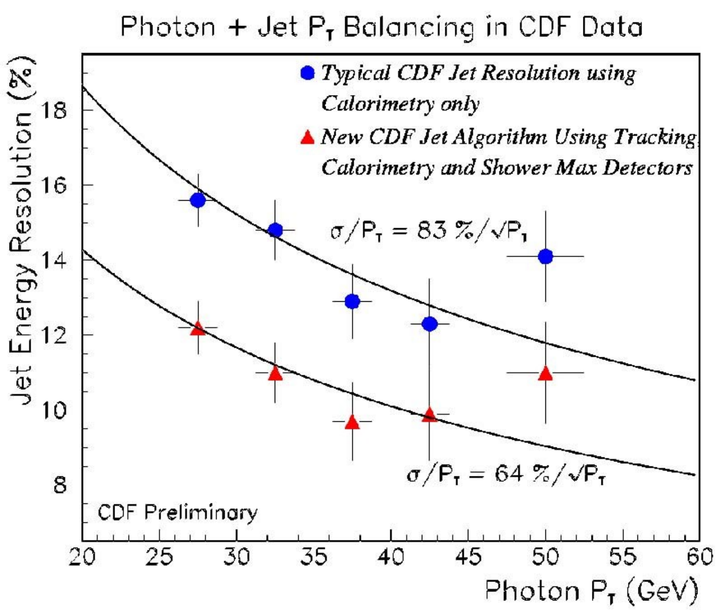
Does the method work ?

Test on existing detectors

ALEPH, CDF, ZEUS, …

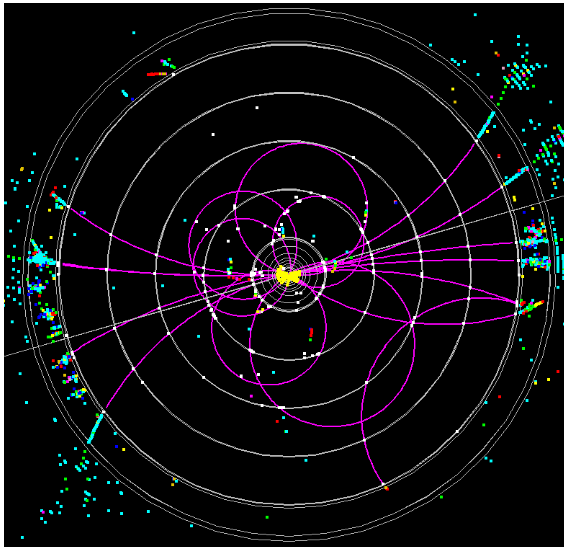
→Significantly improved resolution

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 →

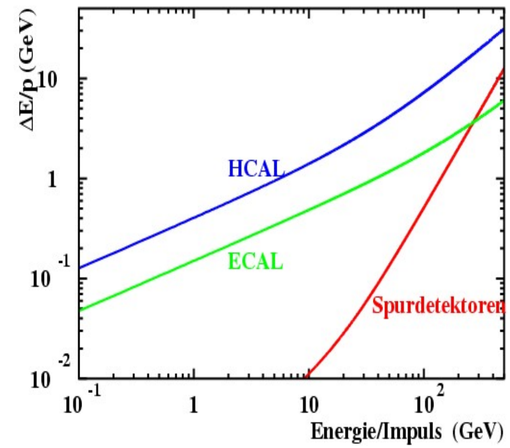
use tracker to reconstruct **e ,μ ,h** (<65%> of E_{jet})

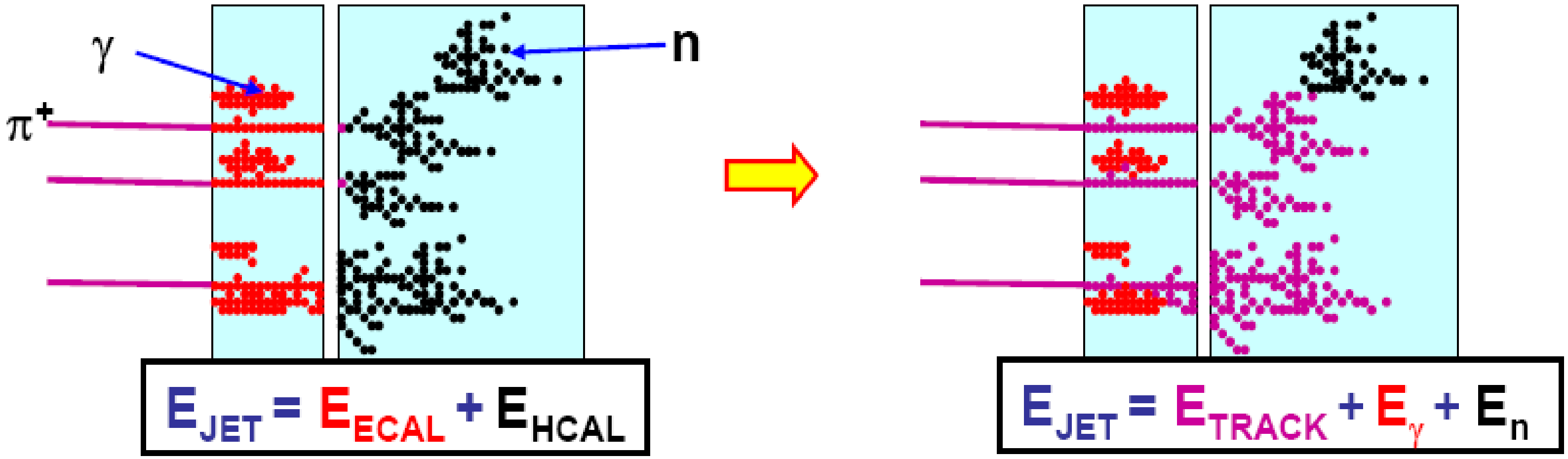
use **ECAL** for γ reconstruction (<25%>)

(ECAL+) HCAL for h^0 reconstruction (<10%>)

HCAL E resolution still dominates E_{jet} resolution

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





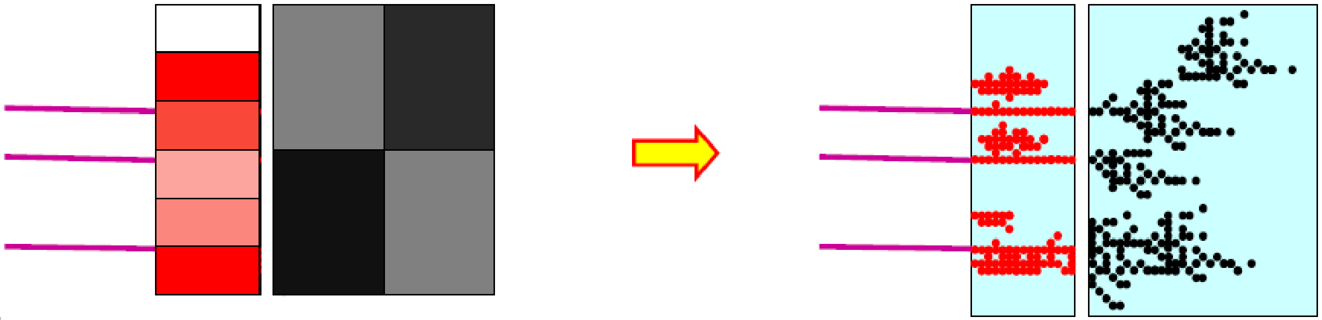
PFLOW calorimetry = Highly granular detectors + Sophisticated reconstruction software

Particle flow calorimetry

Hardware:

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

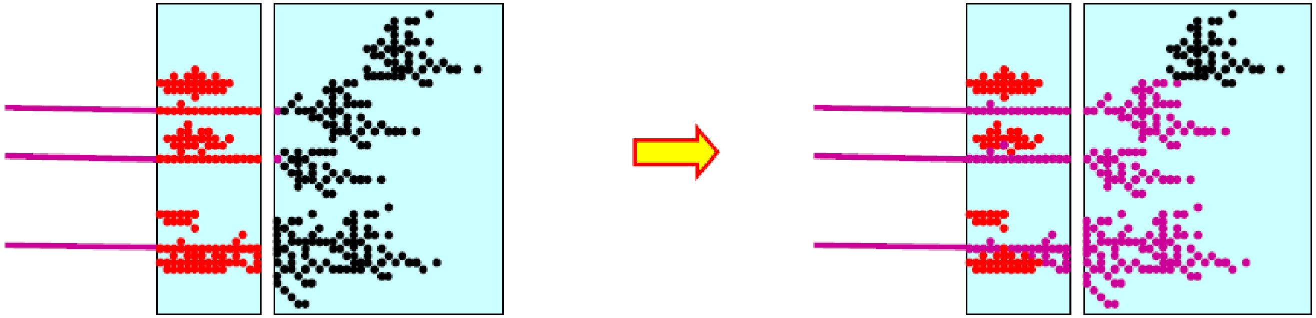
➡ Highly granular detectors (as studied in CALICE)



Software:

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

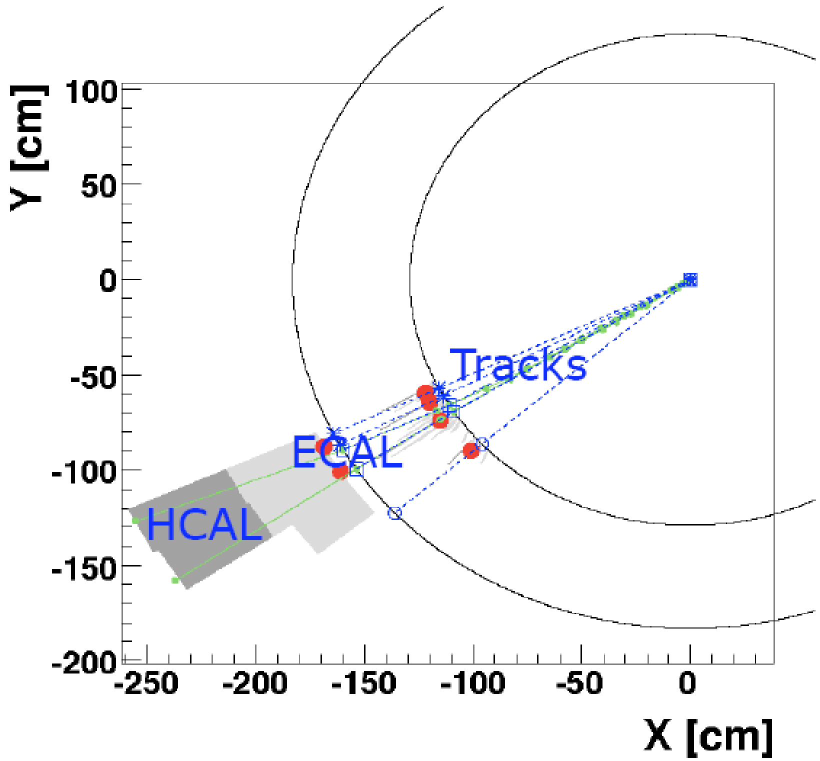
➡ Sophisticated reconstruction software

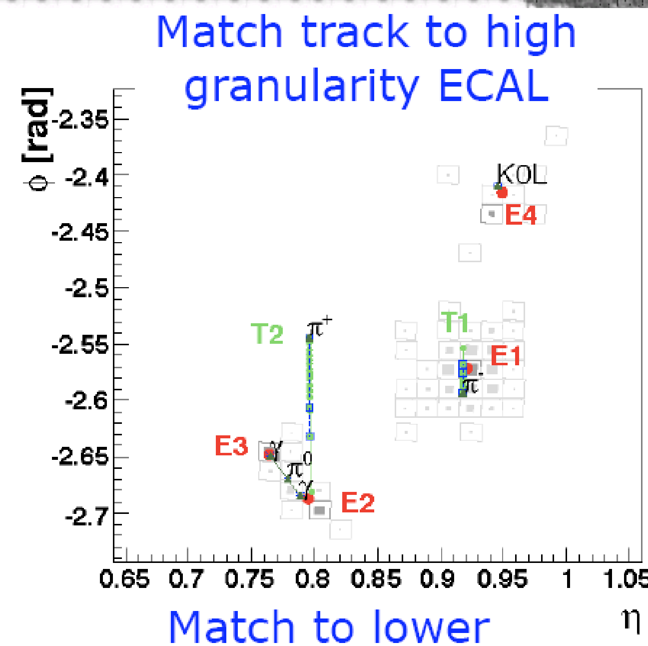


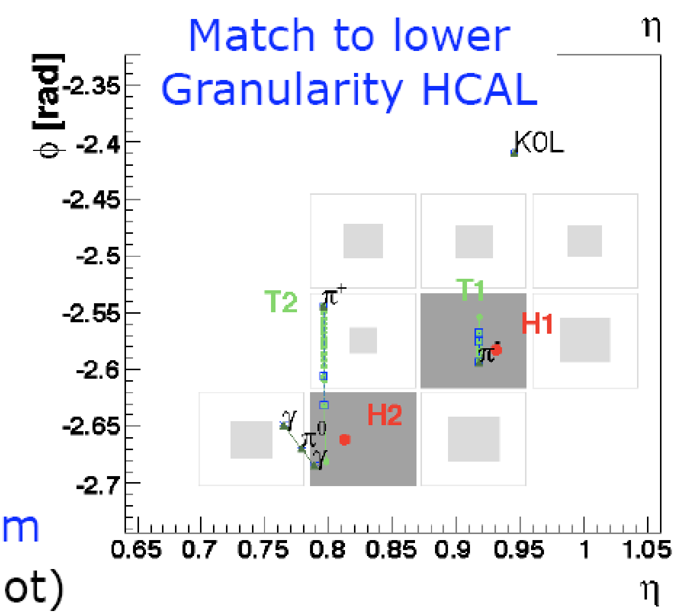
★Particle Flow Calorimetry = HARDWARE + SOFTWARE

Particle Flow @ LHC

CMS



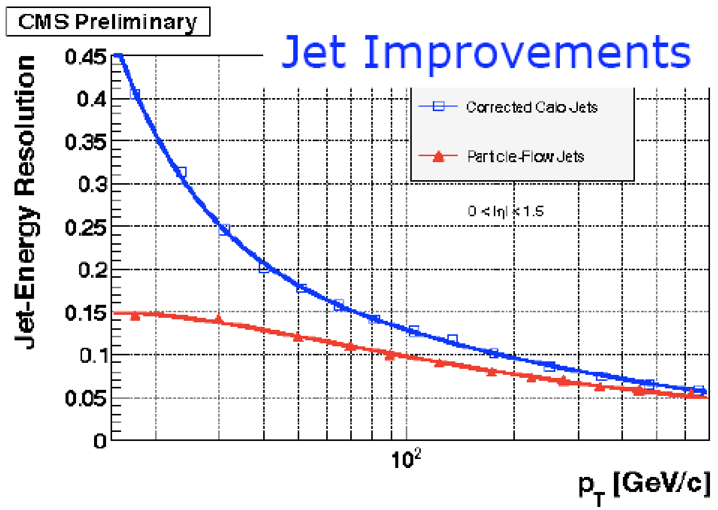


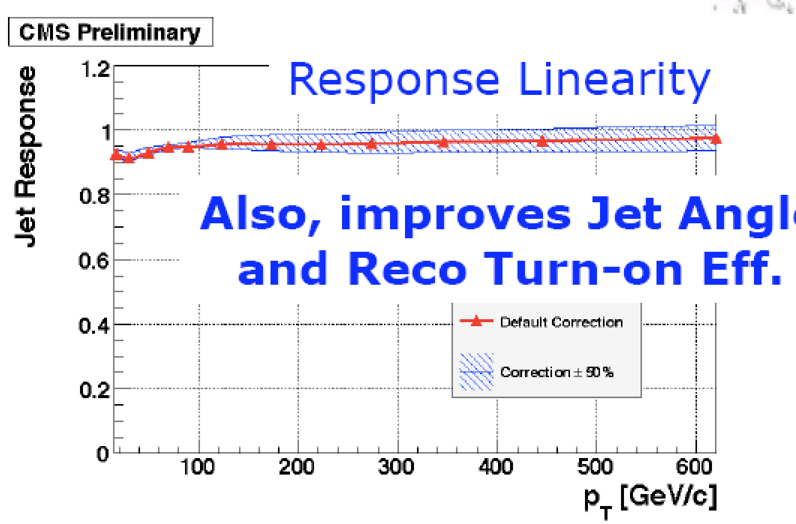


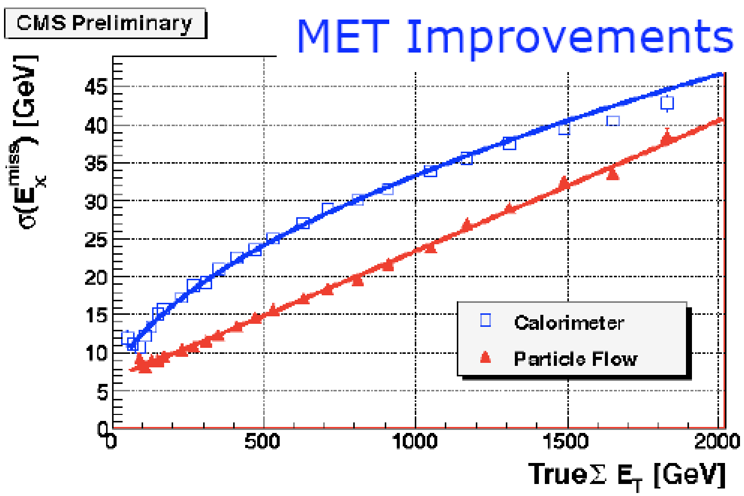
1) Leverage High Precision Tracking
2) And High Resolution ECAL EM-Showers
3) Match and Discard Charged Hadron Showers Replacing with Track Momentum

