# Calorimetry for a Linear Collider Experiment

G.Mavromanolakis, University of Cambridge

Outline

- **General - Introduction**
- **Concepts and Challenges**
- **High granularity calorimetry and CALICE**
- **Si/W ECAL prototype, first results**
- **Summary**

# General

- **an $e^+e^-$ linear collider at $\sqrt{S} = 0.5 - 1\ \mathrm{TeV}$ range seems to be the next facility after the LHC**

- **main advantages**

  : well defined initial state

  : clean experimental environment

- **main goal**

  : to perform precision measurements

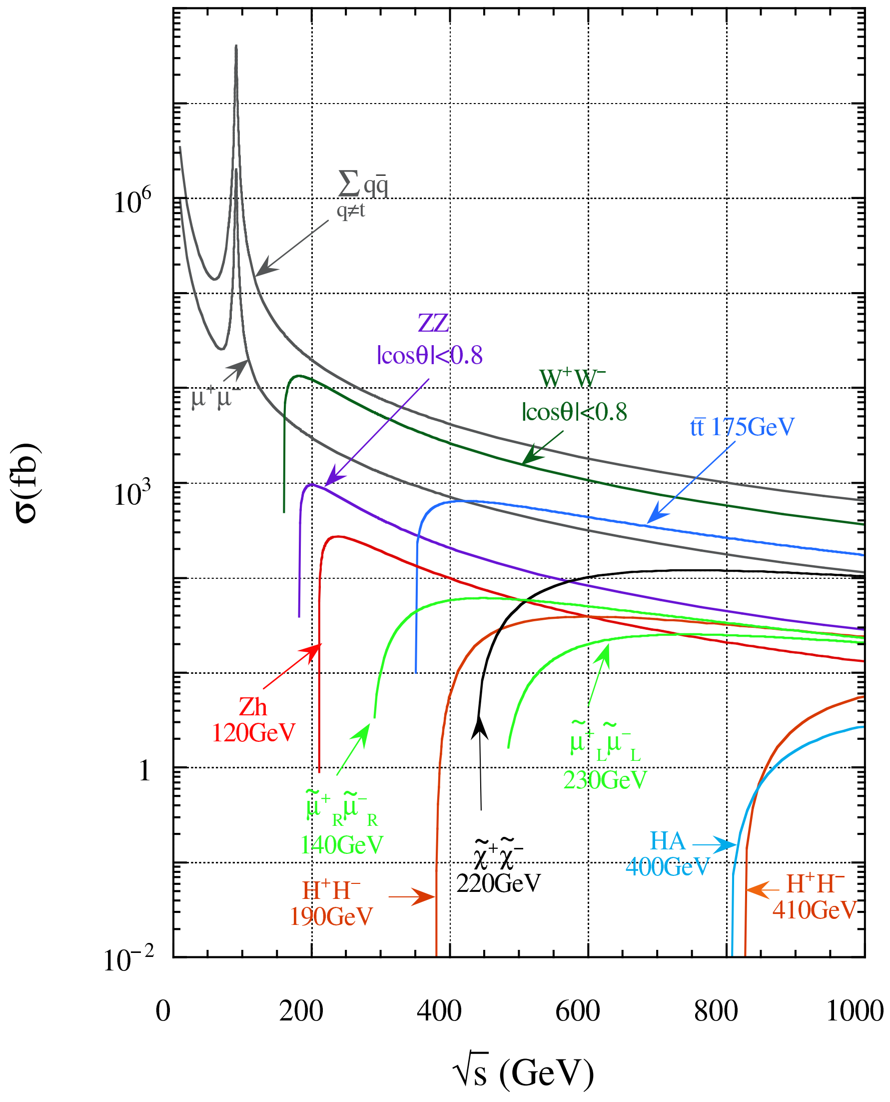
  ▷ Higgs sector

  ▷ SUSY spectroscopy

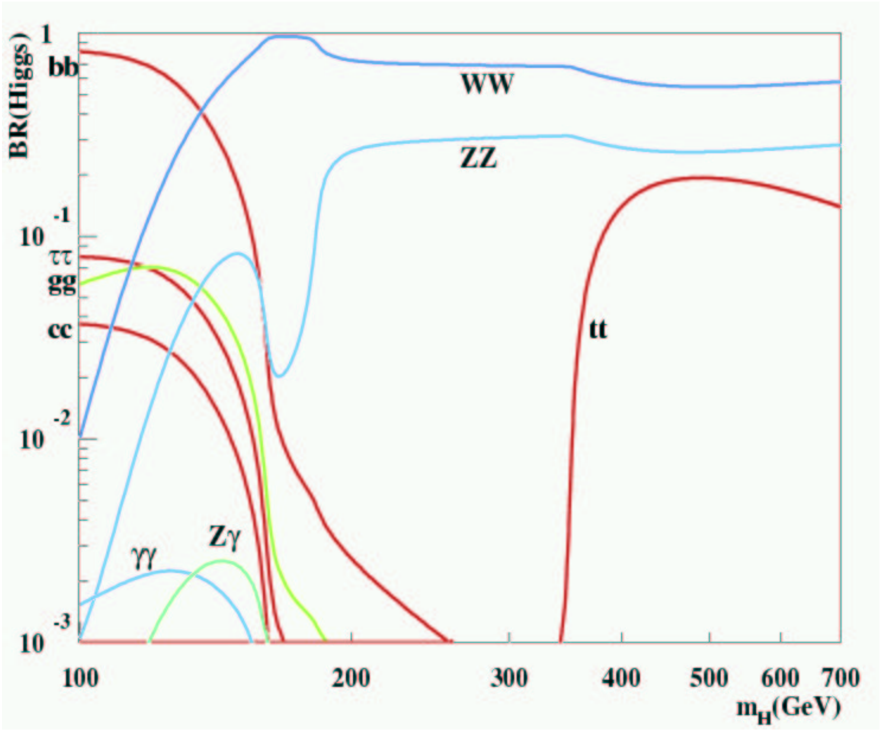
  ▷ DM candidates, extra dimensions

  ▷ ...

# Experimental environment



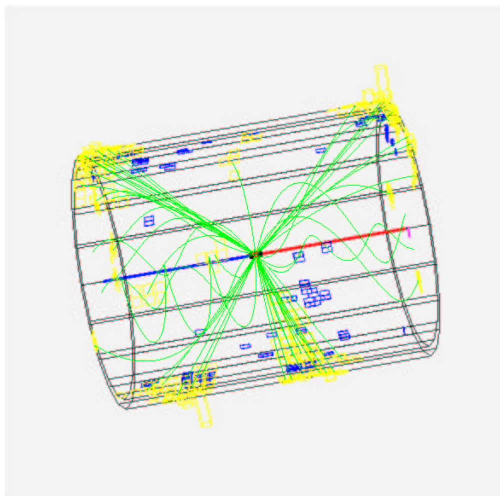

$e^+e^-$ **cross sections**




**Higgs branching ratios**

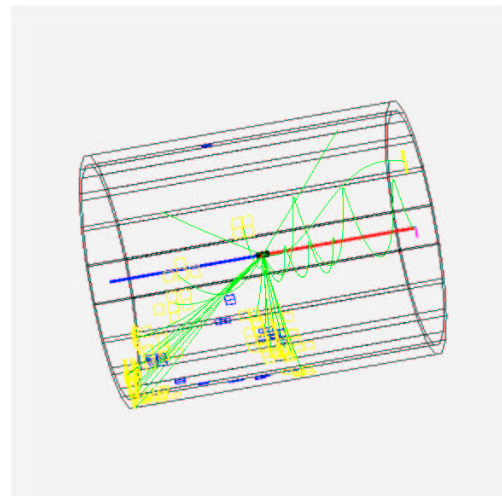
# Experimental environment - example

- an "easy" case, $e^+e^- \to ZH$



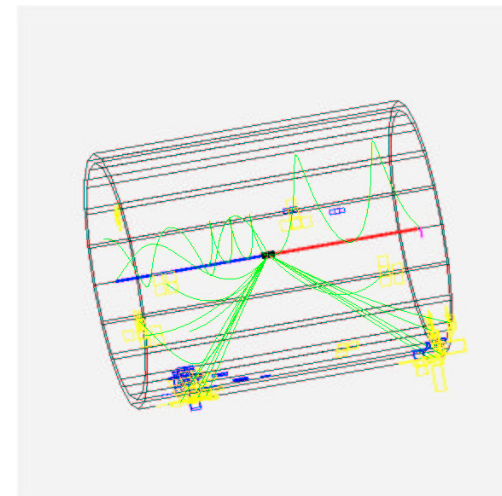
$Z \to q\bar{q}$, $H \to b\bar{b}$

**4 jets**



$Z \to e^+e^-/\mu^+\mu^-$, $H \to b\bar{b}$

**2 leptons + 2 jets**



$Z \to \nu\bar{\nu}$, $H \to b\bar{b}$

**missing E + 2 jets**

: note, for $H \to WW \to qqqq$ then +2 more jets

- **events with**
  - **many jets**
  - **charged leptons**
  - **missing energy**

**need detector with excellent**
- **flavor tagging capability**
- **jet reconstruction efficiency**
- **tracking, momentum resolution**
- **hermeticity**

# Detector requirements

- **vertexing:** $\sigma_{r\phi,z}(IP) \leq 5\ \mu m \oplus \frac{10\ \mu m\ \mathrm{GeV/c}}{p\ sin^{3/2}\theta}$

  : (1/5 $\mathrm{R_{beampipe}}$, 1/30 pixel size, 1/30 thinner wrt LHC)

- **central tracking:** $\sigma(\frac{1}{p_t}) \leq 5 \times 10^{-5}(\mathrm{GeV/c})^{-1}$

  : ($\sim$ 1/10 wrt LHC, 1/6 of material in tracking volume)

- **jet energy resolution:** $\frac{\sigma_{E_{jet}}}{E_{jet}} \simeq \frac{30\%}{\sqrt{E_{jet}(\mathrm{GeV})}}$

  : (1/200 calorimeter granularity wrt LHC)

