Part III

Calorimetry R&D
for the
ILC

The PFLOW paradigm

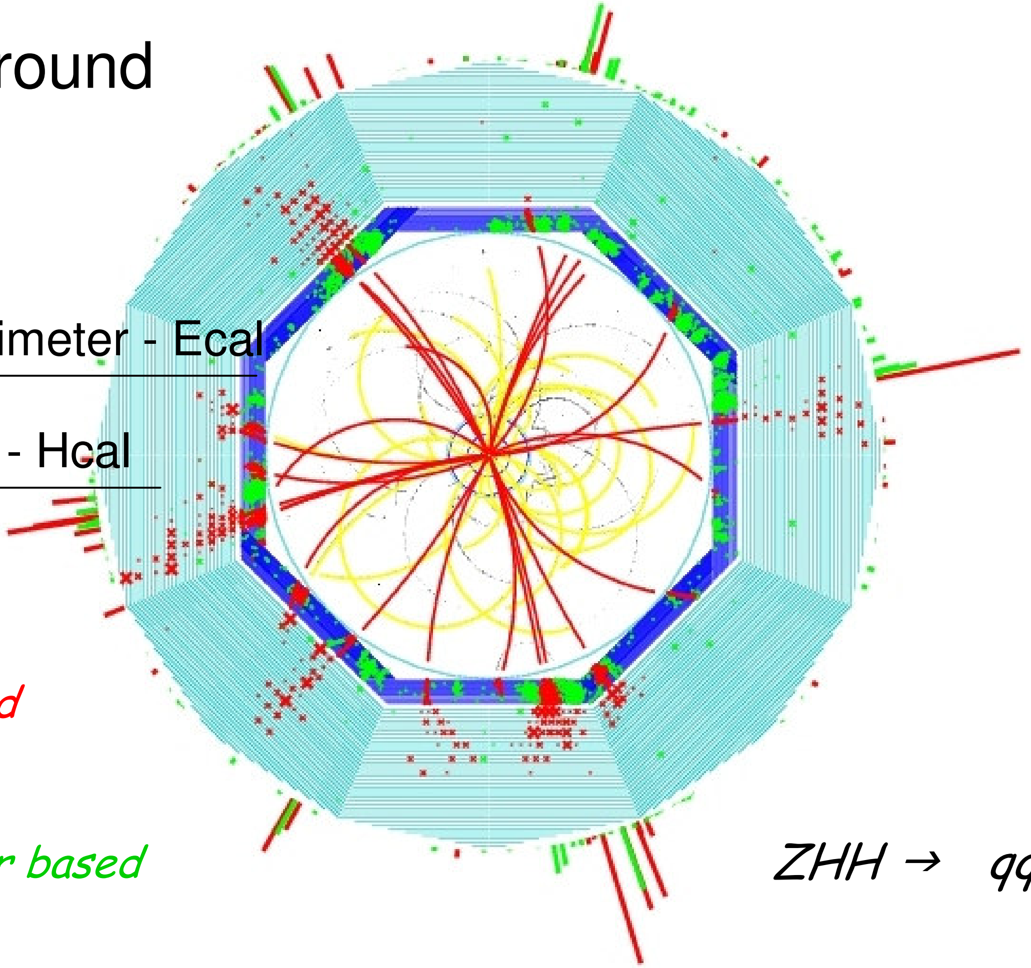
- The confusion term dominates
- Each particle should be reconstructed and measured separately
- For the jet energy measurement spatial resolution / particle separation power is more important than energy resolution

$$E_{\mathrm{jet}} = E_{\mathrm{charged}} + E_{\mathrm{photons}} + E_{\mathrm{neut.\,had.}}$$

$$\sigma^2_{E\mathrm{jet}} = \sigma^2_{E\mathrm{charged}} + \sigma^2_{E\mathrm{photons}} + \sigma^2_{E\mathrm{neut.had.}} + \sigma^2_{\mathrm{confusion}}$$

Imaging calorimetry

Calorimeters sorround Trackers



Electromagnetic Calorimeter - Ecal

Hadronic Calorimeter - Hcal

red: track based

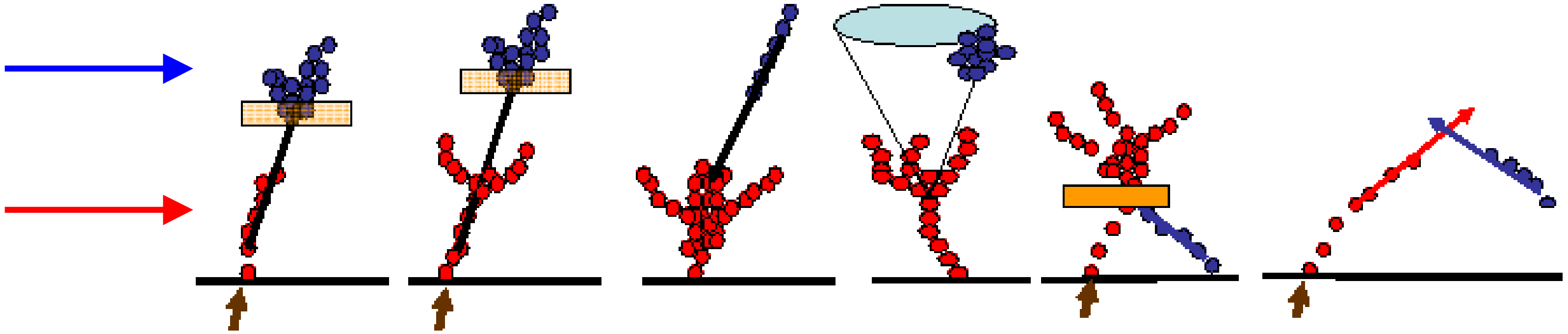
green: calorimeter based

ZHH → qqbbbb

A Particle Flow Algorithm (Extraction)

Pandora Algorithm by M. Thompson Uni Cambridge

Tracing a particle through the detector



Cannot do justice to full complexity of algorithm but …

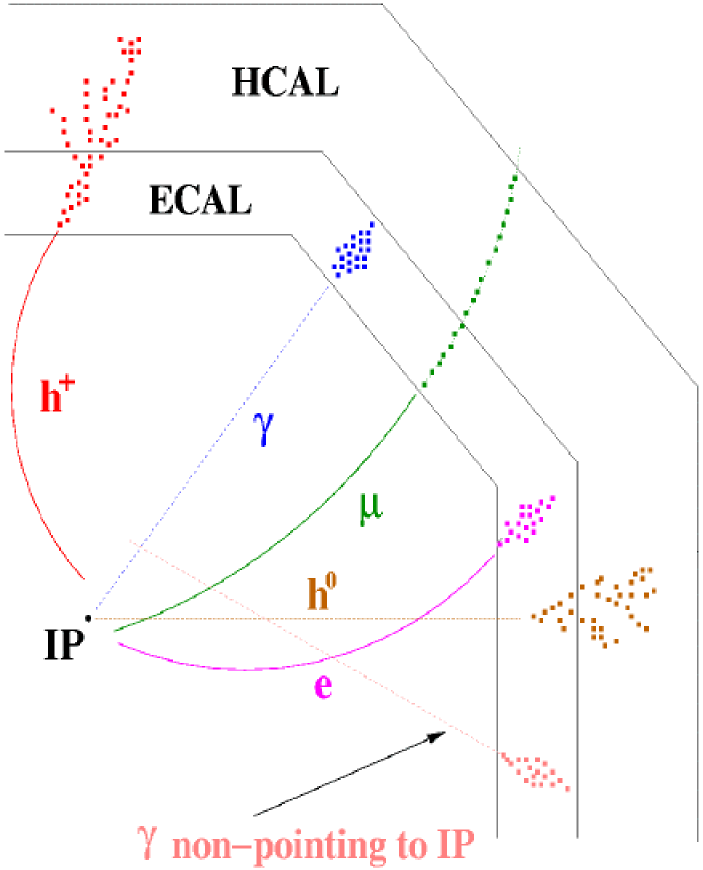
Two main steps:

- Find Individual Clusters created by one particle
- Merge clusters to reconstruct shower of the particle

Algorithms can only be qualified in MC simulation
Need extremely good knowledge in particular of hadronic cascades
Major task for testbeam efforts with (physics) prototypes

Calorimeter concept

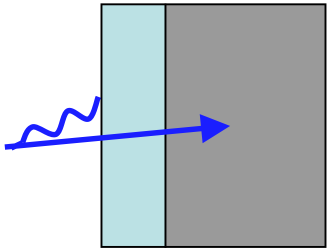
- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- “no” material in front
  - stay inside coil
- small Molière radius
  - to minimize shower overlap
- high granularity
  - to separate overlapping showers

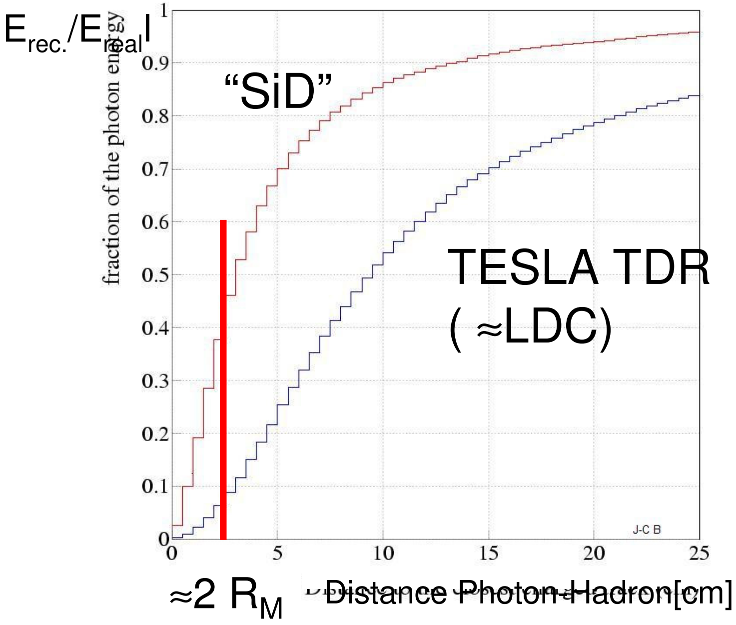


- figure of merit: $B\,R^2_{calo} / (r^2_M + r^2_{cell})$

Ecal - Main Task

Photon measurement and photon/hadron separation





(SD: R=1.27 m, here with 6T, TESLA TDR: R=1.68m, B=4T)

“Known” basic tools: Large R and B
If small R: Force created by Large B-Field might compromise detector stability
Limit: $BR^2 < 60\ Tm^2$

Separation gets difficult if hadron and photon are within R_M
Photon Energy gets assigned to close-by Hadron and vice versa

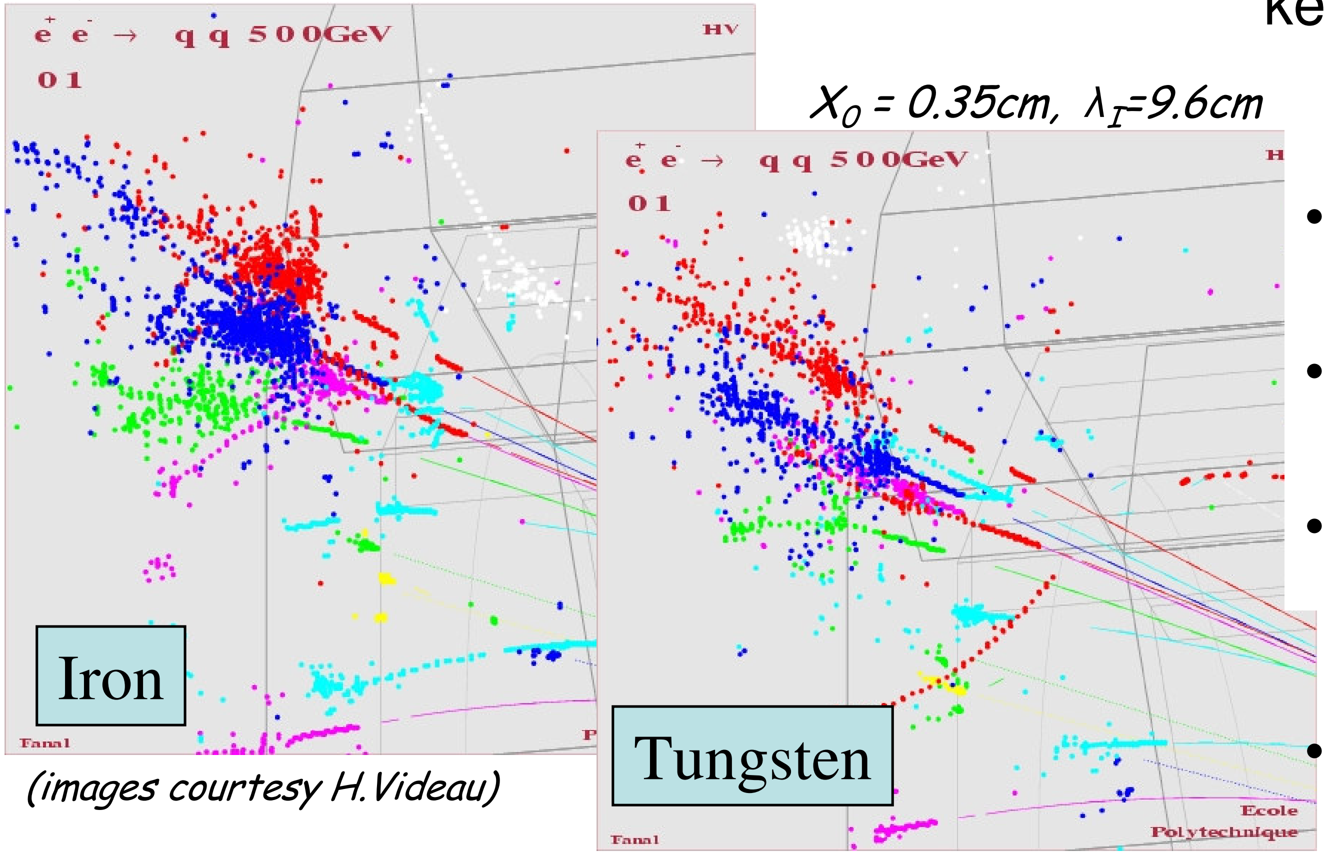
“Calorimetric” tools to improve photon-hadron separation?