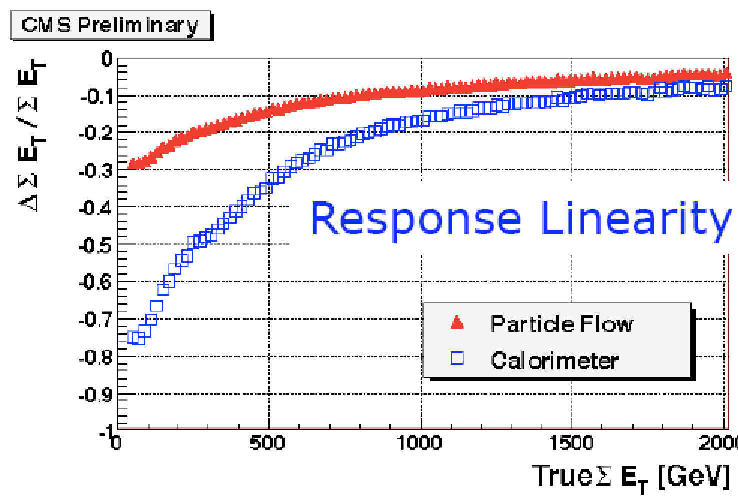
(Courtesy of P. Janot)

PFlow improvements at CMS









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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

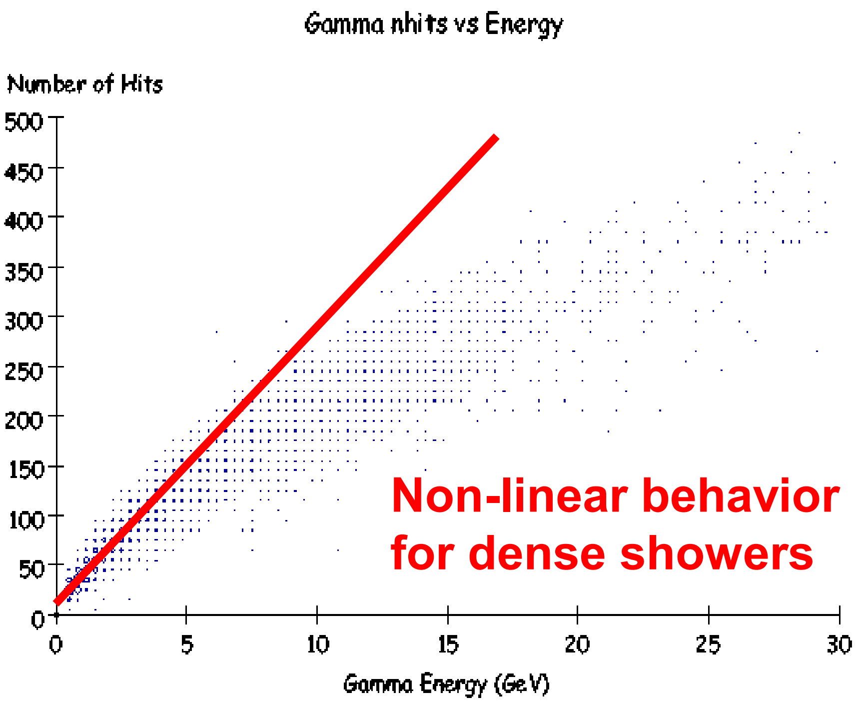
➔ Develop new techniques

Analog .vs. Digital

photon analysis

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

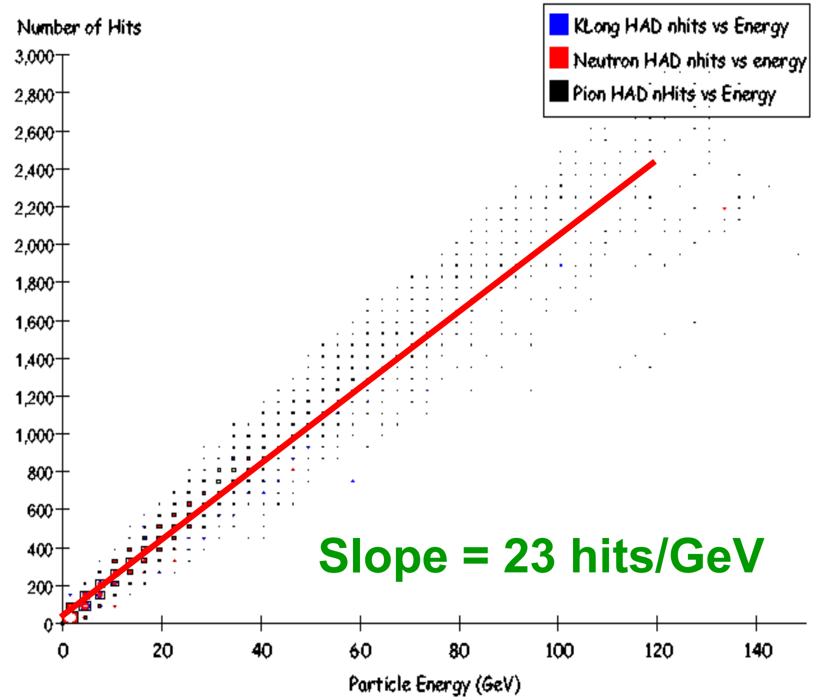
ECAL: Analog readout required



hadron analysis

$$E_h \propto \sum N_i$$

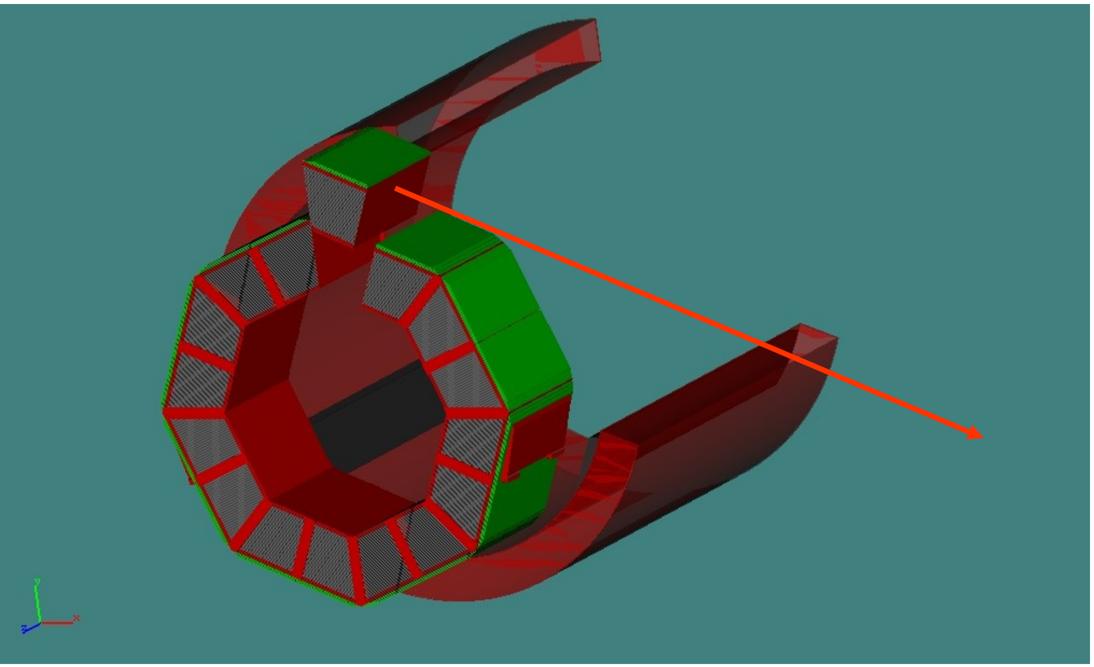
HCAL: either Analog or Digital readout



Calorimeter cell size 1x1cm^2

Analog HCAL with high granularity

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



Mechanics:

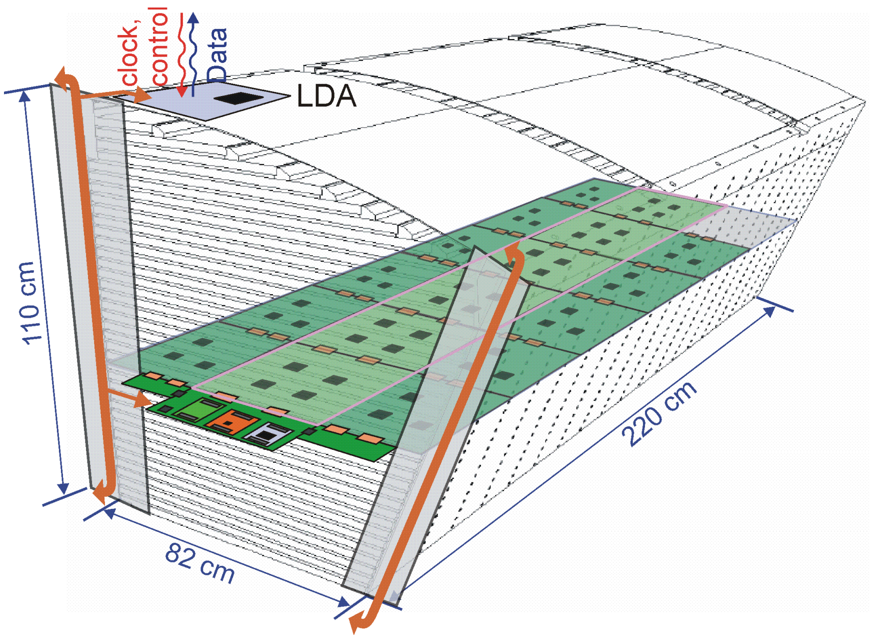
challenging design with no spacers
➔ validated

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

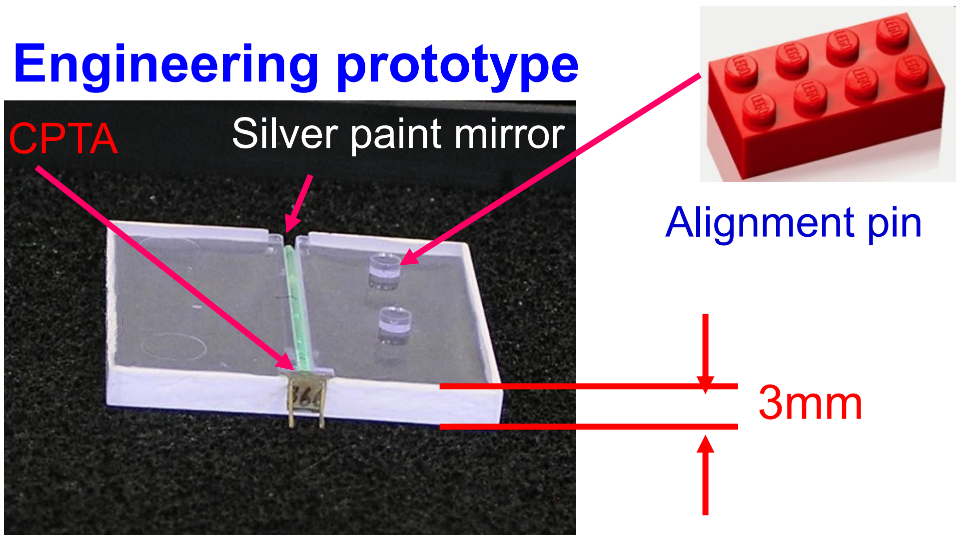
- "no" gap in z in the barrel
- 10cm gap between barrel and endcap