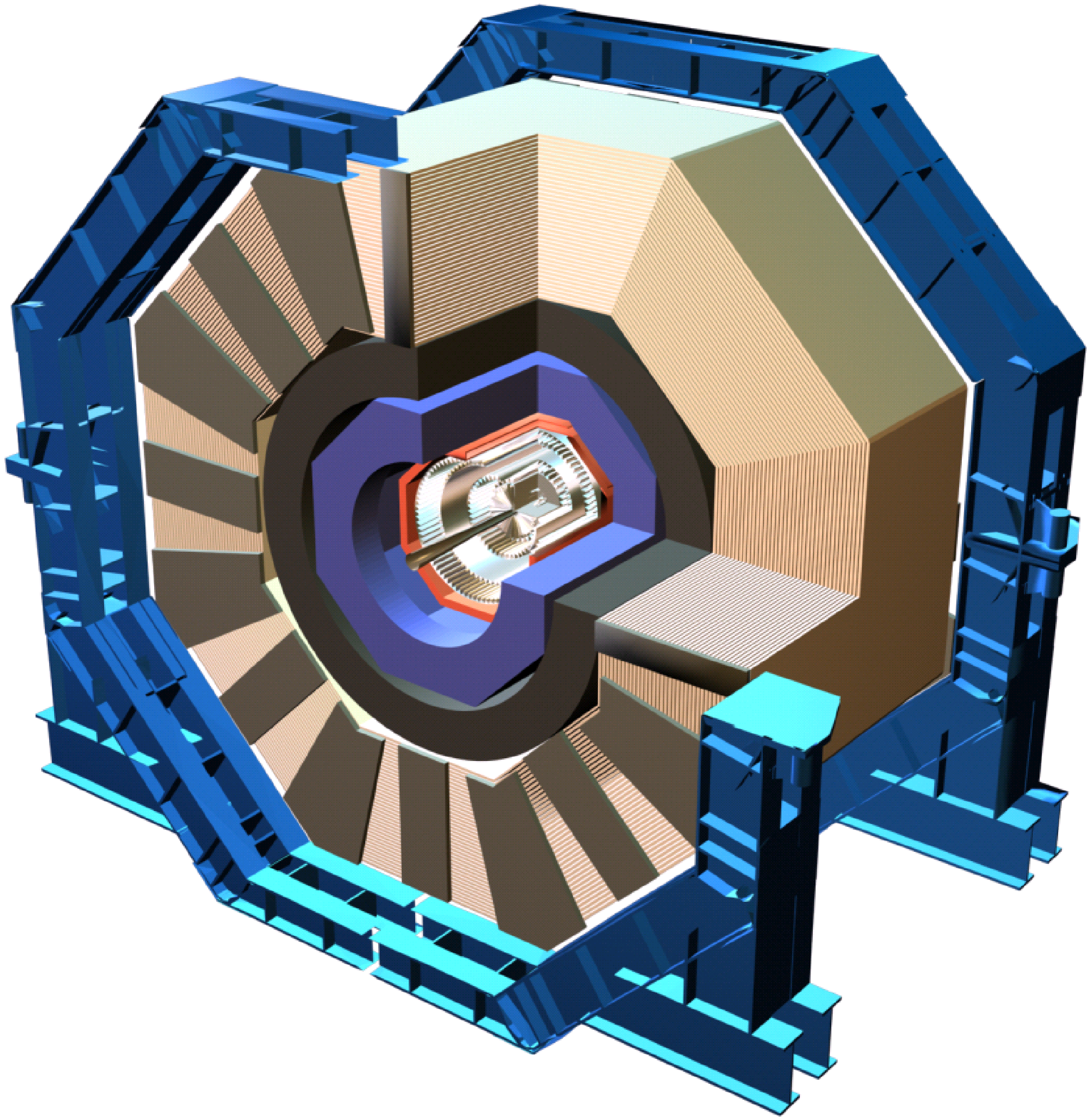
- + **hermeticity**
  + **time resolution**

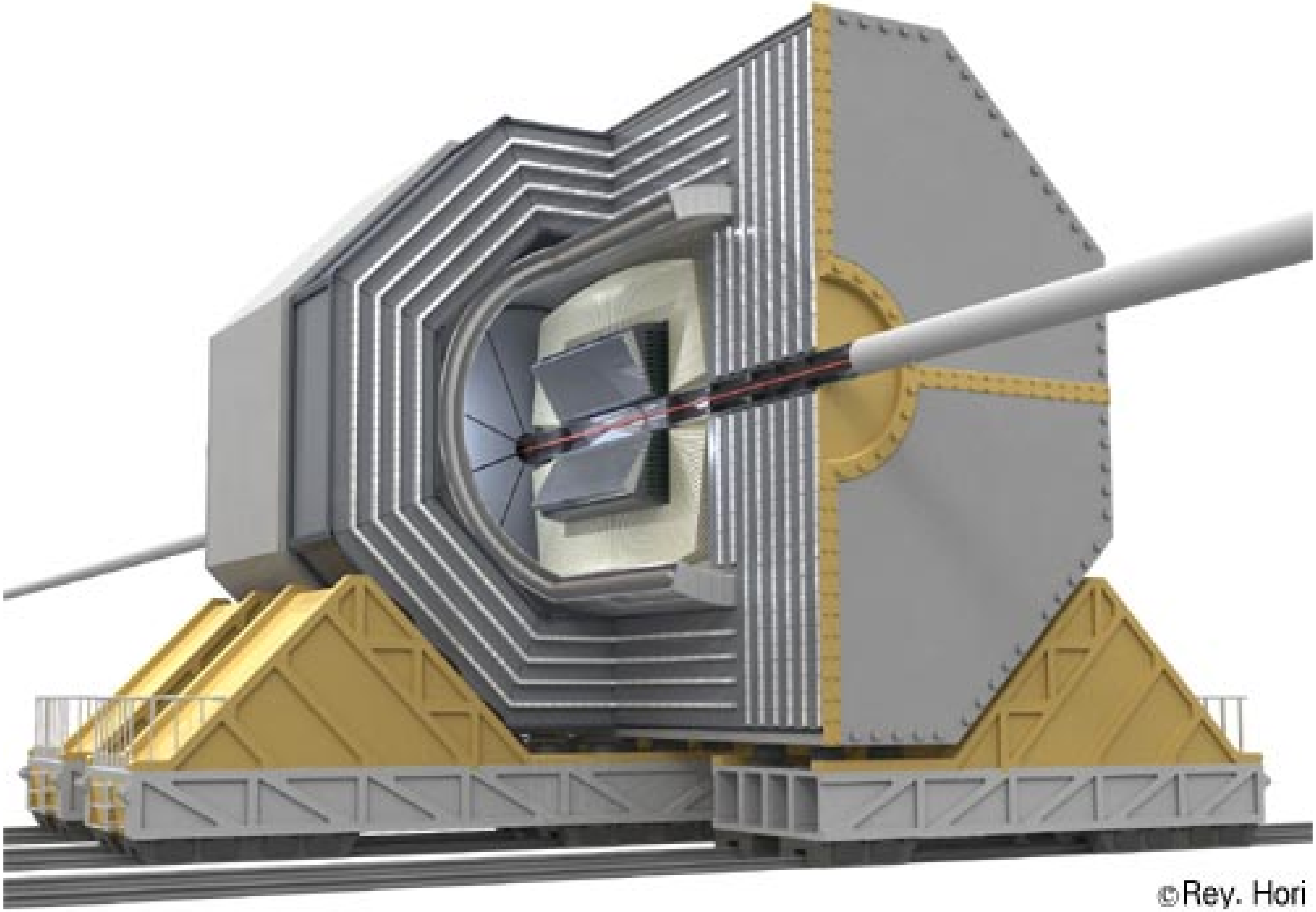
# Detector concepts

- **3 concepts from 3 continents**

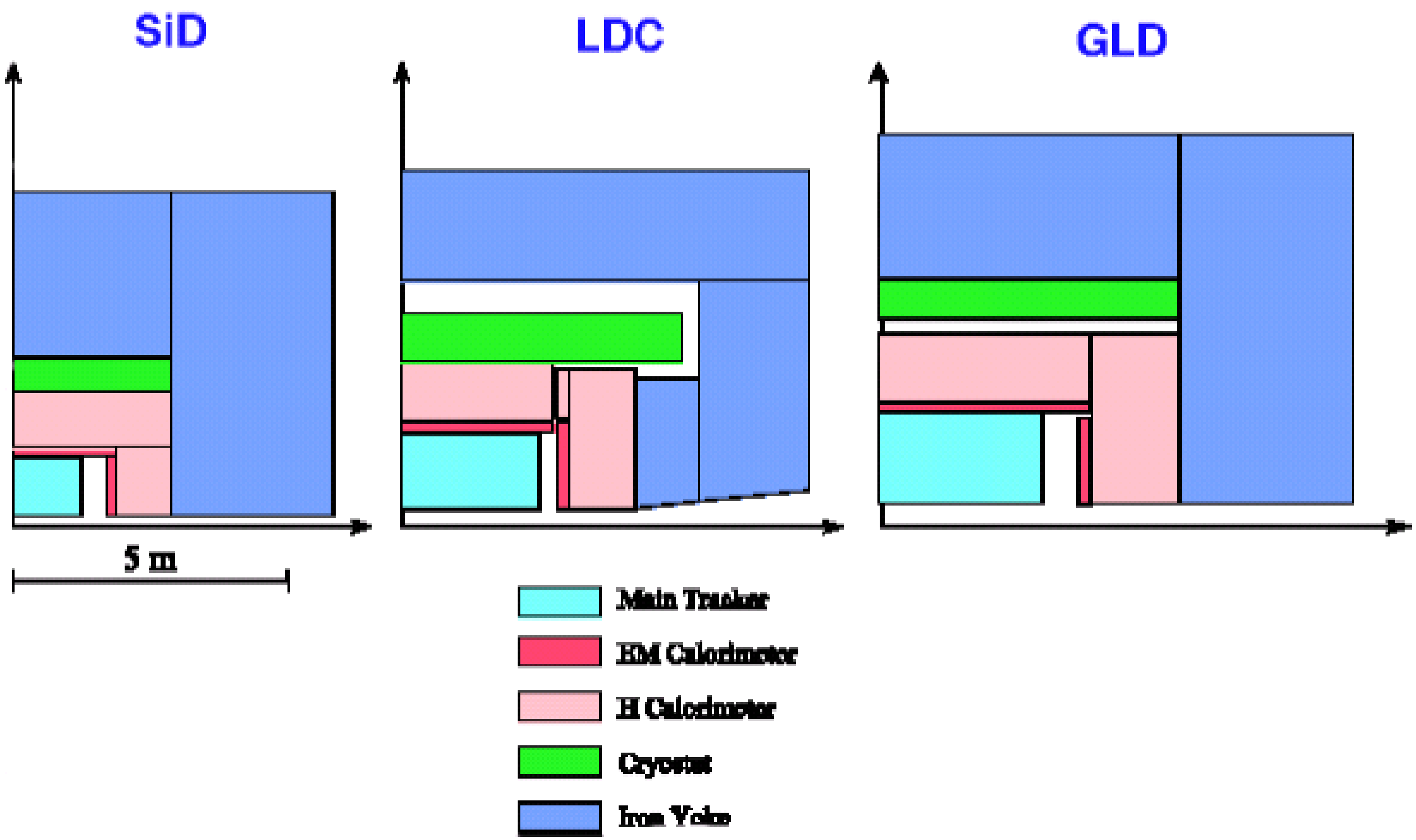
  - COMPACT : **Silicon Detector (SiD)**, American initiative
  - LARGE : **Large Detector Concept (LDC)**, European initiative
  - EXTRA LARGE : **Global Large Detector (GLD)**, Asian initiative