Choice of Absorber Material - Tungsten vs. Iron

- elm./had separation:
  keep X_0 / λ_I small

X_0 = 1.8cm, λ_I=17cm

X_0 = 0.35cm, λ_I=9.6cm



(images courtesy H.Videau)

- Molière Radius for W: R_M = 0.9cm
- Cellzise need to match R_M !
- effectively a factor (1 + Gap / 2.5mm) more
- technology challenge: thin readout gap

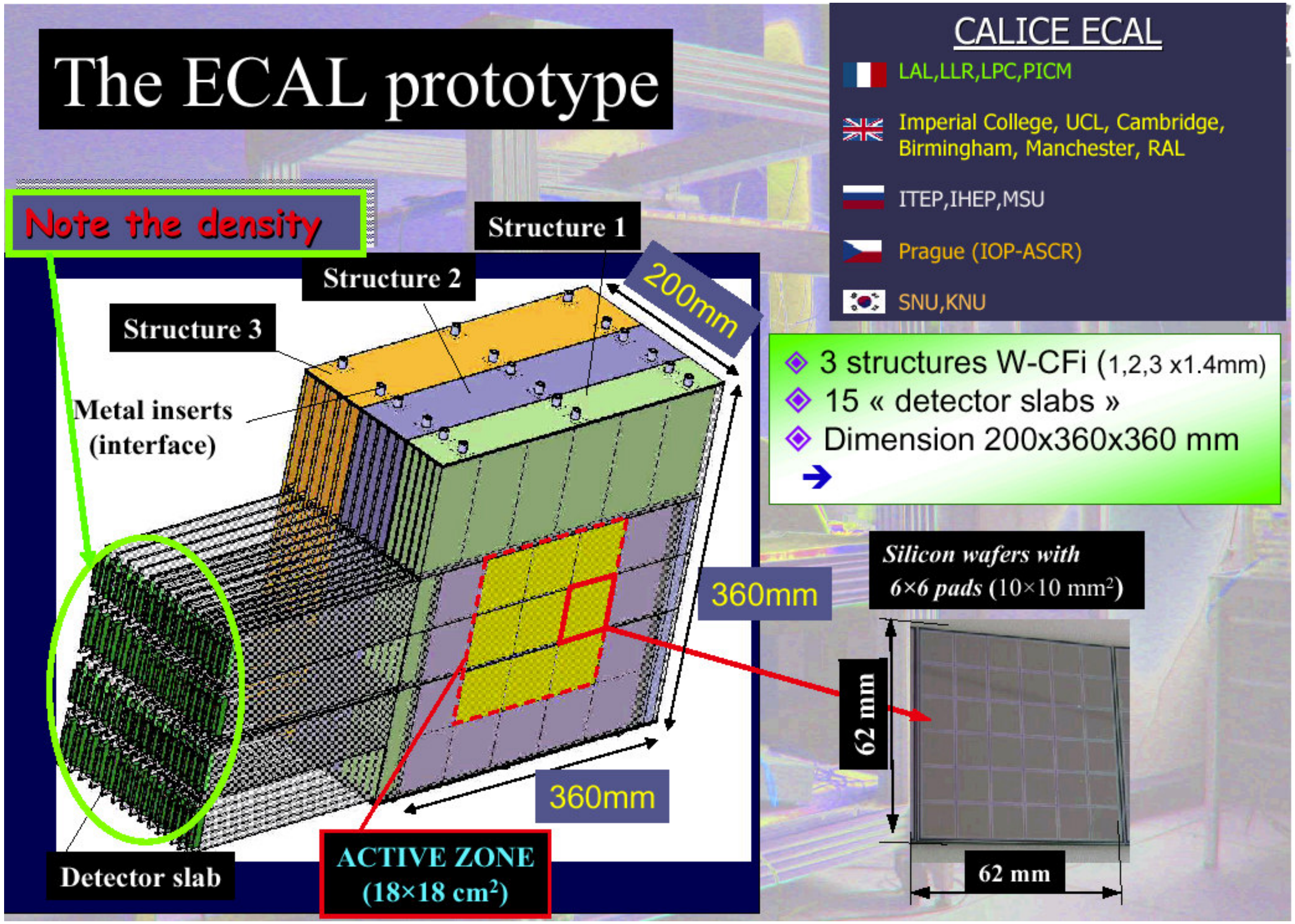
International effort

- Linear collider detector R&D is partially organized in (open) proto-collaborations, e.g. CALICE:

  ~200 Physicists, ~40 Institutes, 10 Countries: 3 Regions

- CALICE performs large scale testbeam 2005-2008(9) whith ‘physics’ protoypes
- ECAL and HCAL together, different options
- First large scale module (‘technological’ prototype for 2008)

Ecal Prototype - CALICE Collaboration



The ECAL prototype

CALICE ECAL

- LAL,LLR,LPC,PICM
- Imperial College, UCL, Cambridge, Birmingham, Manchester, RAL
- ITEP,IHEP,MSU
- Prague (IOP-ASCR)
- SNU,KNU

◈ 3 structures W-CFi (1,2,3 x1.4mm)

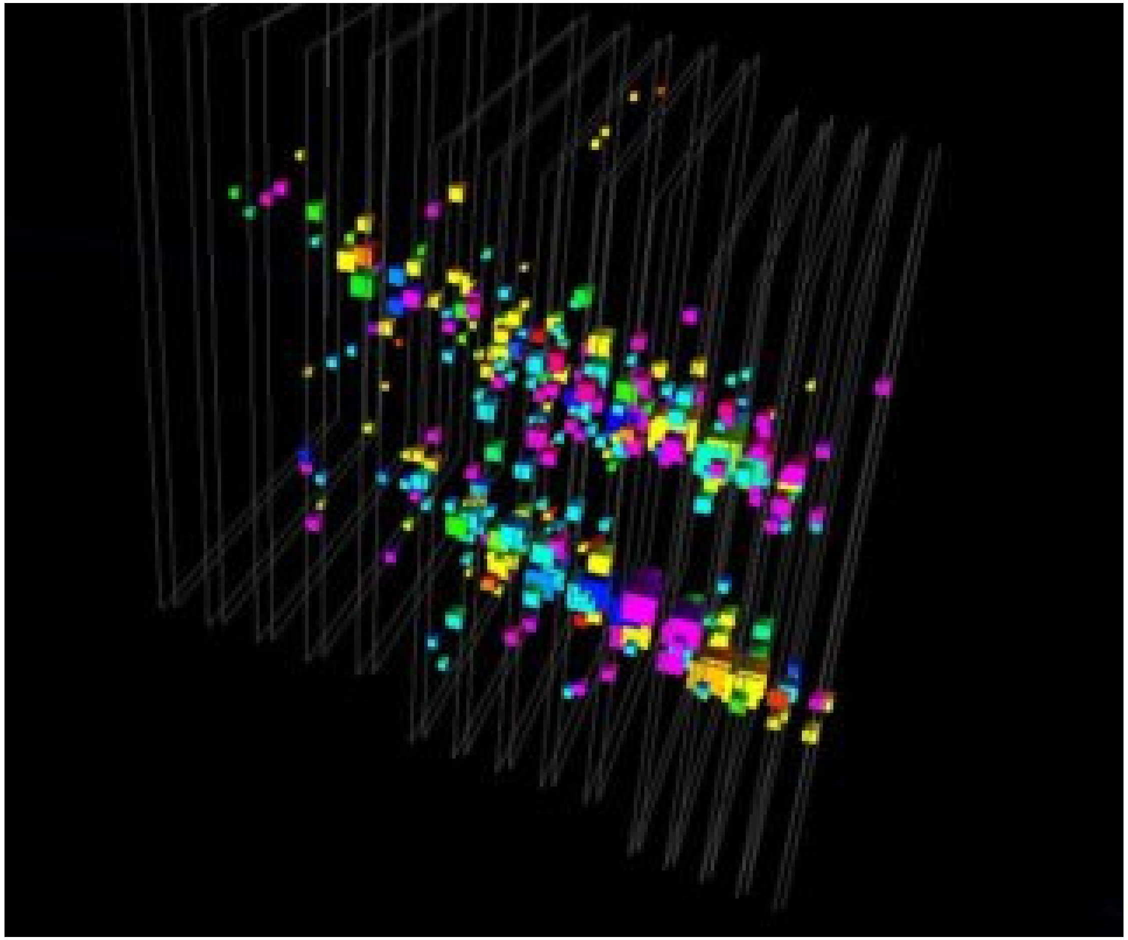
◈ 15 « detector slabs »

◈ Dimension 200x360x360 mm

➔

- Sampling Technique (see Part I)
- W as absorber material
- Signal extraction by “Silicon Wafers”
- Extreme high granularity 1x1 cm^2 cell size
- Detector is optimized for particle separation

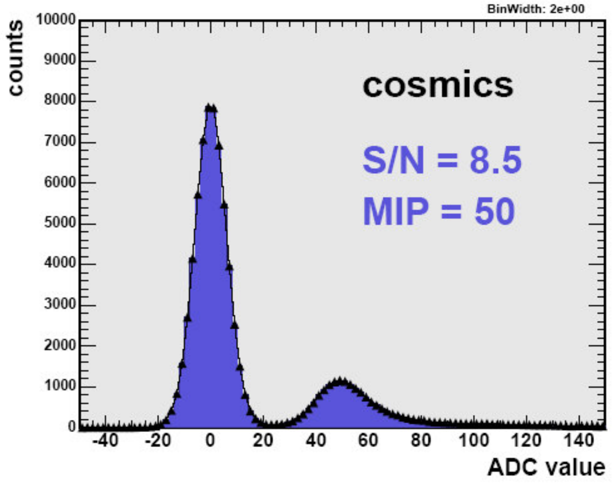
Ecal in Testbeam @ CERN

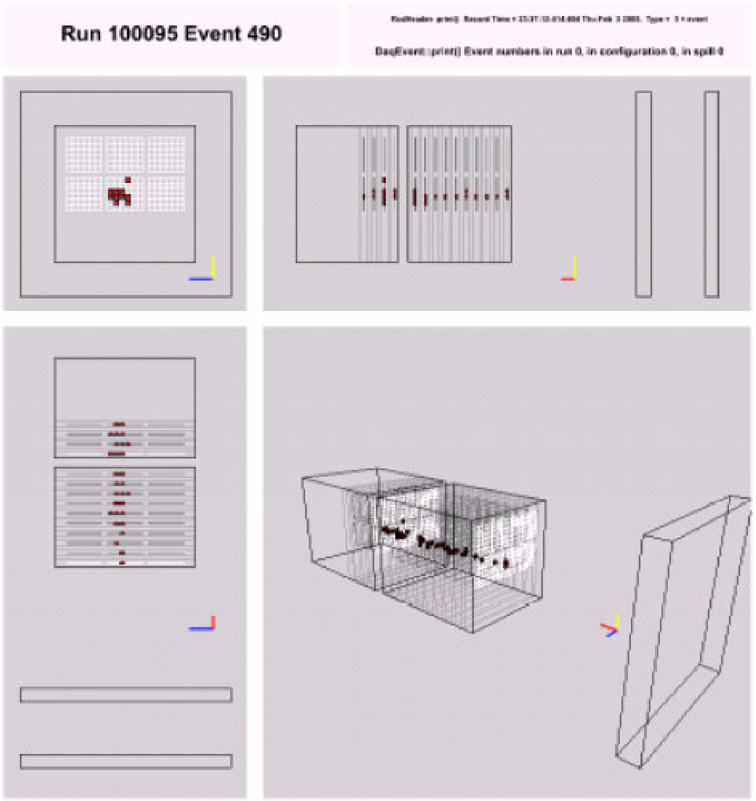


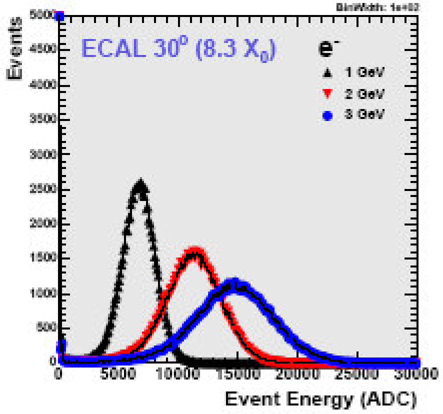
CALICE-ECal - results

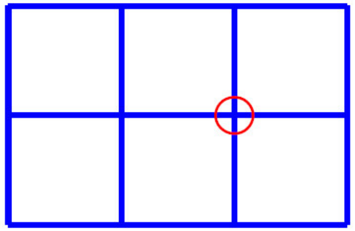
"30%" equipped Si/W prototype

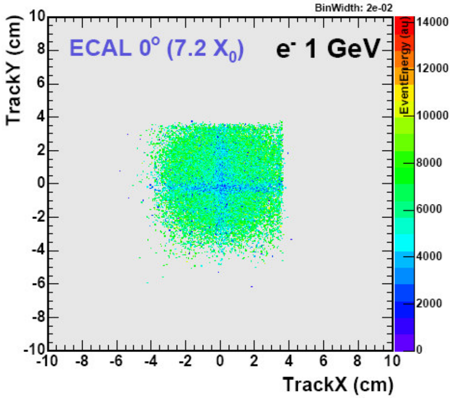
- i.e. 14 W layers (10 at 1.4mm + 4 at 2.8mm) interleaved with 18 × 12 matrix of active Si cells, 1 × 1 cm^2 each,
  total: 3024 channels
- first testbeam at DESY with electrons during Jan/Feb05




Run 100095 Event 490







Hadron Calorimeter

Same imaging requirements as for Ecal
High granularity for single particle identification
Most important task: Measure neutral hadrons !