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

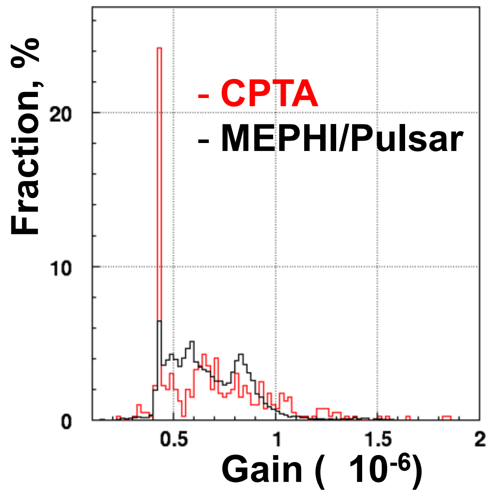
Tile thickness 3mm for ILD design

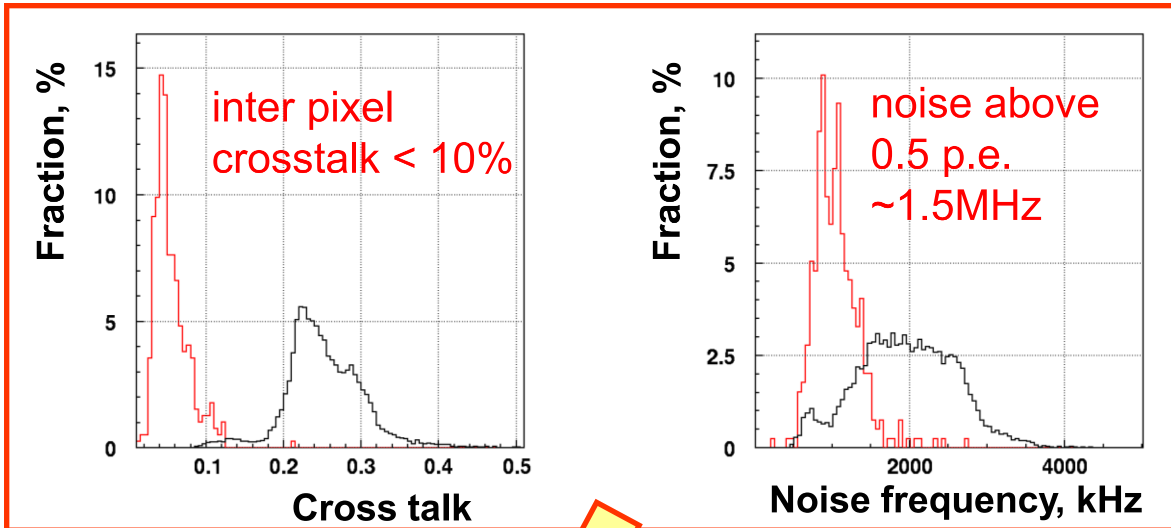
Light yield ~ 10 – 11 p.e. / MIP

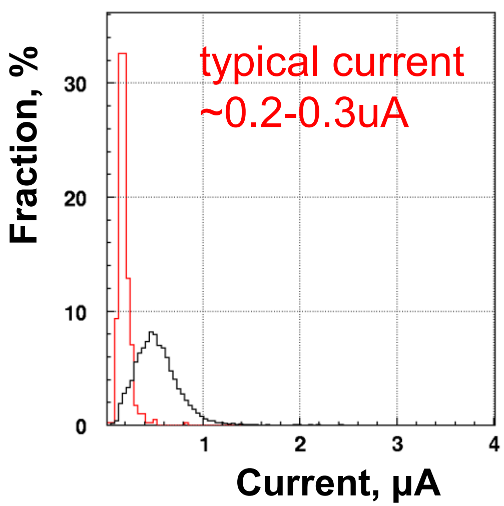
Engineering prototype

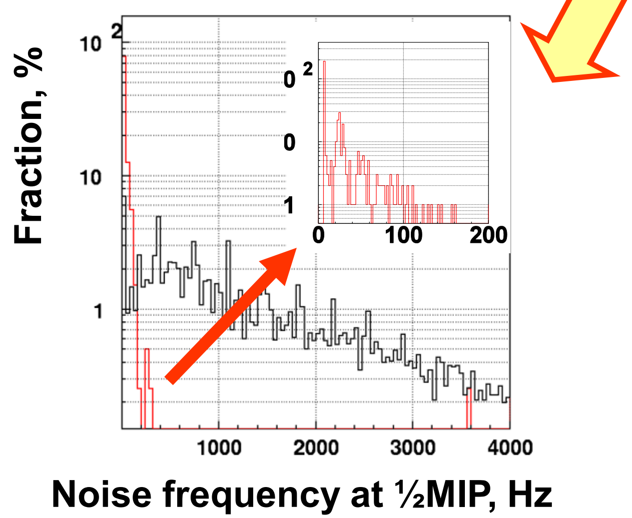


SiPM parameters

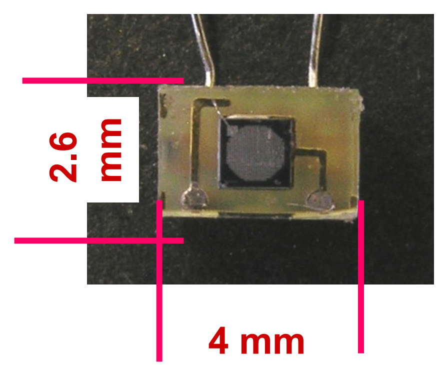




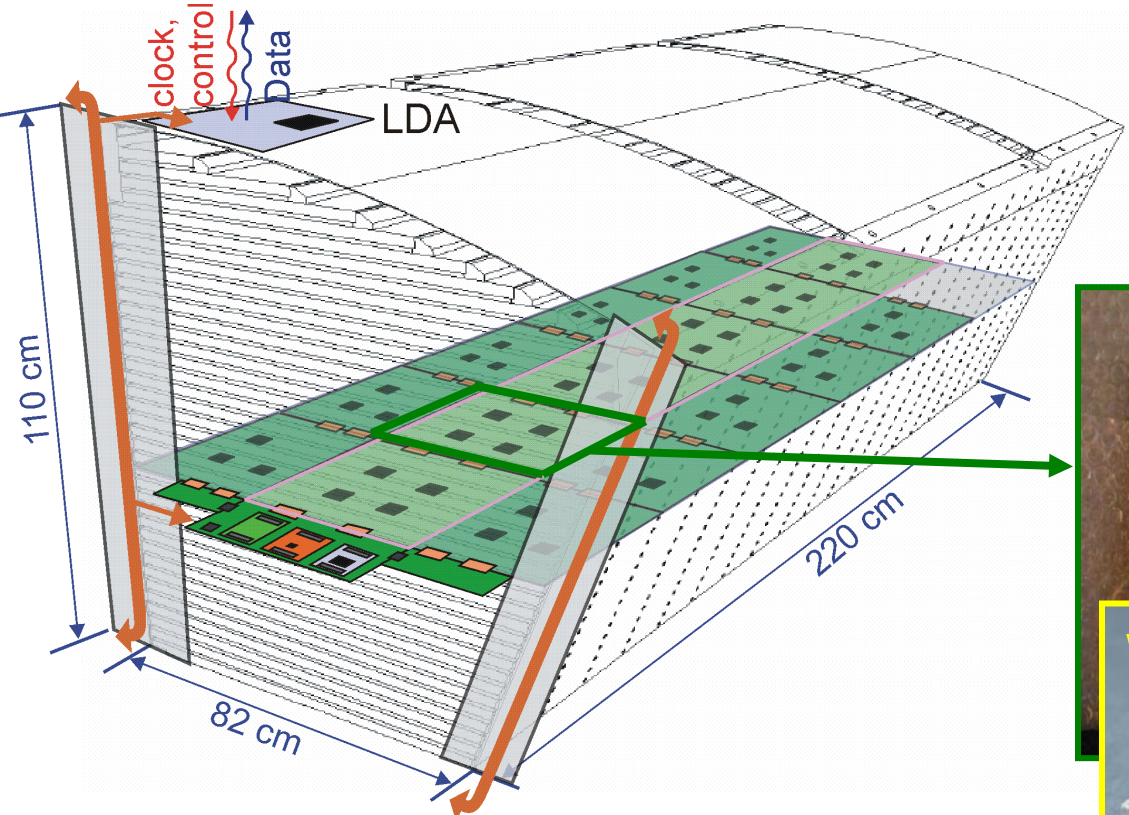




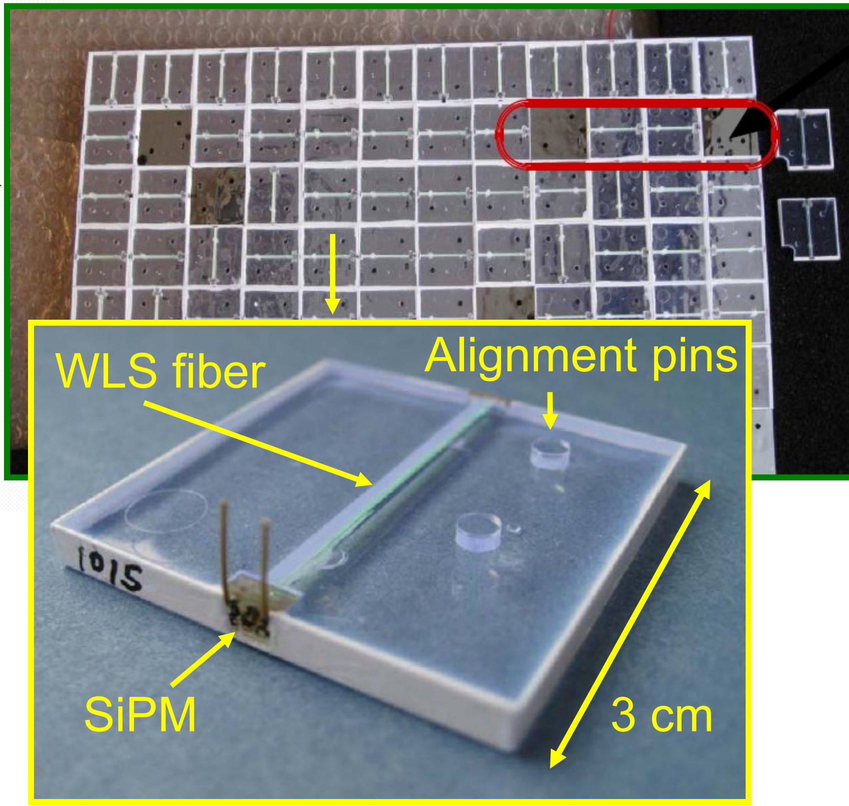
CPTA SiPM



Architecture design (I)

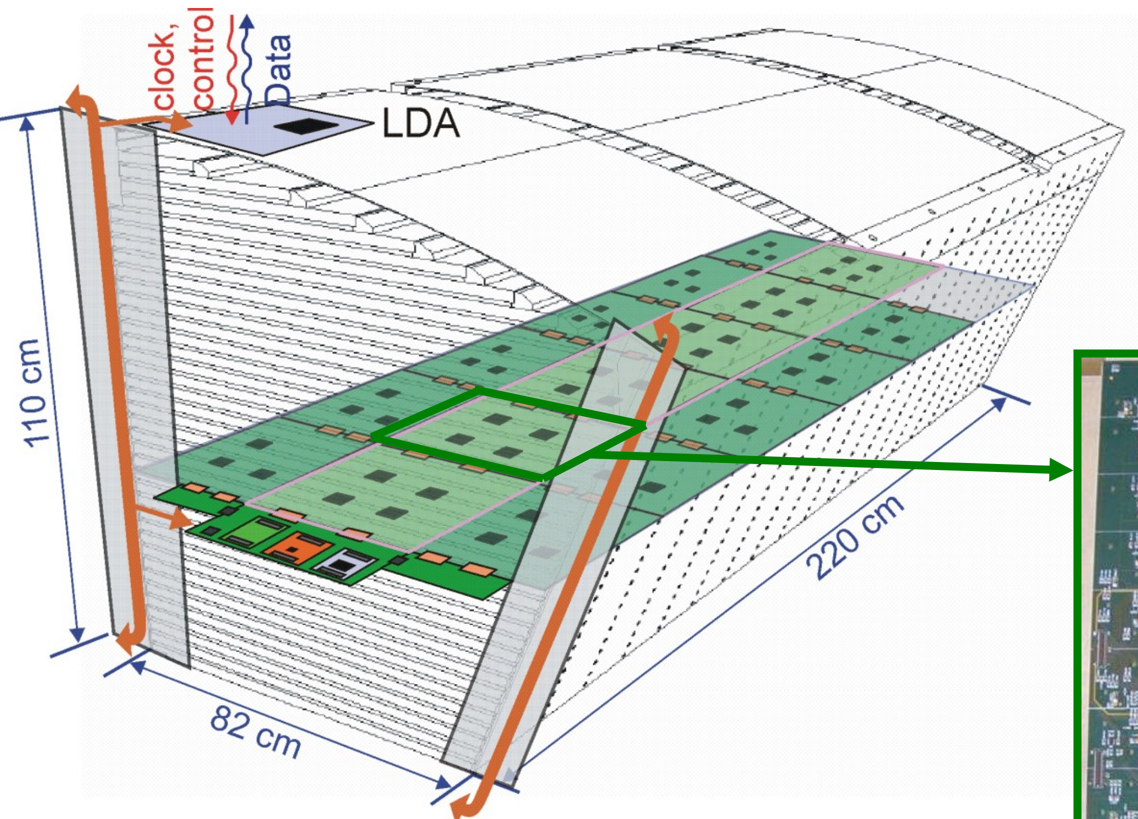


PCB board back side:
- reflector foil layer
- scintillator tiles fixed by alignment pins

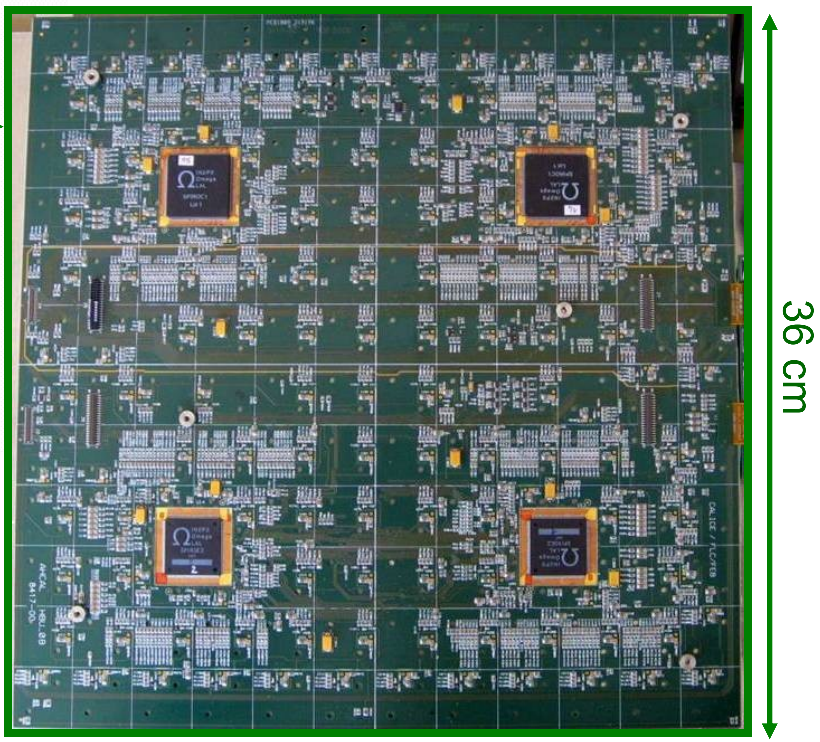


- Front End electronics integrated in active layer
- made of interconnected cassettes (36x36 cm)
- power and calibration modules at barrel edge
- 2.2m long communication lines in the layer

Architecture design (II)



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



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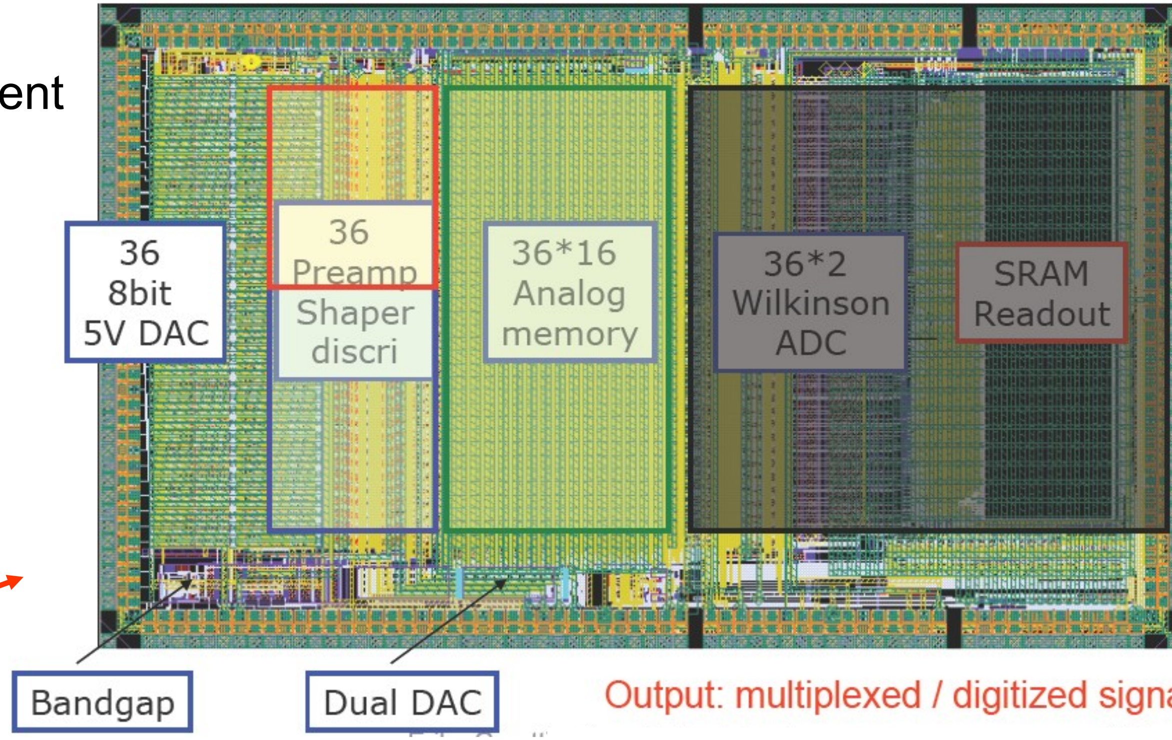
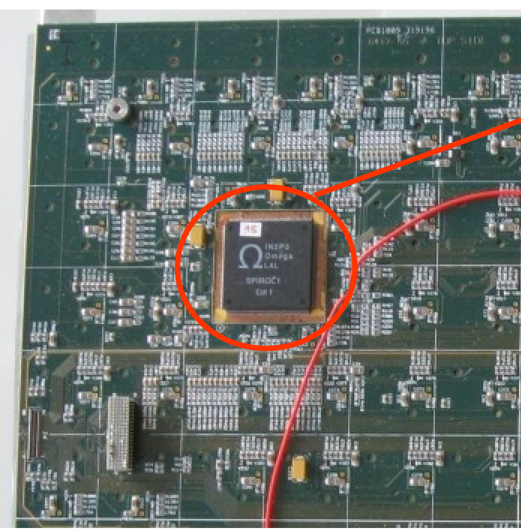
The SPIROC chip

