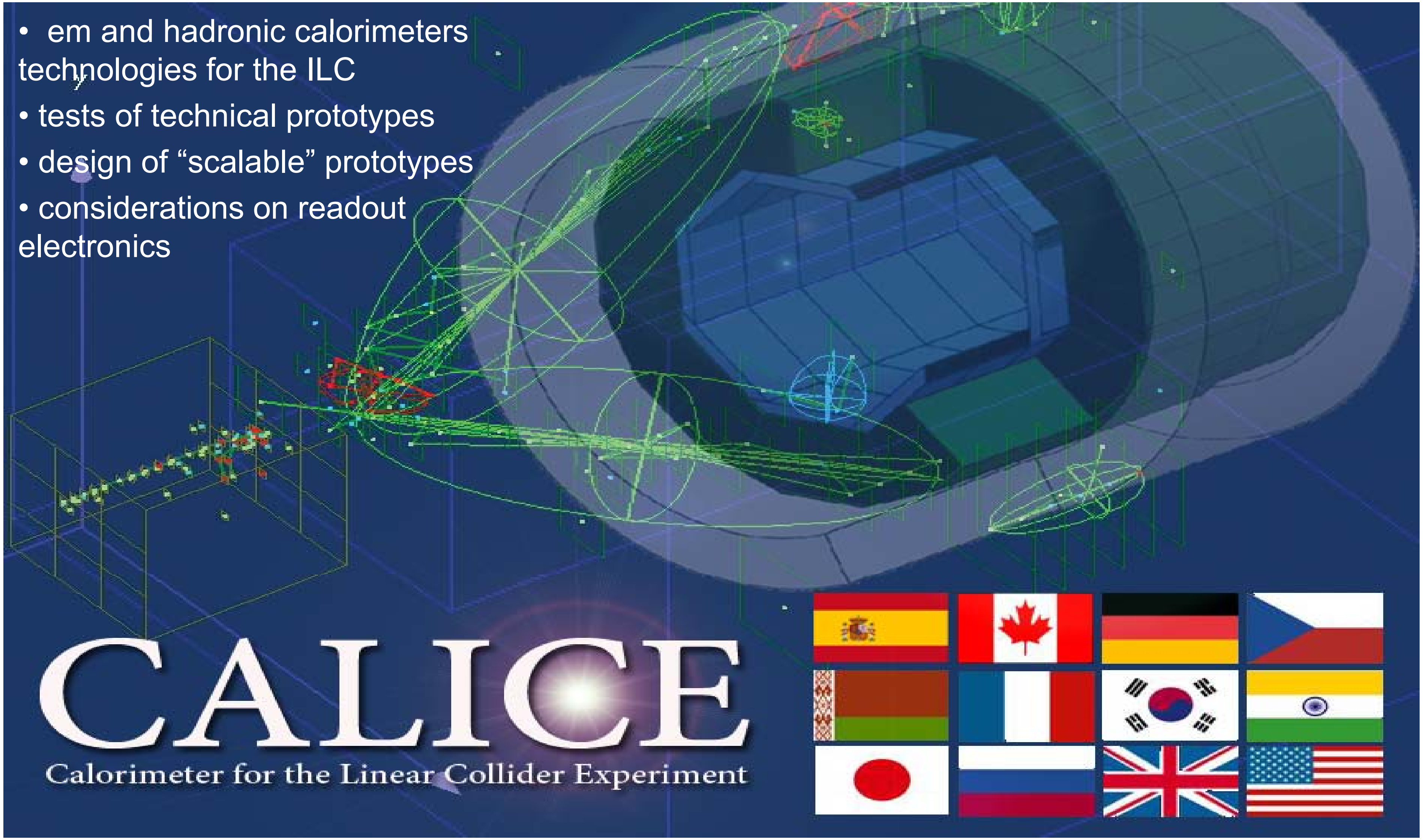
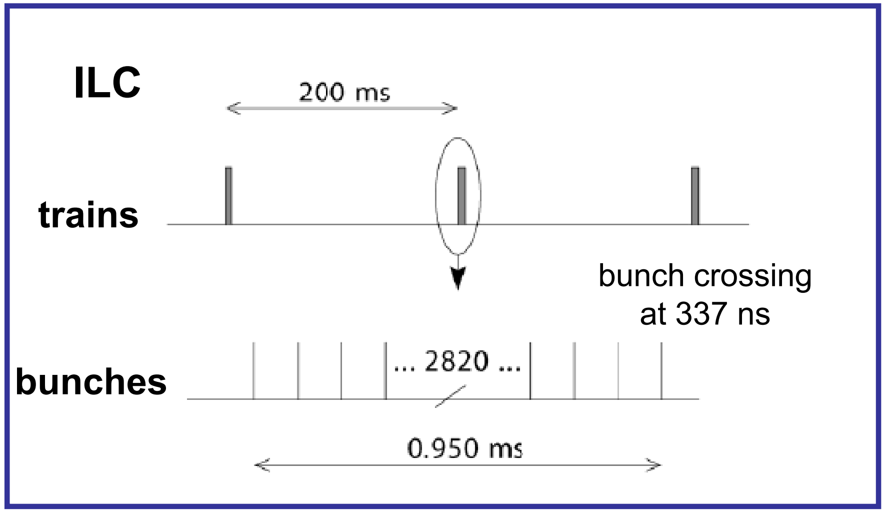
A calorimeter for the ILC

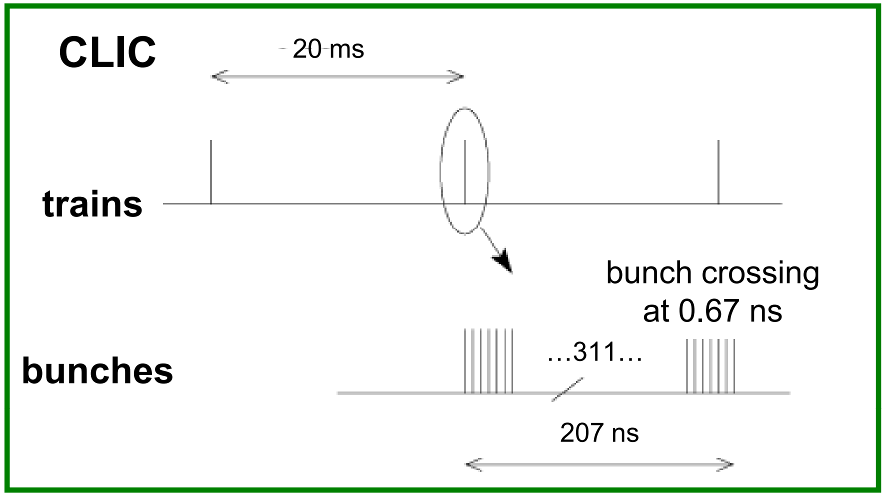
Erika Garutti (DESY)

- em and hadronic calorimeters technologies for the ILC
- tests of technical prototypes
- design of “scalable” prototypes
- considerations on readout electronics



Bunch structure & detector design





e^+e^- collider (~ 33 km)
$\sqrt{s}$ = 500 GeV – 1 TeV
L = $2 \cdot 10^{34}$ cm^{-2} s^{-1}
~ 1 event every 2-4 BX

Consequences for detector:

► Fast electronics: 0.3μs structure and faster for precision

► Power intensive fast analog only for <1% of the time (power cycling)

► Long breaks for data handling

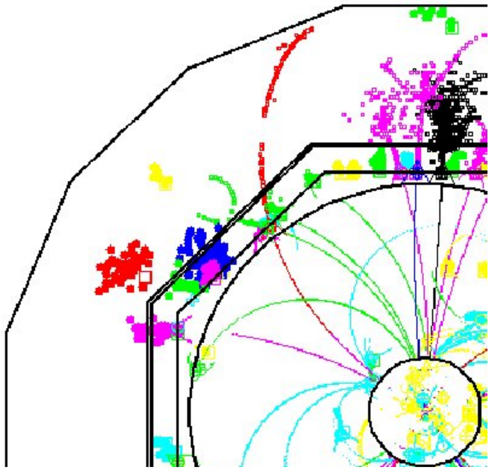
► Low occupancy

► No radiation damage

Paradigm for the ILC detector

P-flow yes / P-flow no

1) jet energy reconstruction with particle flow



<u>reconstruct each particle in every event :</u>

- $e^{\pm}$,$h^{\pm}$: momentum
- γ: em calorimeter
- h^0: had. calorimeter

⇨ $\sigma_{E_j}/E_j < 3.8\%$

<u>Requirements to detector design:</u>

► Separate each particle before the calorimeter

► large B-field and R tracker

►Track particles inside calorimeter

► **<u>high granularity</u>**

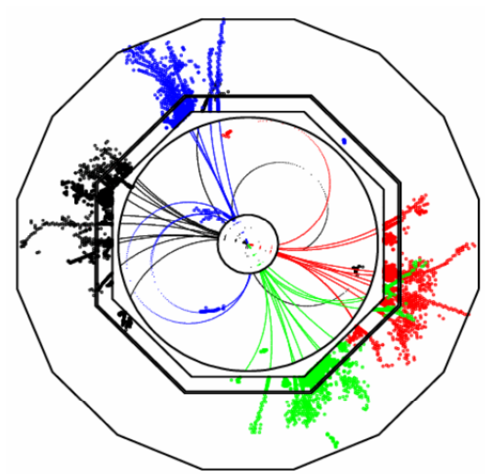
★ **Typical di-jet energies at ILC (100-300 GeV) suggests jet energy resolution goal of** $\sigma_E/E < 0.30/\sqrt{E_{jj}(\mathrm{GeV})}$

2) non-particle flow approach:
complementary measurements of every shower suppresses fluctuations

➢use calorimeters with triple readout to measure separately em component and binding energy from nuclear break-up

P-flow performance today

from Mark Thompson, CALICE-UK, Cambridge



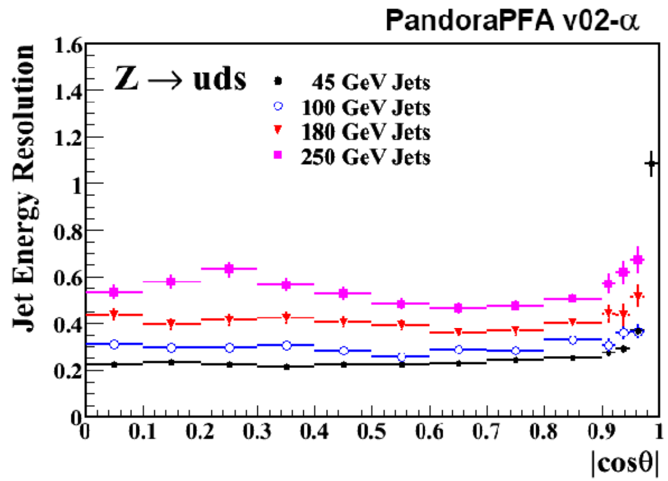
several algorithms are being developed
today best performing:
PandoraPFA (M. Thompson)

PandoraPFA v02-α

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.227	3.4 %
100 GeV	0.287	2.9 %
180 GeV	0.395	2.9 %
250 GeV	0.532	3.4 %

★ **For 45 GeV jets, performance now equivalent to**

23 % / √E



09/2007

energy range > 100 GeV still problematic
but … work in progress !

For CLIC: separation of particles within a jet difficult due to high density
P-flow can work for separations of jets

A detector designed for P-flow

Particle Flow stresses:

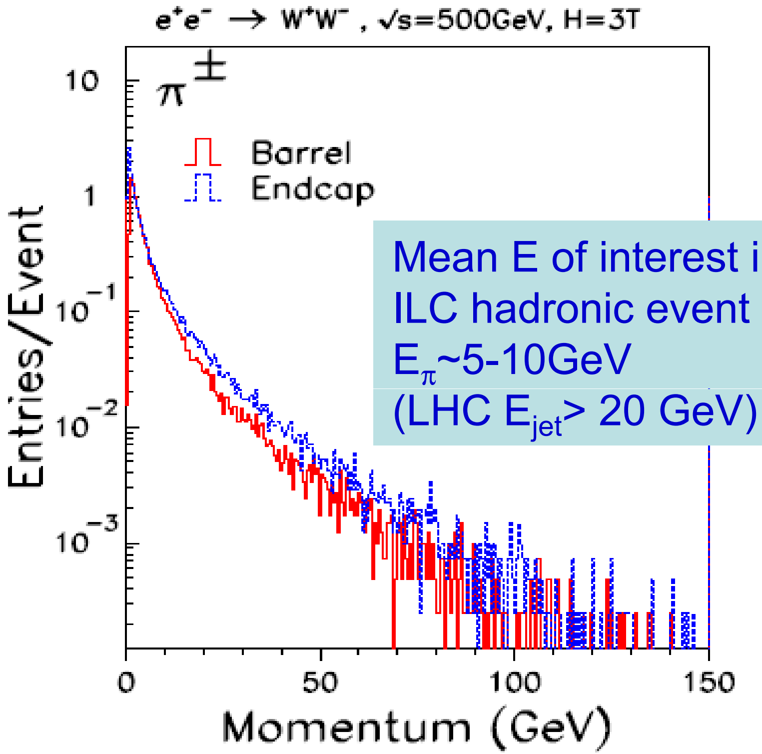
- reconstruction of each particle in an event
- separation of particles
- replacement of E with tracking momentum

Less important:

- single particle energy resolution in calo.

Detector requirements:

- good tracking, in particular in dense jets
- excellent granularity in the ECAL
- good granularity in the HCAL
- excellent matching between tracker / ECAL / HCAL



Mean E of interest in ILC hadronic event E_{π}~5-10GeV (LHC E_{jet}> 20 GeV)

the E of interest does not increase linearly with ⌧s but the multiplicity of particles does!