| concept | Solenoid | VertexDet | Tracker | ECAL | HCAL |
|---|---|---|---|---|---|
| **SiD** | 5 T | Si | Si | Si/W | RPC/Fe, RPC/W, ? |
| **LDC** | 4 T | Si | TPC | Si/W | scint/Fe, RPC/Fe, ? |
| **GLD** | 3 T | Si | TPC | scint/W | scint/Pb |



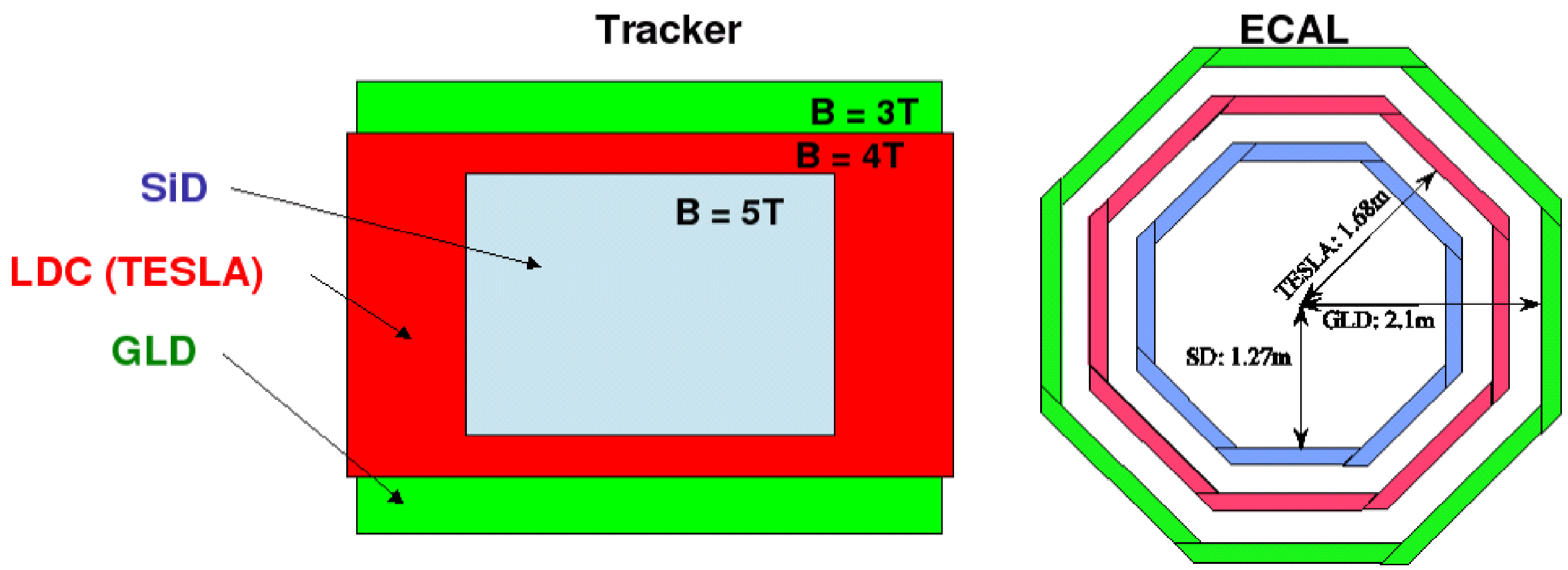

©Rey. Hori

# Detector concepts - relative size




(S.Komamiya)

# Detector concepts - relative size



# Particle flow paradigm

- **try to reconstruct every particle of the event in order to improve the jet energy resolution**

- **visible energy of a typical jet**
  - $\sim$ 60 % charged particles
  - $\sim$ 30 % photons
  - $\sim$ 10 % neutral hadrons

- **particle flow step-by-step**
  - use tracker to measure charged particle momentum
  - use ECAL to measure photon energy
  - use HCAL+ECAL to measure neutral hadron energy
  - use tracker+ECAL+HCAL to disentangle charged from neutrals

# Jet energy resolution

| particles in jet | fraction of energy in jet | detector | single particle resolution | jet energy resolution |
|---|---|---|---|---|
| charged particles | 60 % | tracker | $\frac{\sigma_{p_t}}{p_t} \sim 0.01\% \cdot p_t$ | negligible |
| photons | 30 % | ECAL | $\frac{\sigma_E}{E} \sim 15\%/\sqrt{E}$ | $\sim 5\%/\sqrt{E_{jet}}$ |
| neutral hadrons | 10 % | HCAL+ECAL | $\frac{\sigma_E}{E} \sim 45\%/\sqrt{E}$ | $\sim 15\%/\sqrt{E_{jet}}$ |

- $\sigma_{jet} = \sigma_{charged} \oplus \sigma_{photon} \oplus \sigma_{neutral} \oplus \sigma_{confusion}$

  : confusion term comes from misassignment of energy to wrong particles due to double-counting, overlapping clusters, bad track-shower reconstruction etc

  : improve confusion term by having

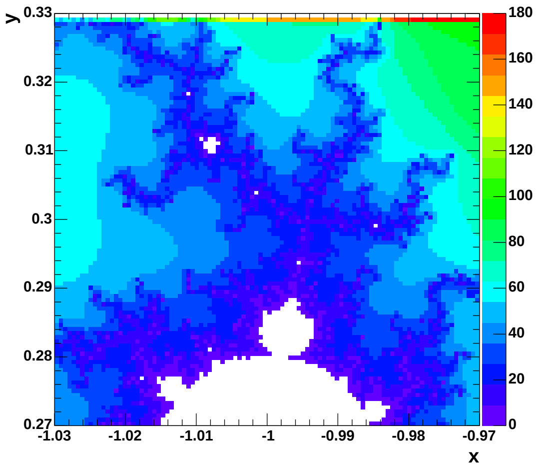
  **better pattern recognition $\rightarrow$ highly granular calorimetry**

# Challenge

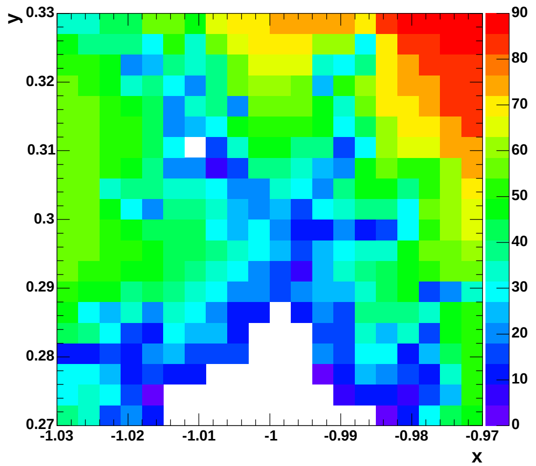
- · **role for calorimeters**

  : not so much as efficient energy measurement devices
  but mostly as
  imaging detectors to provide excellent 3D reconstruction of showers
  for very efficient pattern recognition and particle separation

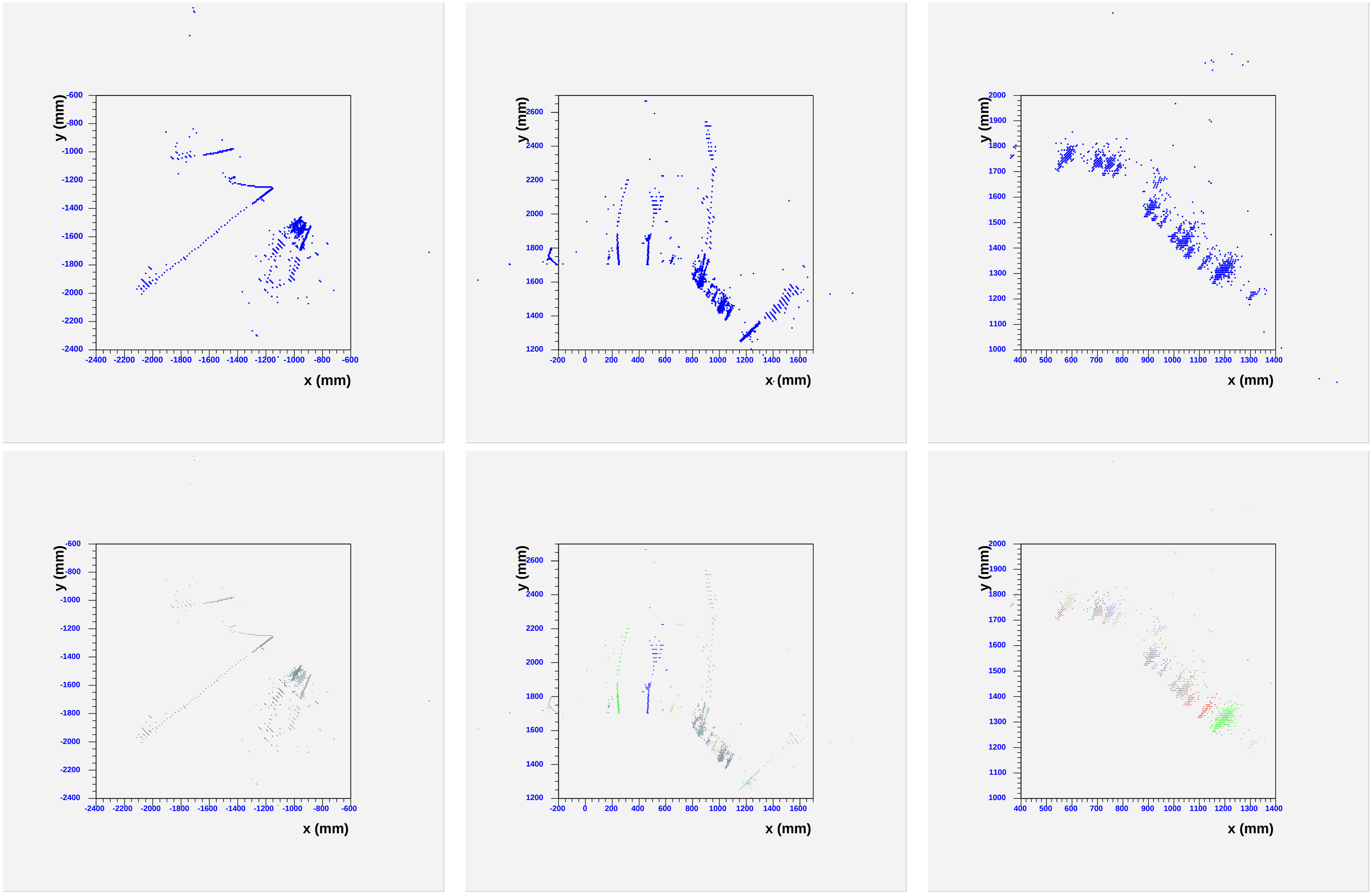
- · **strong interplay between hardware and software**