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)





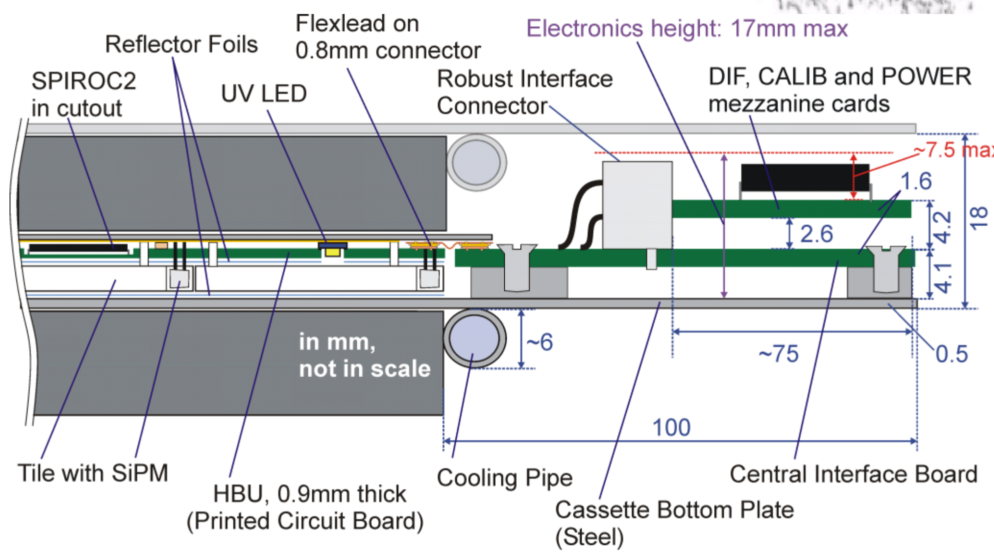
Output: multiplexed / digitized signals

designed by Omega group LAL (Orsay)

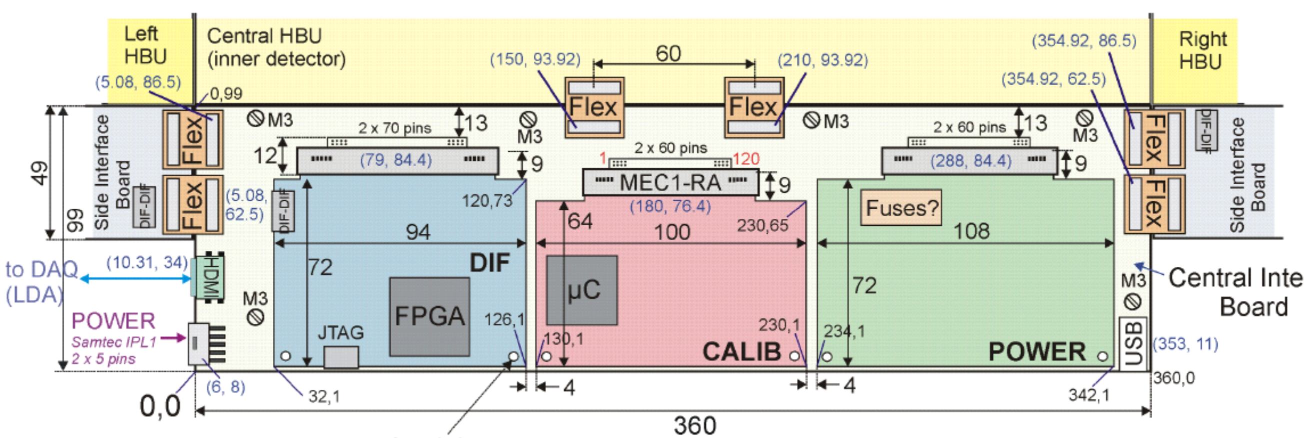
Layer design

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



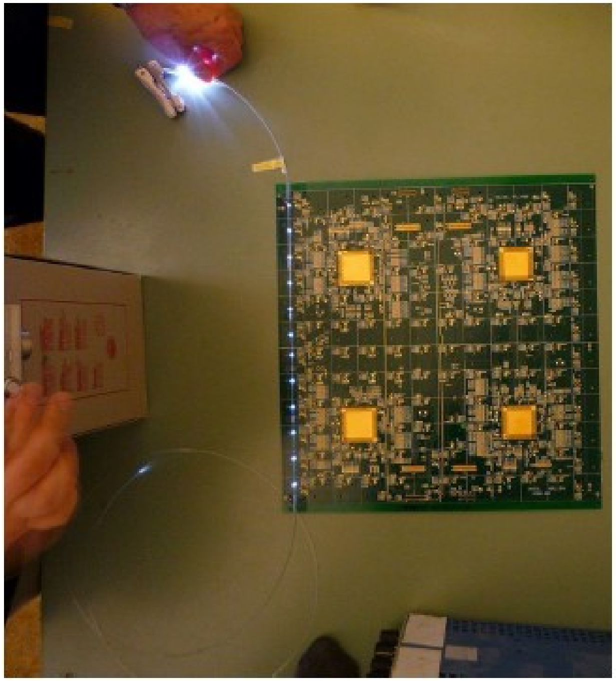
Ultra-thin
Low power consumption
High concentration/data reduction

LED monitoring system(s)

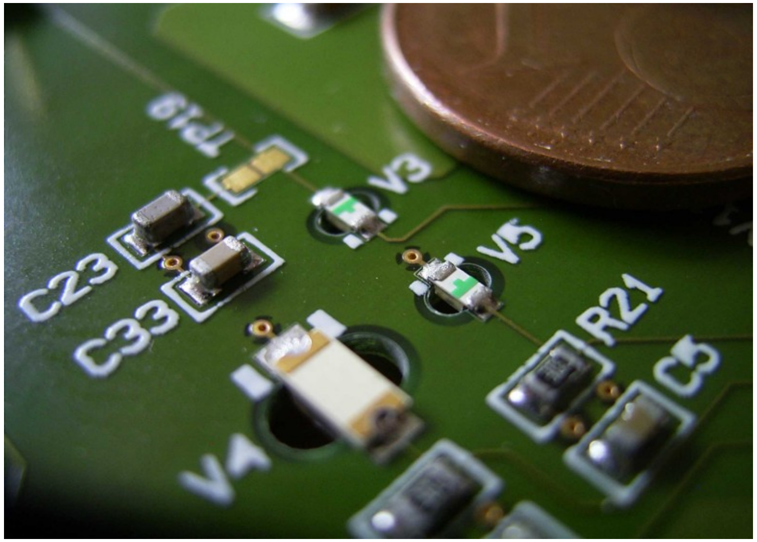
System task: SiPM gain calibration via single photoelectron peak spectra (~1-2 p.e.)
long term stability via response @ medium light (~20-100 p.e.)
measure SiPM saturation level (~2000 p.e.)

Two technological solutions:

Light distributed by notched fibres



Light directly on tile by SMD-LED
- distributed LED



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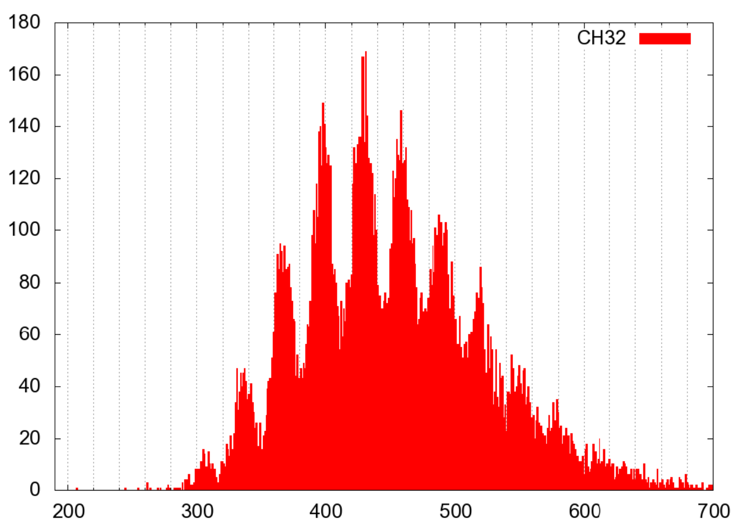
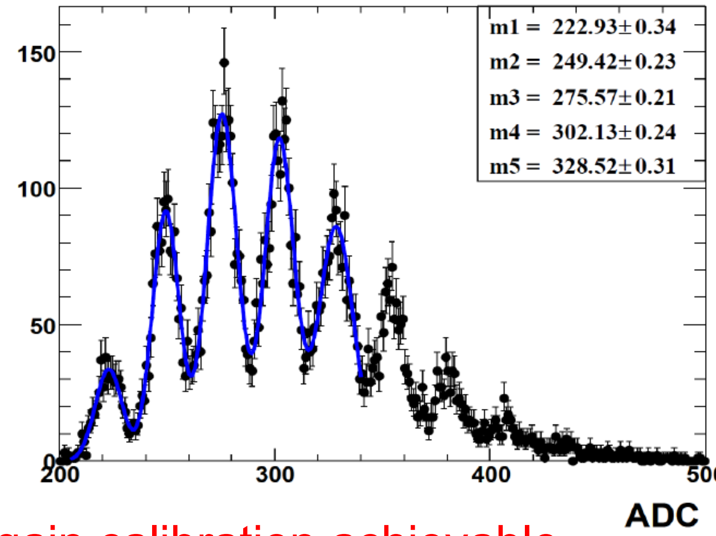


Light directly on tile by SMD-LED - distributed LED



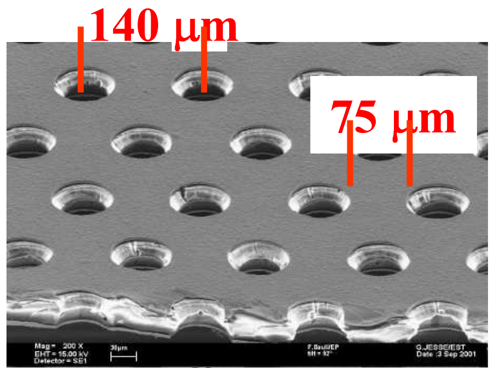
Both systems commissioned ➔ SiPM gain calibration achievable
Next step ➔ reduce spread in light intensity between channels

The Digital HCAL: super-high granularity

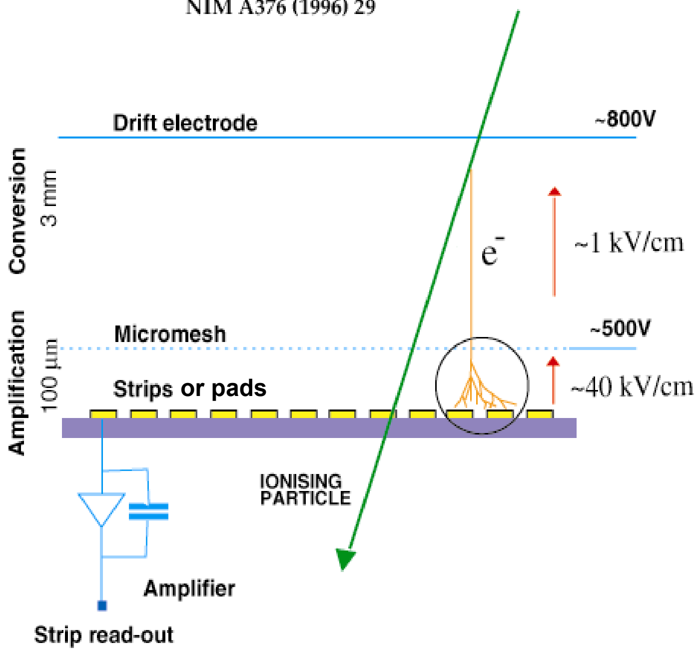
Basic technique for the active media:

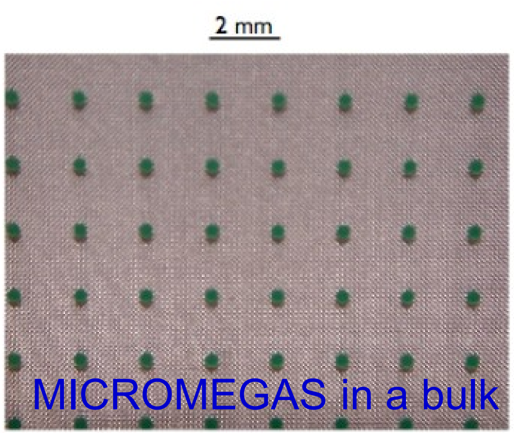
- Ionization-gas chambers with charge amplification (RPC, GEM, MicroMegas)
- digital readout on pads 1x1cm^2
- integrated electronics inside active layer
- high level of data concentration (~0.5 M channels / m^3)

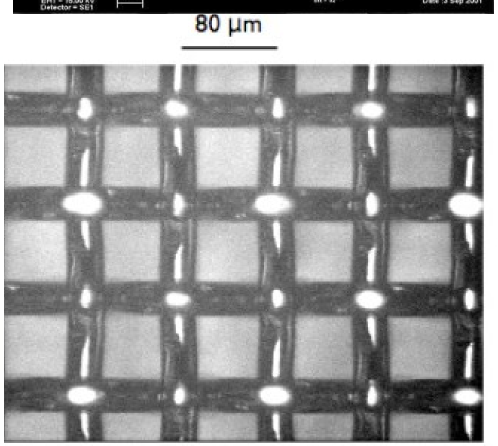
Gas Electron Multiplier foil



Y.Giomataris, Ph. Rebourgeard, J.P Robert and G. Charpak
NIM A376 (1996) 29



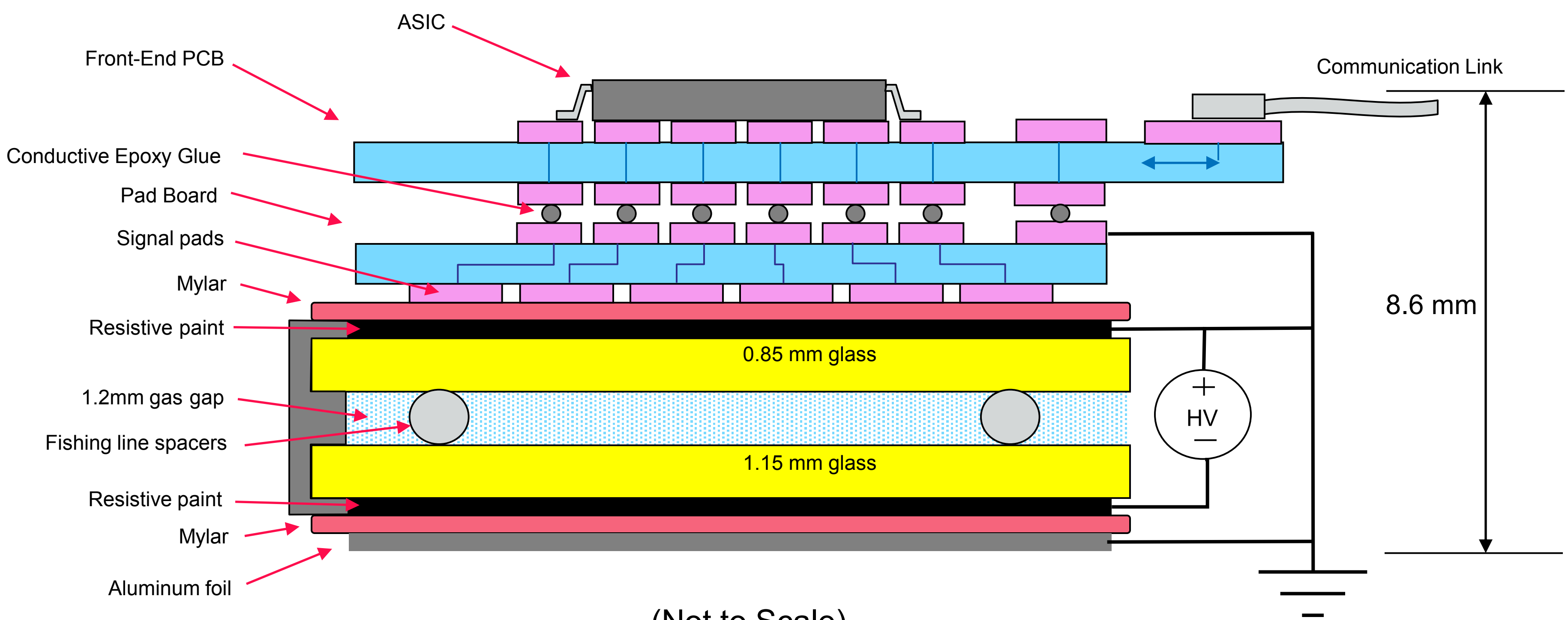




Pillars: 400u Ø, 100u height
Ampl. gap 25-150µm → narrow avalanches
excellent spatial and time resolution