Two Options

Sampling Technique

Digital Approach:

- Exploit statistical nature of (hadronic) shower
- Extreme small cell size 1x1 cm^2
  1 signal/(particle and cell)
  N_{cells} with signal ~ Energy of primary Particle
- Fe or W as Absorber
  (W very expensive !!!)
- Gaseous Detector (RPC see later) as active Element

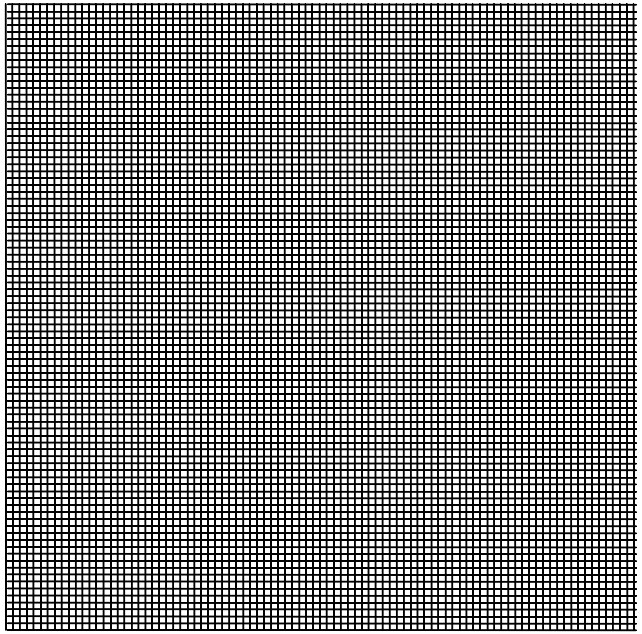
Analogue Approach:

- More “classical” Approach
- Measure energy deposition in cell
- Still small cell size O(3x3 cm^2)
- Fe or W as Absorber
- Scintillator as active Element
  Amount of light ~ deposited energy
  Appetizer: Novel photosensitive devices will be employed (see later)
- RPC also considered as active element

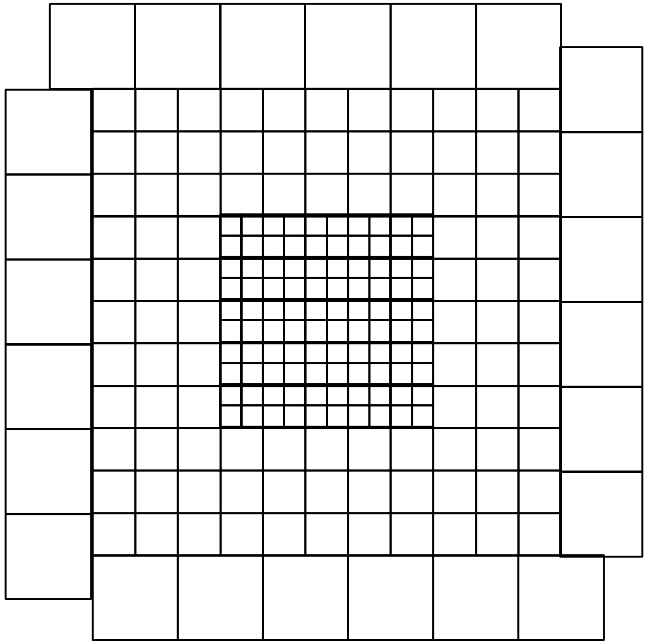
Hcal -Comparison of Granularities

Cell Grids

Digital Option



Analogue Option



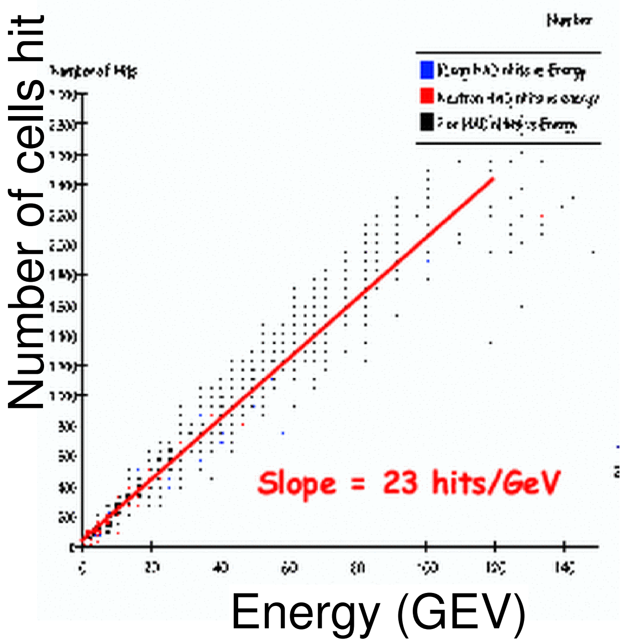
Challenging to assemble
Keep in mind: Need also
r/o devices

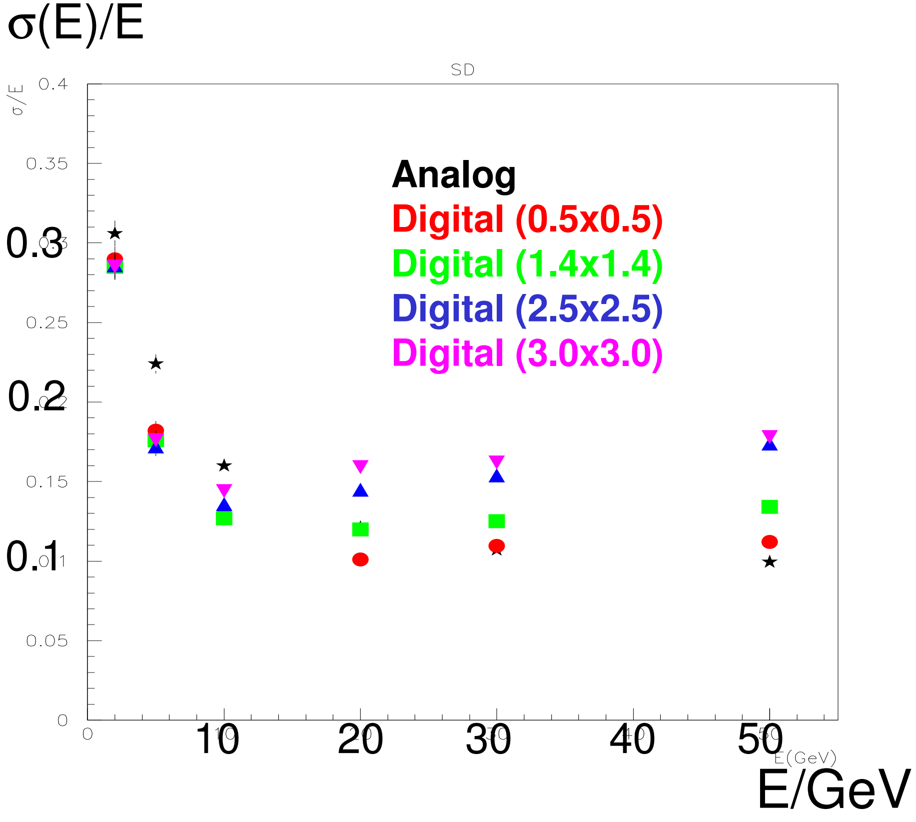
Cell Grid for a Hcal Prototype
with finely granulated inner core

Analog vs. Digital

- Digital: pad size 1cm asymptotic value
- suppress Landau fluctuations: at low E superior to analogue

- need ideas for high E, e.g. multiple thresholds (semi-digital)





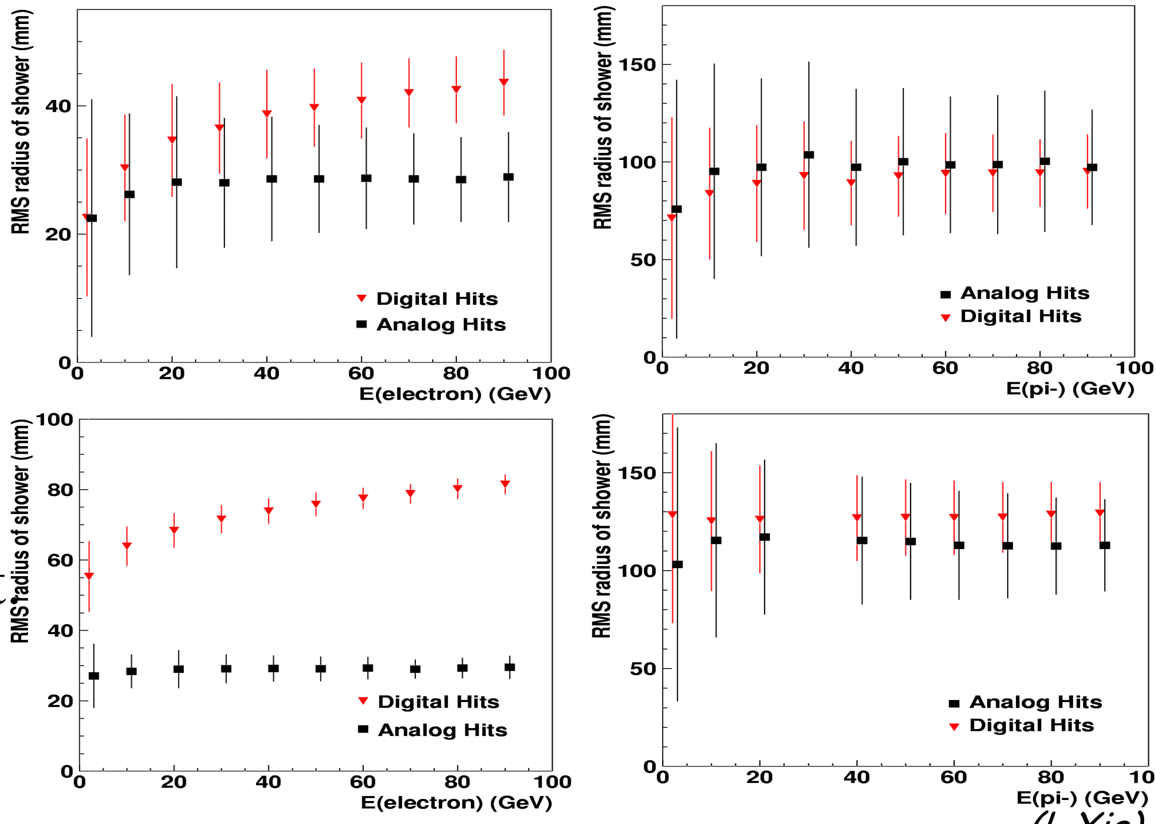
Gas vs. Scintillator

Regard lateral extension of shower: Want to have narrow showers

- width of shower pattern appears larger in scintillator
- will be recovered using amplitude or density information