▷ **best "eye"**




▷ **best "brain"**


y (mm)
x (mm)
-600 -800 -1000 -1200 -1400 -1600 -1800 -2000 -2200 -2400
-2400 -2200 -2000 -1800 -1600 -1400 -1200 -1000 -800 -600
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2600 2400 2200 2000 1800 1600 1400 1200
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y (mm)
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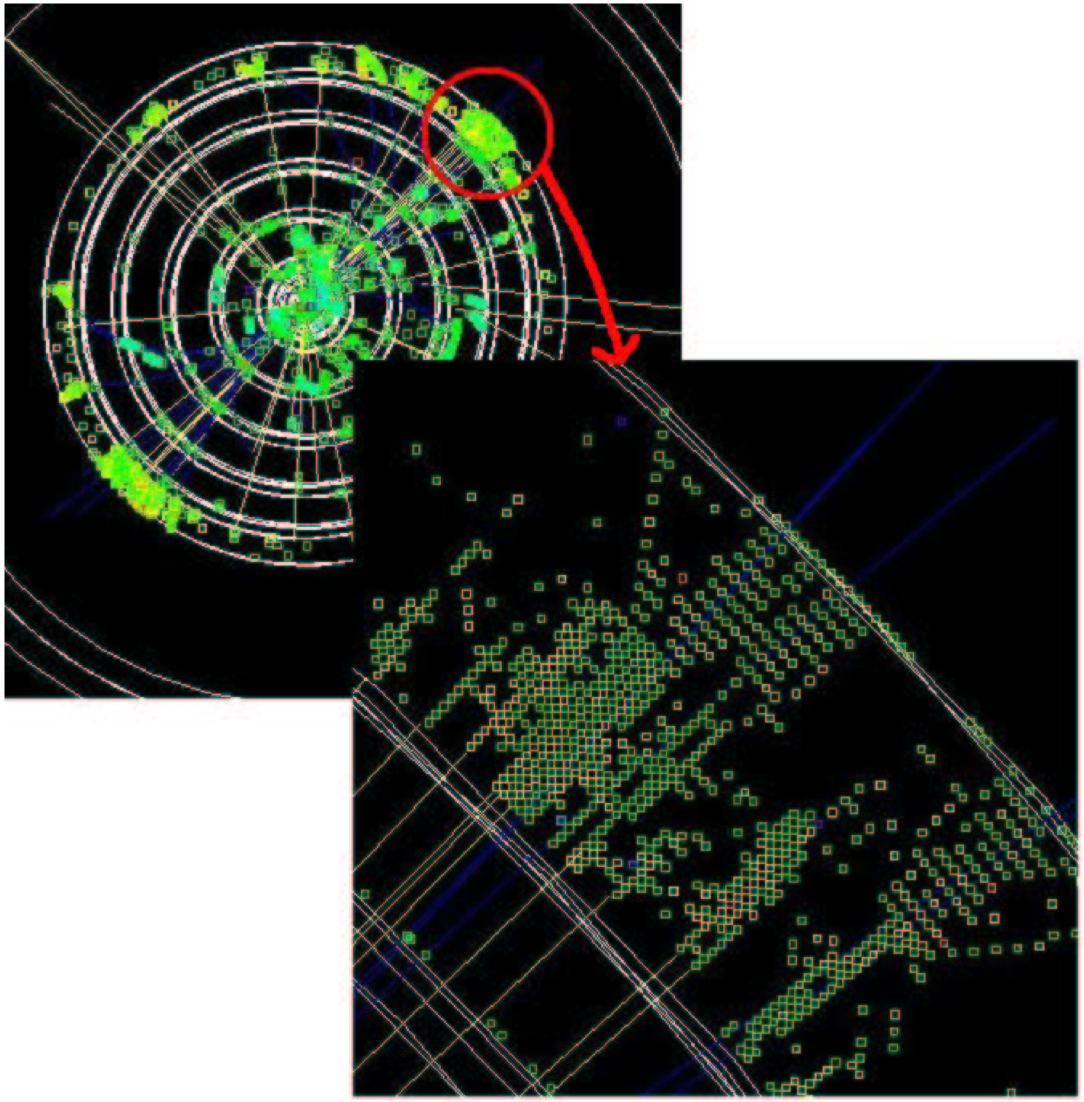
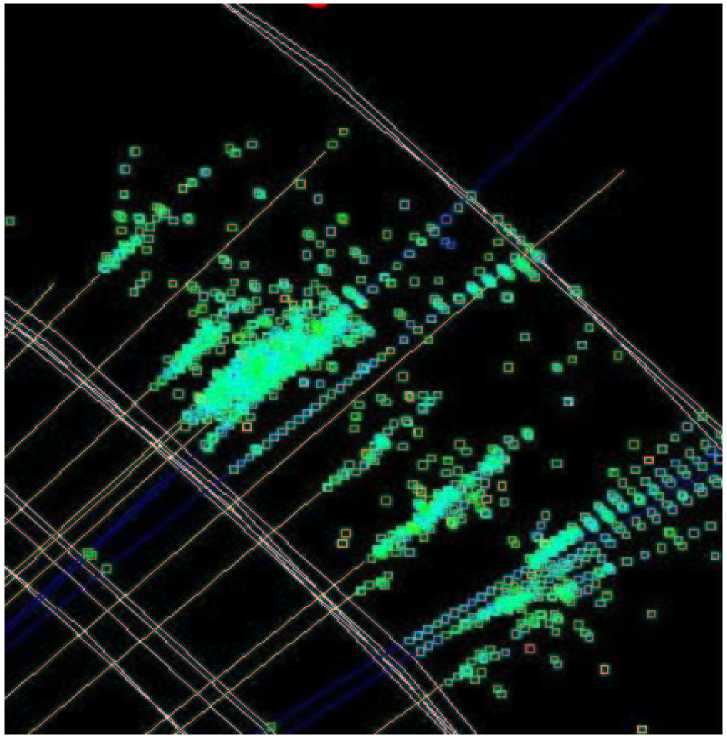
# Granularity to the limit





(J.Lilley)

Si pads ($4\times4\ \mathrm{mm}^2$)

MAPS pixels ($50\times50\ \mu\mathrm{m}^2$)

# CALICE Collaboration

- ► .
  : formed to conduct the R&D effort needed to bring initial conceptual designs for the **calorimetry** to a final proposal suitable for an experiment at the future linear collider

- ► .
  : 32 institutes from 9 countries from Europe, America, Asia,
  about 200 physicists and engineers

- ► .
  : strong participation from UK institutes
    - ▷ Birmingham University
    - ▷ Cambridge University
    - ▷ Imperial College London
    - ▷ Manchester University
    - ▷ Rutherford Appleton Laboratory
    - ▷ Royal Holloway University of London
    - ▷ University College London

# CALICE Collaboration

► . **objectives**

: build and operate very highly granular calorimeters
and demonstrate proof of principle

: do extensive individual and combined testbeam studies
towards detector optimisation

► . **roadmap**

: debug technology/detector concept(s)

: detector characterisation

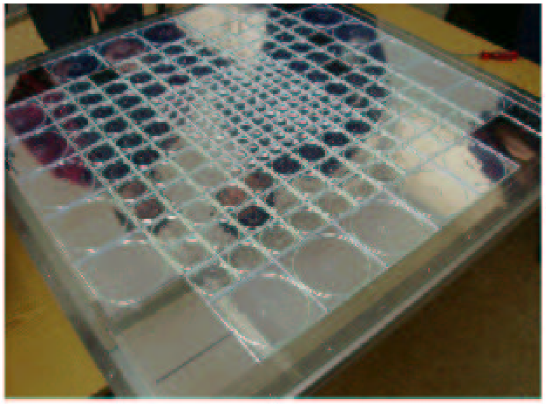
: test "particle flow paradigm", interplay between hard/soft-ware

: test-validate-improve simulation codes and shower packages

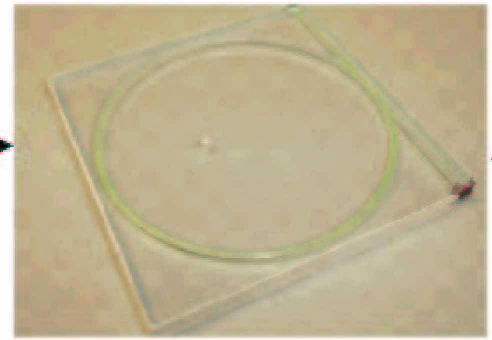
# Concepts to study

- **ECAL**
  - Si pads and W absorber, **$1 \times 1$ cm$^2$ granularity**, prototype with 30 layers, 24 $X_0$, total: $\sim$ 10000 channels
  - advantage: stability of Si properties
  - disadvantage: cost
- **HCAL**
  - scintillator tiles and steel absorber, central part with **$3 \times 3$ cm$^2$ granularity**, 1 m$^3$ prototype with 40 layers, $\sim 4.5\ \lambda_I$, total: $\sim$ 8000 channels
  - advantage: conventional technology
  - disadvantage: complexity of operation