Resistive Plate Chamber readout

Chamber Construction:

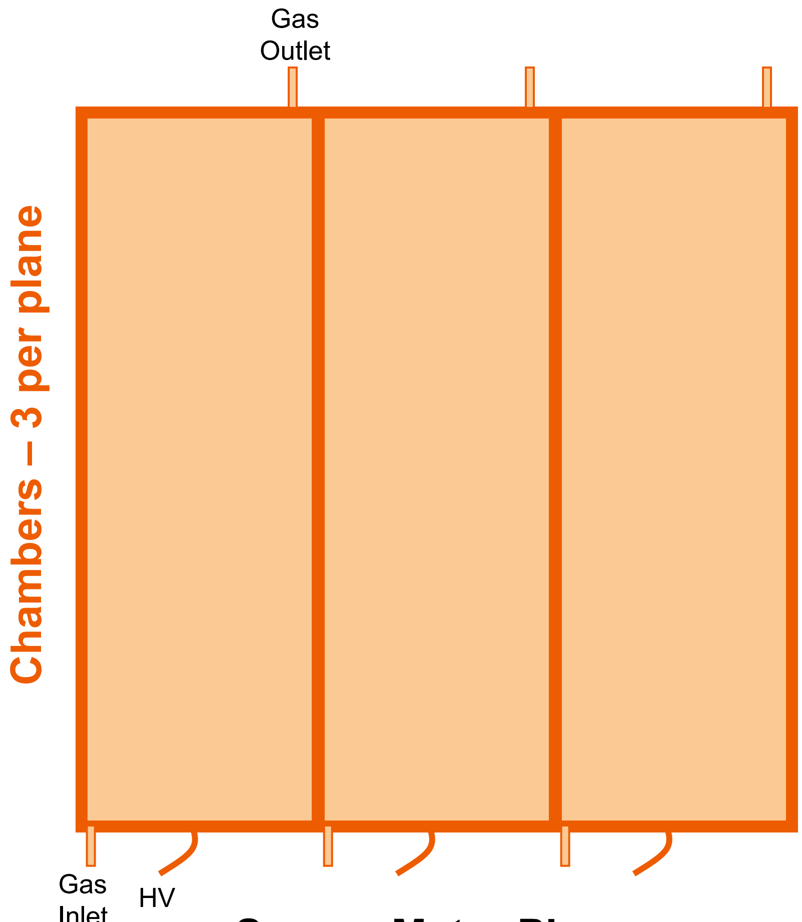


(Not to Scale)

Avalanche mode:

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

Digital HCAL with RPC readout

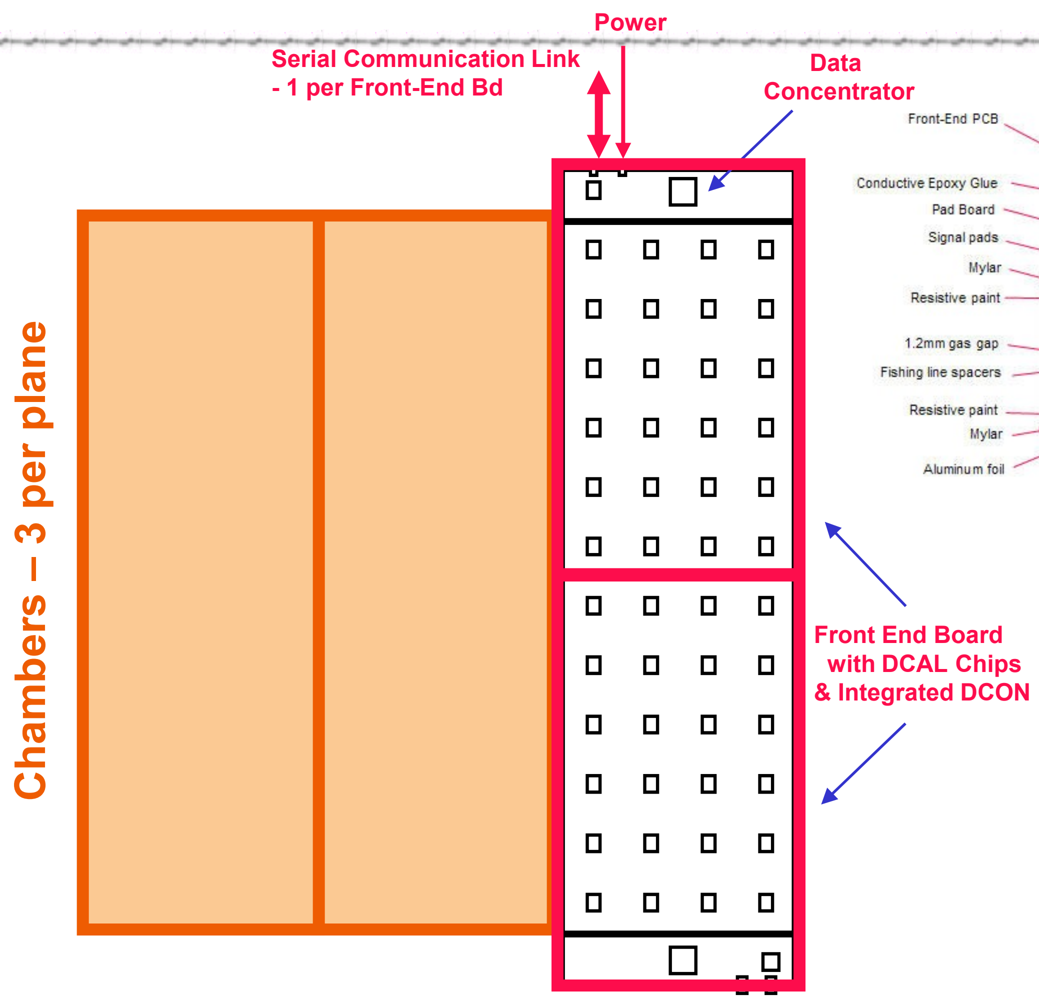


Square Meter Plane
(3) 32 cm X 96 cm chambers

Plane Construction

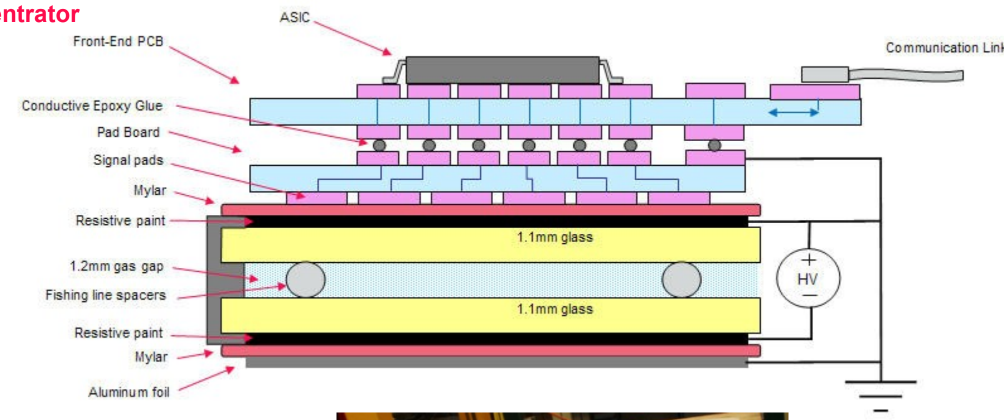
- A plane consists of 3 independent chambers

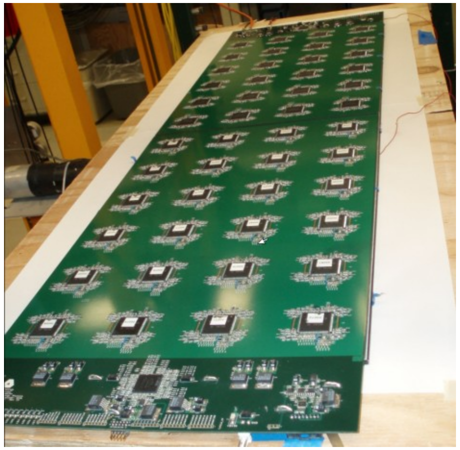
Digital HCAL with RPC readout



Square Meter Plane

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





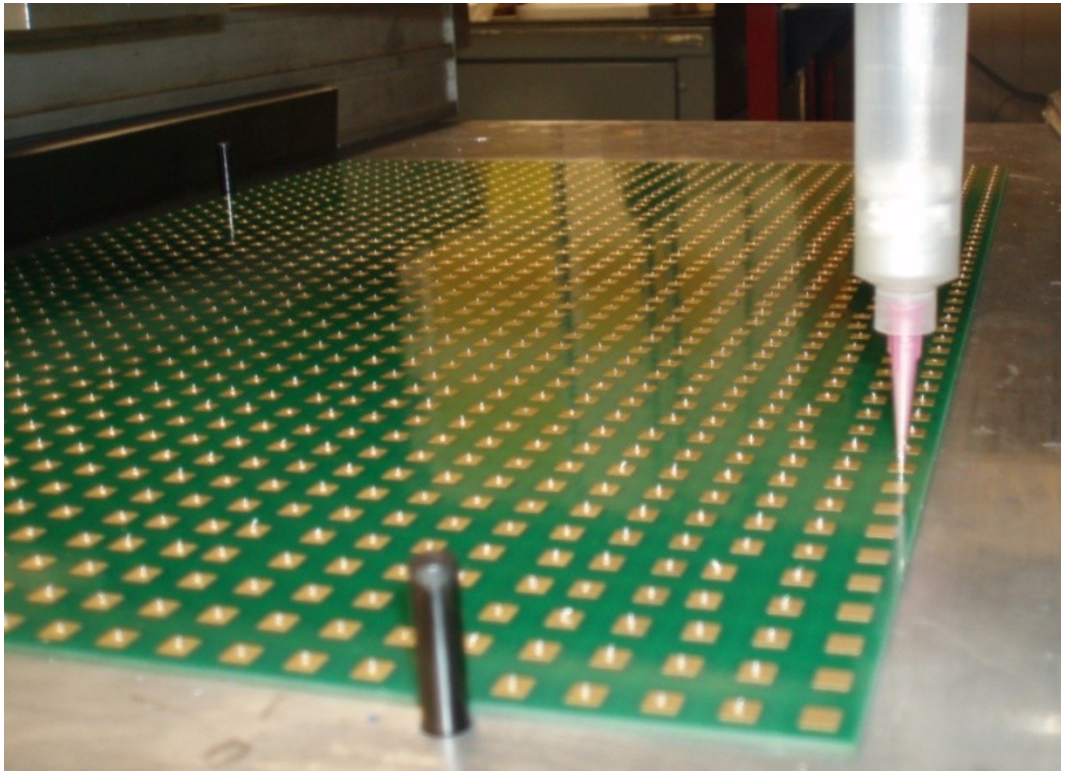
Front End Board

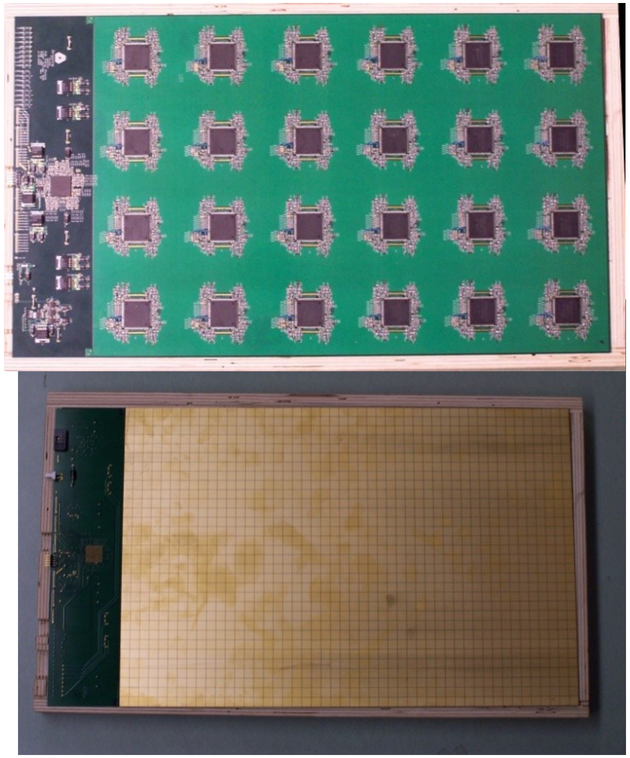
- (24) 64-Ch Chips / Bd
- 1536 Channels / Bd