RPC

Scint



(L.Xia)

$$\sqrt{\frac{\sum E_i \Delta^2 r_i}{\sum E_i}}$$

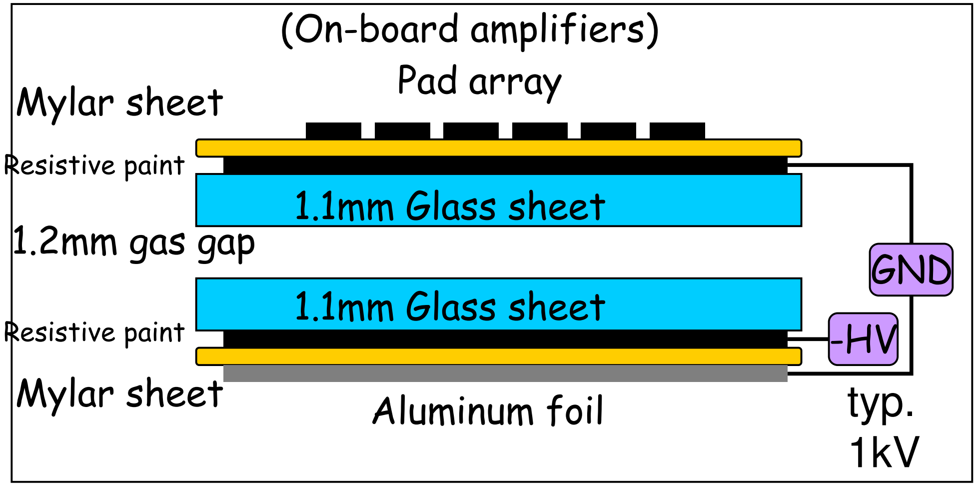
analogue
energy weighted
distance from
shower axis

$$\sqrt{\frac{\sum \Delta^2 r_i}{N}}$$

digital
distance from
shower axis

Hcal - Active Media (not only) fot Digital Concept

Resistive Plate Chamber (RPC):

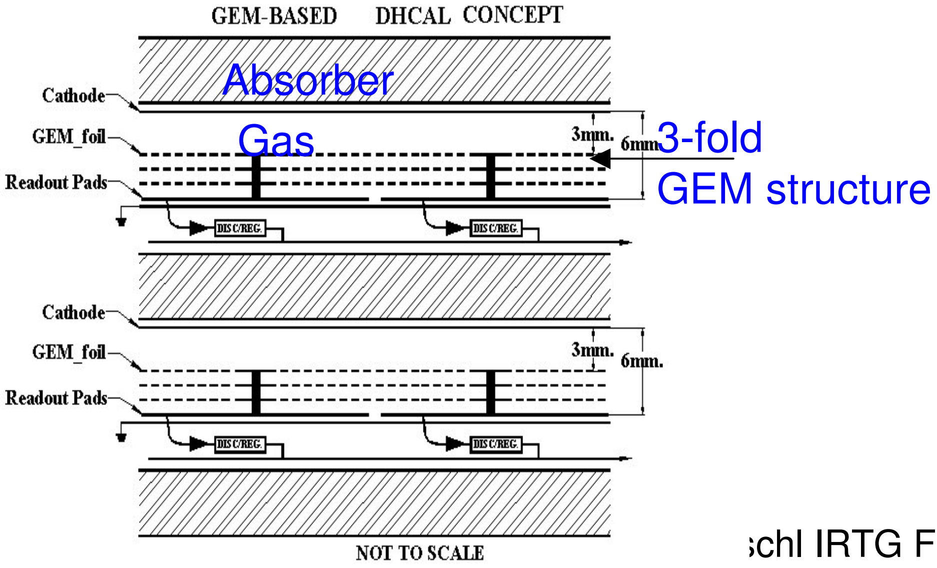


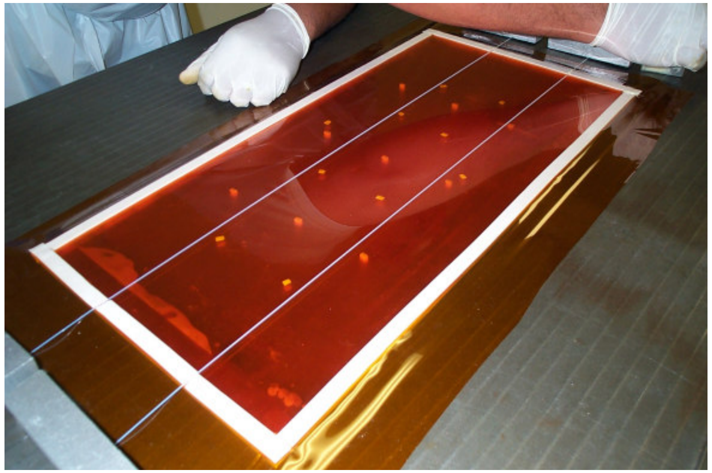
- Gaseous Detector

  Freon as chamber gas
- Spark by gas ionisation generates current in Pad Array
- RPC's can be built in small units at low cost

  (need to equip a huge calorimeter with 1x1 cm^2 cells)

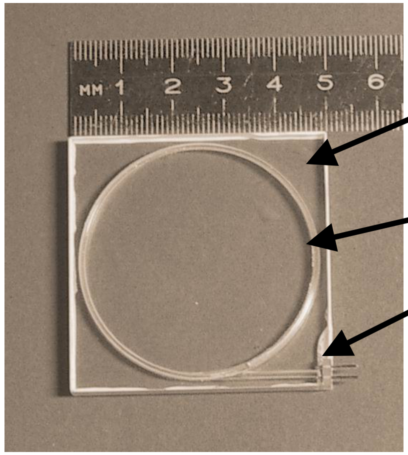
Alternative Option GEM's:



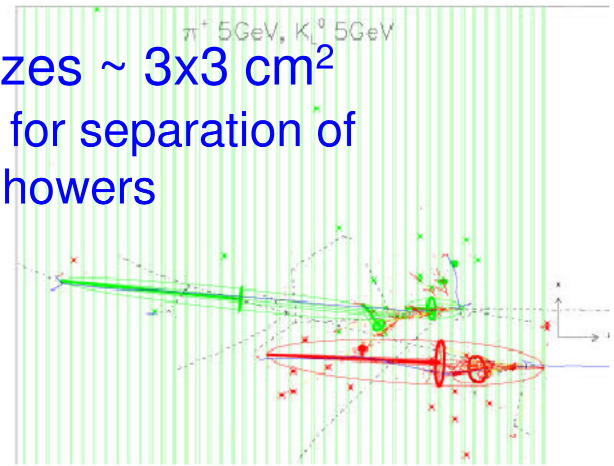


Hcal - Active Media (not only) for Analogue Concept

Scintillating Tiles with wavelength shifting fibres (also employed in alternative Ecal Concepts)



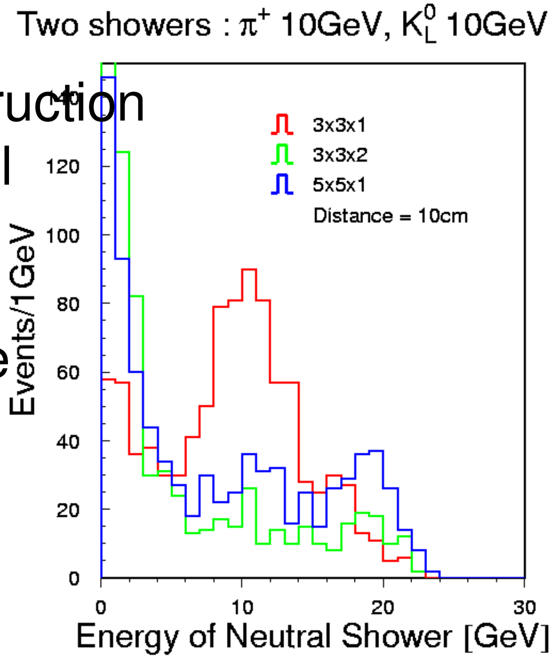
- Light production in scintillating tiles
  ~ 200 photons/MeV
- Light transport in fibres
- Measurement in photosensitive device
  Silicon Photomultipliers (details later)



Tile Sizes ~ 3x3 cm^2

Optimized for separation of hadronic showers

Reconstruction of neutral particles in analogue Hcal

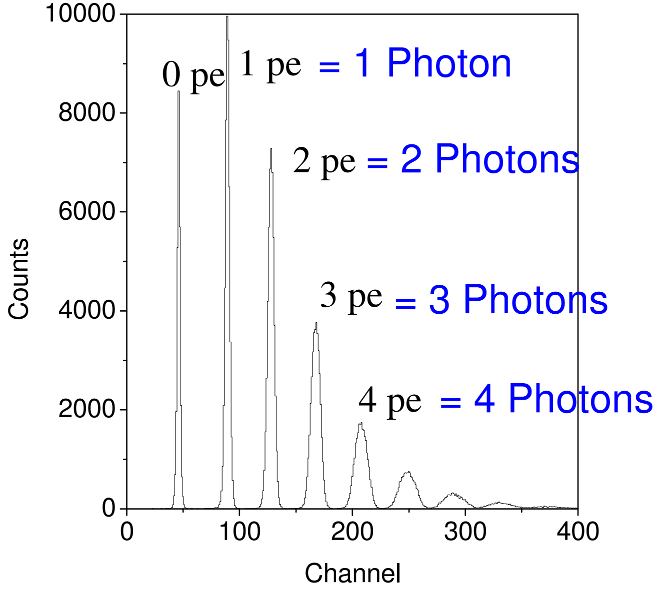


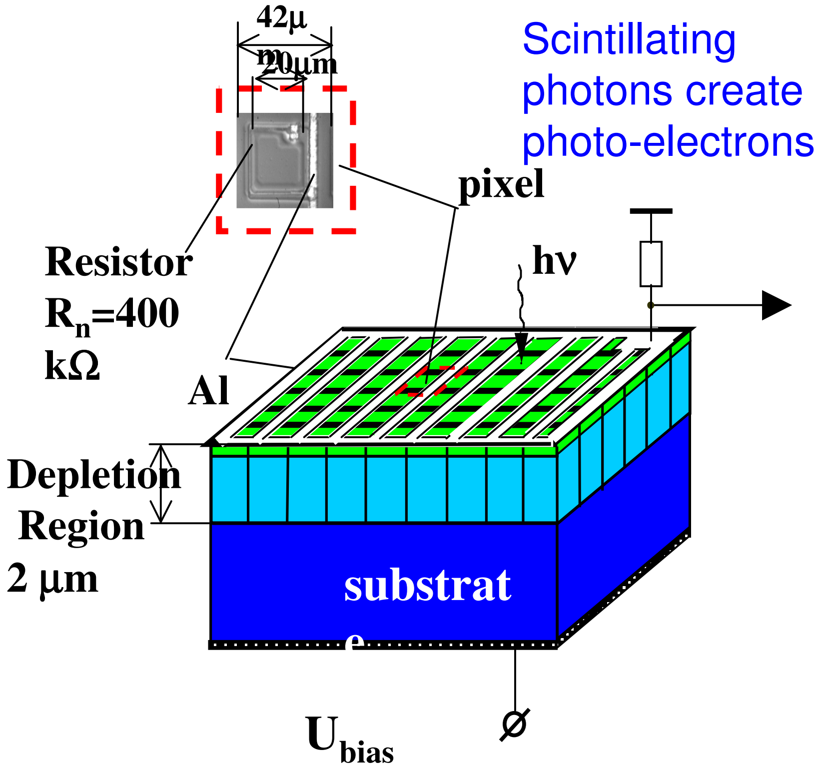
Silicon Photomultipliers SiPM

- A pixilated solid state Geiger counter (Semi Conducting)
  - 1000 pixels on 1mm^2
  - Gain 10**6, efficiency 10..15%
  - At 50 V typical bias voltage

Single Photon Signals

Signal - analog sum





Scintillating photons create photo-electrons

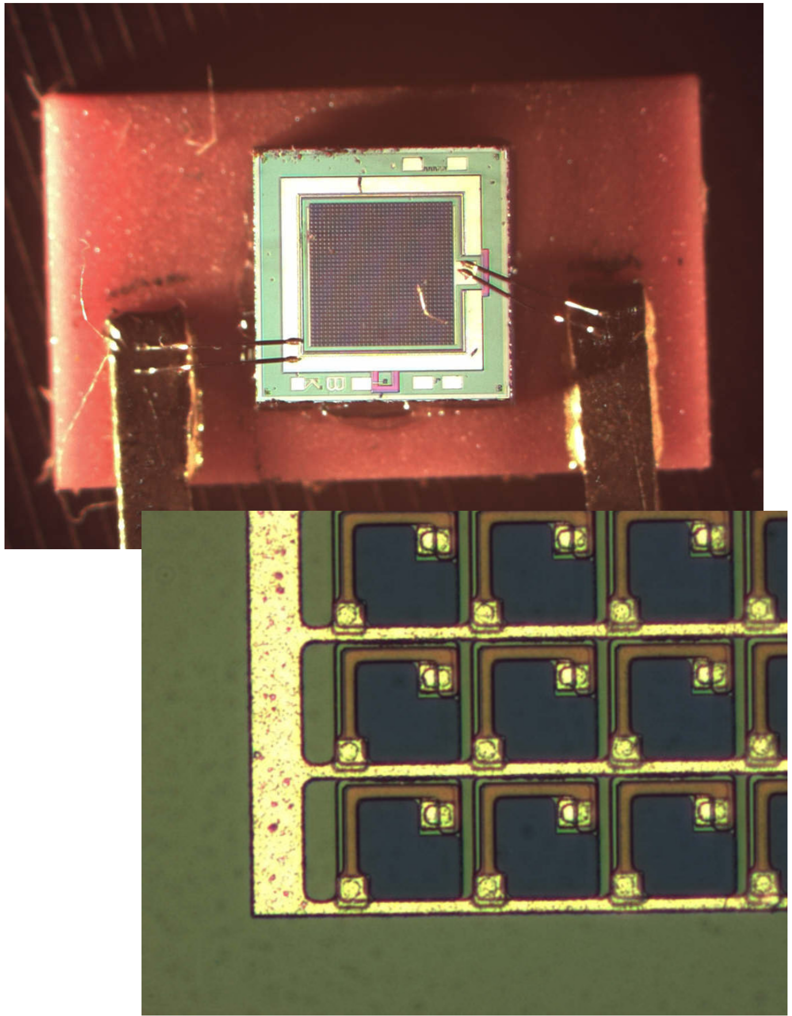
Silicon Photomultipliers cont'd

- Insensitive to magnetic fields

  Has to operate in O(4 T) magnetic Field

  Big advantage w.r.t. traditional PMTs)
- Dark rate ~ 2 MHz
- Interpixel Crosstalk 20-30%