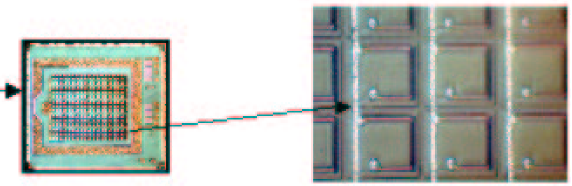
# HCAL readout chain



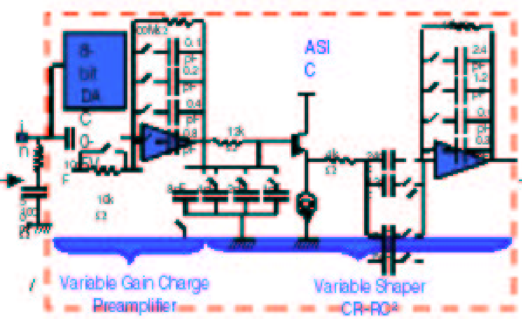
Read out 216 tiles/module
~8000 channels



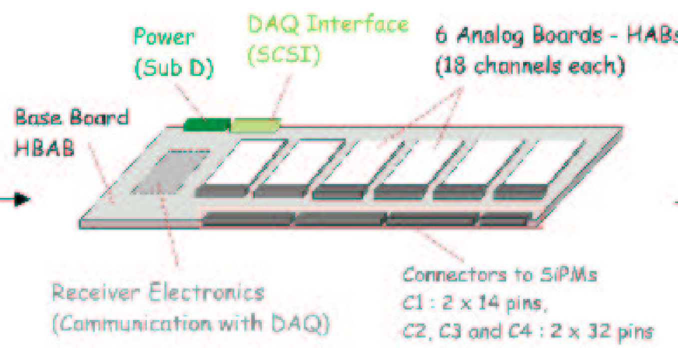
Single tile readout with SiPM



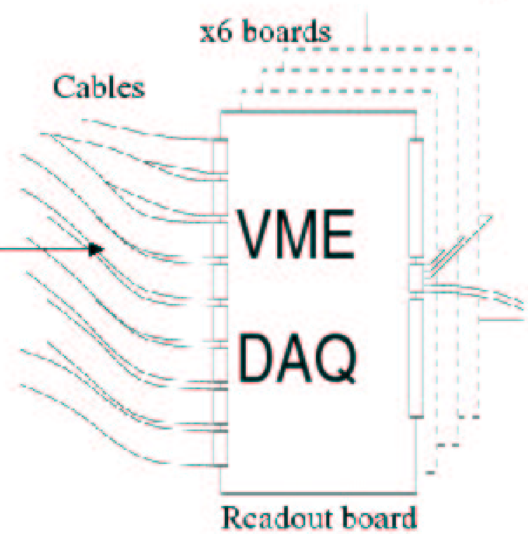
SiPM: pixel device operated in Geiger mode




ASIC: amplification + shaping + multiplexing




VFE: control 6 ASICs connect to SiPM




**(M.Groll)**

# Concepts to study (continued)

- **digital HCAL RPC**
  - Resistive Plate Chambers and steel absorber, **1 $\times$ 1 cm$^2$ granularity**, 1 m$^3$ prototype with 40 layers, $\sim 4.5\ \lambda_I$, total: **400000 channels**
  - advantage: very high granularity, simple operation
  - disadvantage: digital concept to be proven
- **digital HCAL GEM**
  - Gas Electron Multipliers and steel absorber, **1 $\times$ 1 cm$^2$ granularity**, 1 m$^3$ prototype with 40 layers, $\sim 4.5\ \lambda_I$, total: **400000 channels**
  - advantage: very high granularity
  - disadvantage: digital concept and technology to be proven

# A common problem from the start

- **detector design optimisation is a long and labor intensive process of simulation studies**

- **common sense**
  : a final detector with about a billion channels and xxx Meuros cost, then better be sure that simulation codes used are close to reality

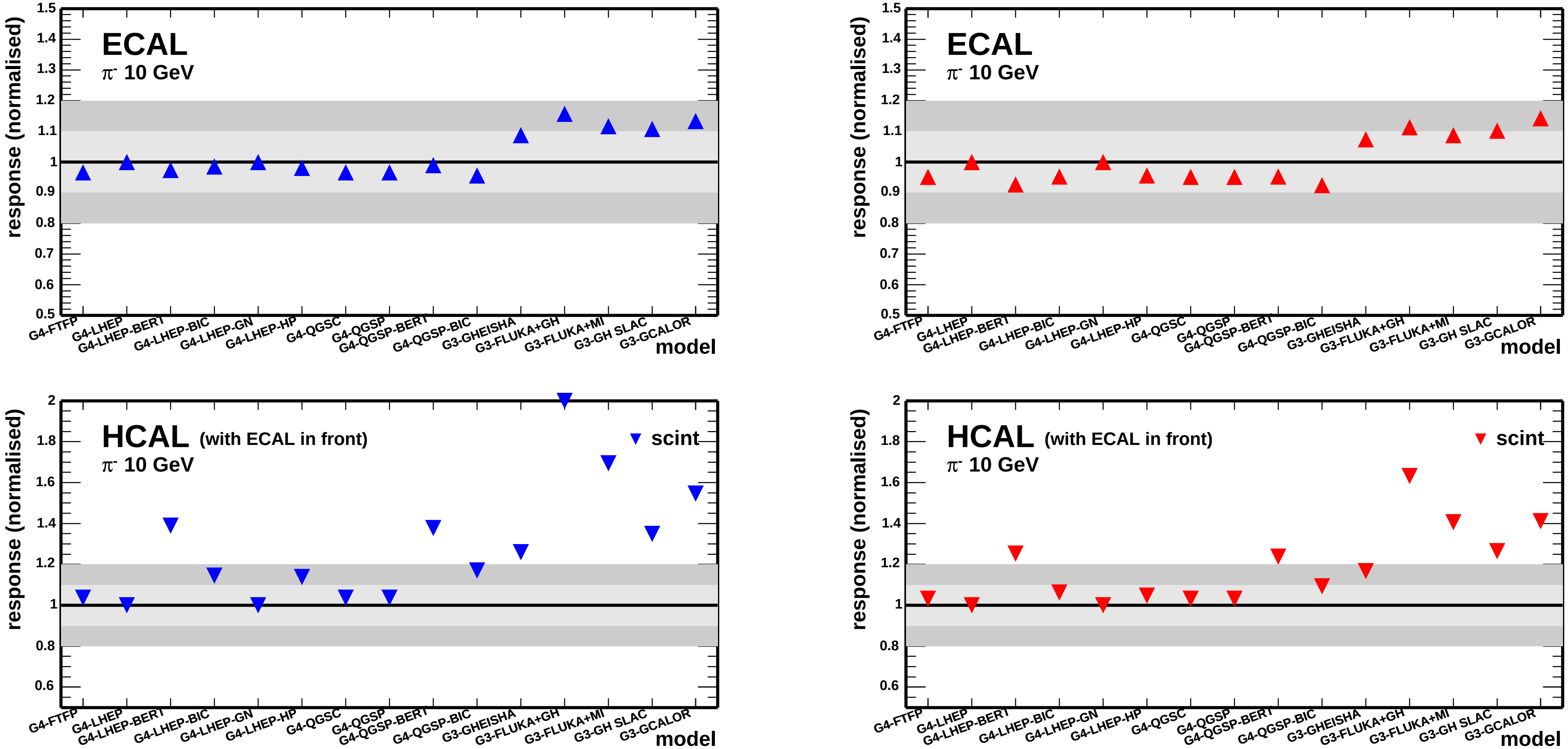
- **the problem from the very start**
  : simulation studies reveal significant discrepancies among shower packages, thus preventing model independent predictions on calorimeter performance and reliable detector design optimization

- **solution**
  : testbeam program with CALICE ECAL+HCAL prototypes to resolve the situation and reduce the current large uncertainty factors