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

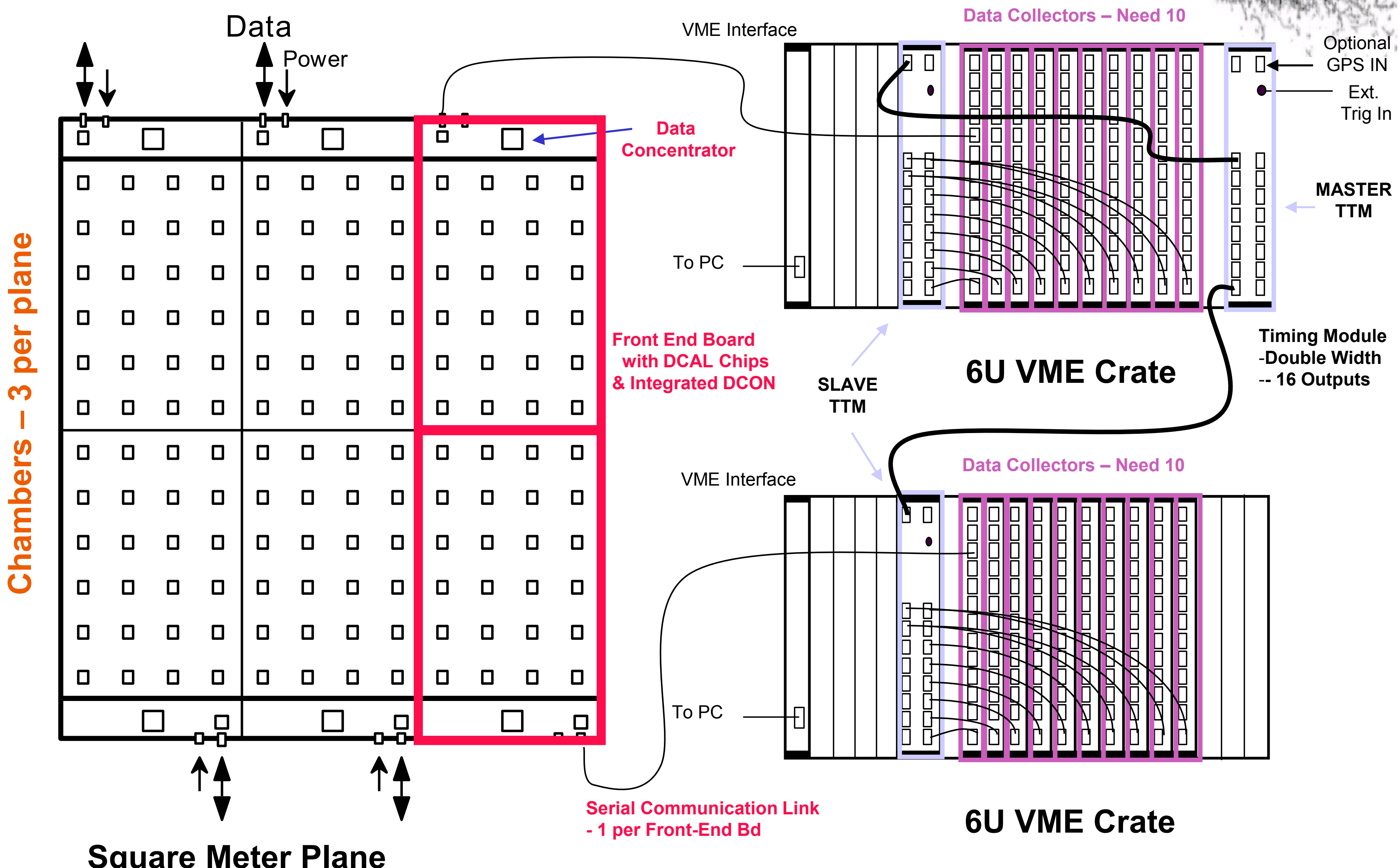




Digital HCAL with RPC readout

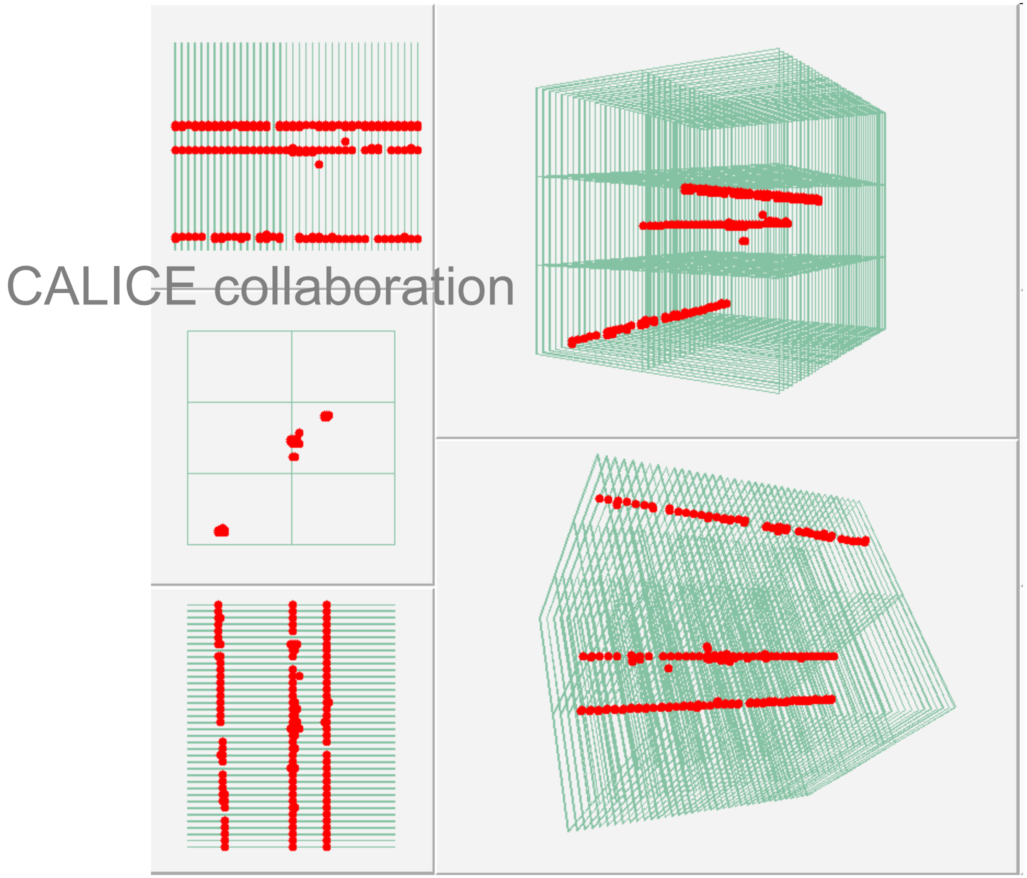
Square meter plane mounted on cassette
using prototype Front End Boards

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!!



The first multi tracks from muons recorded

Different readout approach: semi-digital

Semidigital RPCs

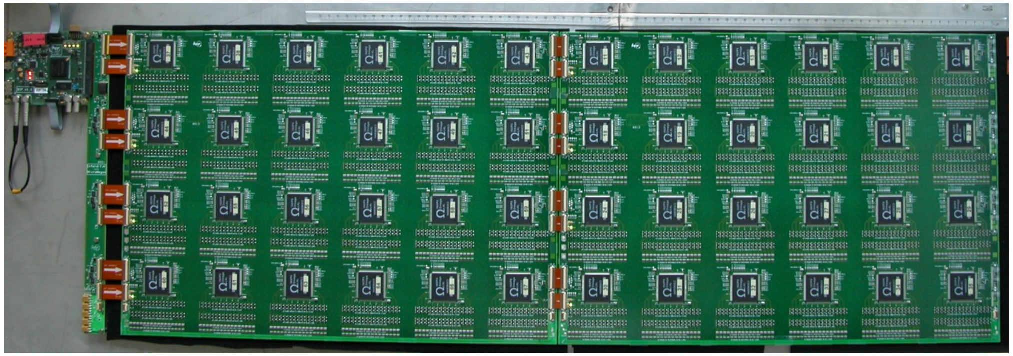
Biggest challenge: integrate electronics in 6mm PCB ➔ special chip design

ASIC - HARDROC (Ω LAL)

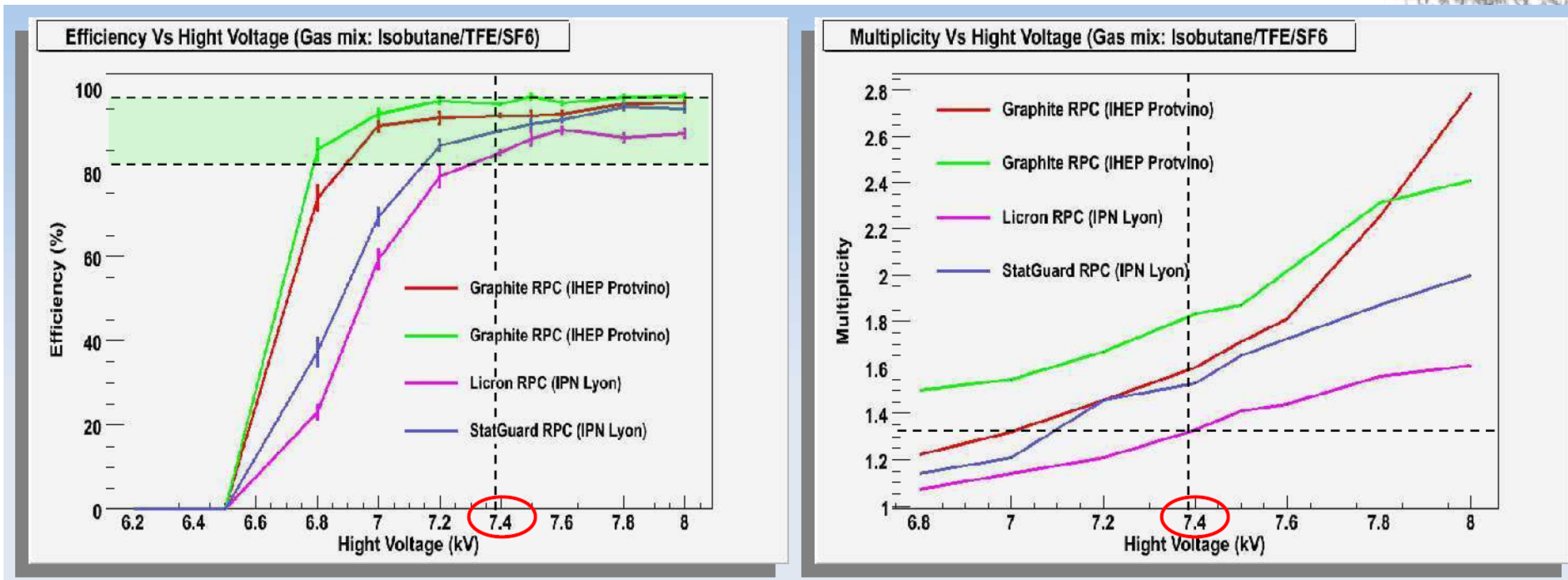
- 3 thresholds, masks, optimized power pulsing
- controlled in a fully automatic way using a robotic system used for CMS trackers

- 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

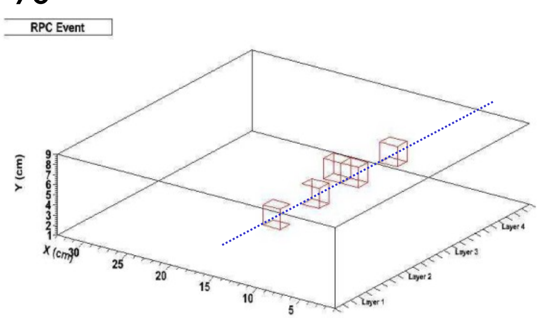


Using muon signal as MIP + tracking

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

➔ Lower multiplicity is preferred

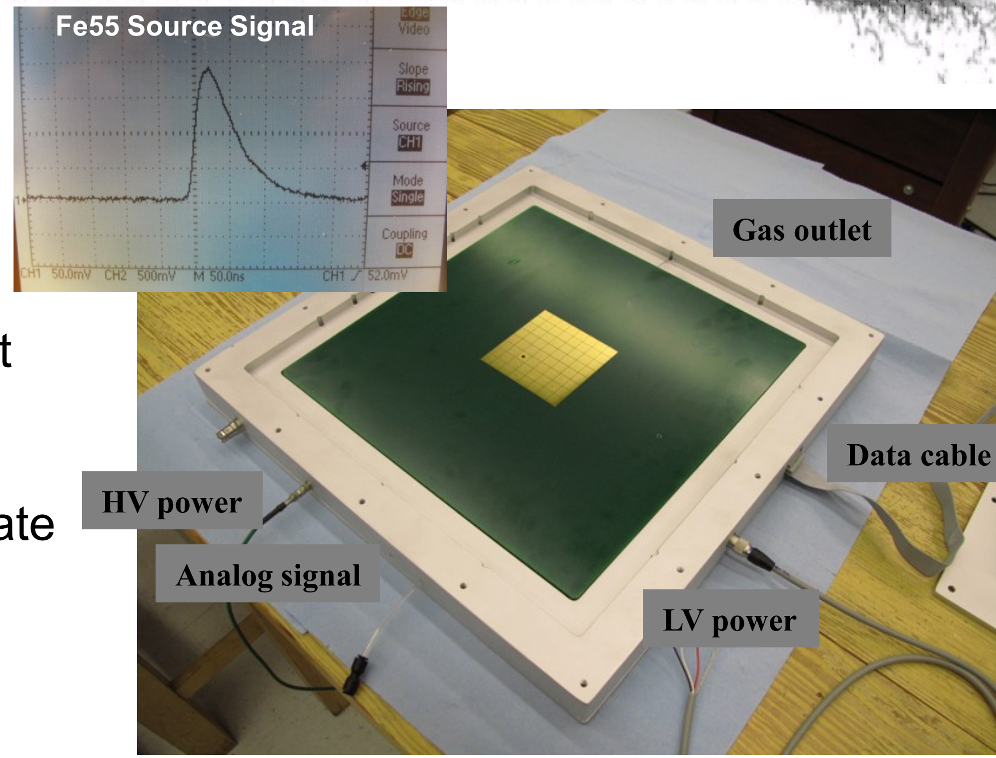
➔ Best ratio multiplicity/efficiency: around 7.4 kV

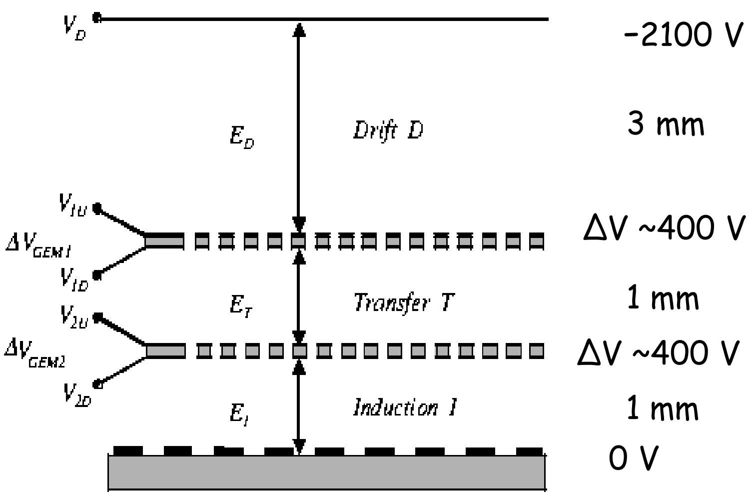


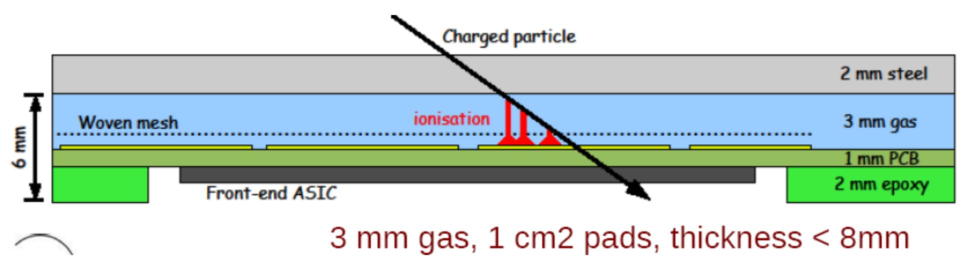
Different gas amplification method:
GEMs or Micromegas