- Gain, efficiency, Xtalk (thus noise rate) depend on bias and temperature
  - Overall 7% / 0.1V, -4% / K
- Need to carefully optimize individual working point

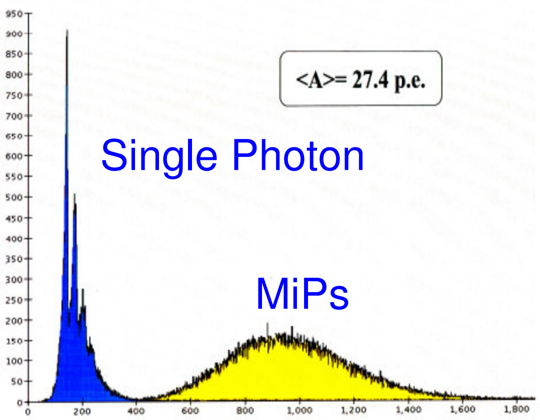


SiPMs at work I

- High gain, low bias, small size:
- Mount directly, no fiber routing
- Coax cable readout, no preamp

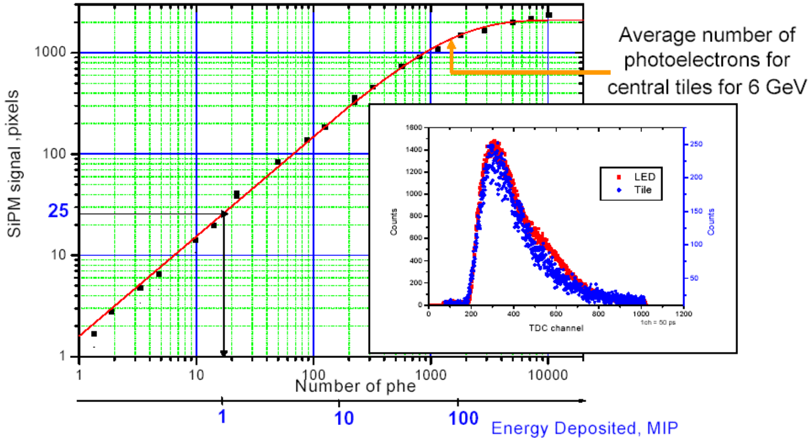
Spectra from SiPM

Picture from PC screen: LED and electron spectra



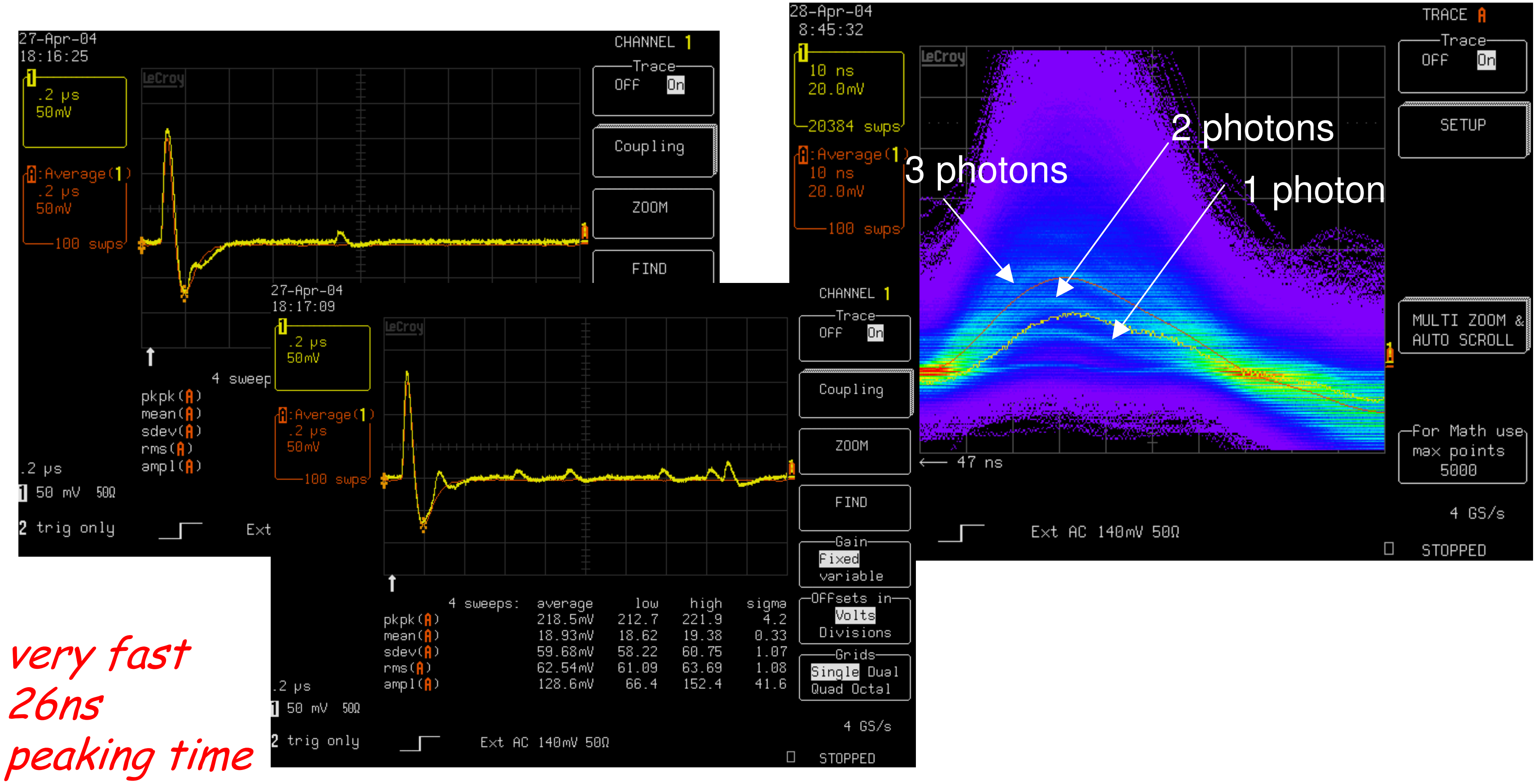
Saturation Curve

caused by limited number of pixels


Average number of photoelectrons for central tiles for 6 GeV

SiPMs at work II - A view in the lab

- tests with SiPM minical cassette



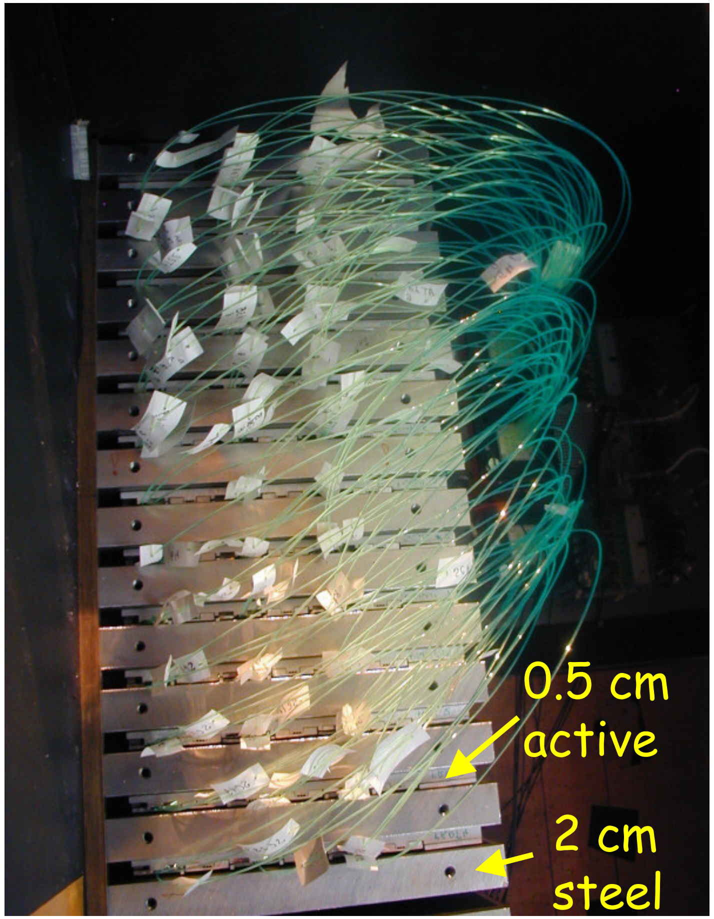
```
                4 sweeps:  average    low    high   sigma
pkpk(A)                    218.5mV  212.7   221.9     4.2
mean(A)                    18.93mV  18.62   19.38    0.33
sdev(A)                    59.68mV  58.22   60.75    1.07
rms(A)                     62.54mV  61.09   63.69    1.08
ampl(A)                    128.6mV   66.4   152.4    41.6
```

very fast
26ns
peaking time

Intensive R&D to understand properties of SiPMs

First Testbeam Experience - MiniCal

- 108 scintillator tiles (5x5cm)
- Readout with
  - Hamamatsu APD S8664 – 55 spl
  - 16 ch. MAPM (H6568) for ref.
  - Silicon Photomutipliers
    - Joint development
      - Moscow Engineering Physics Inst.
      - PULSAR, Moscow
      - DESY

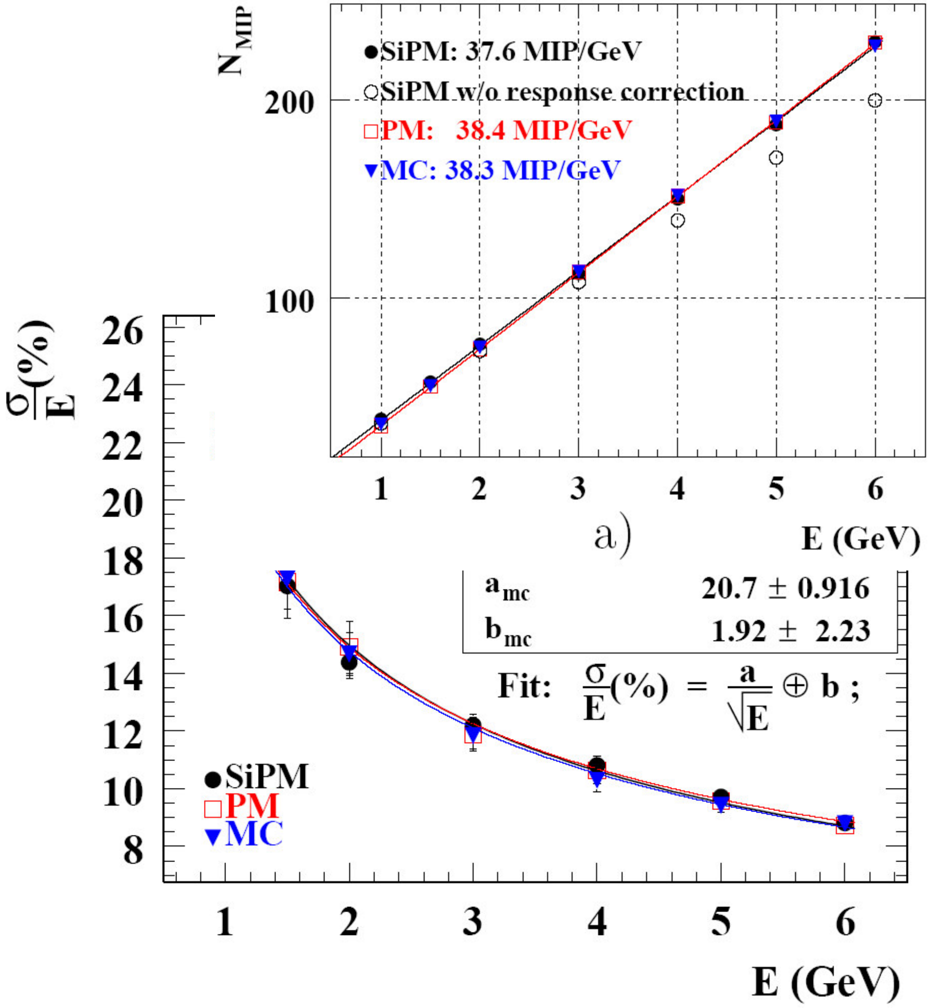


First Testbeam Experience - MiniCal

- DESY 6 GeV e beam
- Non-linearity can be corrected
  - Need to observe single photo signals for calibration
  - Does not affect resolution