| 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 |

# ECAL+HCAL scint "response" vs model, $\pi^-$ 10 GeV

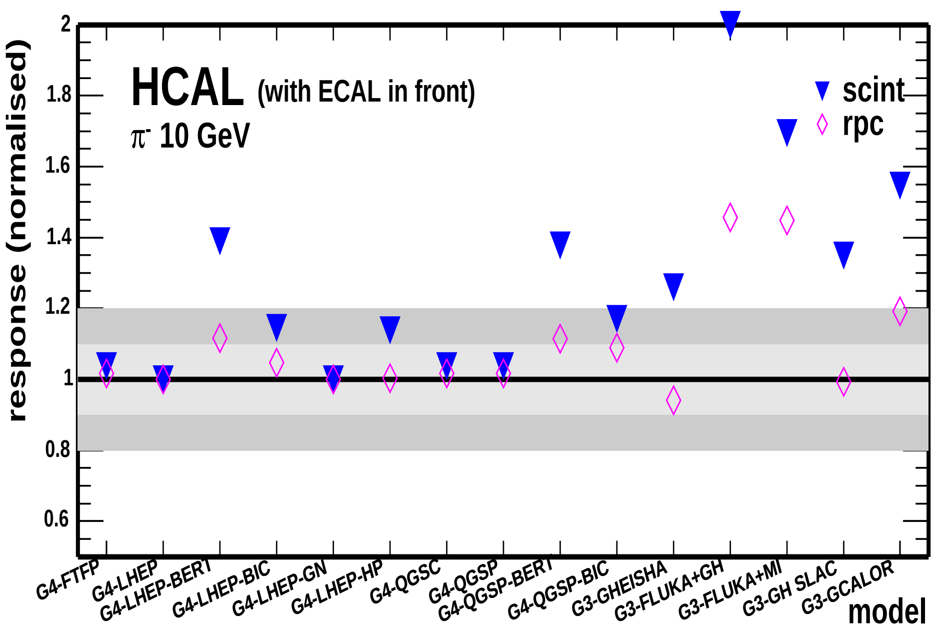
**N cells hit** | **E deposited**



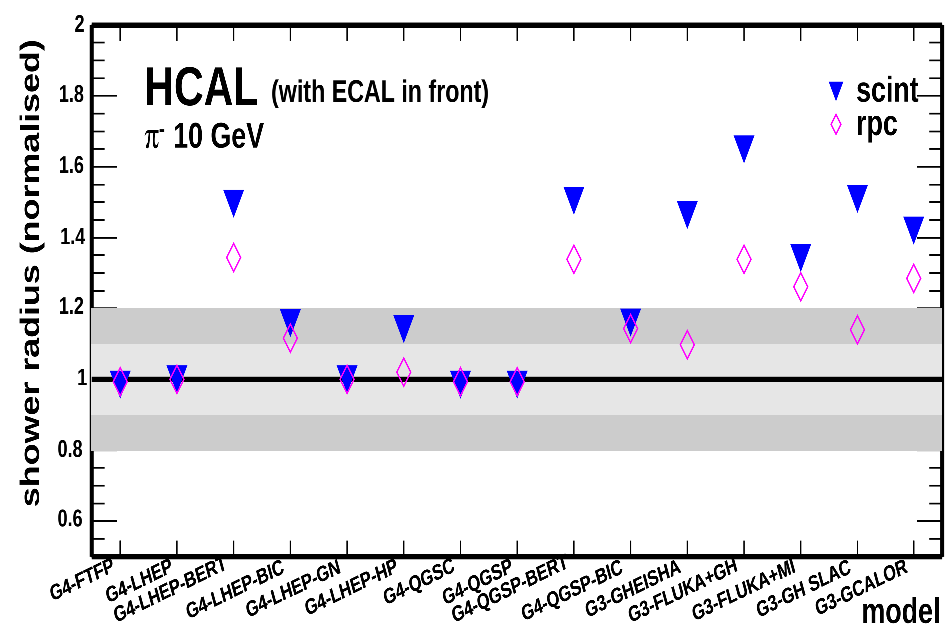

- ▷ different models predict different calorimeter response
- ▷ HCAL more sensitive than ECAL
- ▷ EM discrepancies between frameworks seen by ECAL

# HCAL scint - HCAL rpc

## N cells hit




## shower width




▷ **strong model dependent prediction of shower width**

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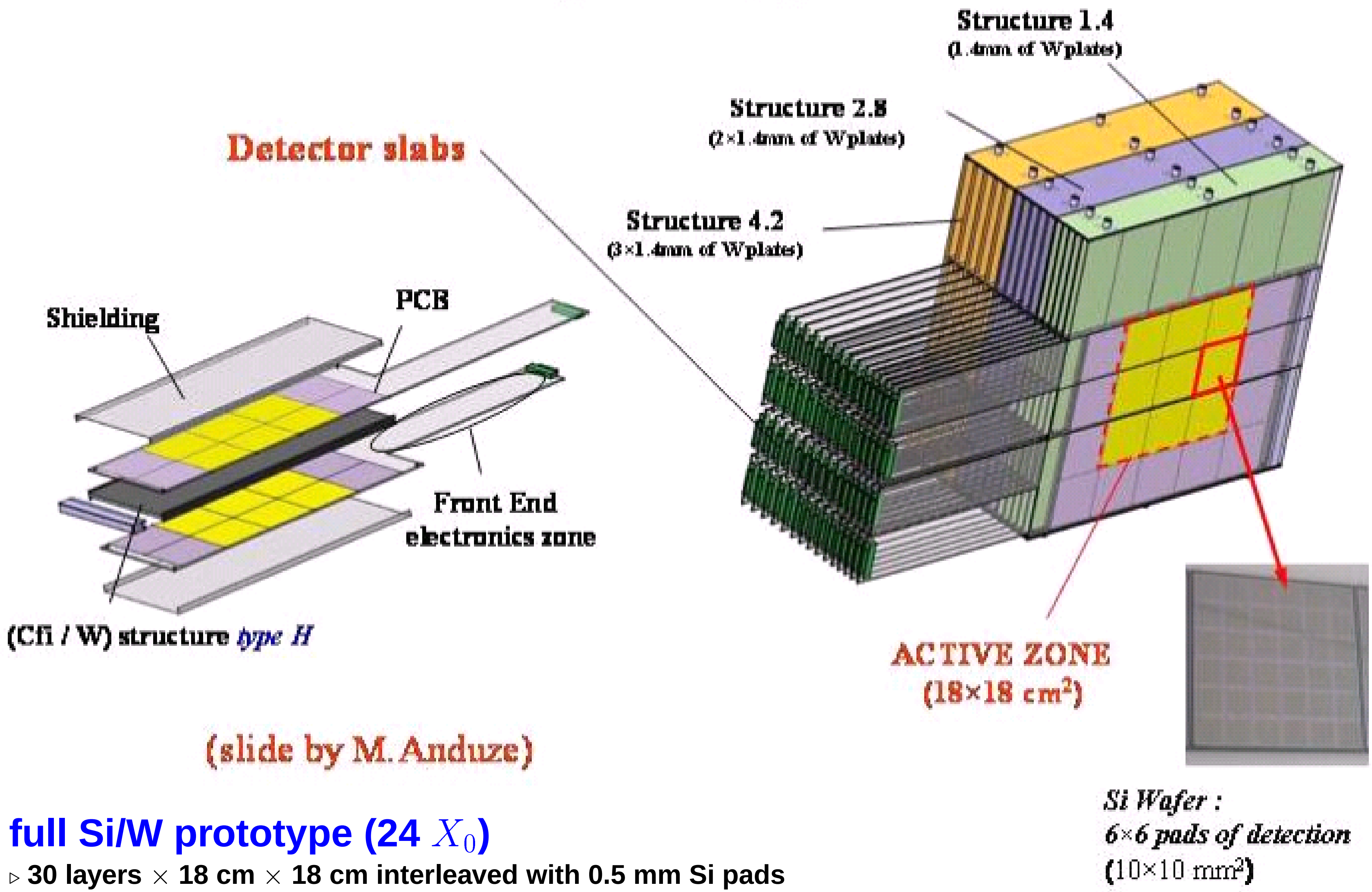
- High granularity calorimetry and CALICE
- **Si/W ECAL prototype, first results**
- Summary

# CALICE ECAL prototype




**full Si/W prototype (24 $X_0$)**

- **30 layers $\times$ 18 cm $\times$ 18 cm interleaved with 0.5 mm Si pads**
- **W absorber, 10+10+10 layers, 1.4 mm:2.8 mm:4.2 mm thick per respective layer**
- **readout by 1 $\times$ 1 cm$^2$ cells, total: 9720 channels**

# ECAL board

6 active wafers

- 36 silicon PIN diodes each $\longrightarrow$ 216 channels per board.
- Diode size: $1 \times 1\,\mathrm{cm}^2$.

Calibration chips

- 2 calibration switches chips.
- 6 calibration channels per chip.
- 18 diodes per calibration channel.

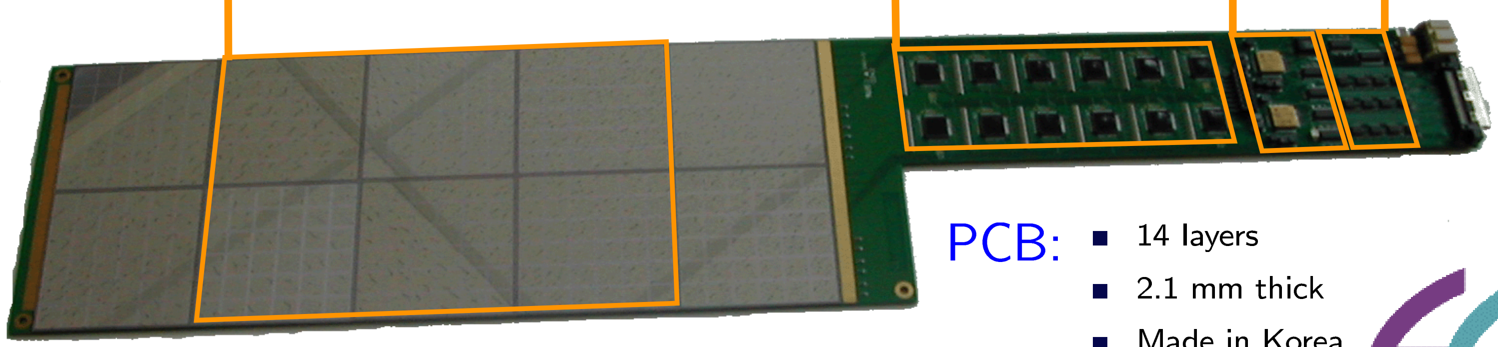
Line buffers

- To DAQ part
- Differential.