Optimization of the calorimeter

Sandwich structure chosen for ECAL and HCAL

Absorber material and readout granularity

➔separation of individual particles from E_{vis}

compact showers: small X_0 and $r_{Moliere}$

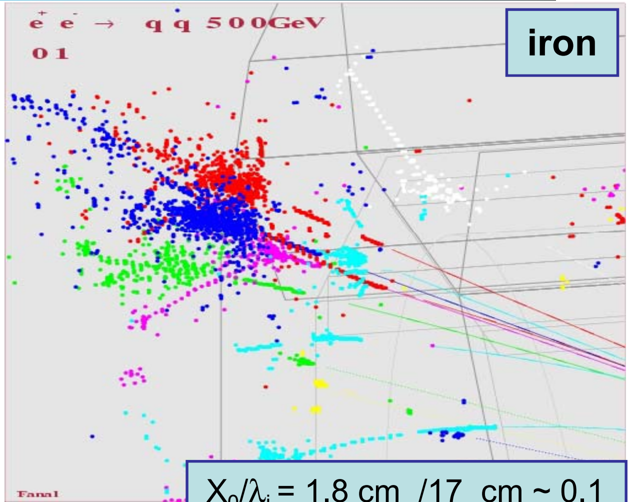
high lateral granularity: $r^2_{cell} \sim r^2_{Molier}$

➔discrimination between em / hadronic showers

different longitudinal scale: small X_0/λ_{had}

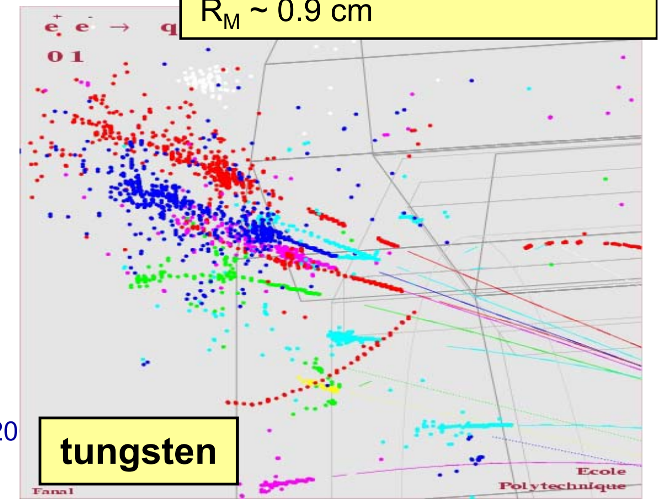
high longitudinal segmentation

➔containment of EM showers in ECAL



X_0/λ_i = 1.8 cm /17 cm ~ 0.1
R_M ~ 1.9 cm

X_0/λ_i = 0.35 cm/9.6 cm ~ 0.04
R_M ~ 0.9 cm



Hardware or software compensation

➔ high granularity allows separation of em / hadronic components of shower

➔ hardware compensation not mandatory

ILC: W-ECAL + Fe-HCAL

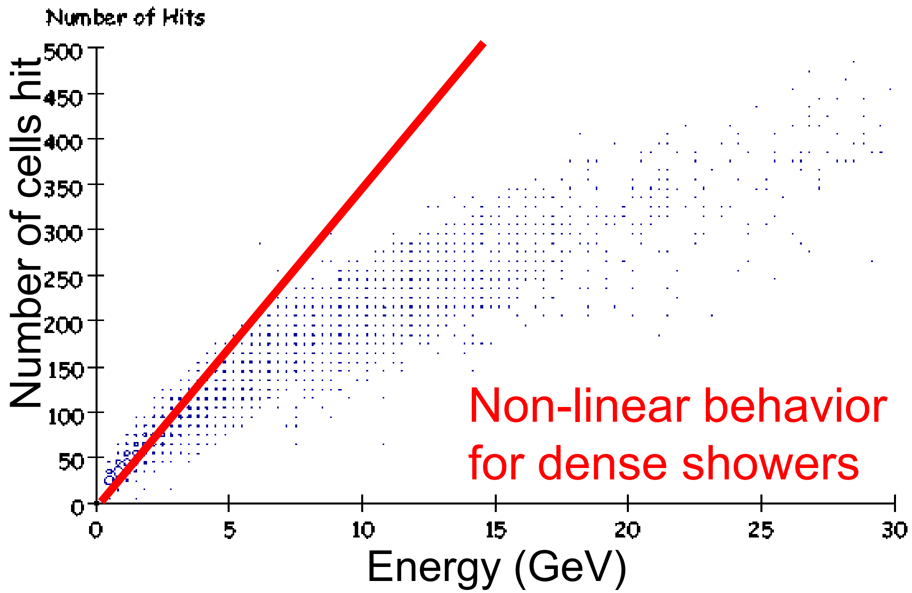
CLIC: W-ECAL + W-HCAL ?

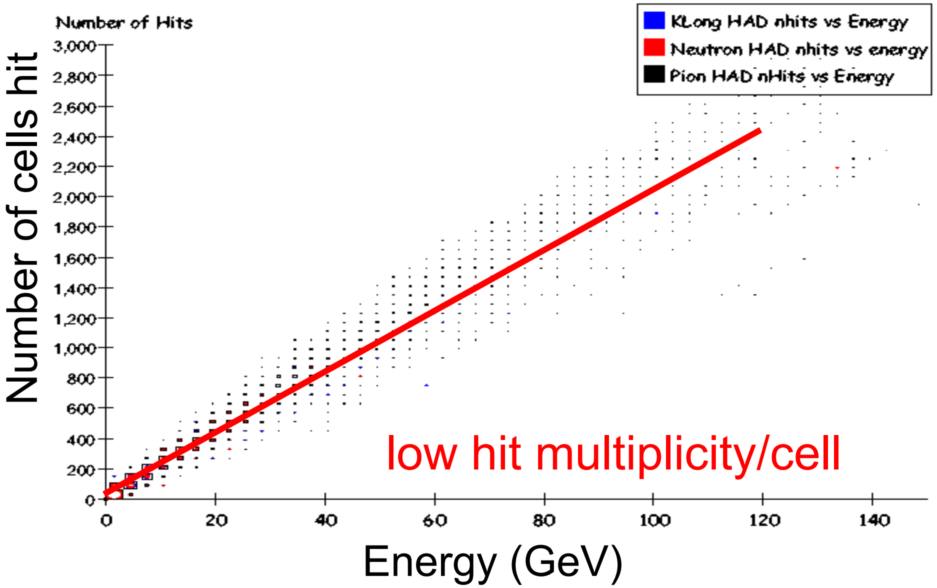
Calorimeter readout

From photon analysis:
ECAL requires Analog readout

From hadron analysis:
for HCAL either Analog or Digital readout

Correspondence between energy and number of cells hit

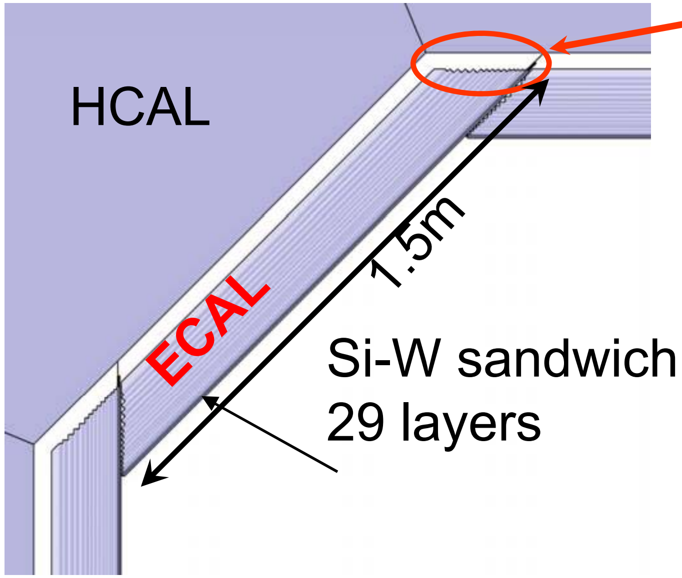




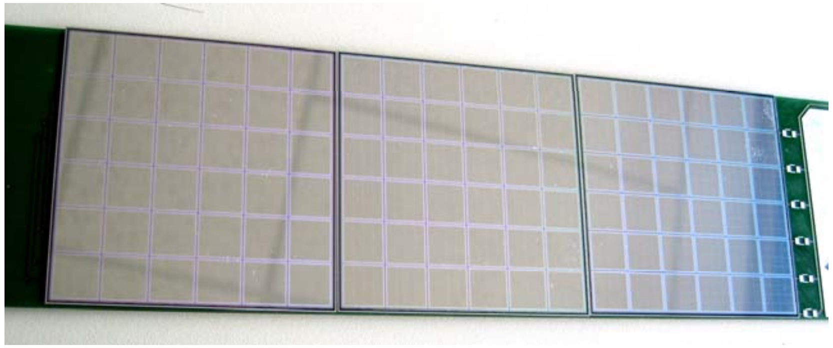
ECAL cell size: 0.5x0.5 cm^2

HCAL cell size: 1x1 cm^2 cells

The EM calorimeter (ECAL)



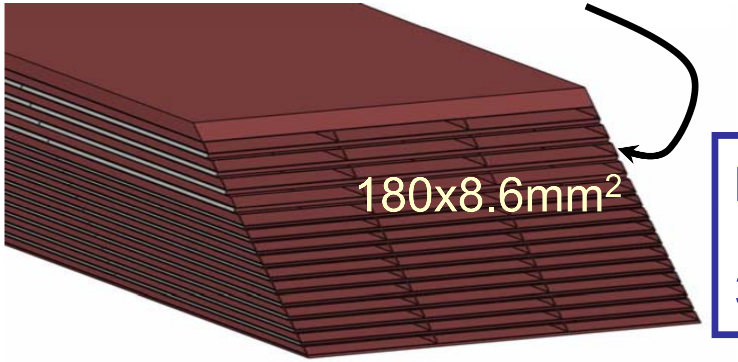
Space for end-gap electronics and infrastructure



Si-diodes for ILC-ECAL:

thickness	300µm
size	0.5x0.5cm^2
wafer	4" or 6"
channels	80 million

1.5 m long alveolar structure hosting Si-diode slabs and electronics



physics-prototype operated at CERN & DESY TB:
1x1cm^2 diodes, 36 per wafer
30 layers = 24 X_0, ~10000 channels

Si-W ECAL (II)

from R. Frey, SiD meeting

Tile W with hexagonal 6” wafers
- ~ 1300 m^2 of Si
- 5x5 mm^2 pads

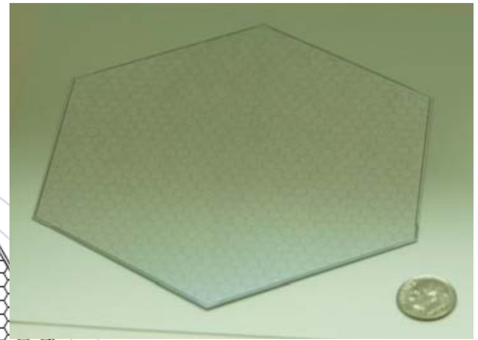
Readout by single chip (KPiX)
- 1024 channels, bump-bonded
- 4-deep buffer (low occupancy)
- bunch crossing time stamp for each hit

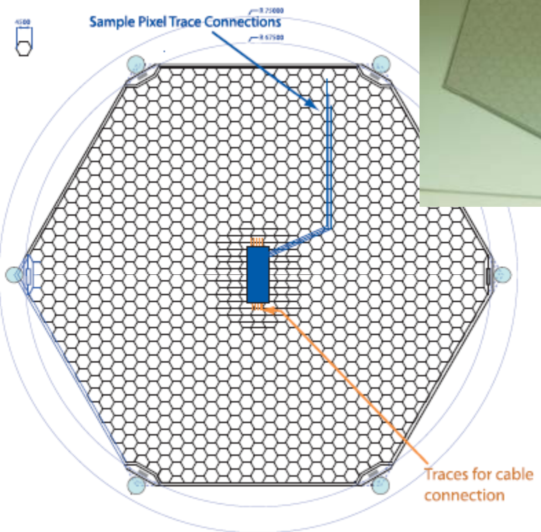
Single MIP with S/N > 7

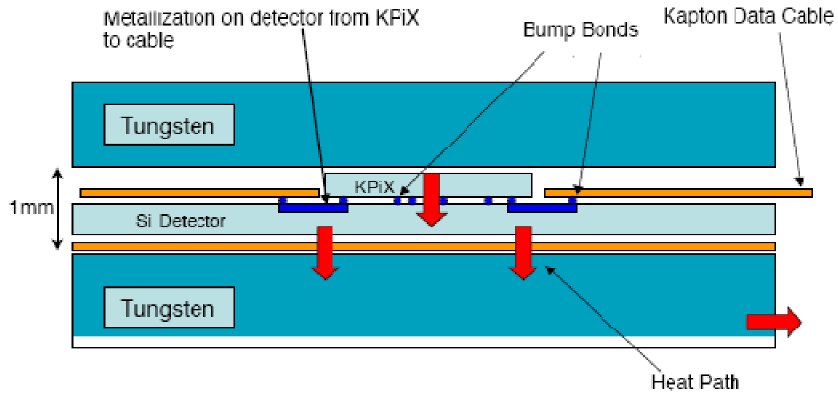
Dynamic range of 2500 MIPs
- < 2000 e- noise