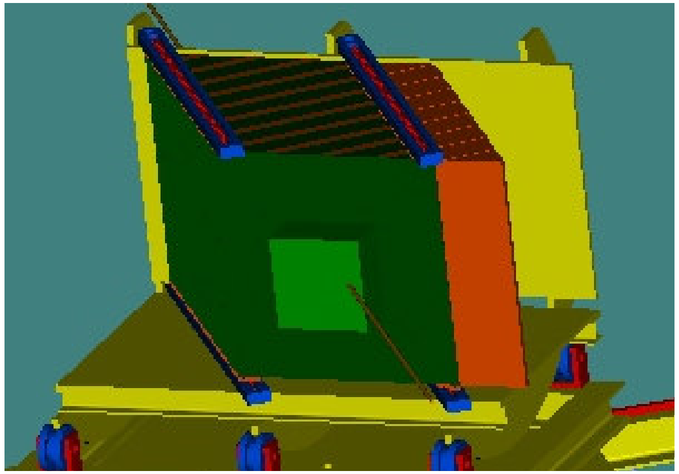
- Resolution as good as with PM or APD

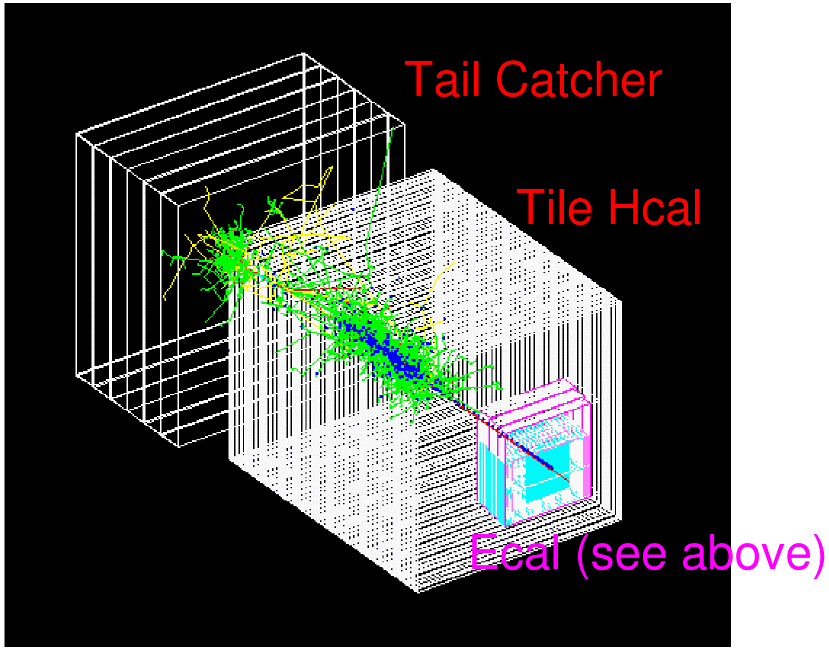
- Stability not yet challenged

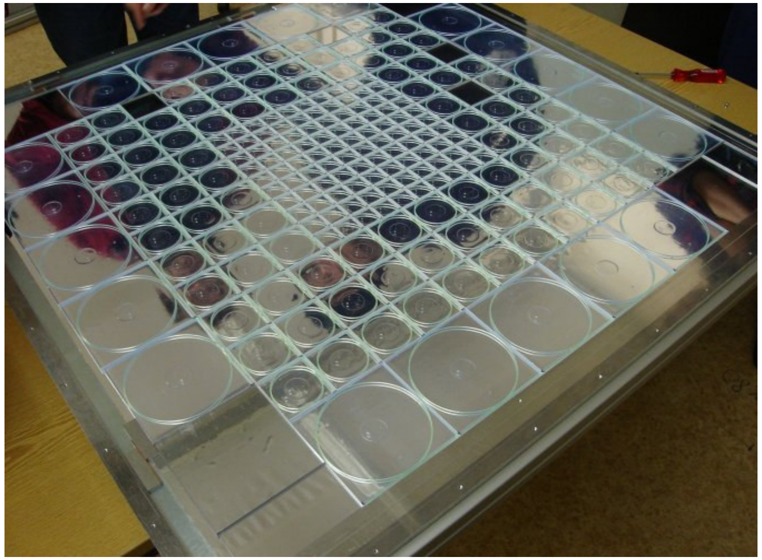


Cubic Meter Prototype for large scale Testbeam

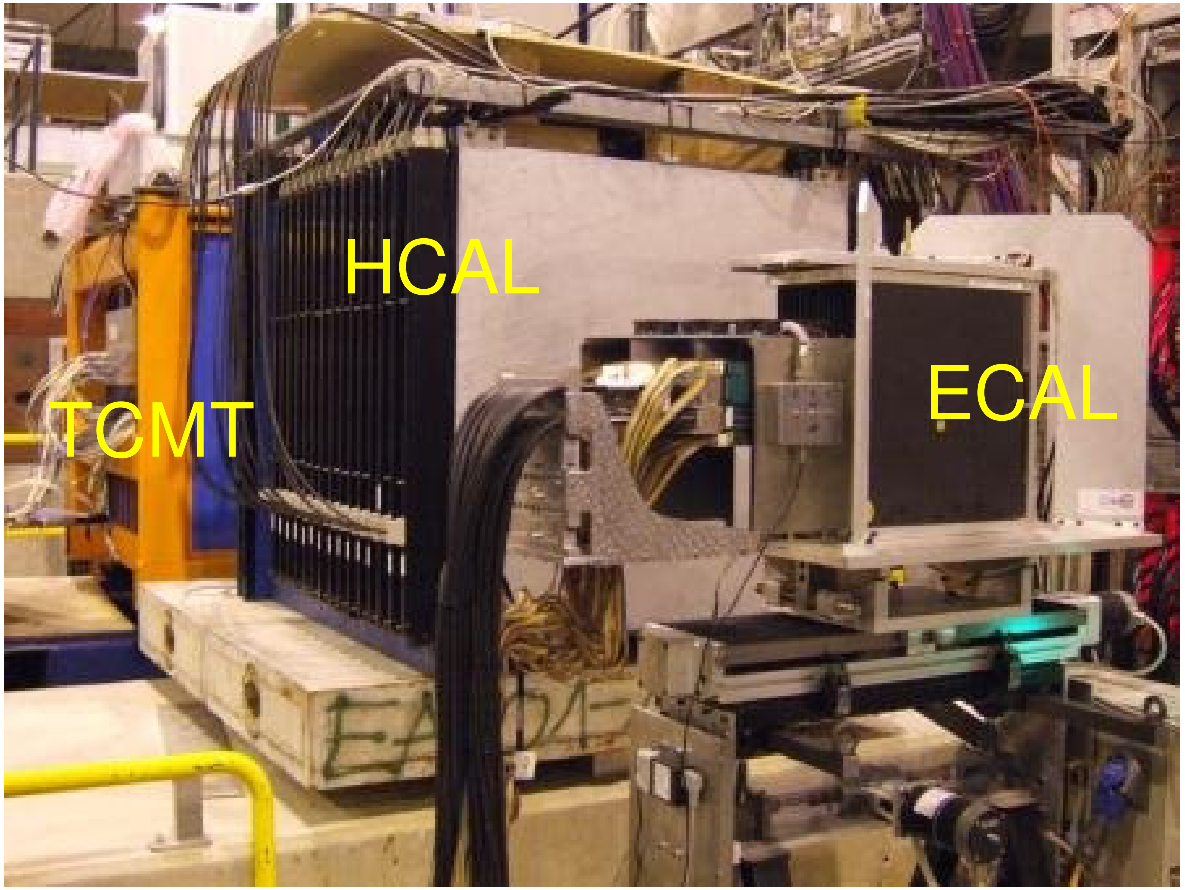
- 8000 channels
- Hadron test beam in 2006-2008
- Includes scintillator strip muon detector with SiPMs



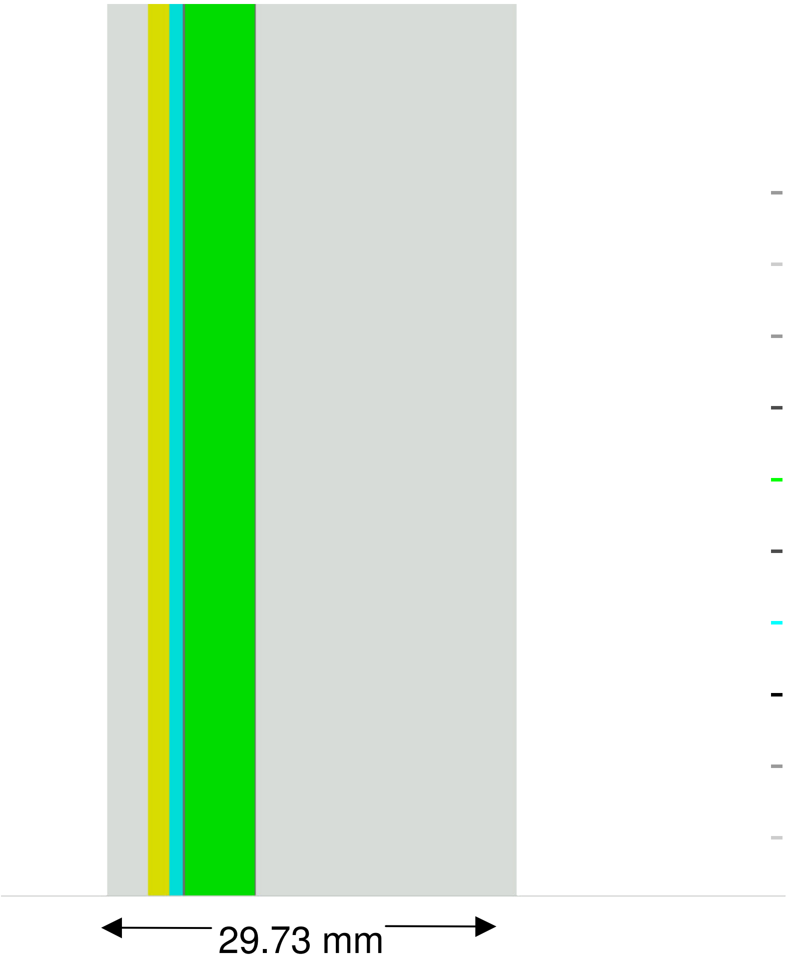




Testbeam Setup at CERN 2006/07



Layer Composition of Prototype



- 16 mm Steel, S235 as Main Absorber
- 1mm Air Gap
- 2mm Scintillator Housing – Front Plate
- 0.115 mm 3M Foil
- 5 mm Scintillator
- 0.115 mm 3M Foil
- 1mm FR4
- 1mm Cable Fibre Mixture (PVC. Fibre)
- 2 mm Scintillator Housing – Rear Plate
- 1mm Air Gap

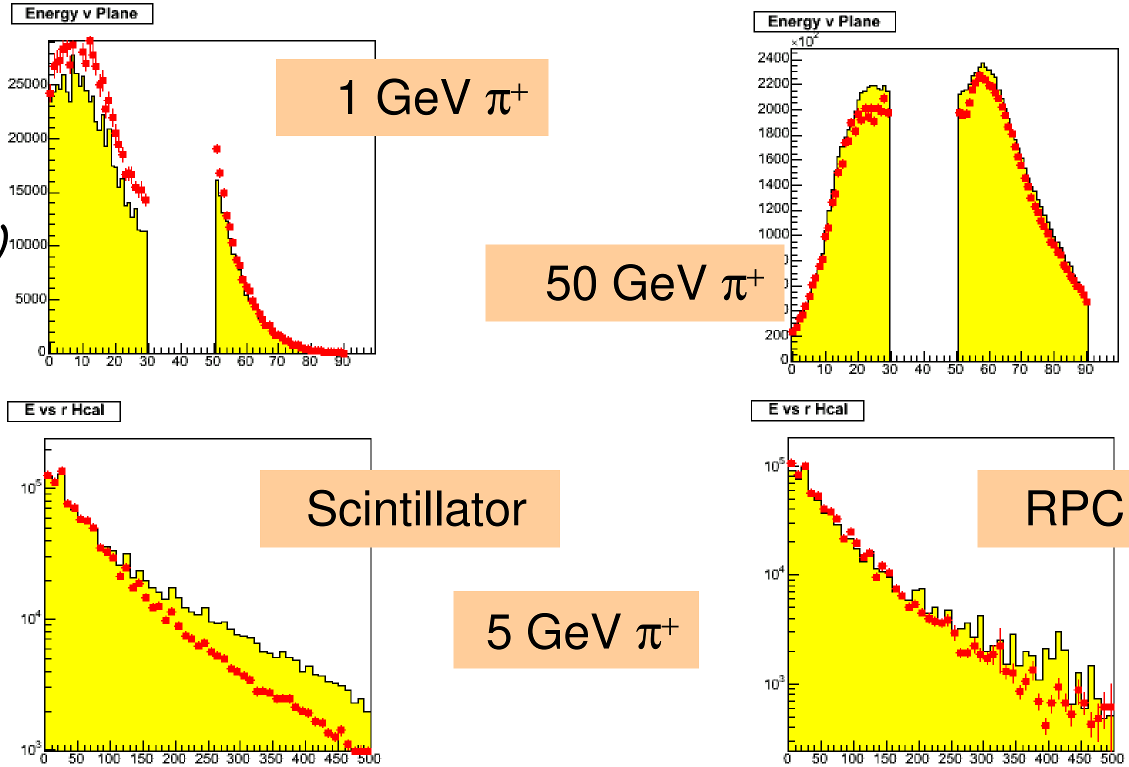
Approx. 1.14 X_0

39 Layers

Approx. 4.7 $\lambda \approx$ Needed Thickness for final Detector

Testing Hadronic Models

- 10’000 particles, compare Geant 3 (histo) vs. Geant 4 (points)



longitud. (ECAL+HCAL)