Front-End chip

12 FLC_PHY3 front-end chip

- 18 channels / chip
- 13 bit dynamic range



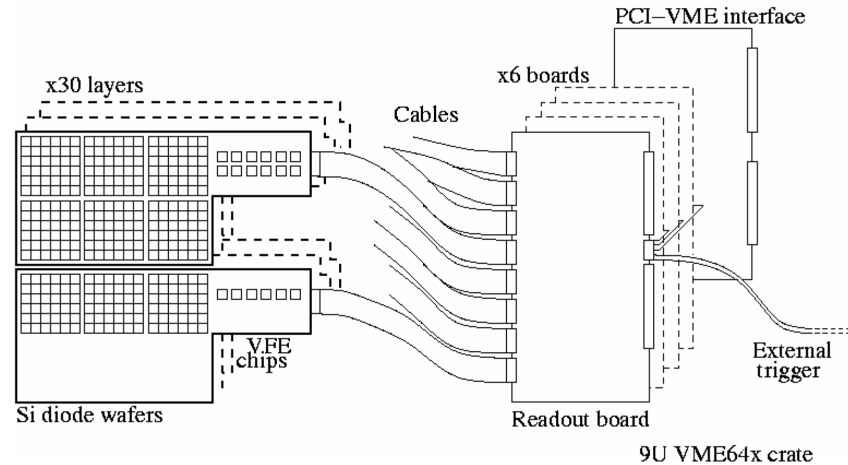
PCB:

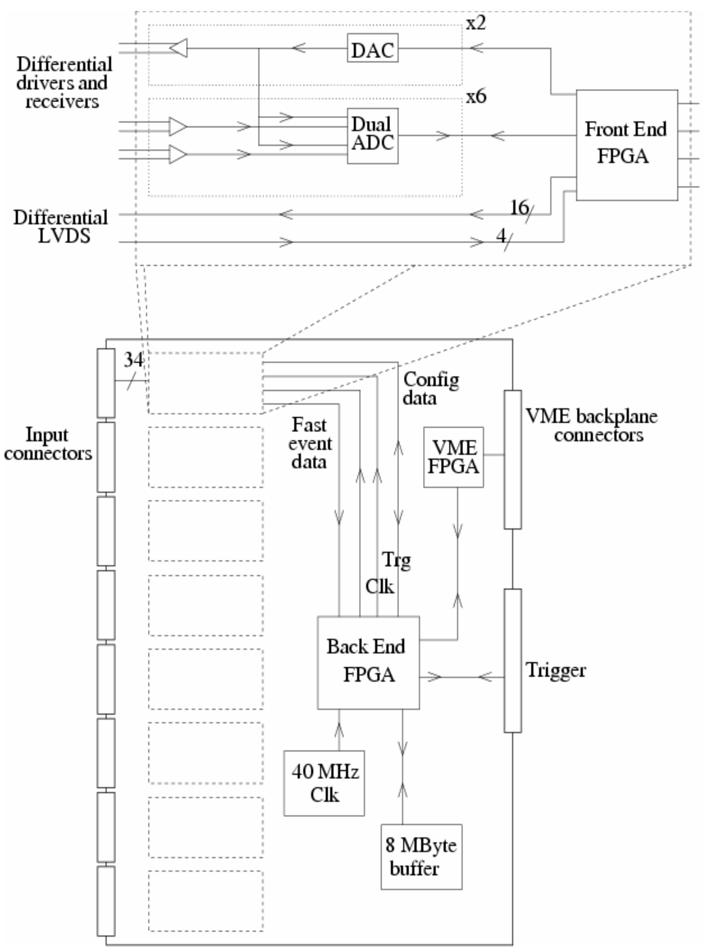
- 14 layers
- 2.1 mm thick
- Made in Korea

**(G.Gaycken)**

# CALICE readout card

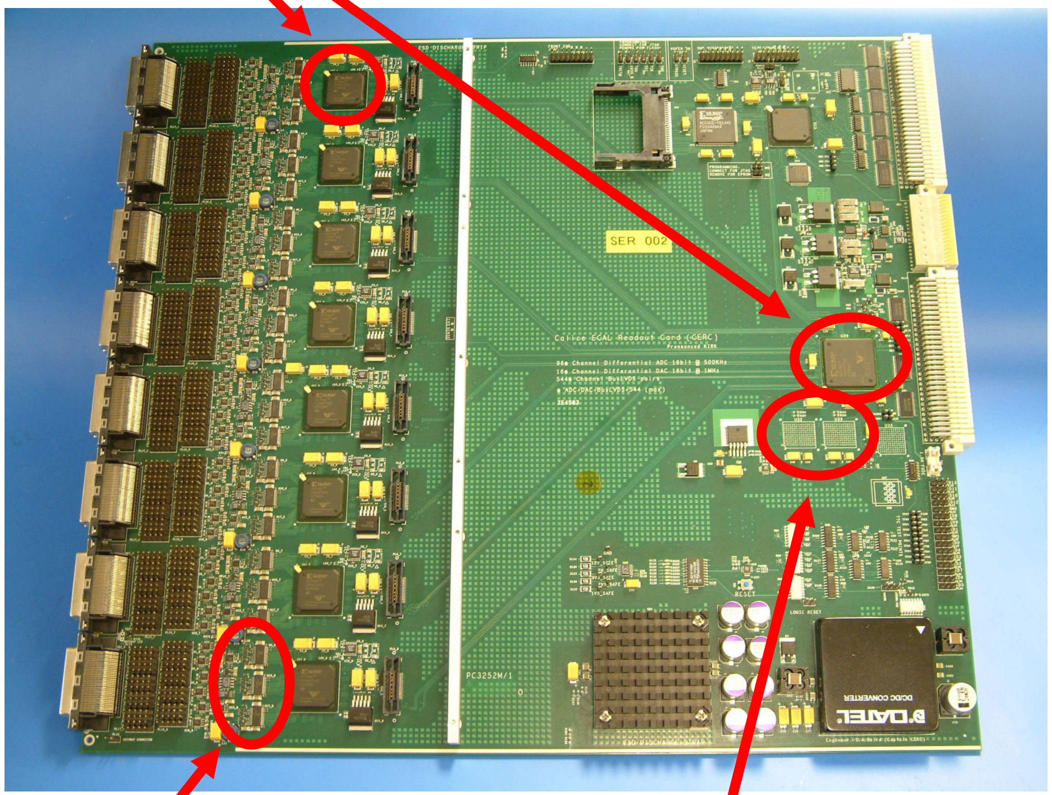
- Calice Readout Card (CRC) VME board
  - Modified CMS silicon tracker readout board
  - Does VFE PCB control, digitisation and data buffering
  - Also does trigger control