Power: < 40 mW/wafer through (power pulsing !)
- Passive edge cooling

Minimize active layer thickness < 1 mm



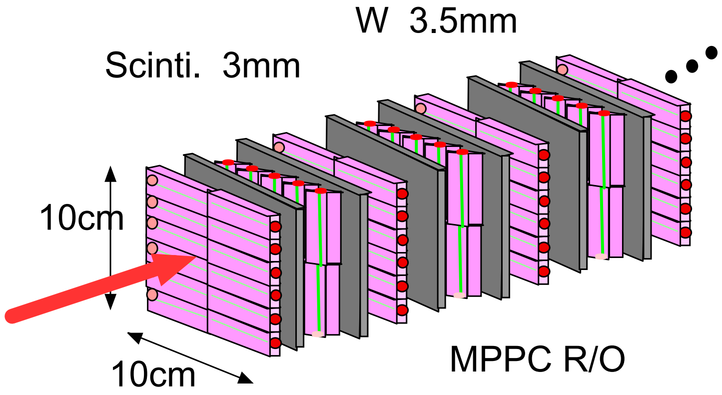


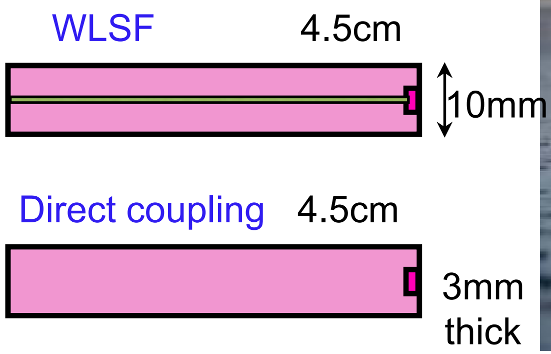


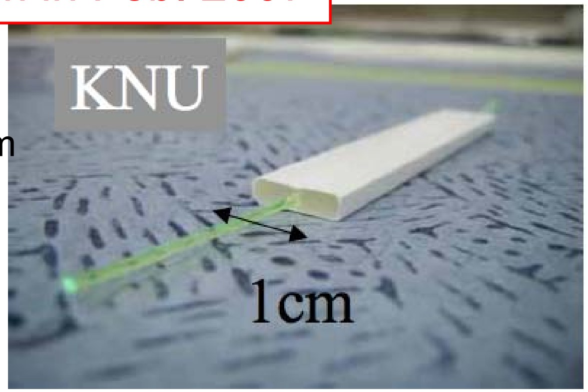
The ECAL: alternative R&D

Scintillator – Tungsten sandwich structure

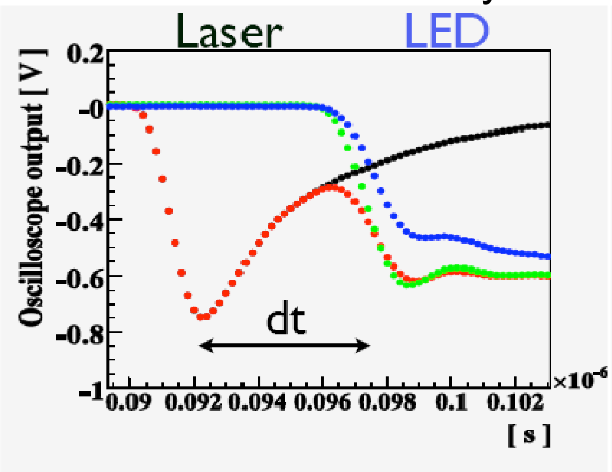
tested @ DESY test beam in Feb. 2007

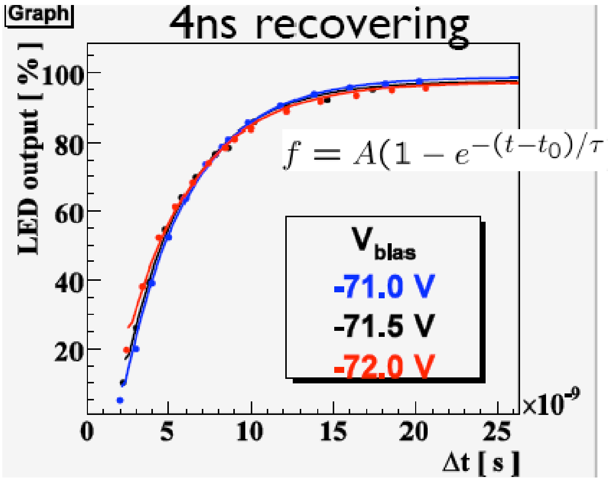


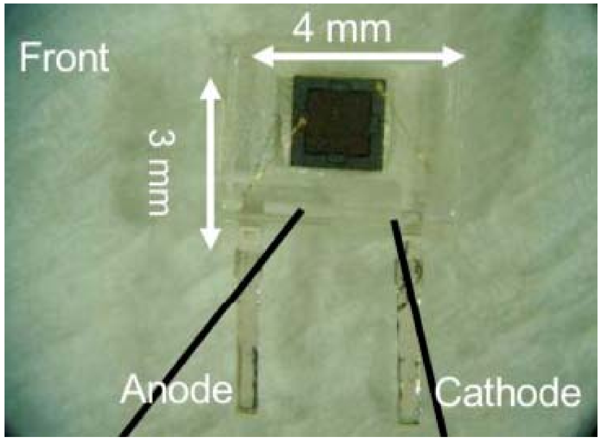




measured MPPC recovery time:







Multi-Pixel Photon Counter from Hamamatsu

The ECAL: alternative R&D

MAPS based ECAL design

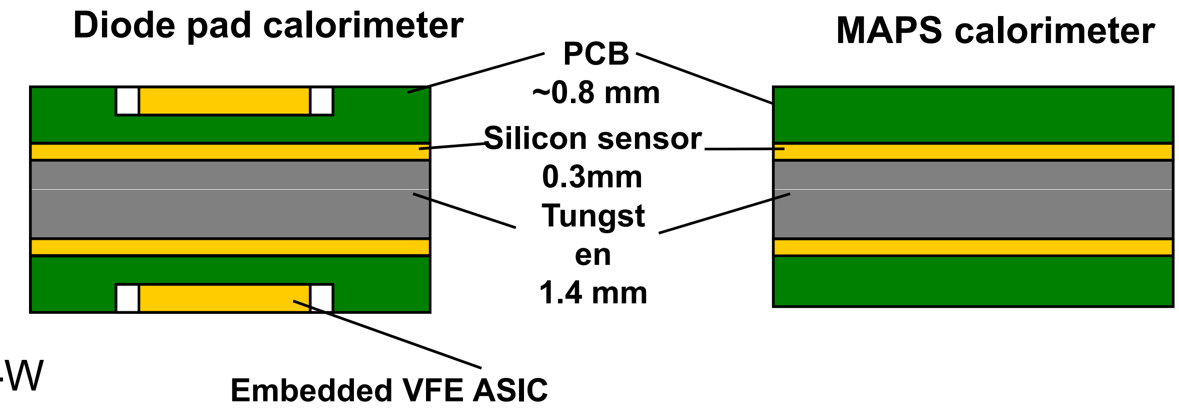
Monolithic Active Pixel Sensor

can the ECAL be digital!?

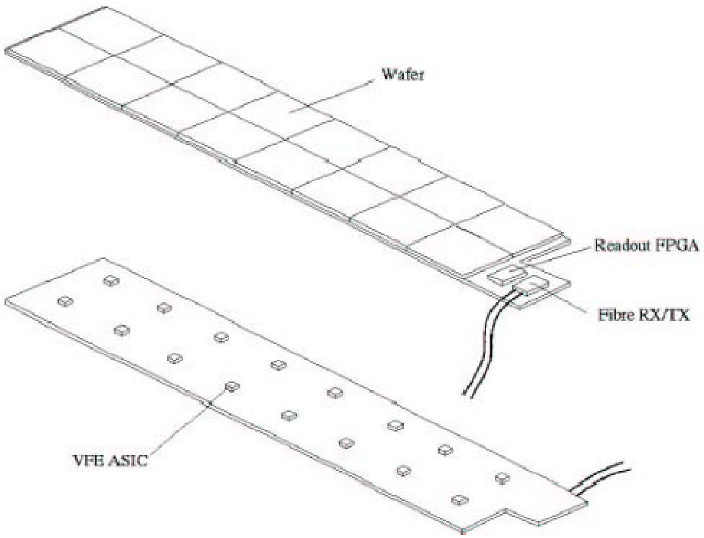
E ƒ N_{hits} ?

need extremely small cells

~ 50x50 um^2 ➔ MAPS



same slab mechanics as for Si-W

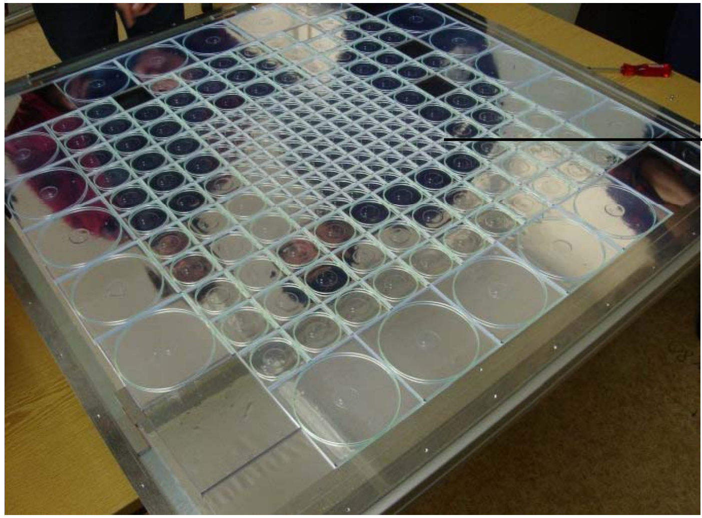


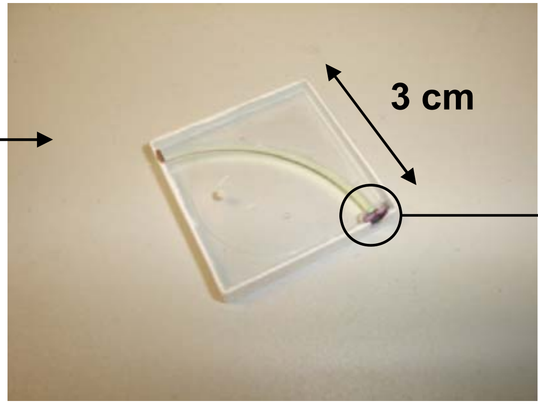
- use CMOS technology (no high resistive Si)
- electronic readout constructed on PCB (no extra ASIC)
- 50x50um² MAPS + binary readout
- Simplified assembly (single sided PCB, no grounding substrate)
- total ECAL ~10^{12} pixels
- multiplicity in a pixel ~ 1, noise level < 10^{-6}

The HAD calorimeter (HCAL)

Calorimeter for ILC

Scintillator – Steel sandwich with analog readout

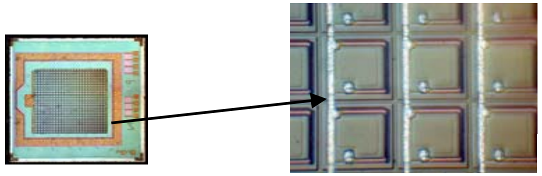




Single tile readout with SiPM:

1156 pixels / mm^2

1 mm

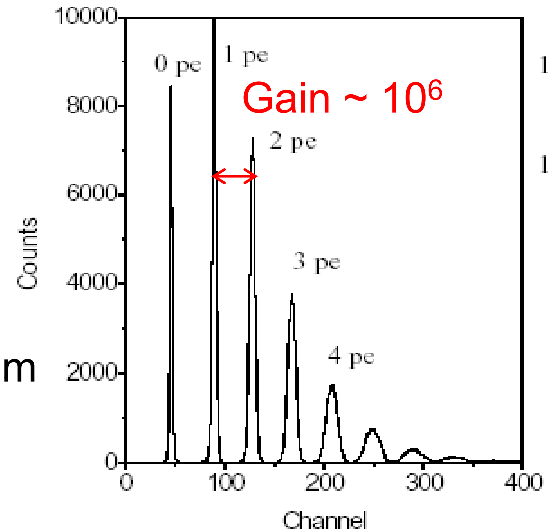


Silicon – Photomultiplier multi pixel device operated in Geiger mode

S/N ~ 10 at MIP level
dynamic range 0.5 – 100 MIP / tile

ASIC r/o chip for test beam:
2 gains for physics and calibration ➔
shaping + multiplexing

➔ next generation adapted to ILC beam



B insensitive!

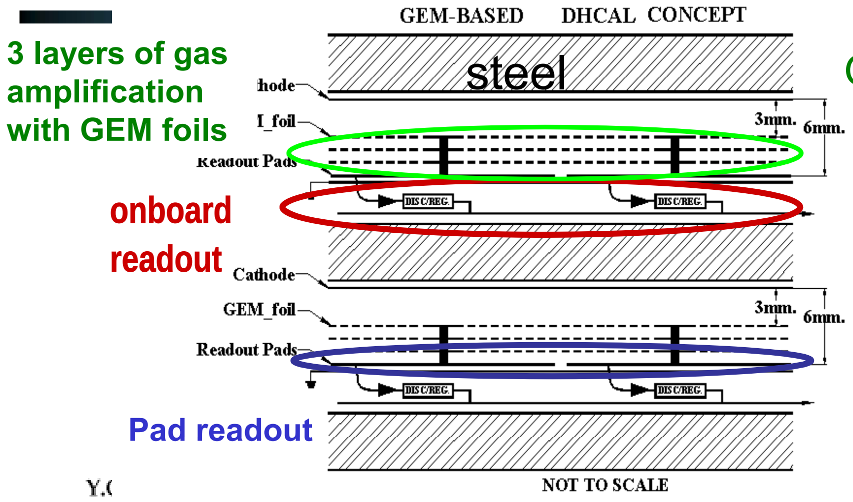
pixel sensitive to single γ

Readout Σ of pixel charge
➔ proportional to E_{vis}

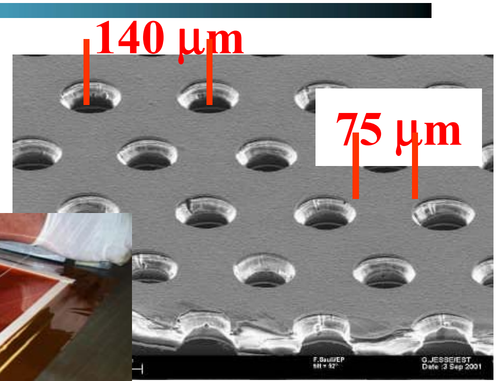
Mounted directly on tile
➔ allows high granularity

The Digital HCAL

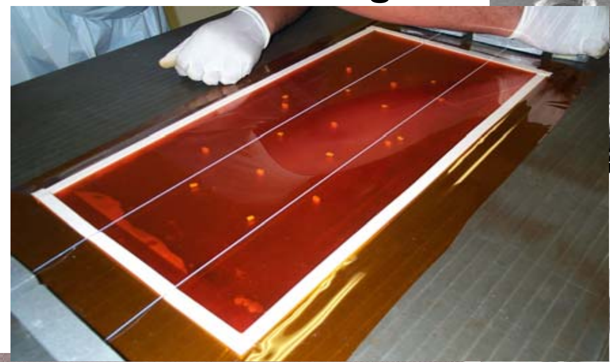
Sandwich structure of steel and gas chambers



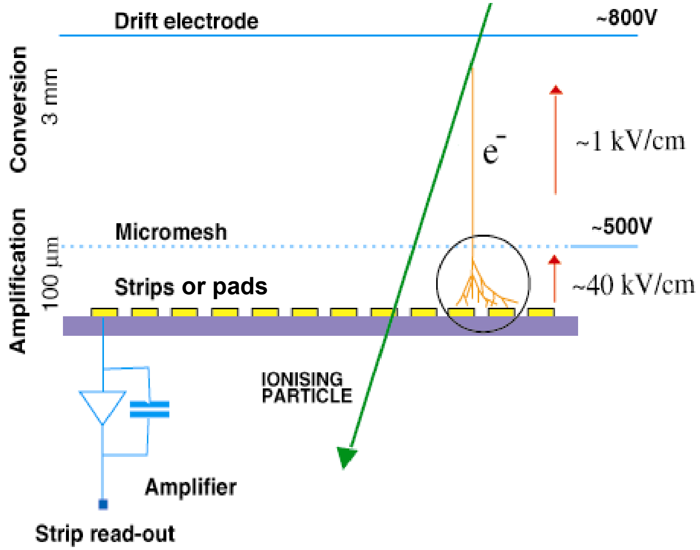
Gas Electron Multiplier foil

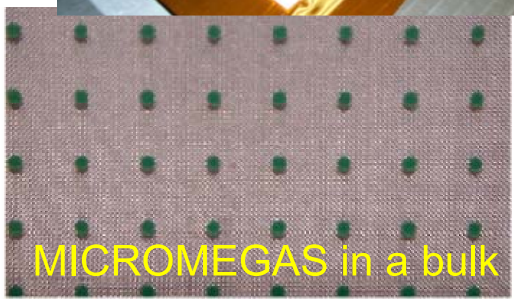


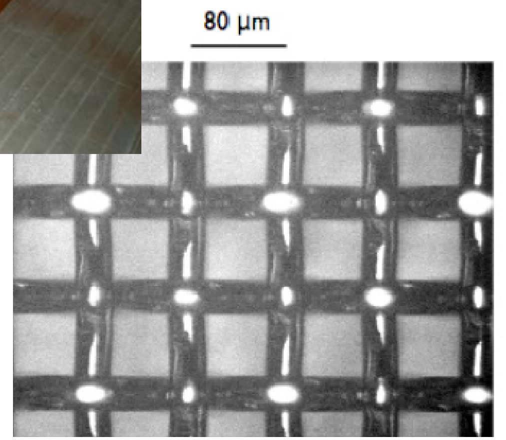
mechanic challenge !