1 GeV π^+

50 GeV π^+

(study by D.Ward)

transverse in HCAL

Scintillator

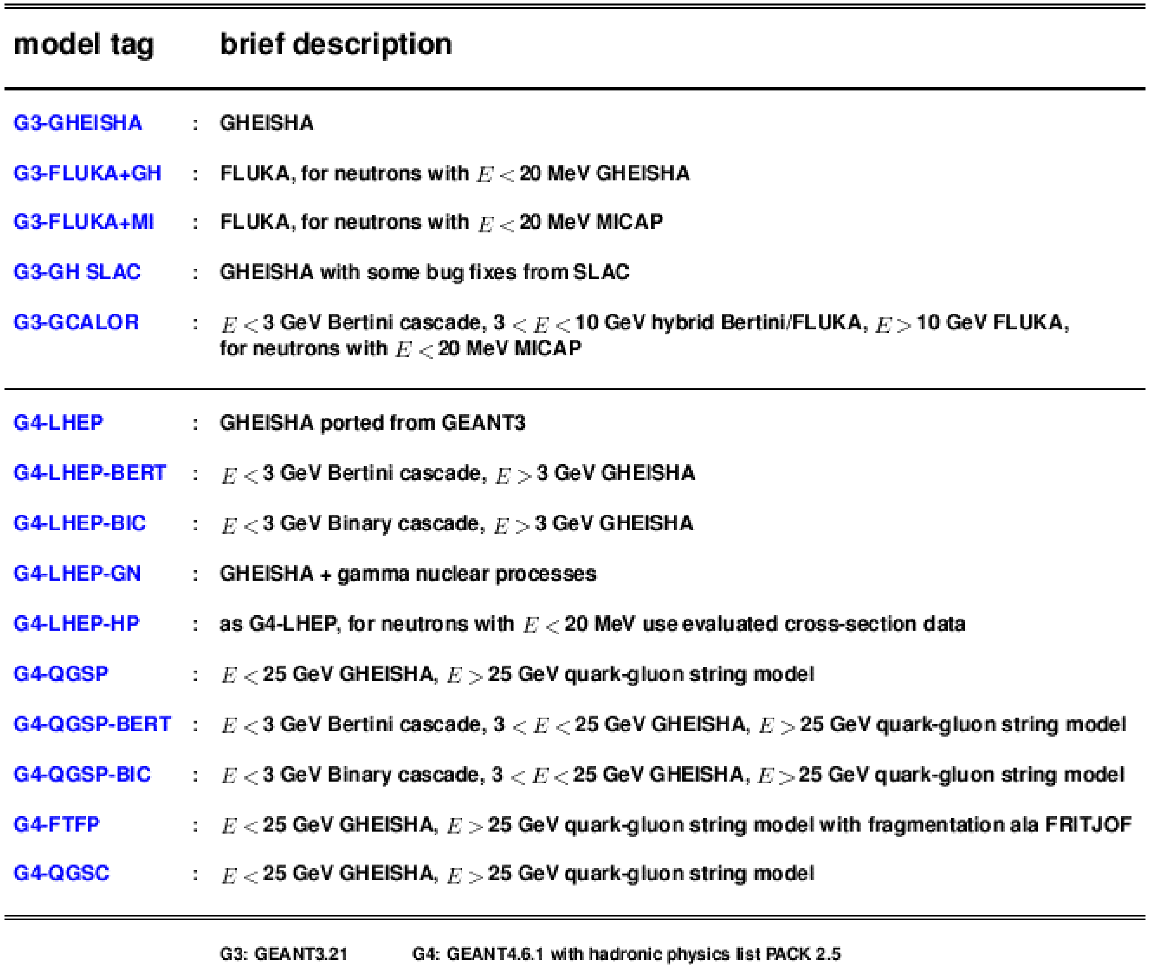
5 GeV π^+

RPC

- differences vary with energy, particle type, detector material,…

Overview on Hadronic Models

Large Variety of hadronic models



model tag	brief description
G3-GHEISHA	GHEISHA
G3-FLUKA+GH	FLUKA, for neutrons with $E < 20$ MeV GHEISHA
G3-FLUKA+MI	FLUKA, for neutrons with $E < 20$ MeV MICAP
G3-GH SLAC	GHEISHA with some bug fixes from SLAC
G3-GCALOR	$E < 3$ GeV Bertini cascade, $3 < E < 10$ GeV hybrid Bertini/FLUKA, $E > 10$ GeV FLUKA, for neutrons with $E < 20$ MeV MICAP
G4-LHEP	GHEISHA ported from GEANT3
G4-LHEP-BERT	$E < 3$ GeV Bertini cascade, $E > 3$ GeV GHEISHA
G4-LHEP-BIC	$E < 3$ GeV Binary cascade, $E > 3$ GeV GHEISHA
G4-LHEP-GN	GHEISHA + gamma nuclear processes
G4-LHEP-HP	as G4-LHEP, for neutrons with $E < 20$ MeV use evaluated cross-section data
G4-QGSP	$E < 25$ GeV GHEISHA, $E > 25$ GeV quark-gluon string model
G4-QGSP-BERT	$E < 3$ GeV Bertini cascade, $3 < E < 25$ GeV GHEISHA, $E > 25$ GeV quark-gluon string model
G4-QGSP-BIC	$E < 3$ GeV Binary cascade, $3 < E < 25$ GeV GHEISHA, $E > 25$ GeV quark-gluon string model
G4-FTFP	$E < 25$ GeV GHEISHA, $E > 25$ GeV quark-gluon string model with fragmentation ala FRITJOF
G4-QGSC	$E < 25$ GeV GHEISHA, $E > 25$ GeV quark-gluon string model

G3: GEANT3.21 G4: GEANT4.6.1 with hadronic physics list PACK 2.5

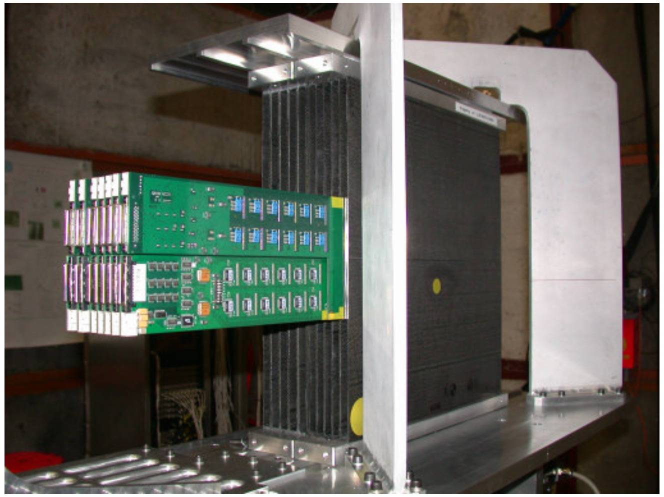
Citation from GEANT4 webpage:
“For very fine grain calorimeter like in the case of several LC designs the physics lists … might not be adequate”

Need testbeam data to tune hadronic models for ILC purposes
E.g. for optimization of particle flow algorithms

The Step towards the Real Detector - EUDET Module

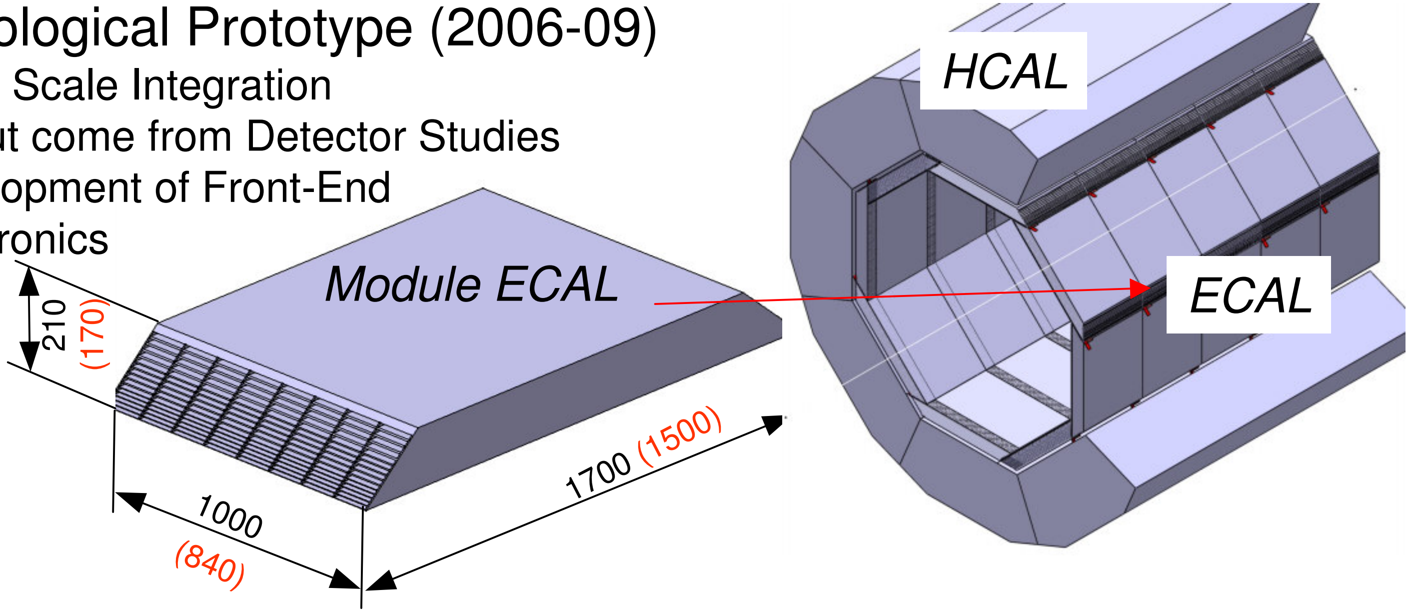
Physics Prototype

- Demonstrate Physics Performance
- Validate Simulation Tools
- Running at DESY since Jan. ‘05
- Large Scale Test Beam in ‘06



Technological Prototype (2006-09)

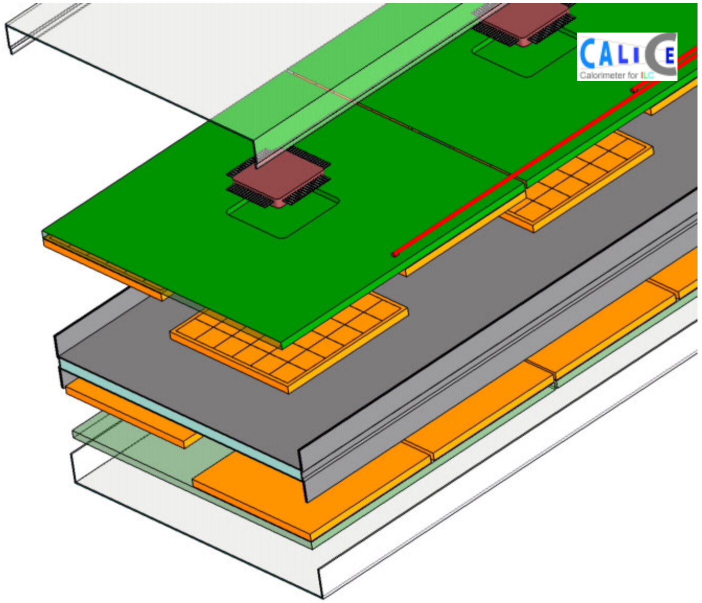
- Large Scale Integration
- Layout come from Detector Studies
- Development of Front-End Electronics

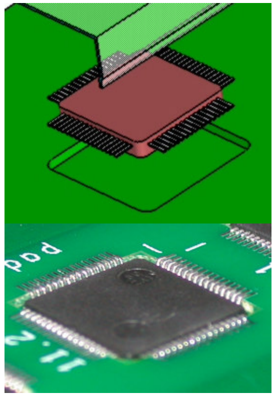


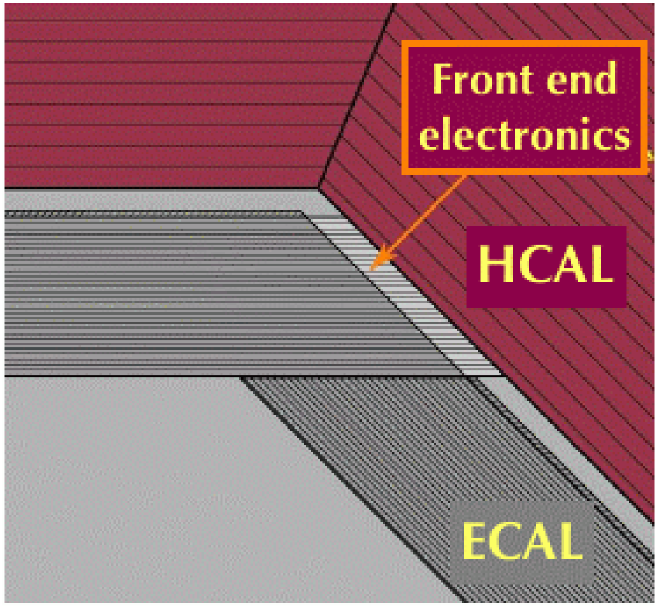
R&D sample

- ➢ Eeasier for mechanical construction
- ➢ Smaller Molière radius
- ➢ Industruial way of assembling
- ➢ DAQ based on FPGA
- ➢ VFE ASICs more integrated
  (ADC, more channel, zero suppress …)
- ➢ Smaller silicon pixel
  (glue, ac/dc coupling, thickness)
- ➢ 2x thinner than protoype