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

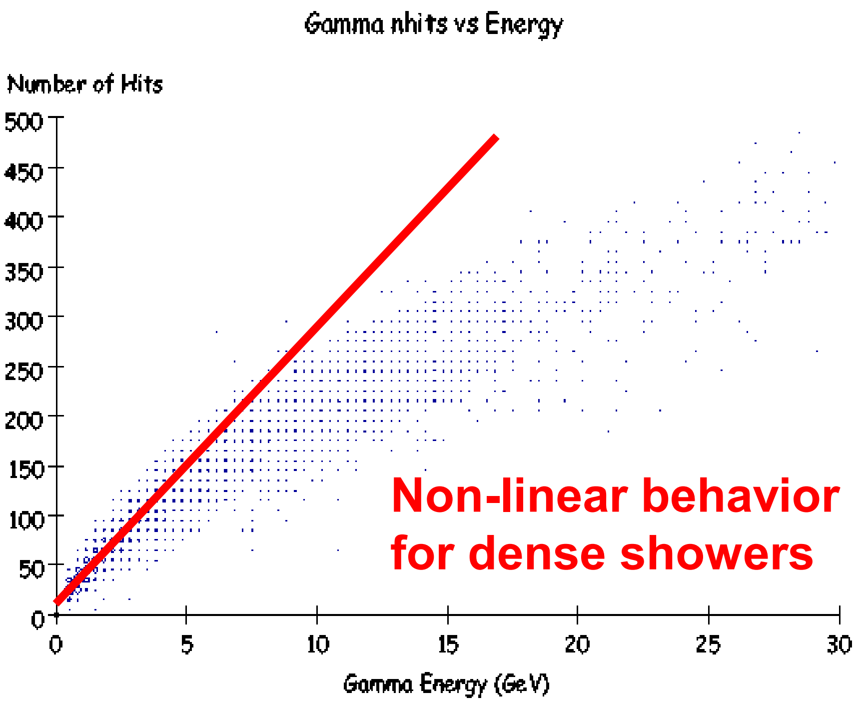
hadron analysis

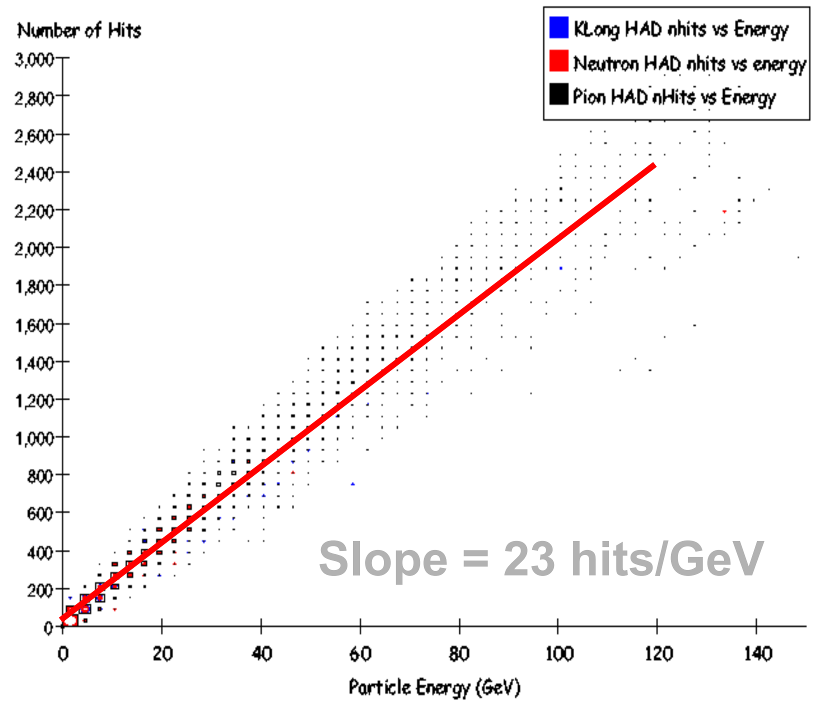
$$E_\gamma \neq \sum N_i$$

$$E_h \propto \sum N_i$$

ECAL: Analog readout required

HCAL: either Analog or Digital readout





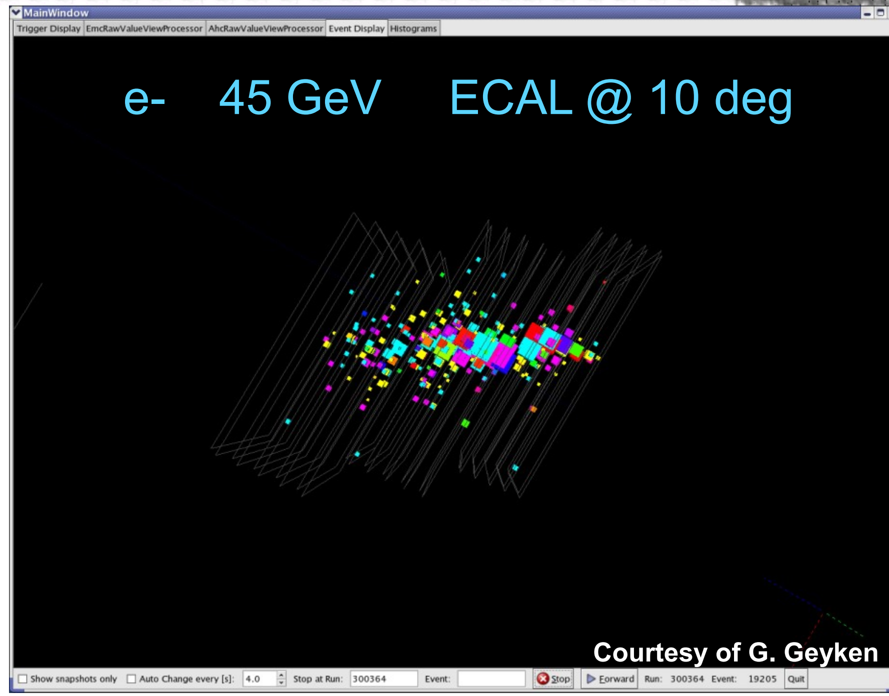
Calorimeter cell size 1x1cm^2

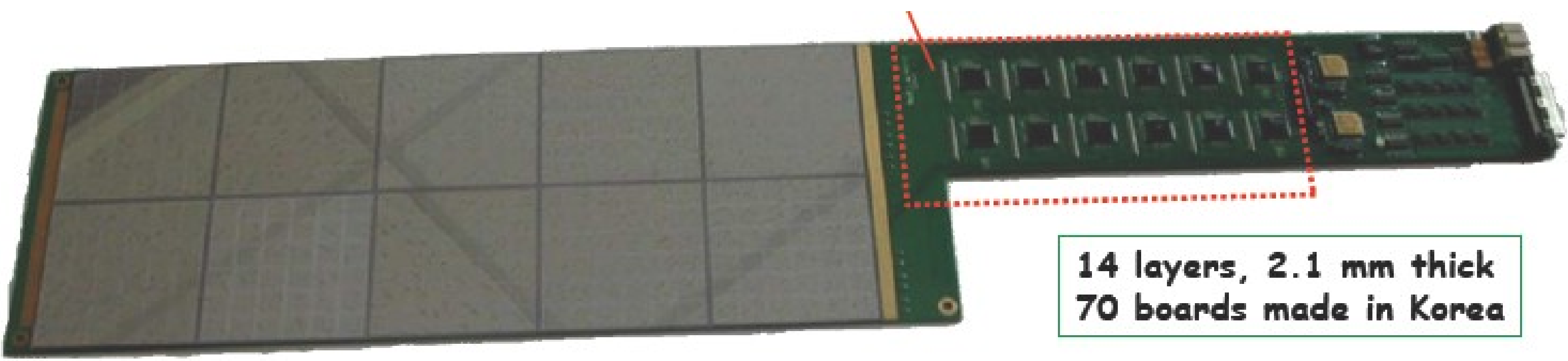
Highest granularity ECAL

CALICE:
Si-W with analog readout

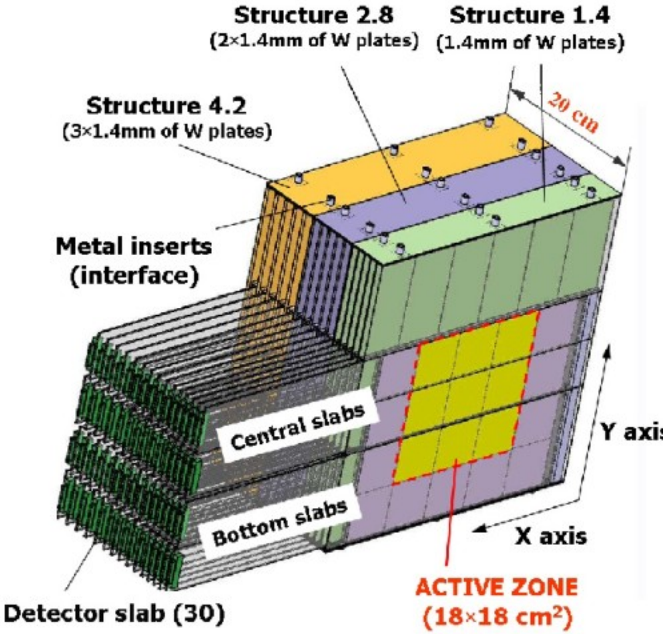
30 layers W-Si
1 cm^2 Si-PADs (next version with 0.5x0.5 cm^2 Si-PADs)
~10000 channels

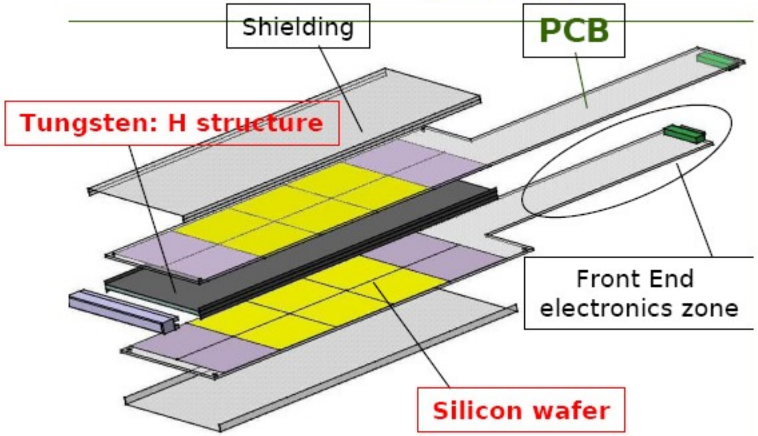
➔ Imaging calorimeter!!





Si-W ECAL





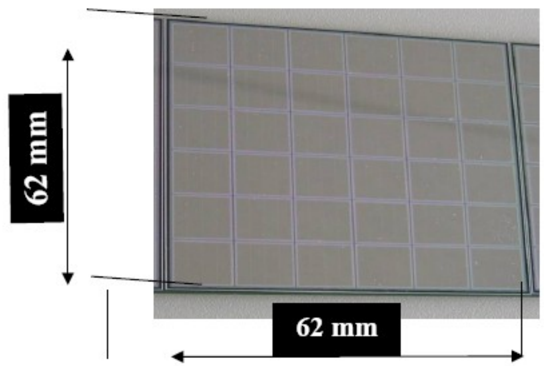
30 layers of Tungsten:

- 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



Thickness:
525μm

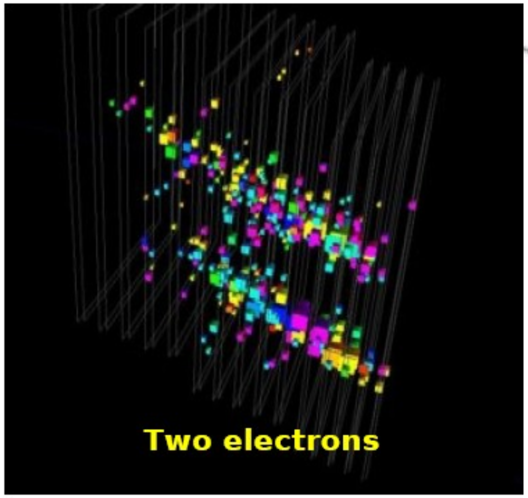
Total: 9720 Pixels/Channels

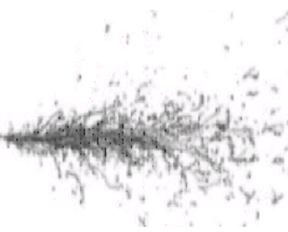
8

Experimental Setup

Zoom into Ecal

Particle Distance~ 5 cm
→ No Confusion !!!



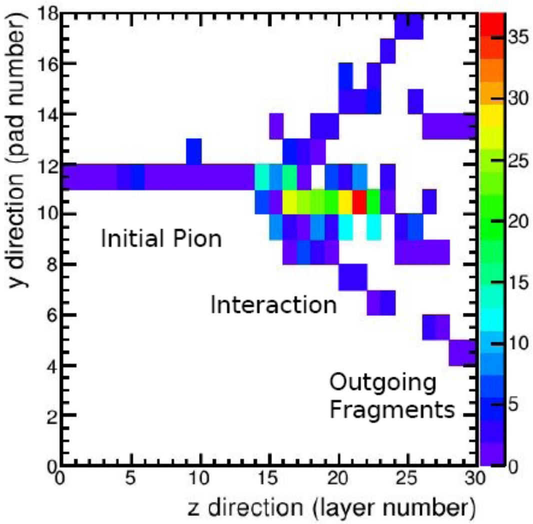


(Start of) Hadronic Showers in the SiW Ecal

Imaging calorimeter

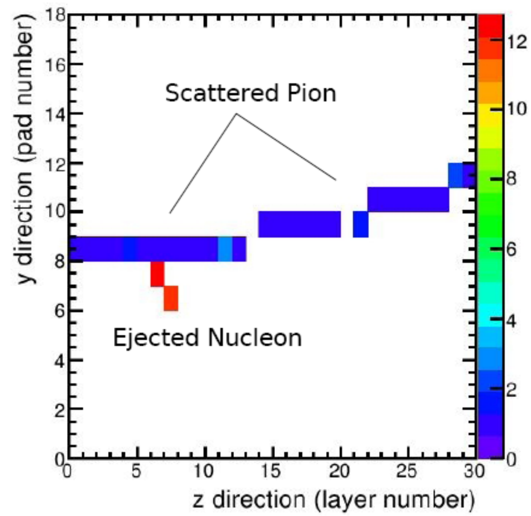
CALICE Si-W ECAL data

Complex and Impressive



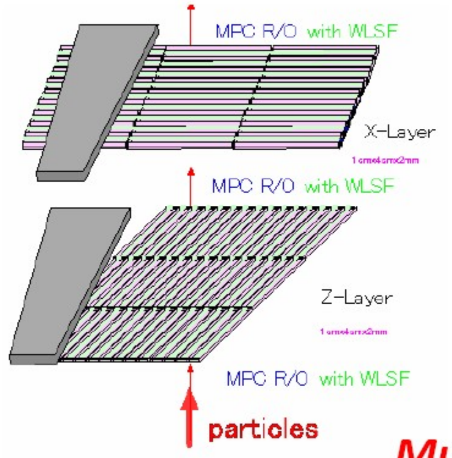
Inelastic Reaction in SiW Ecal

Simple but Nice



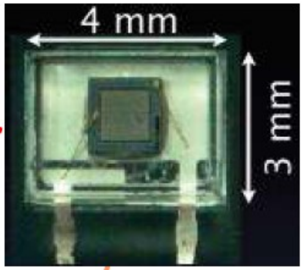
Nucleon Ejection in SiW Ecal

High granularity scintillator ECAL



Elementary Components
(Scintillator-Strip & Photo-Sensor)

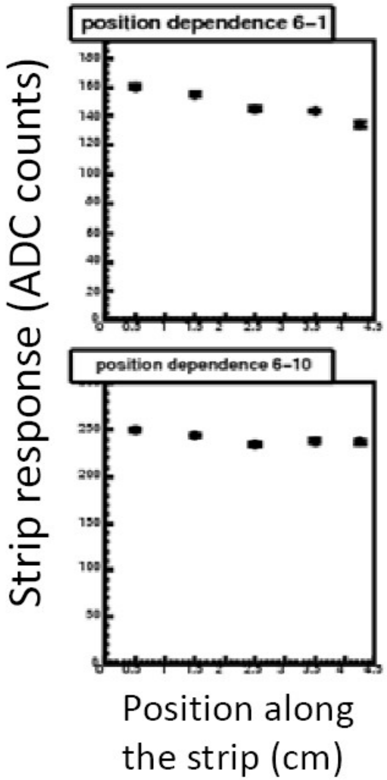
Multi-Pixel Photon Counter (MPPC)