Micro mesh gaseous structure







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

-2x(50x100 cm^2) ~ 4608 channels

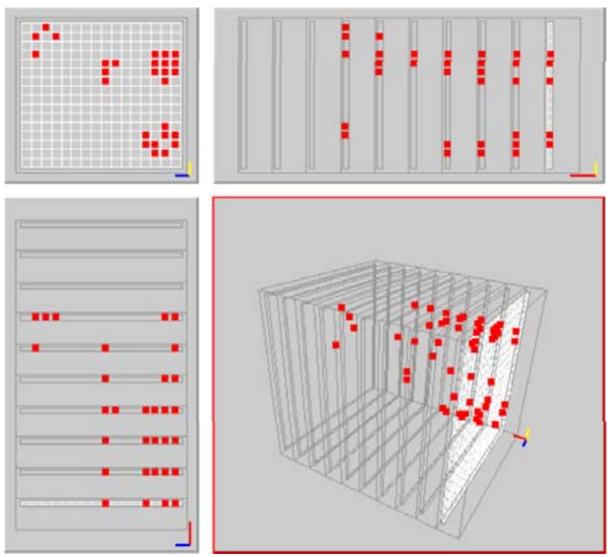
Digital HCAL with RPC

from J. Repond, CALICE meeting

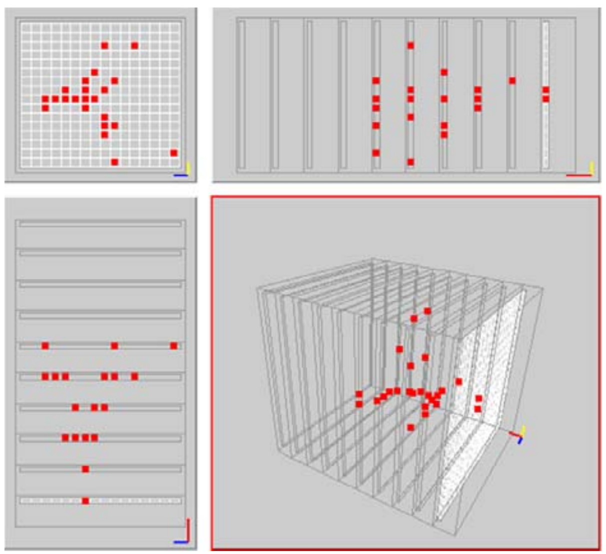
first test prototype of Digital HCAL with Resistive Plate Chamber readout tested at Fermilab TB in summer 2007:

Equipped 9 chambers 20 x 20 cm^2
with 4 chips ASIC each
256 channels/chamber $\rightarrow$ **2300 channels total**
System can be extended to 1 m^2

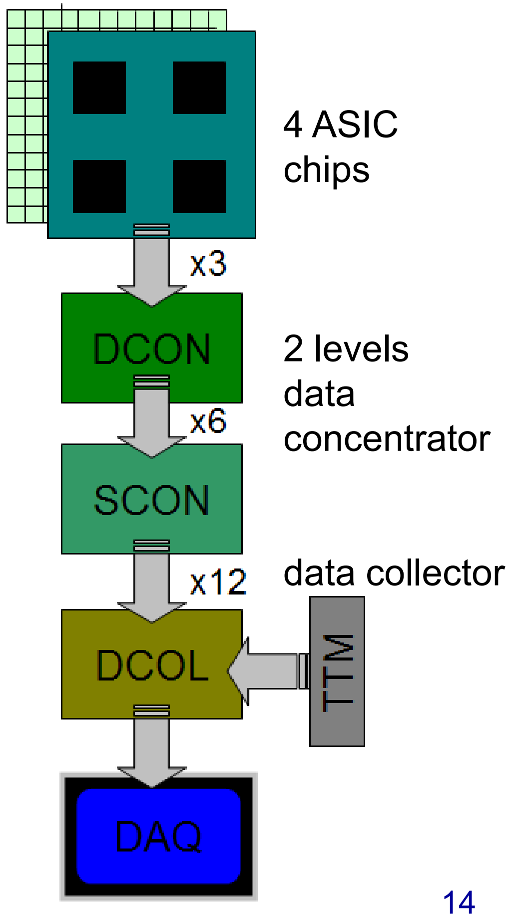
2-π event (upstream shower?)



8 GeV π^+ event (early shower)

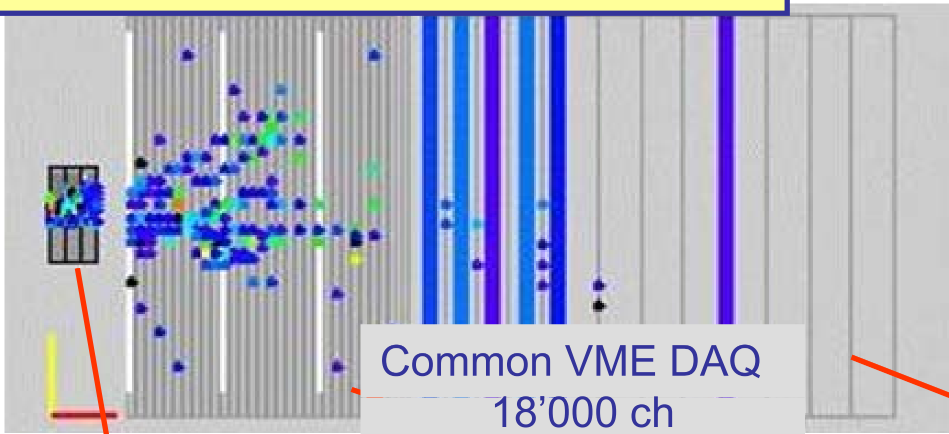


digital readout scheme



The test beam prototypes

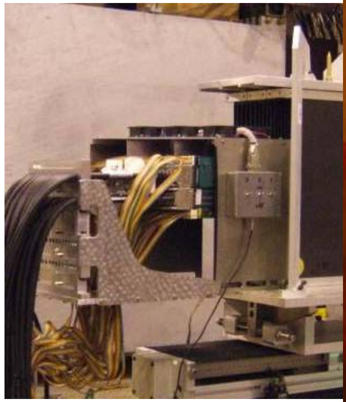
10 GeV pion shower @ CERN test beam

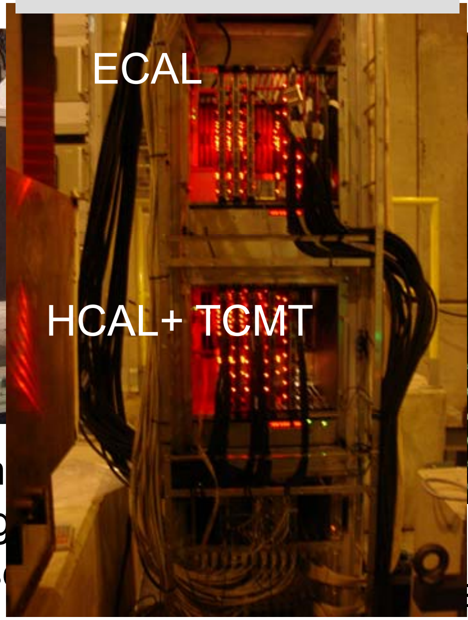


goal of prototype calorimeters:

- establish the technology
- collect hadronic showers data with unprecedented granularity to:
  - tune reco. algorithms
  - validate MC models

Common VME DAQ
18'000 ch



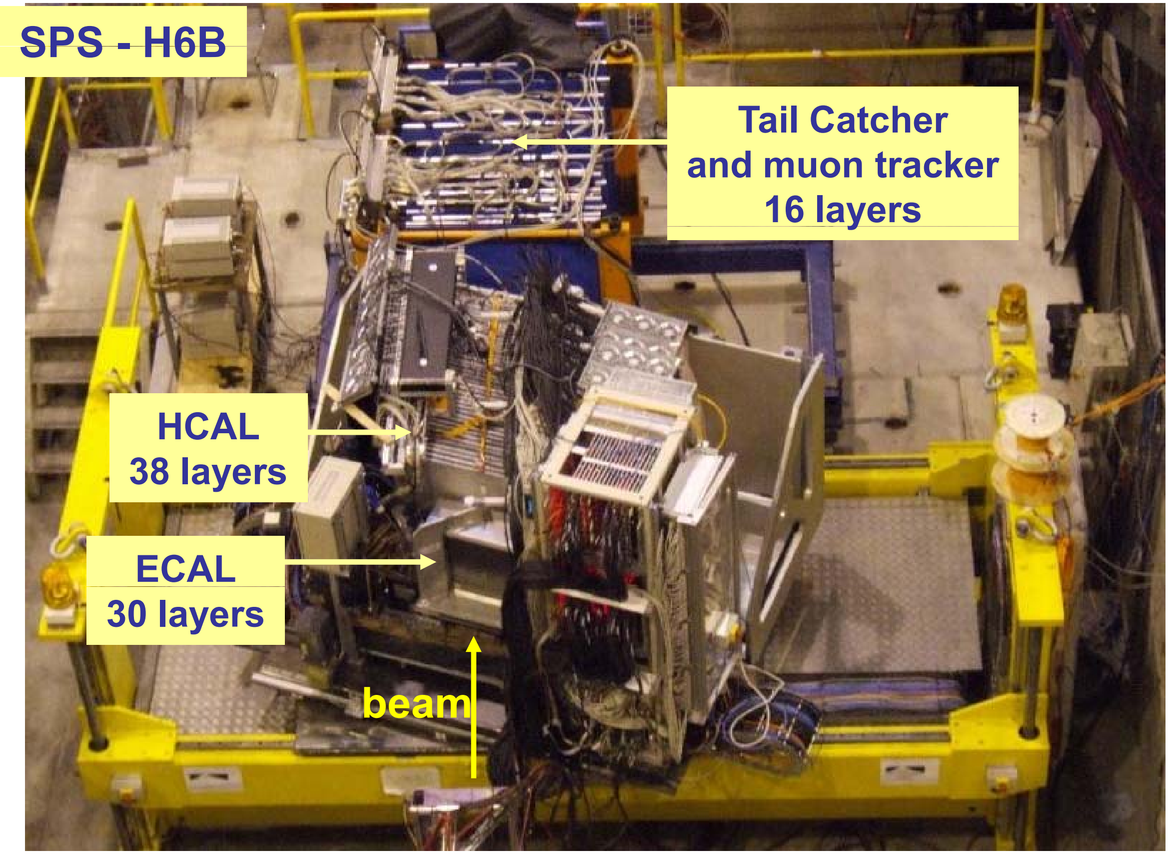


Si-W Electromagn
$1x1cm^2$ lateral seg
1 X_0 longitudinal s
~1λ total material

e hadronic calor.
al segmentation
~4.5 λ in 38 layers

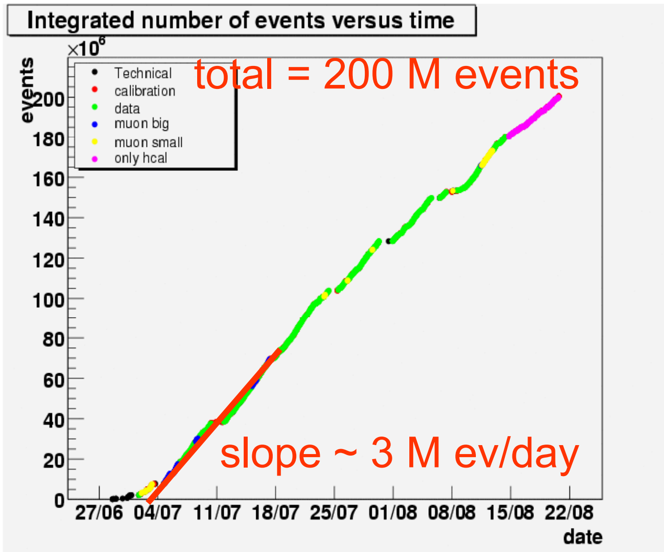
Scint. Strips-Fe Tail Catcher
& Muon Tracker
$5x100cm^2$ strips
~5 λ in 16 layer

The CERN installation



Physics: $\pi^{\pm}/e^{\pm}/p$, E= 6 - 180 GeV, Θ= 0 - 30 deg.