Production at industrial level





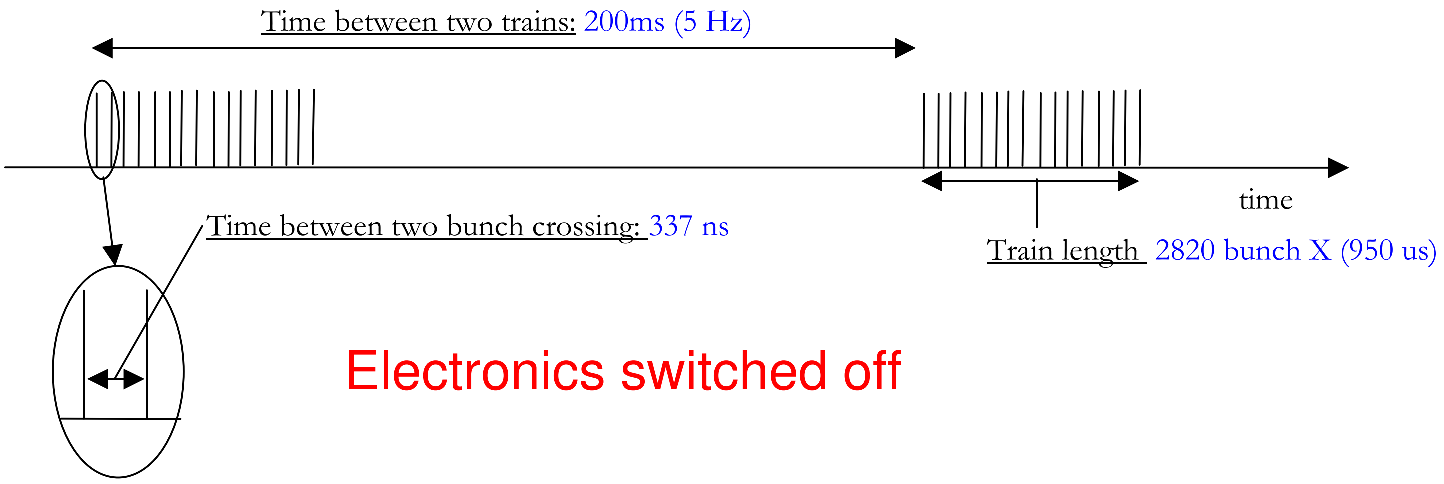


FE Electronics has to fit into ~3cm gap between Hcal and Ecal …

…and the electronics has to consume no power

- The goal is 25μW/ch. (with Power Pulsing)

Remember Ecal+Hcal O($5x10^8$) Channels

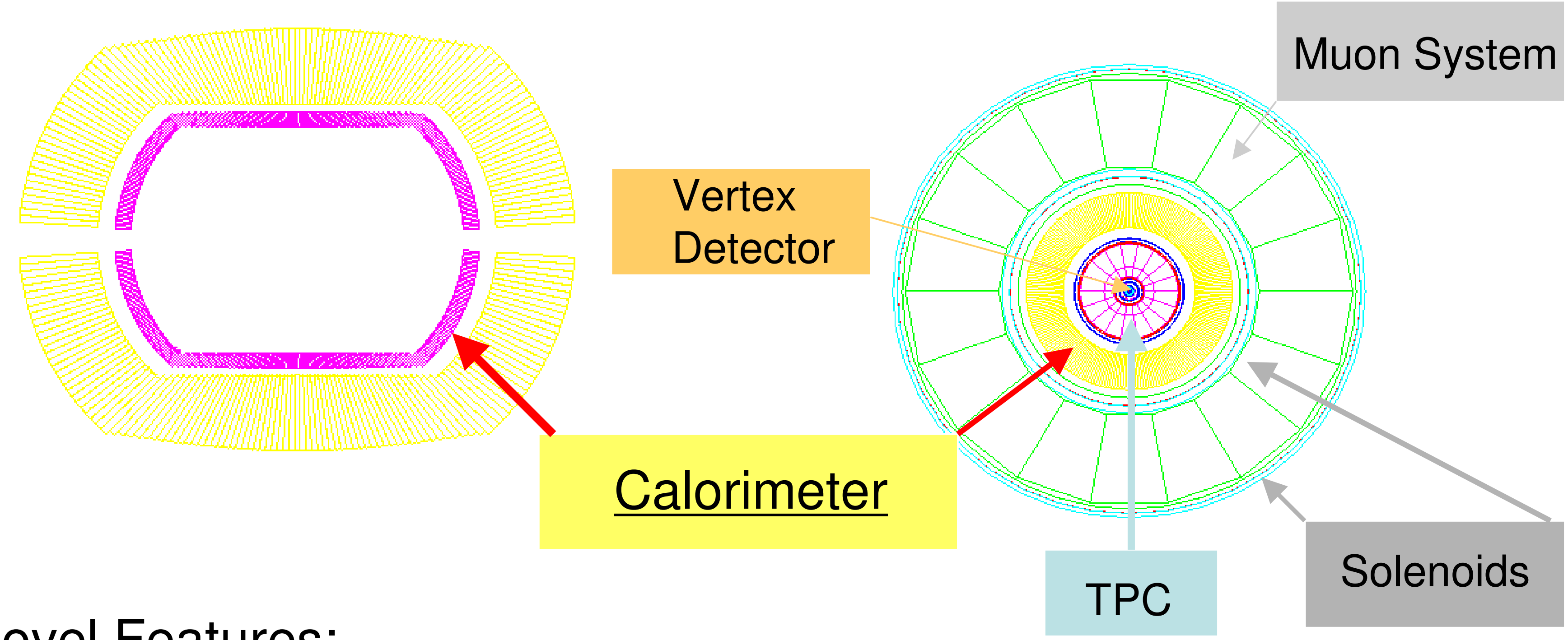


Electronics switched off

Electronics active

Electronics active

The 4th concept



Muon System

Vertex Detector

Calorimeter

TPC

Solenoids

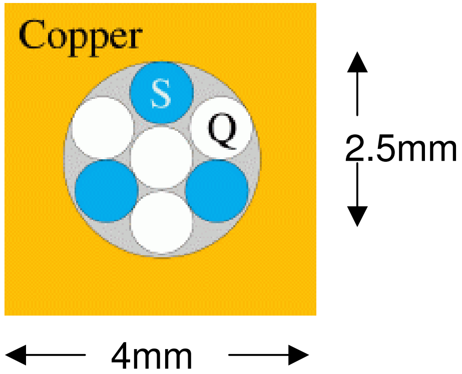
Novel Features:

muon system embedded in solenoidal field

‘traditional’ calorimeter but:
multiple calorimeter readout to overcome
typical deficiencies of hadron calorimetry
based on Results of DREAM calorimeter testbeam

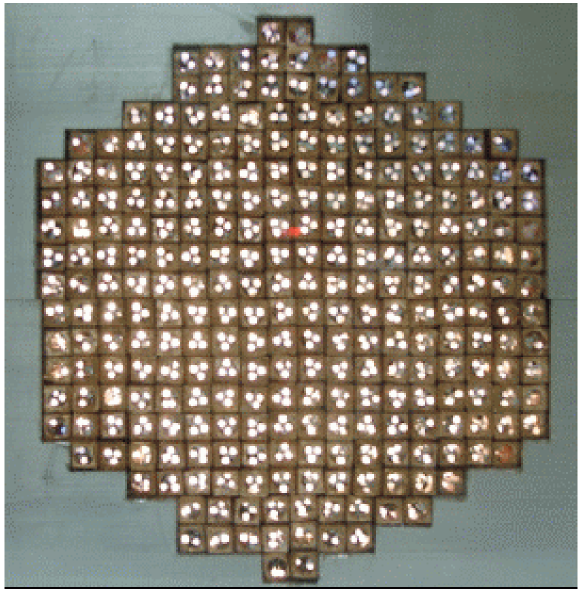
The DREAM Calorimeter - Wigmans et al.

A Dream Cell



Dual REAdout Module

DREAM Calorimeter - Front View



Quartz Fibres: To measure Cerenkov Light from relativistic particle in shower ~ electromagnetic Fraction

$$C = [f_{em} + \frac{1 - f_{em}}{\eta_c}] \bullet E$$

C = Cerenkov Signal
η_C=S(e)/S(h) for Cerenkov Signal
E = Shower Energy

Scintillator Fibres: To measure scintillation light in shower
Integral Signal from all particles

$$S = [f_{em} + \frac{1 - f_{em}}{\eta_S}] \bullet E$$

S = Scintillator Signal
η_S=S(e)/S(h) for Scintillator Signal

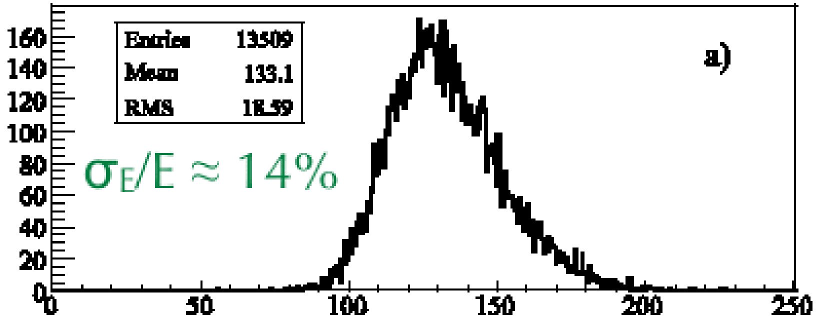
Two Equations to determine unknowns f_{em} and E
=>Full control over fluctuating f_{em}

DREAM - Testbeam Results

Response to 200 GeV Pions

- Scintillator only

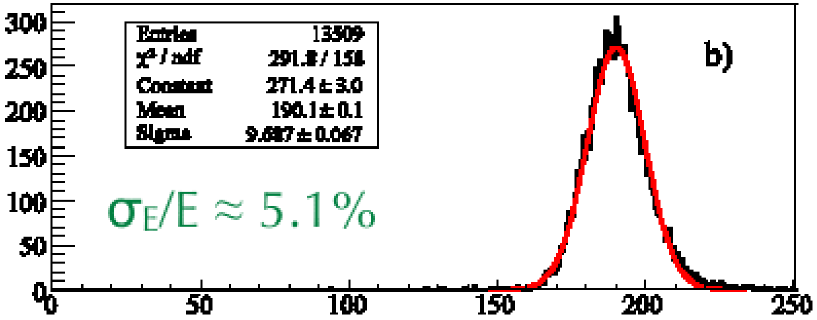
200 photoelectrons/GeV



-Cerenkov and Scintillator

$$f_{em} = [\frac{C}{E_{shower}} - \frac{1}{\eta_c}]$$

lateral leakage

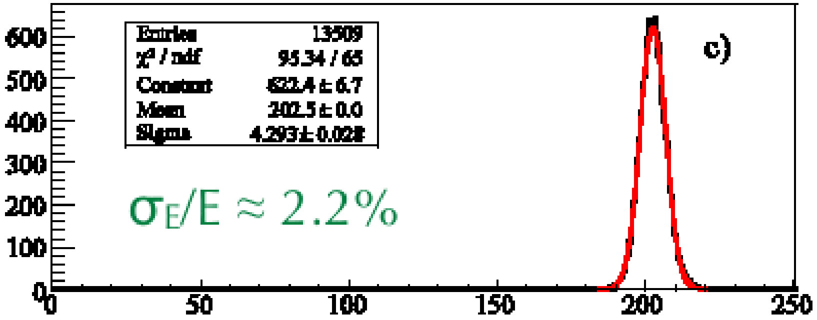


-Cerenkov and Scintillator

$$f_{em} = [\frac{C}{E_{beam}} - \frac{1}{\eta_c}]$$

'no' lateral leakage

fem constrained by Beam Energy



Summary

- ILC opens a new frontier for calorimetry

  Challenges are addressed in worldwide collaborations like Calice
- Need sophisticated hardware and software development to achieve the goals envisaged for the ILC
- Calorimeters are tailored for particle

  Flow algorithms rather than on energy resolution

  but 4th concept follows alternative approach
- Testbeam are maybe more than ever vital to reach precision and therefore physics goals envisaged for the ILC

These people kindly let me use their material

Dietrich Wegener, University of Dortmund … for Part1
Lutz Feld, RWTH Aachen … Introduction to semi-conductors
CALICE Collaboration … on calorimetry
Victoria Field, Uni of Edinburgh for material on 4th Calorimeter and slides from her Presentation at Ambleside
+ many other people whose talks I have exploited for this lecture