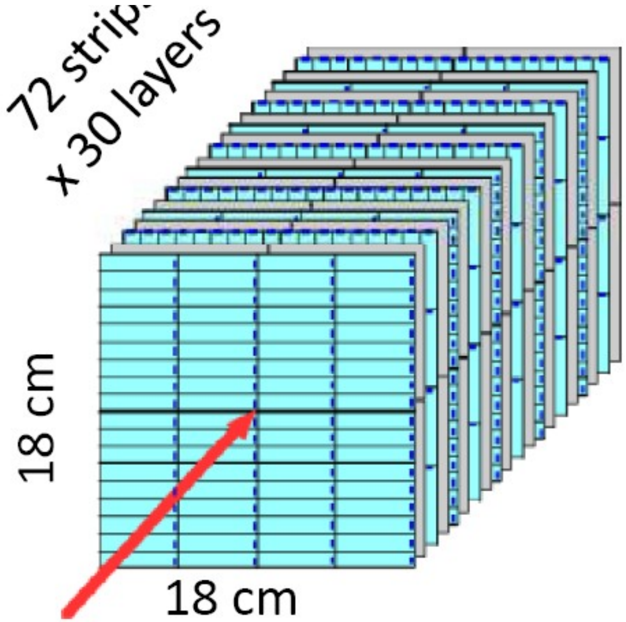
Wavelength Shifting Fiber (Y11 1mmϕ)

4.5 x 1 x 0.2 cm

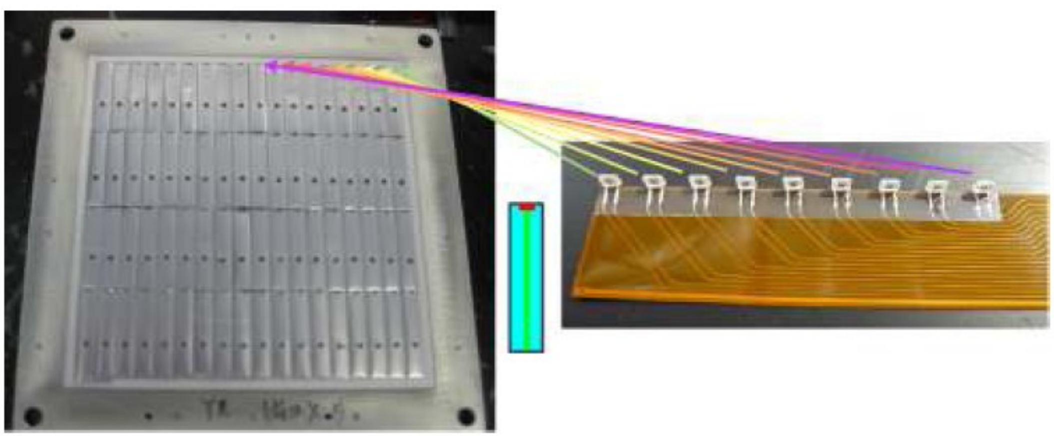
Plastic scintillator strip by extrusion technique

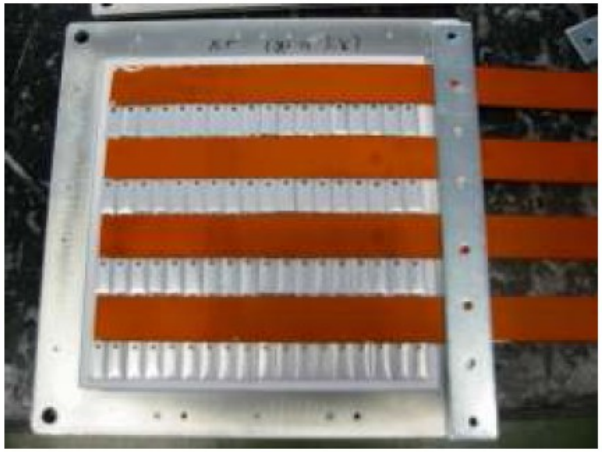


High granularity scintillator ECAL

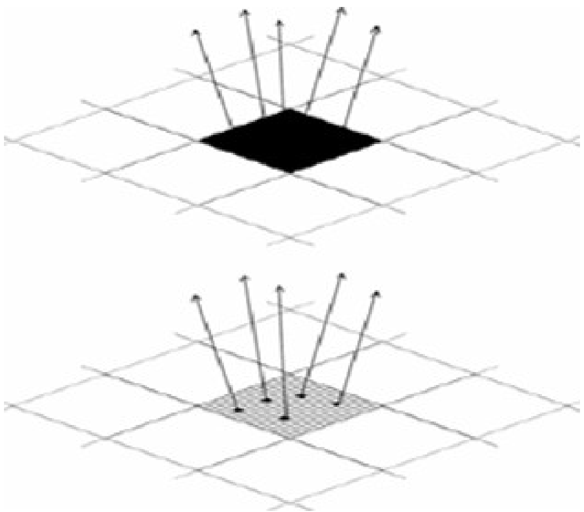


- The technical prototype to establish the ScECAL feasibility.
- Sandwich structure with scintillator-strips (3 mm) and tungsten layers (3.5 mm).
- Extruded scintillator and the MPPC are fully adopted.
- Strips are orthogonal in alternate layers.
- 72 strips x 30 layers = 2160 channels.



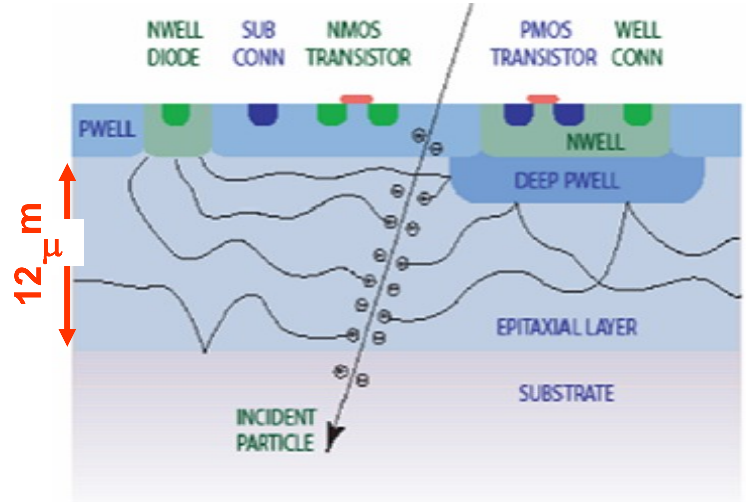


Digital ECAL



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

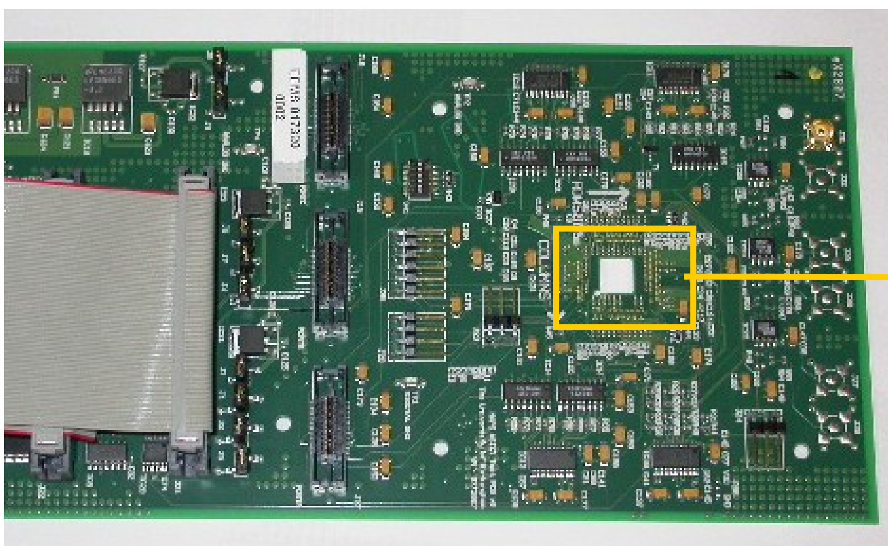
➔MAPS (Monolithic Active Pixel Sensors)

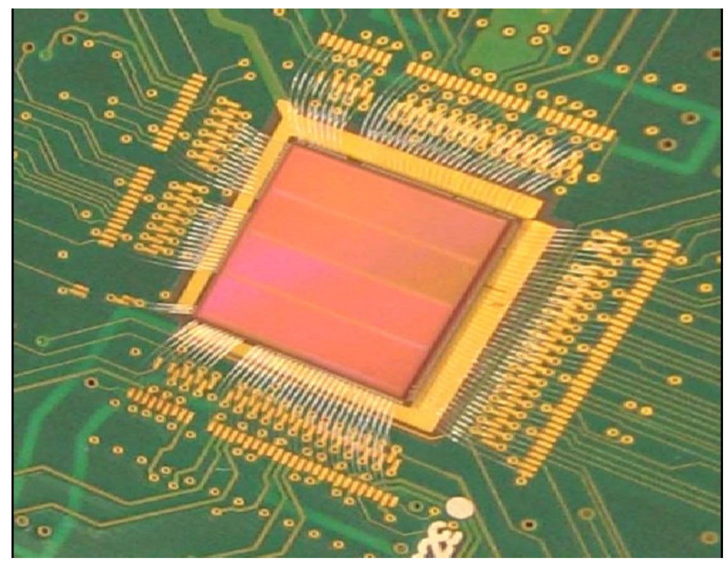
- developed for vertex detectors

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



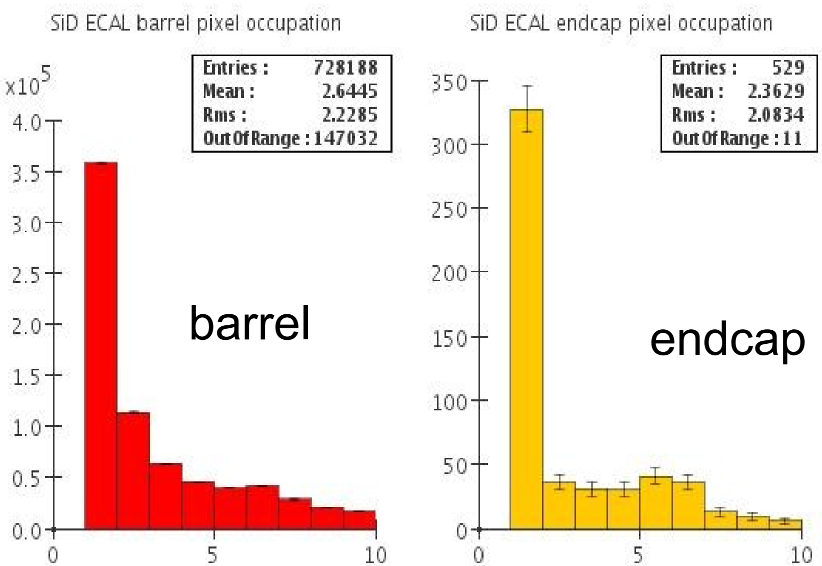


8.2 million transistors
□ 28224 pixels; 50x50 μm^2

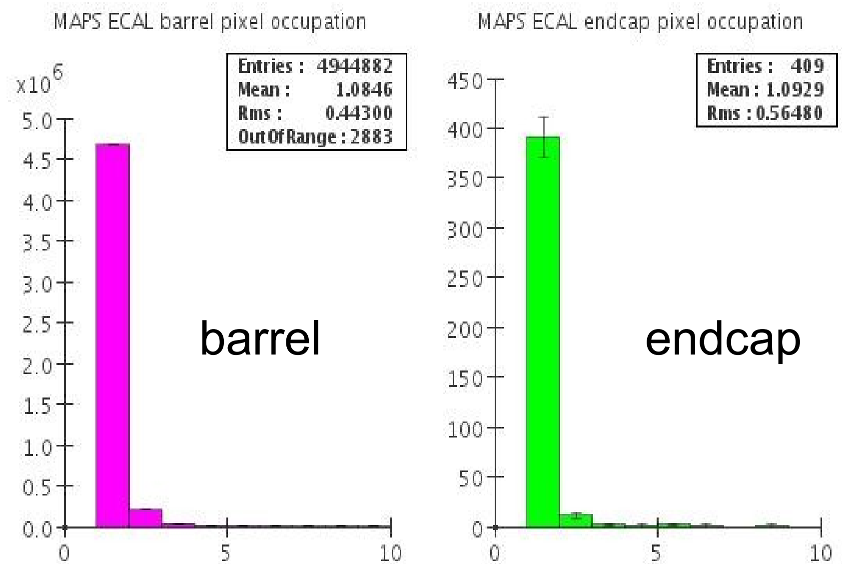
Pixel Occupancy

MAPS concept requires binary readout...
➔ need at most 1 hit per pixel or else lose information

Si-W ECAL, 100GeV electrons



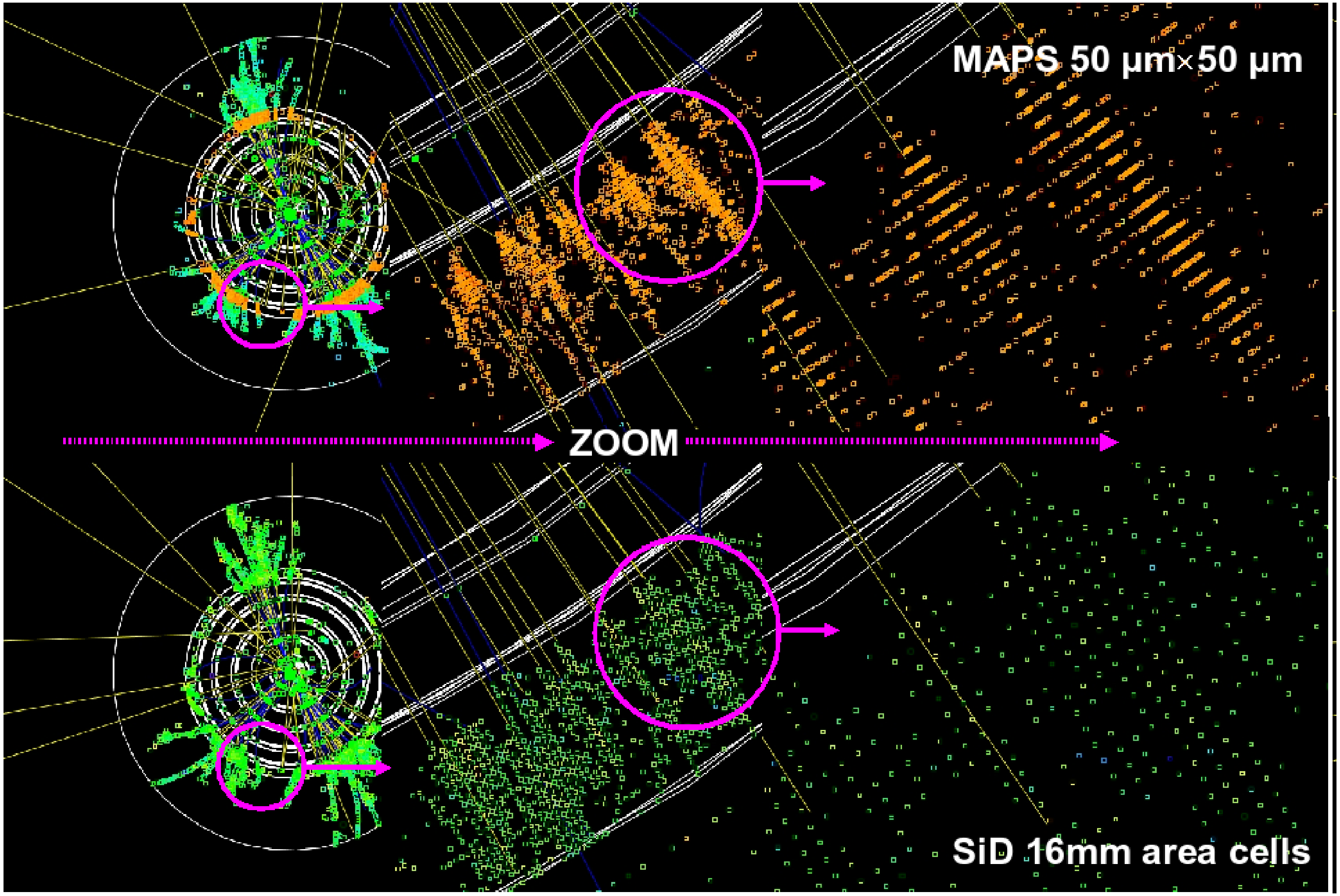
MAPS ECAL, 100GeV electrons



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