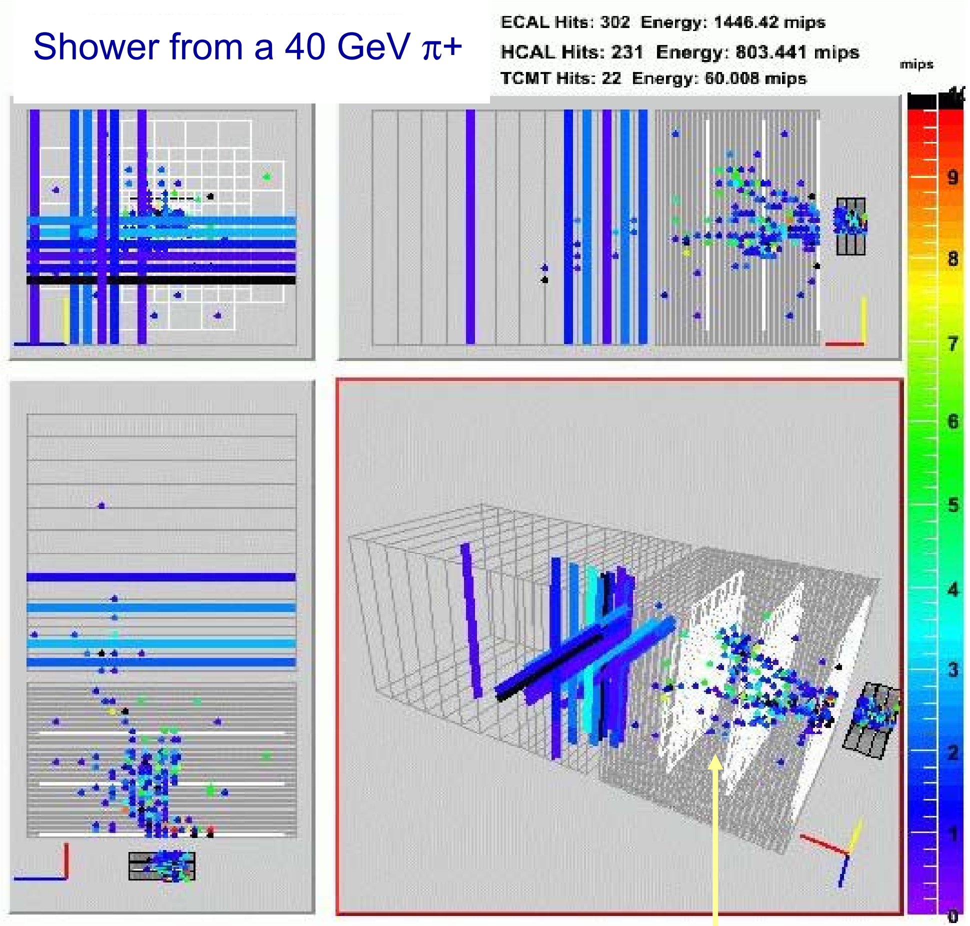
7 weeks test in 2007

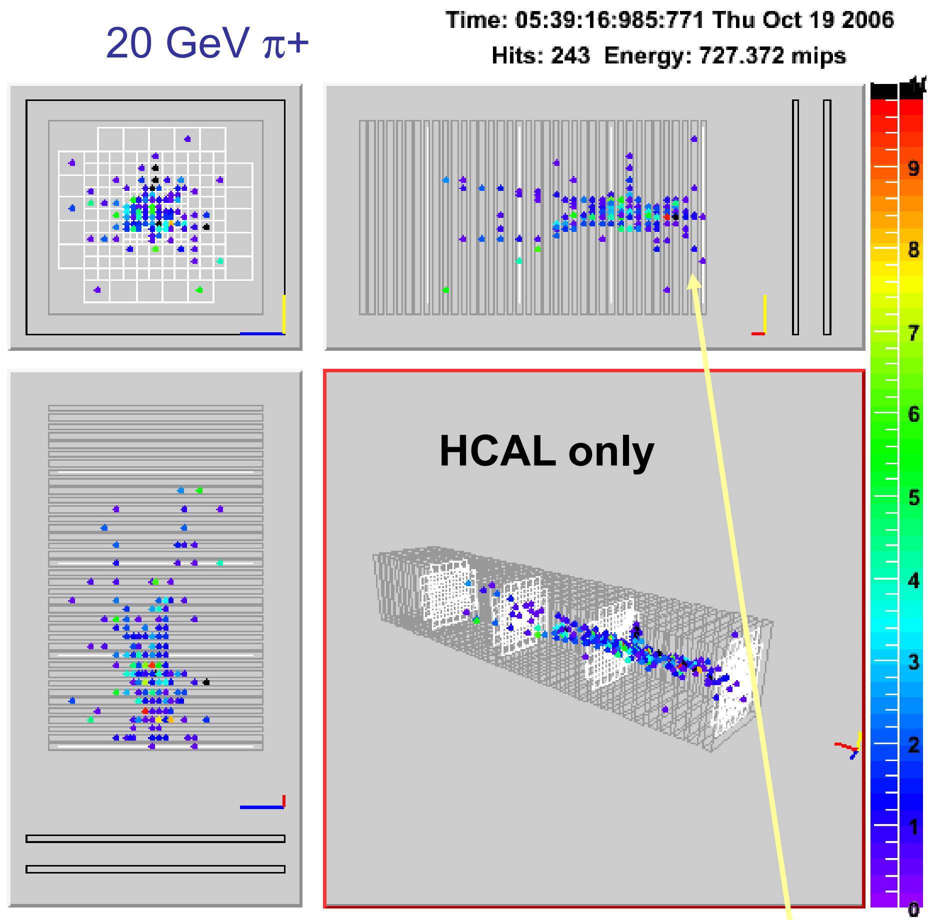


- 15 TByte data on the Grid
- 45 Hz average DAQ rate over whole period
- 80% of time beam data taking
- tested: calibration procedure, long term operation ('06-'07)

Event display

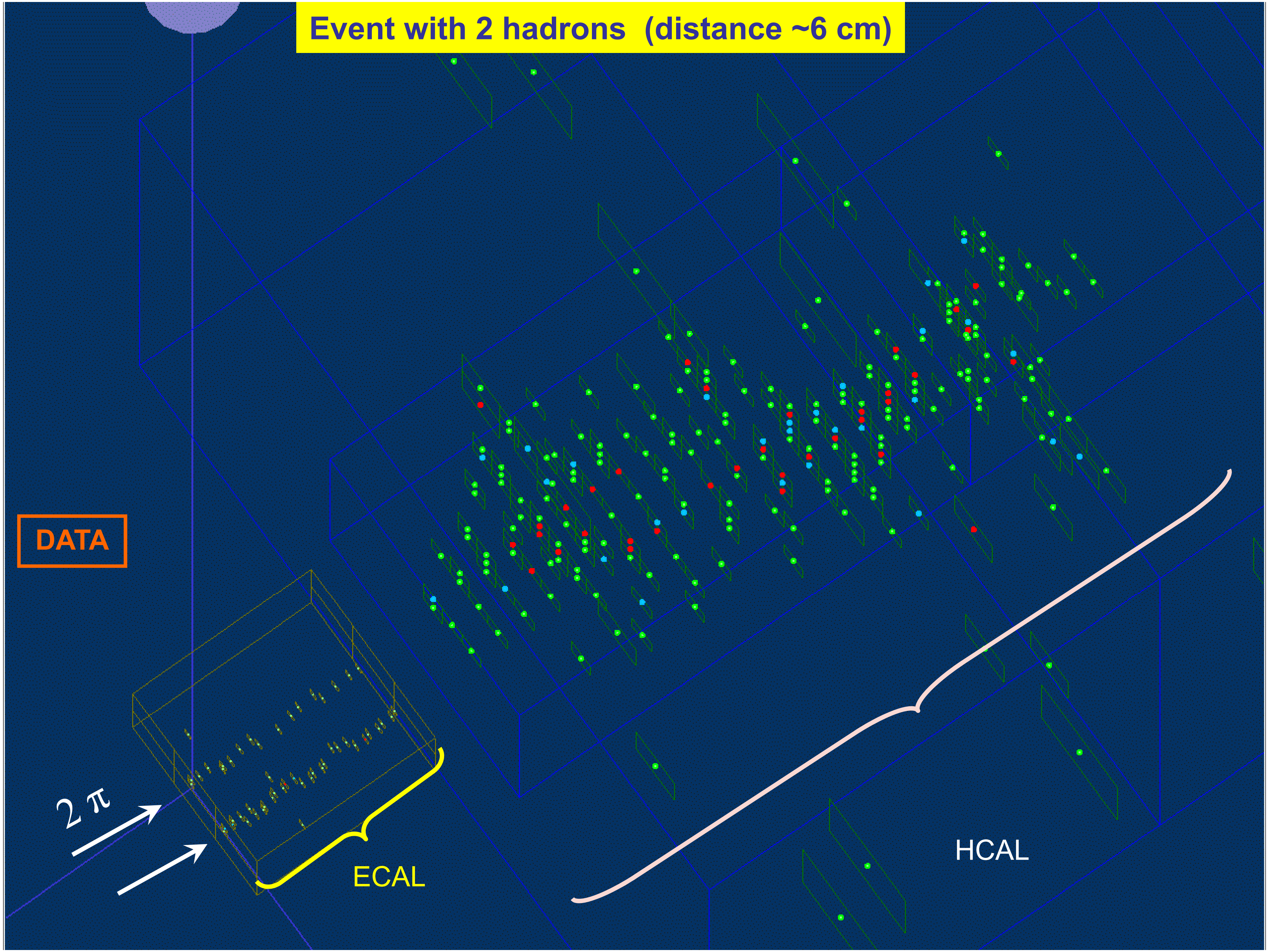
REAL DATA!

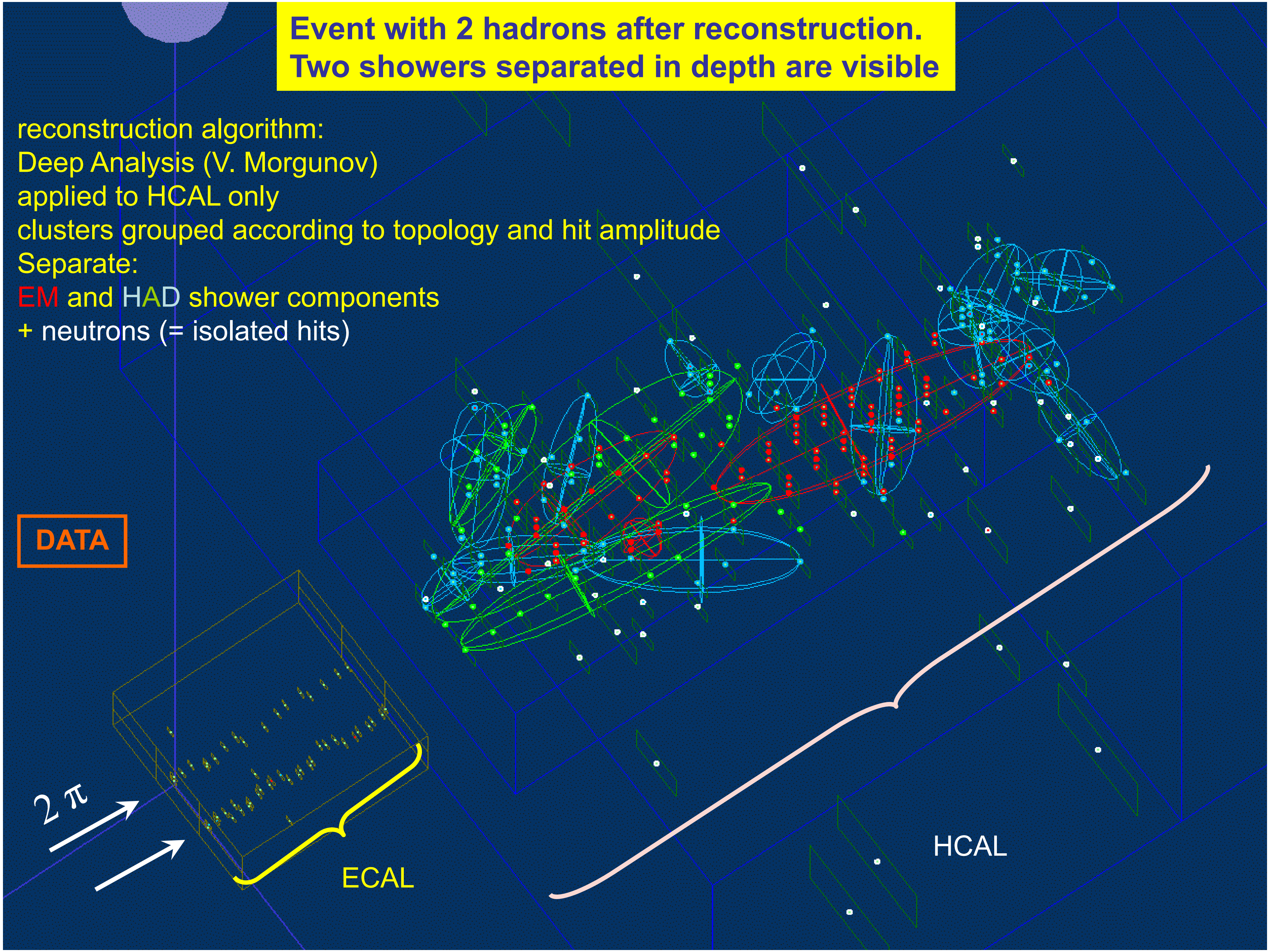




Clear structure visible in hadronic shower

Back-scattered particle

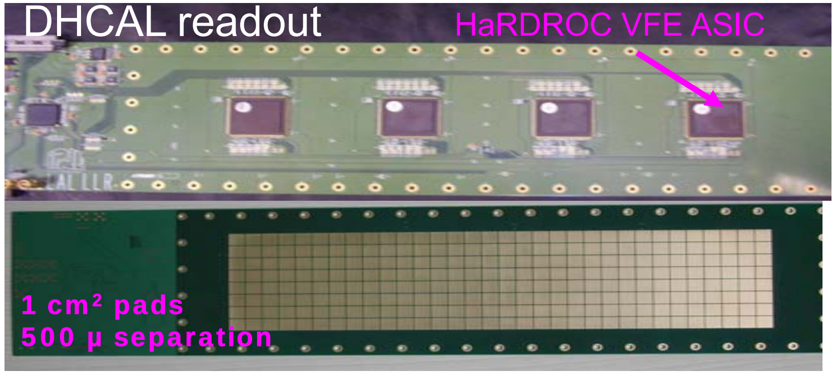

Event with 2 hadrons (distance ~6 cm)
DATA
2 π
ECAL
HCAL



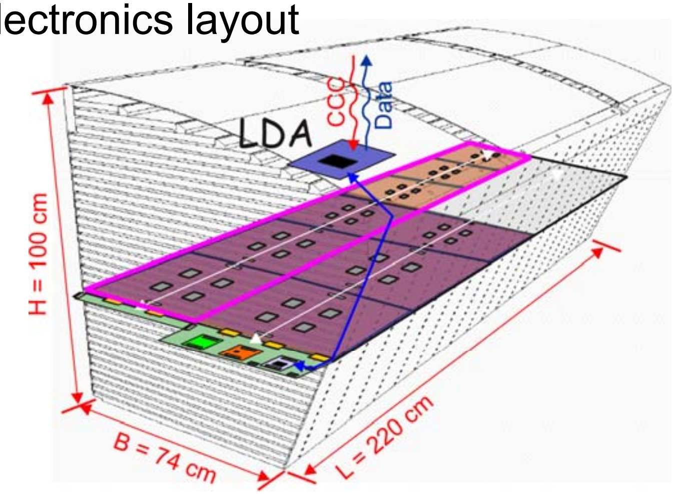
Event with 2 hadrons after reconstruction.
Two showers separated in depth are visible
reconstruction algorithm:
Deep Analysis (V. Morgunov)
applied to HCAL only
clusters grouped according to topology and hit amplitude
Separate:
EM and HAD shower components
+ neutrons (= isolated hits)
DATA
2 π
ECAL
HCAL

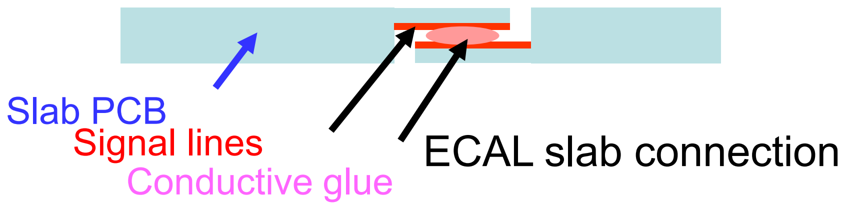
Next step – realistic electronics

- Now moving to large scale (1.5m) technological prototypes :
  2^{nd} generation ASICs and DAQ
- Front-end ASICs embedded in detector
  - High level of integration, low thickness
  - Ultra-low power with pulsed mode
  - Essential to demonstrate detector feasibility
- All communications via edge
  - ~4,000 ch/slab, minimal room, access, power
  - small data volume (~ few 100 kbyte/s/slab)
- « Stitchable motherboards »
  - Minimal connections between boards
- <u>Low Cost and industrialization are the major goals</u>

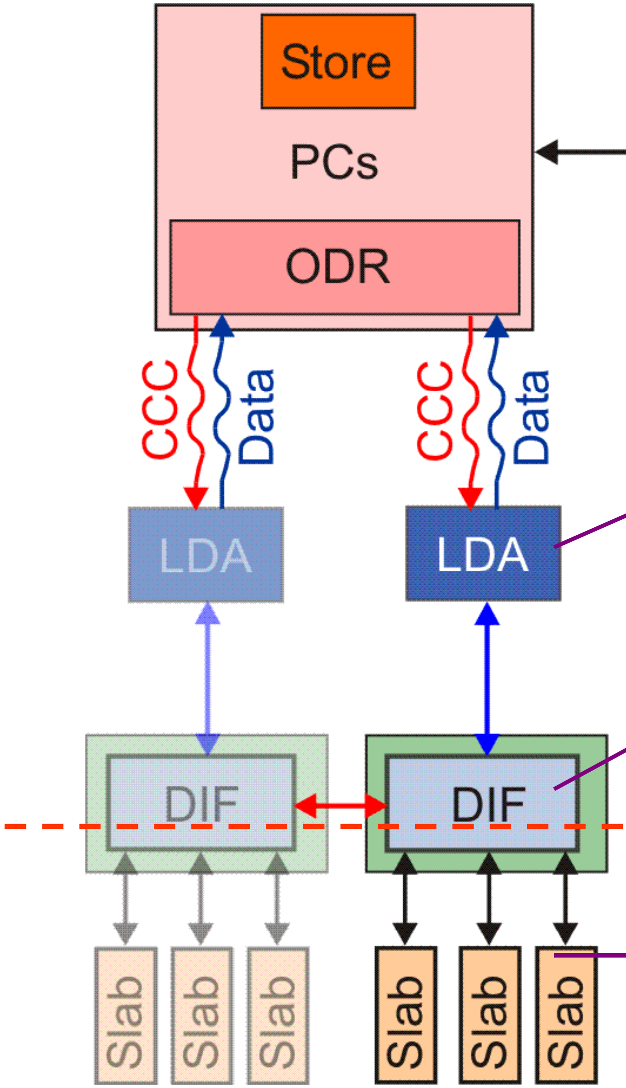


AHCAL electronics layout





General concept for DAQ

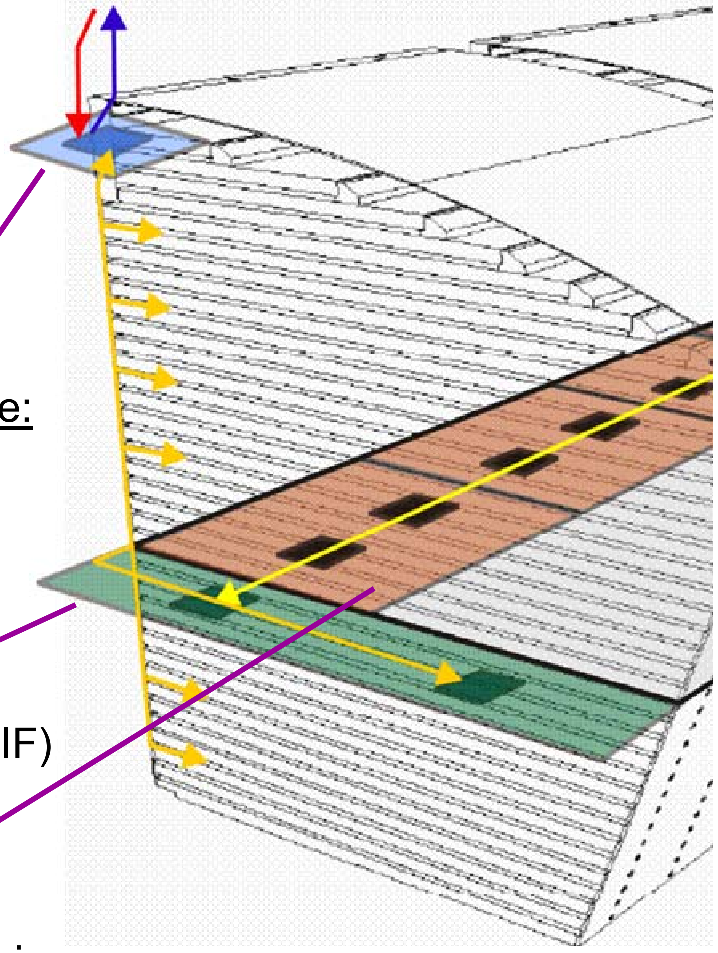


Out of detector:
data collection, sorting,
no global triggering

<u>Data Aggregator input data rate:</u>
max. 105MBit/bunch train
(38 DIFs connected)

<u>Det Interface input data rate</u>:
max 2.8MBit/bunch train.
(failsafe setup: up to 6 slabs/DIF)

<u>Slab output data rate:</u>
max. 460kBit.
up to 24 ASICs in a r/o chain,
~19kbit data per ASIC



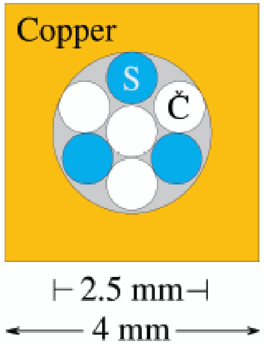
Analog handling
Self triggering of each sensor

Non-Pflow / multiple-readout calorimeter

from J. Hauptman, ECFA workshop, Valencia

Idea: complementary measurements of every shower suppresses fluctuations

1. Spatial sampling with Scint. fibers every 2mm
2. Remove fluctuations in EM fraction of E_{shower} by double r/o of Č light
   Photon separation / reconstruction
   - electrons and photons limited by photo-statistics
   - study dual readout of single PbWO4 crystal of smaller area (1x1 cm2 ?)



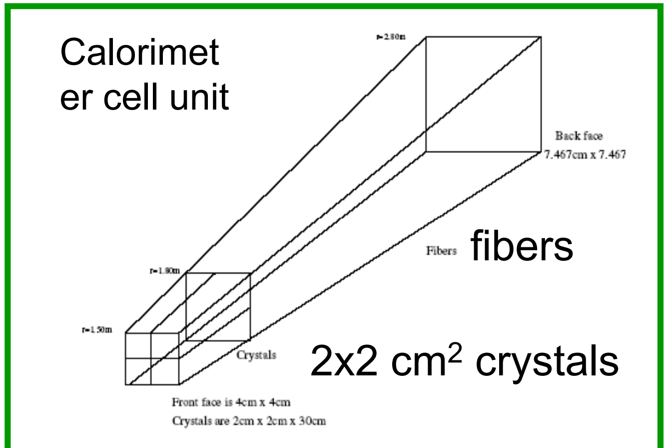
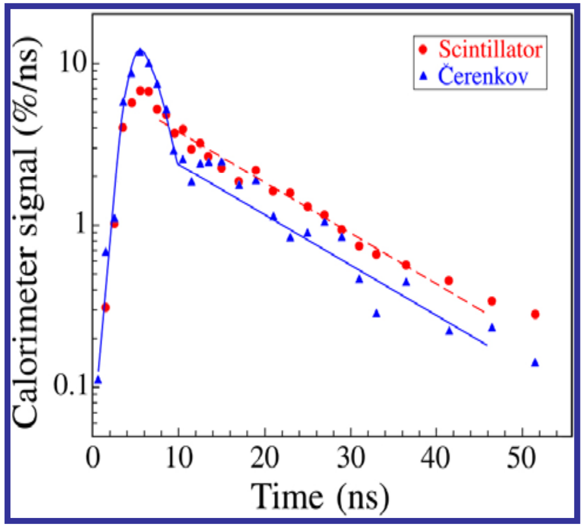


Figure 12: The unit cell of the calorimeter showing the $4 \times 4\text{cm}^2$ front face with four $2\times2\text{cm}^2$ dual readout crystals. These four crystals match the 1-meter deep triple readout fiber calorimeter.



3. Readout of MeV neutrons from hadronic shower (reduce binding energy fluctuation)
   - Fast-Slow discrimination on time spectra of Scint. and Ch. light pulses
   - using a third type of scint. fiber: “hydrogen-rich”, Lithium-loaded or Boron-loaded

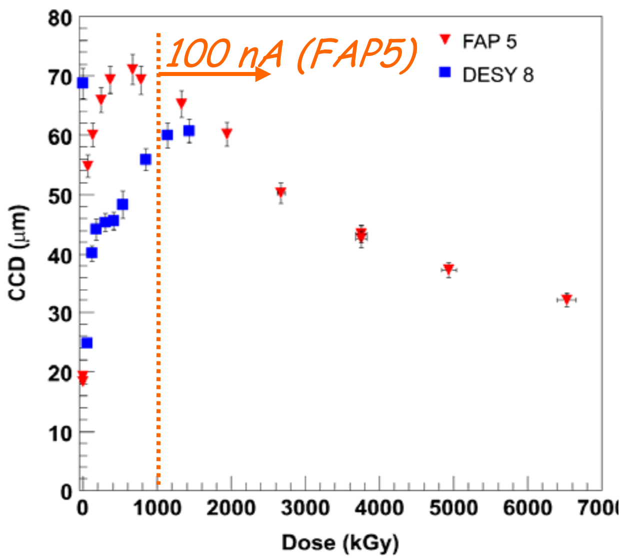
Forward calorimetry: the BeamCal

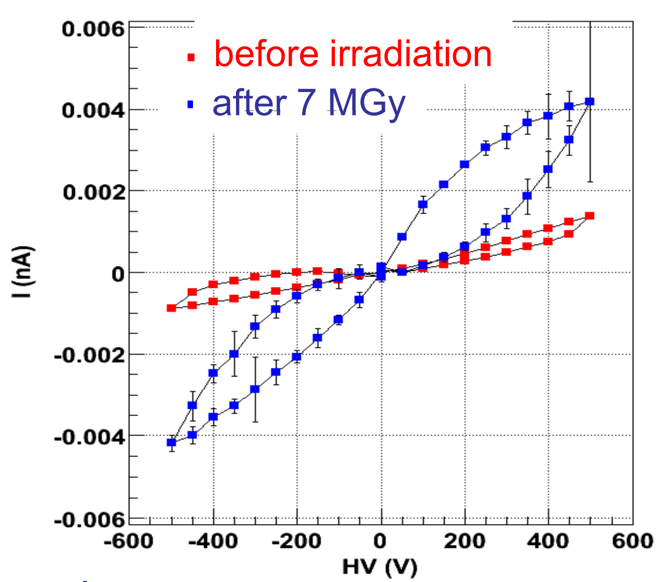
from C. Grah, ECFA workshop, Valencia

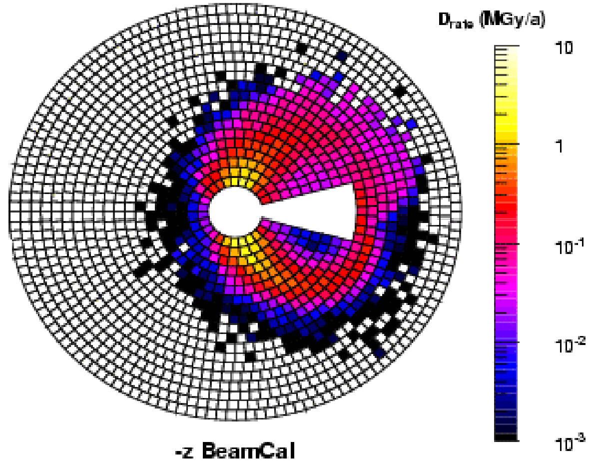
~15000 e^+e^- per BX from beamstrahlung into BeamCal

~ 10 MGy per year ➔ radiation hard sensors

Test beam at CERN PS and at ≈ 5 MGy/a
Superconducting DArmstadt LINear ACcelerator







Polycrystalline
Chemical Vapor Deposited
Diamonds

High dose from 10MeV electrons shows:
-all CVD diamonds stay functional after 7MGy
-degradation of the signal at high doses
-wide variation of the signal sizes as a function of the absorbed dose is an issue

Conclusion

-Investigate also other materials (GaAs, SiC)
-Successfull irradiation-testbeam at S-DALINAC
 to be repeated with other types of sensors

Conclusions

- ILC detector: world-wide R&D effort internationally coordinated
- many new technologies developed for a ILC calorimeter
- technologies and physics tested and test beams

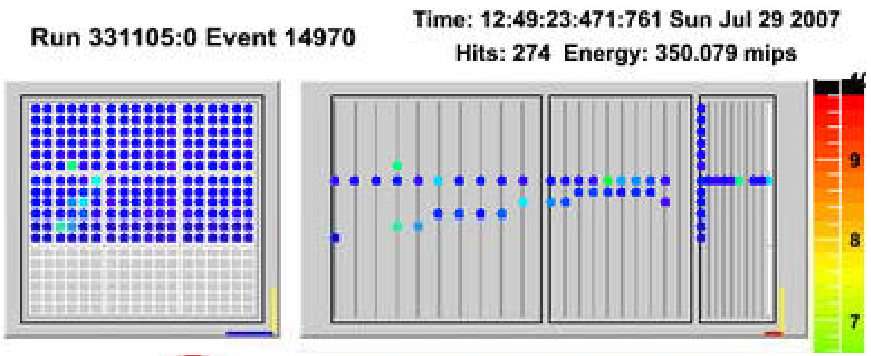
next steps:

- build a realistic and scalable detector for the ILC
- electronics integrated in active layer ➔ require more tests
- power cycling is driving the electronics design
- take into account mechanic constraints ➔maximum hermeticity

- … build the best possible calorimeter system for the ILC

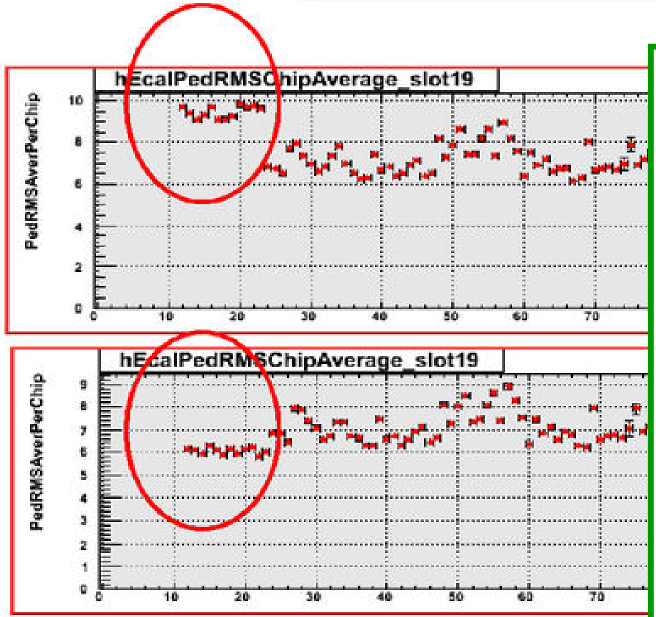
backup

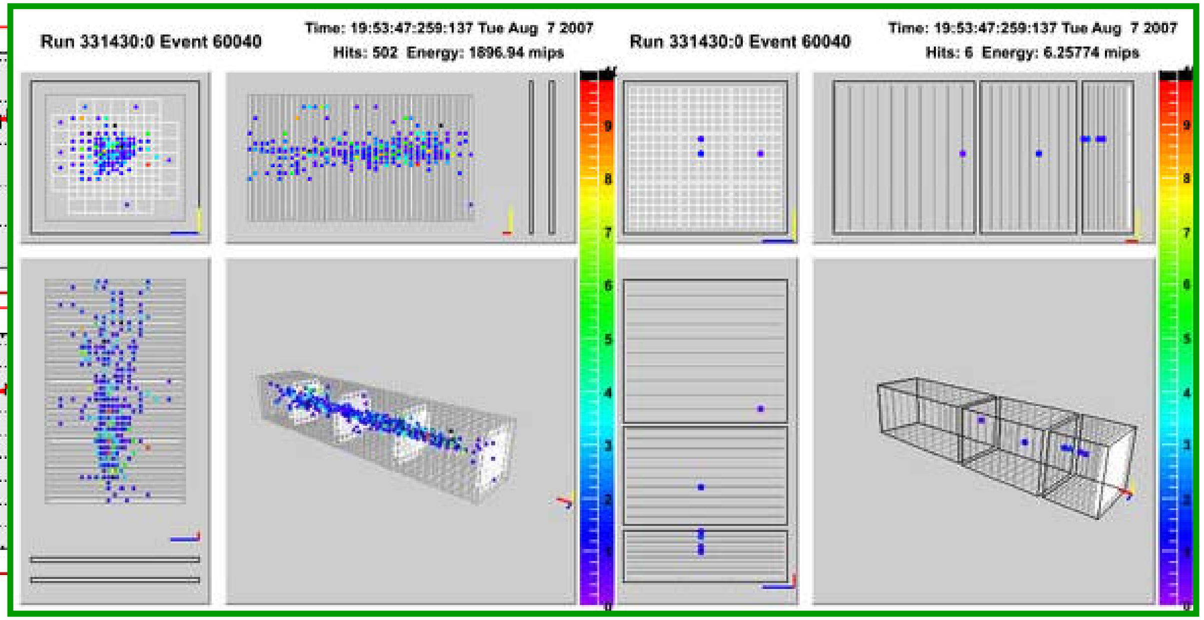
ECAL noise



known effects of noisy layers and pedestal fluctuations also this year

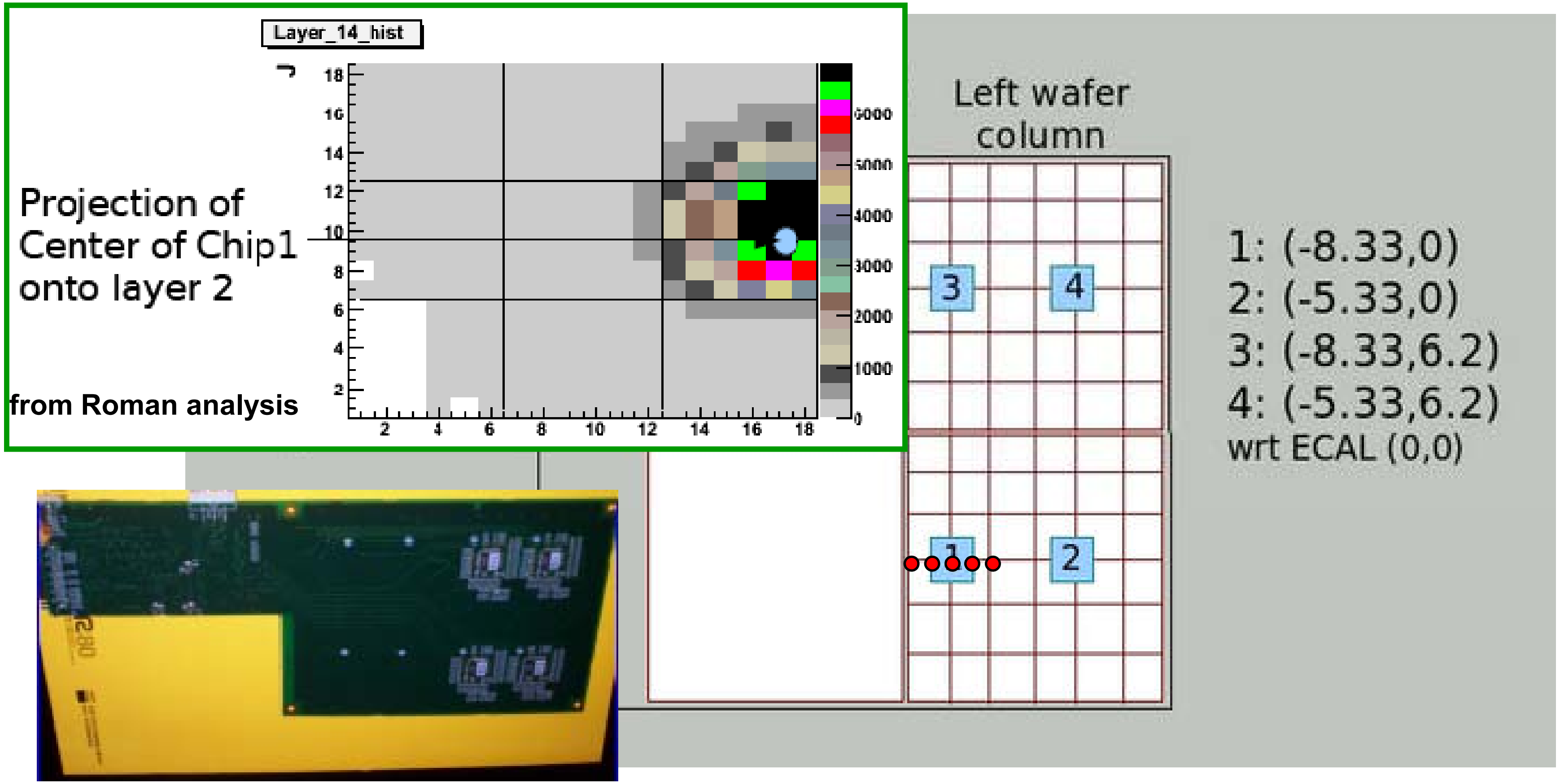
80GeV hadrons at ECAL (0,+3)
The hadron passes the ECAL (almost) undetected and generates showers in the HCAL
A gap effect?





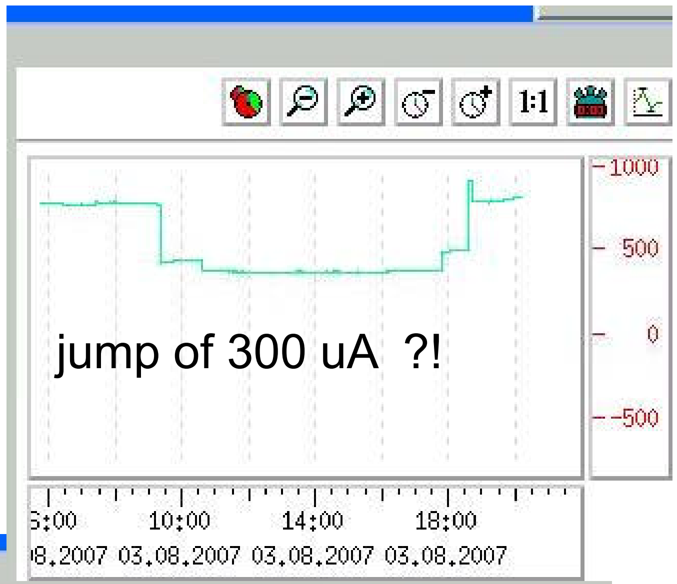
pedestal fluctuation during one run (slot 19, run 330774)

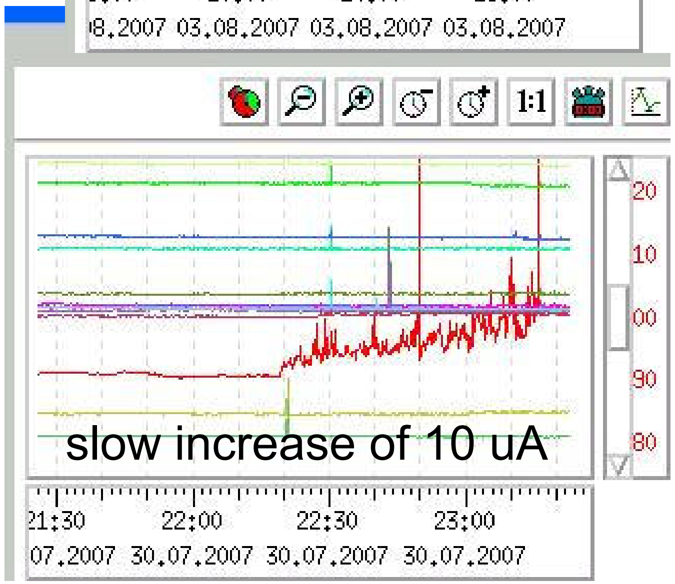
ECAL chip irradiation

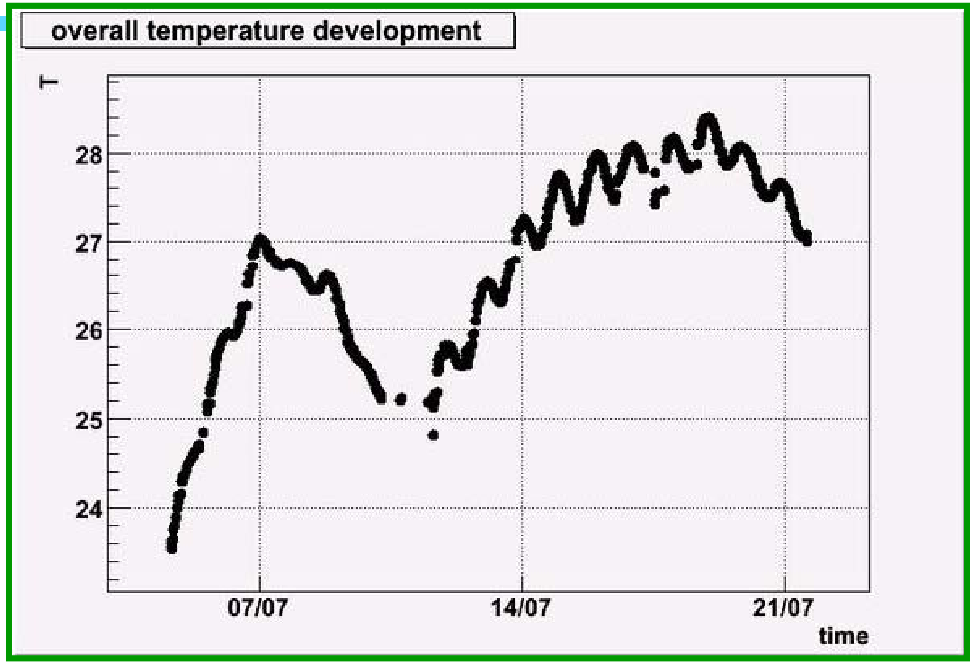


5 position scan for each of the 4 chips on the special ECAL slab
-90 GeV electron beam used
~1.2 M events per chip

Current and temperature







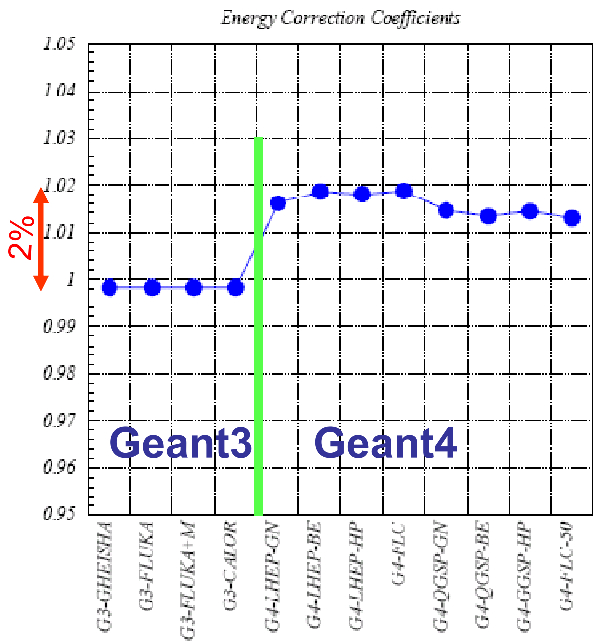
large temperature variations:
~ 0.5 K day-night
> 4 K over 3 weeks
➔ to be accounted in SiPM calibration

for some channels current limit was continuously increased over time ➔ study of ped RMS will tell if "radiation" damage is observed in SiPM

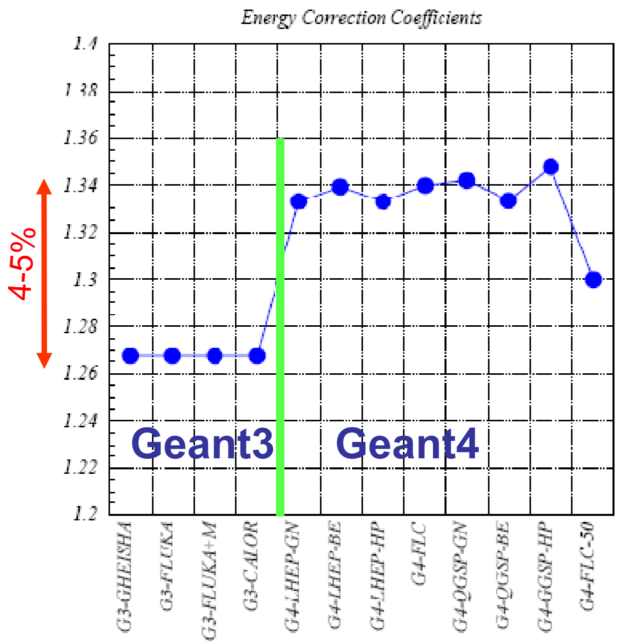
Models comparison

Integrated quantities

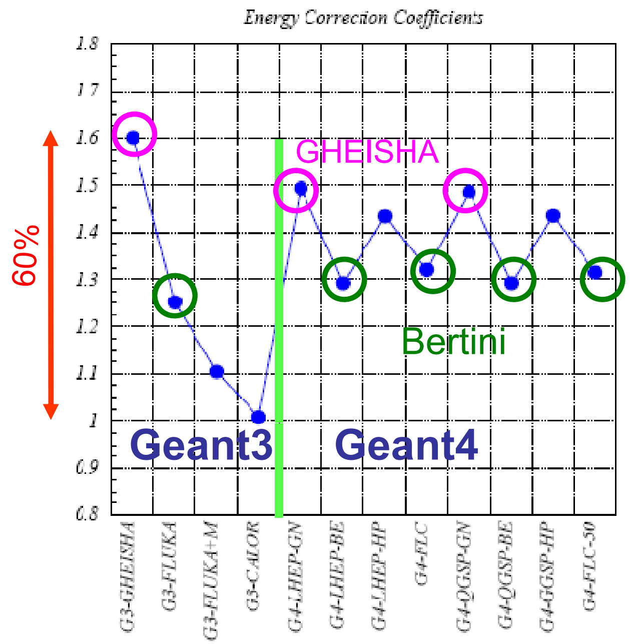
Energy correction coefficient = E_generated / E_reconstructed



Muon 2 GeV



Electron 2 GeV

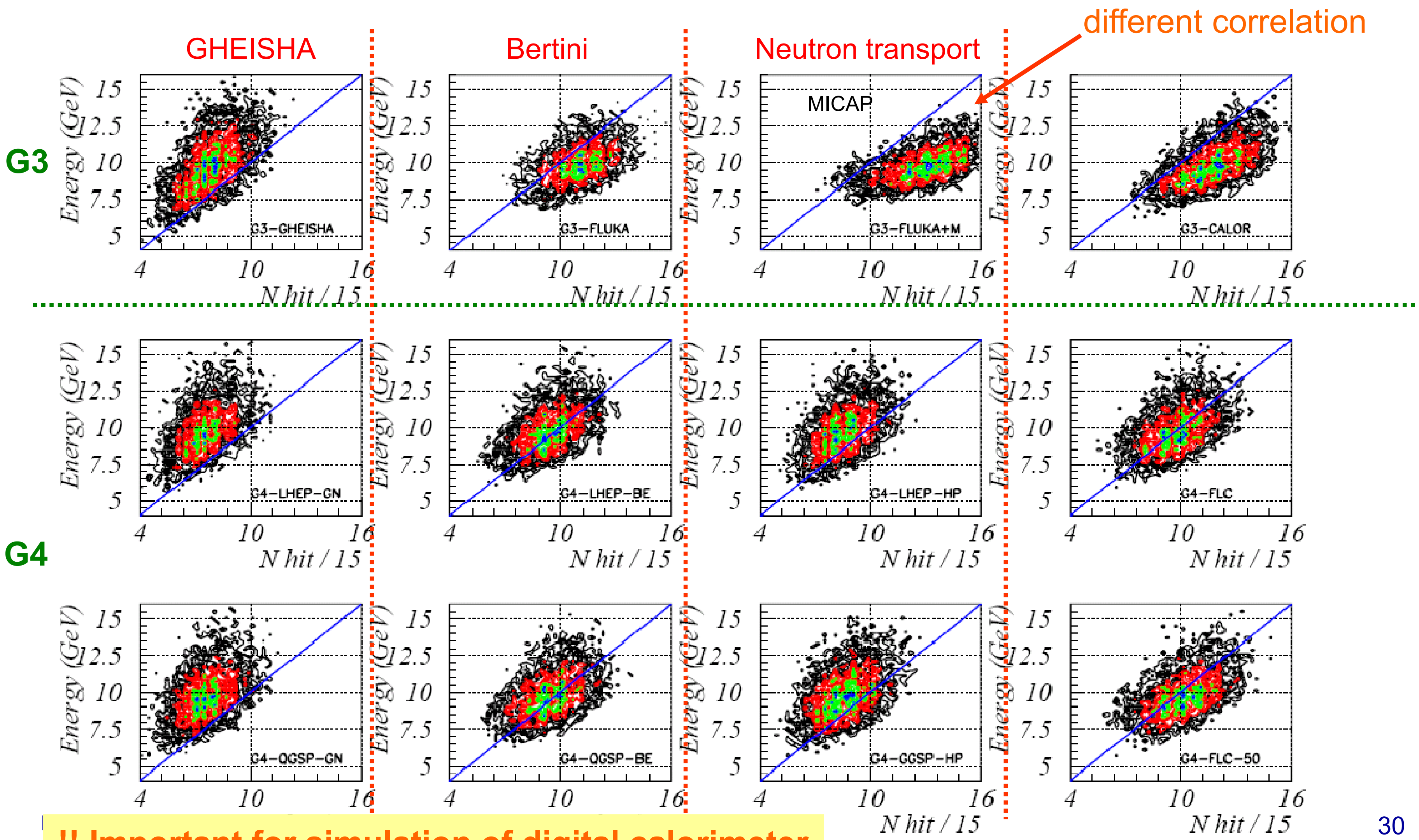


Pion + 10 GeV

Materials, geometry, energy cutoff optimized to be as similar as possible (@ 2% level, see muon)

Models comparison

Integrated quantities

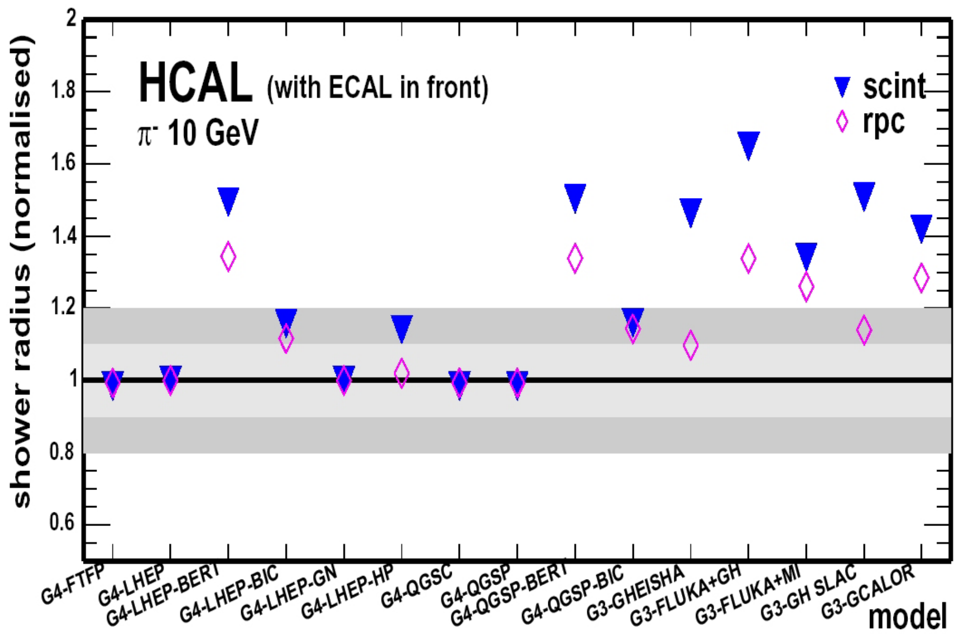


!! Important for simulation of digital calorimeter

Models comparison

Differential quantities

Study on hadronic shower profiles, G. Mavromanolakis (2004)



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

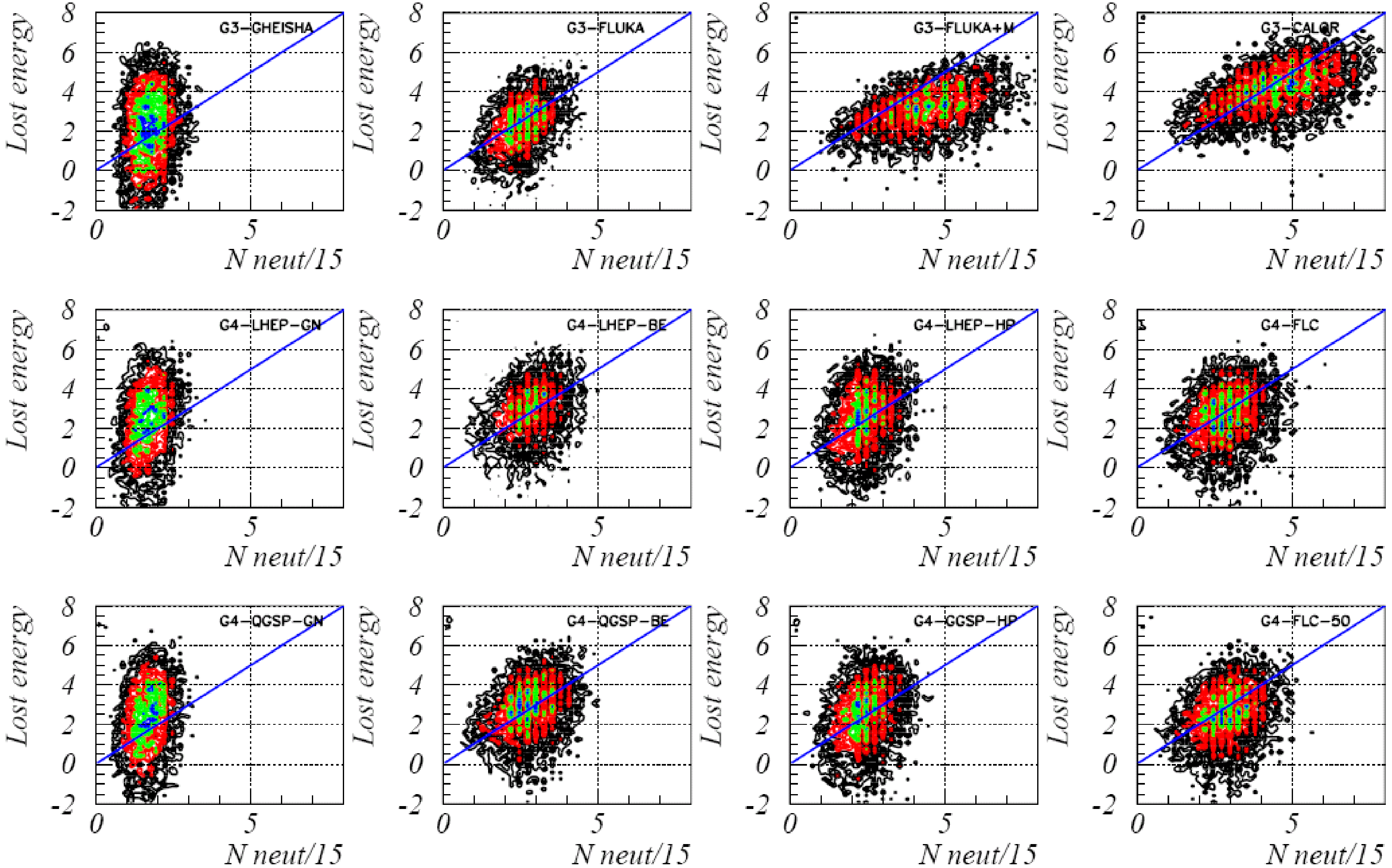
- 38 points for longitudinal profile (if ECAL and TCMT included up to 84)
- 9 points for lateral profile

A deeper comparison

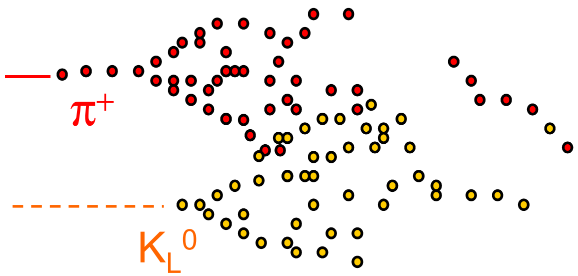
Shower composition

Binding / Lost Energy = $E_{beam} - (E_{EM} + E_{HAD})$ .vs. # of reconstructed neutrons

New benchmark for data/MC comparison



Key issue:
High Granularity



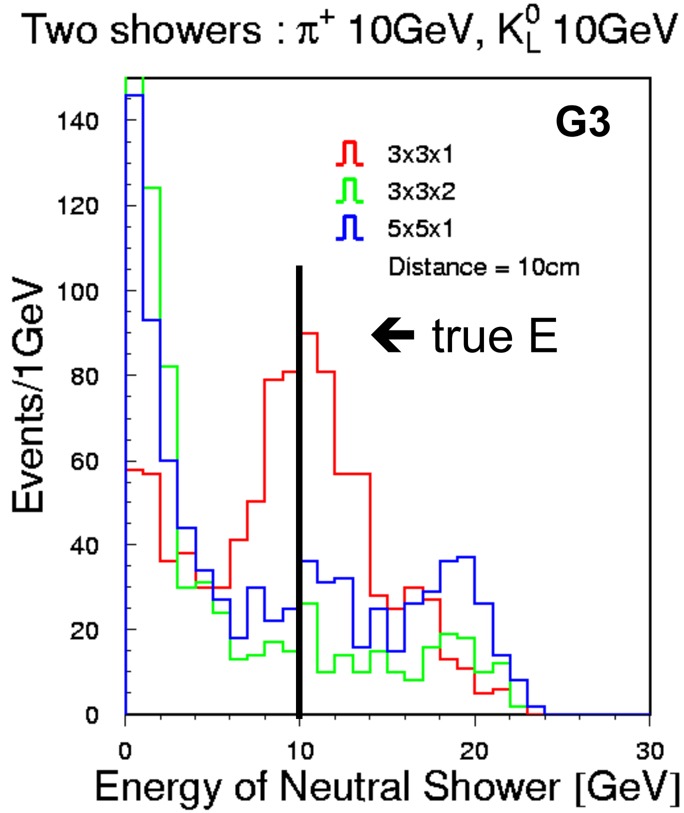
Calorimeter geometry optimization:

➔ Shower separation

Generate two 10 GeV showers initiated by
π+ and K_0^L
Use track information for π+
Use complete shower reconstruction algorithm
(V. Morgunov)

Test three options of tile size and readout scheme:
- 1 layer of 3x3 cm^2 tiles (best "realistic" case)
- 2 layers of 3x3 cm^2 tiles (worse long. segment.)
- 1 layer of 5x5 cm^2 tiles (worse lateral segment.)

Compare to ideal particle flow algorithm



A. Raspereza

The ECAL

The recommendations from Henri:

1) mind the gap !
   - gap < 5 cm (?)
   - extend end cap (+8 cm)

2) many samples but not too many samplings for W ECAL 2 samplings are a good compromise
   E <2 GeV for 30% γ in $\nu\nu WW$
   ➔ thinner sampling in first layers

3) pay good price for electronics dynamic range up to 3500 MIPs in one 5x5 mm pad (from 500 GeV e @ 45 deg)