Virtex-II FPGAs

*Imperial/RAL/UCL*

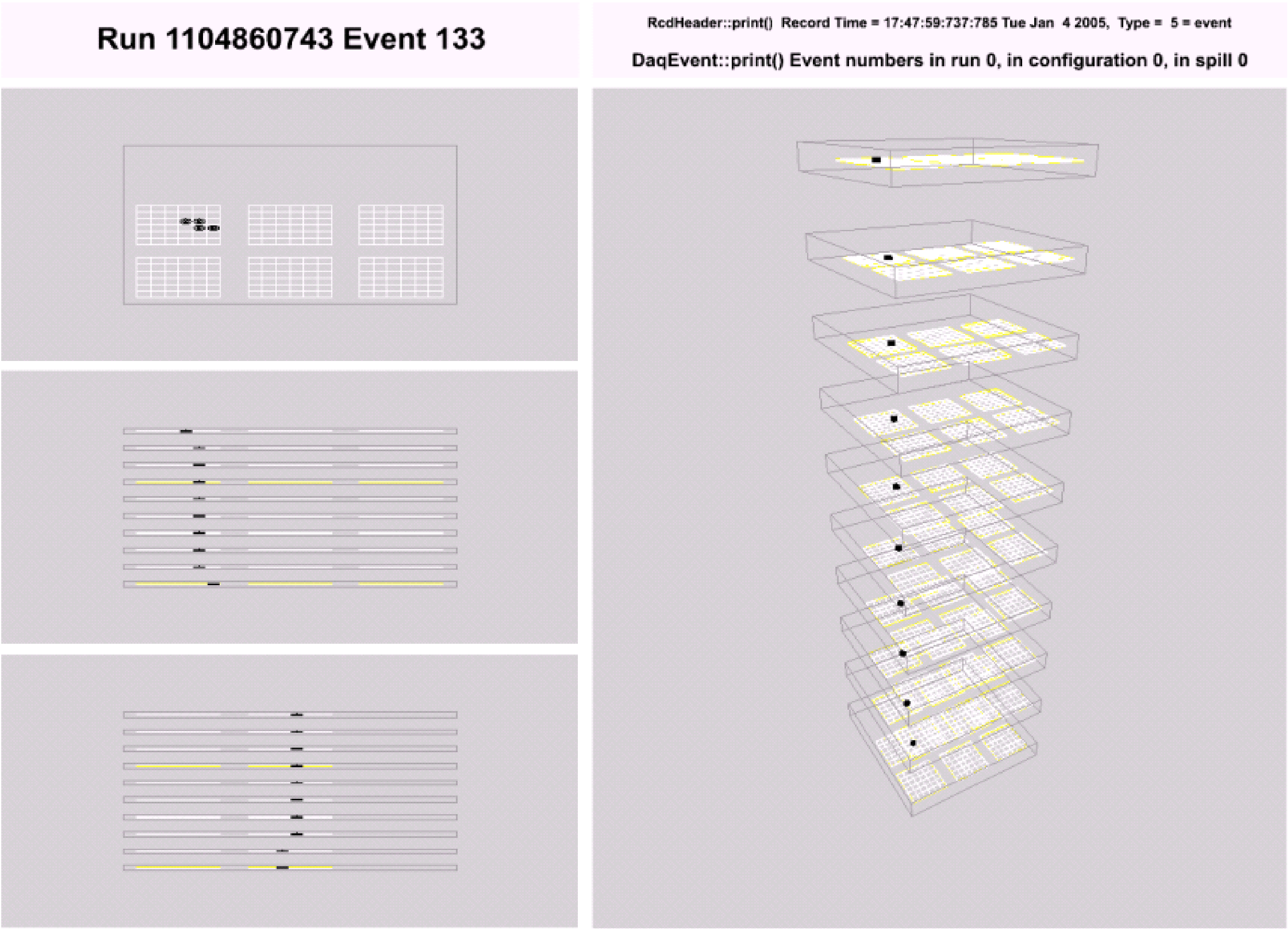


16-bit dual ADCs

8MByte buffer

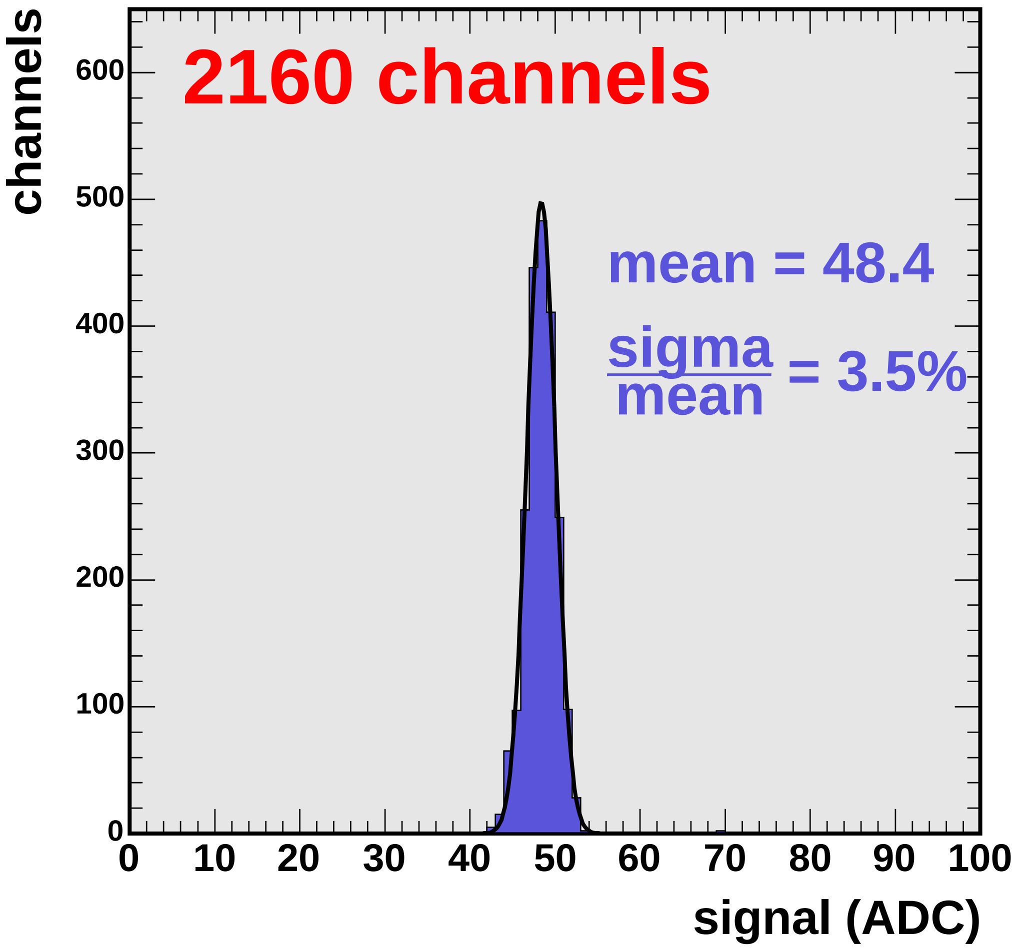
**(P.Dauncey)**

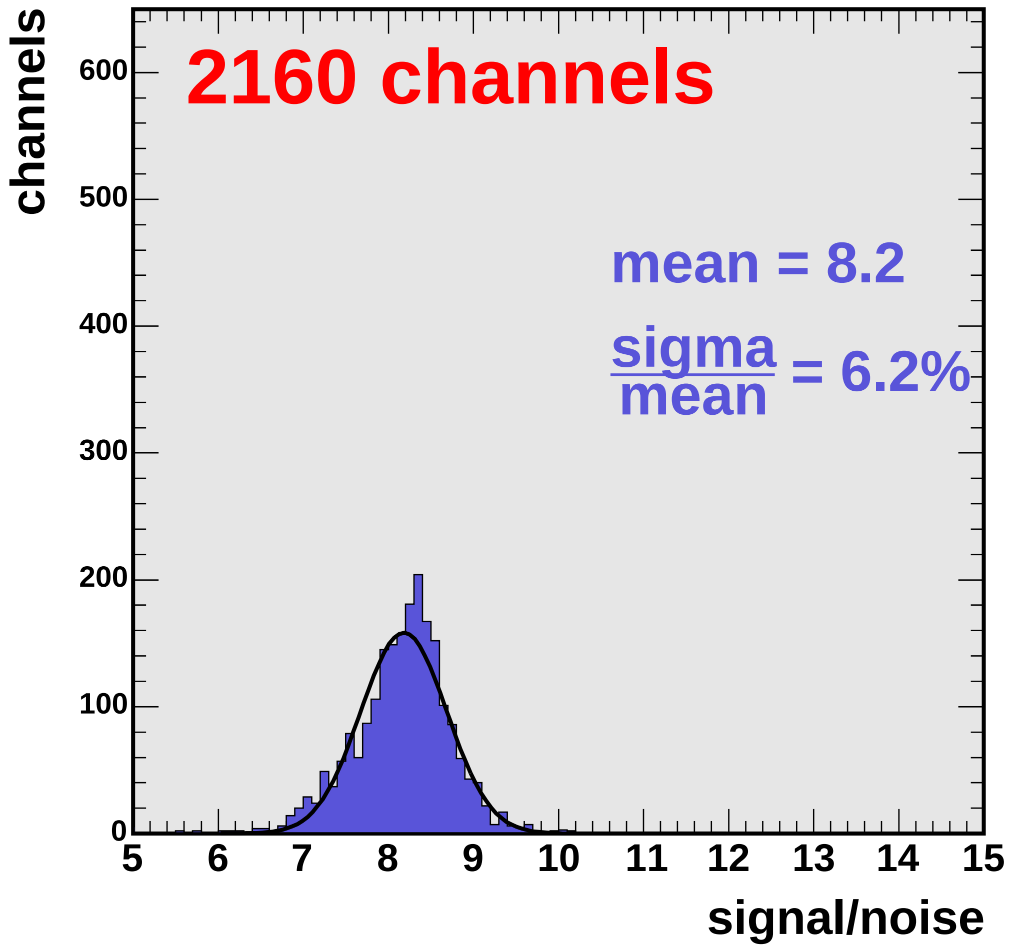
# Cosmics



Run 1104860743 Event 133
RcdHeader::print() Record Time = 17:47:59:737:785 Tue Jan 4 2005, Type = 5 = event
DaqEvent::print() Event numbers in run 0, in configuration 0, in spill 0

# Calibration with cosmics

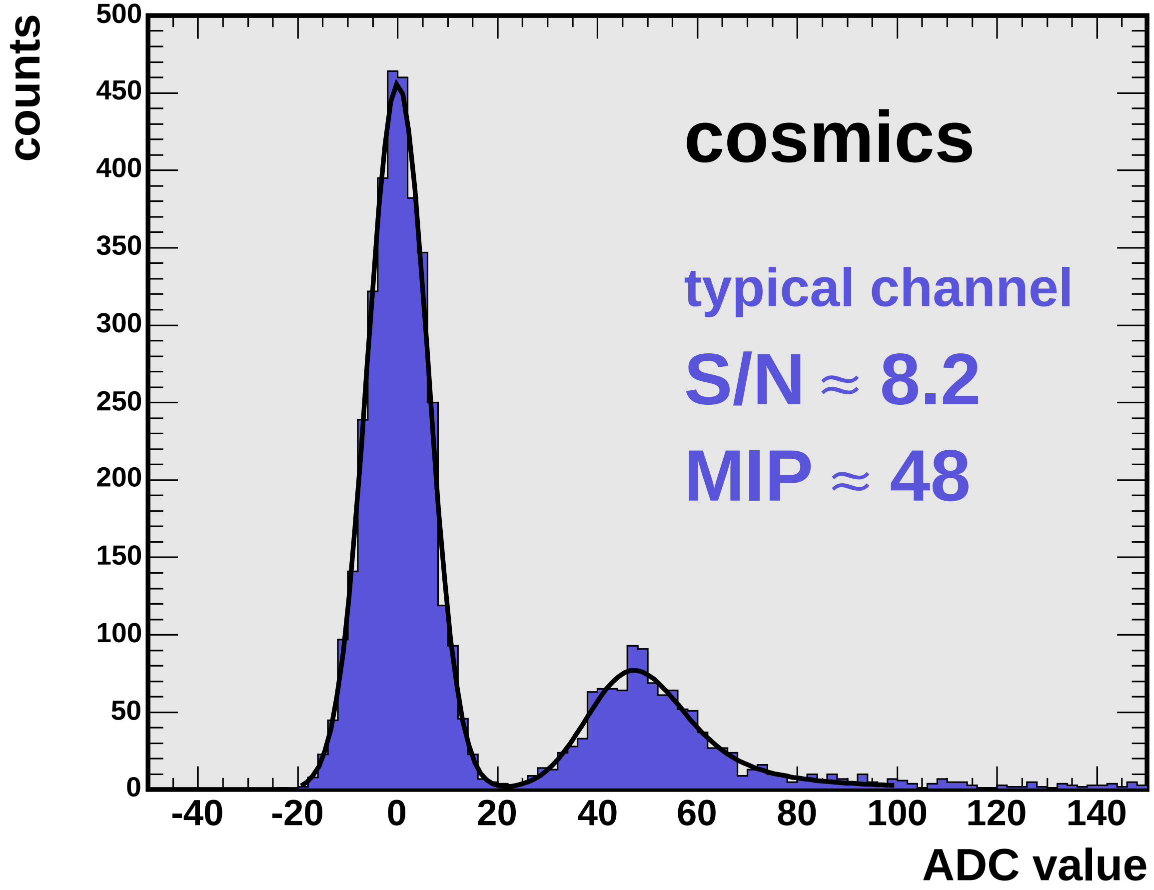



▷ **10 layers (2160 channels) calibrated with cosmics (1 Mevents)**

**(LLR-Paris, Dec04)**

# Calibration with cosmics




▷ a typical channel: gaussian noise, landau signal

# CALICE-ECAL testbeam at DESY

- **"30%" equipped Si/W prototype**

  : i.e. 14 W layers (10 at 1.4mm + 4 at 2.8mm) interleaved with $18 \times 12$ matrix of active Si cells, $1 \times 1$ cm$^2$ each,
  total: 3024 channels

  : first testbeam at DESY with electrons during Jan/Feb05

- **in summary (configurations: position $\times$ energy $\times$ angle)**

  : position scan (center - edge - corner of wafers)
  energy scan (mainly 1, 2, 3 GeV, some runs at 4, 5, 6 GeV)
  angle scan (0$^\circ$, 10$^\circ$, 20$^\circ$, 30$^\circ$)

  : total: $\sim$ 25 Mevents ($\sim$ 230 GB)

- **next round in Jan06 with more layers-channels**

# In brief

- **"1/3" of CALICE Si/W ECAL prototype**

  : 3024 channels of 1 $\times$ 1 cm$^2$, 7.2 $X_0$

  : first testbeam at DESY with $e^-$ (Jan/Feb05), a lot of data collected

- **data analysis**

  : in progress, mostly qualitative for basic understanding and debugging of the system

  : quantitative analysis still possible

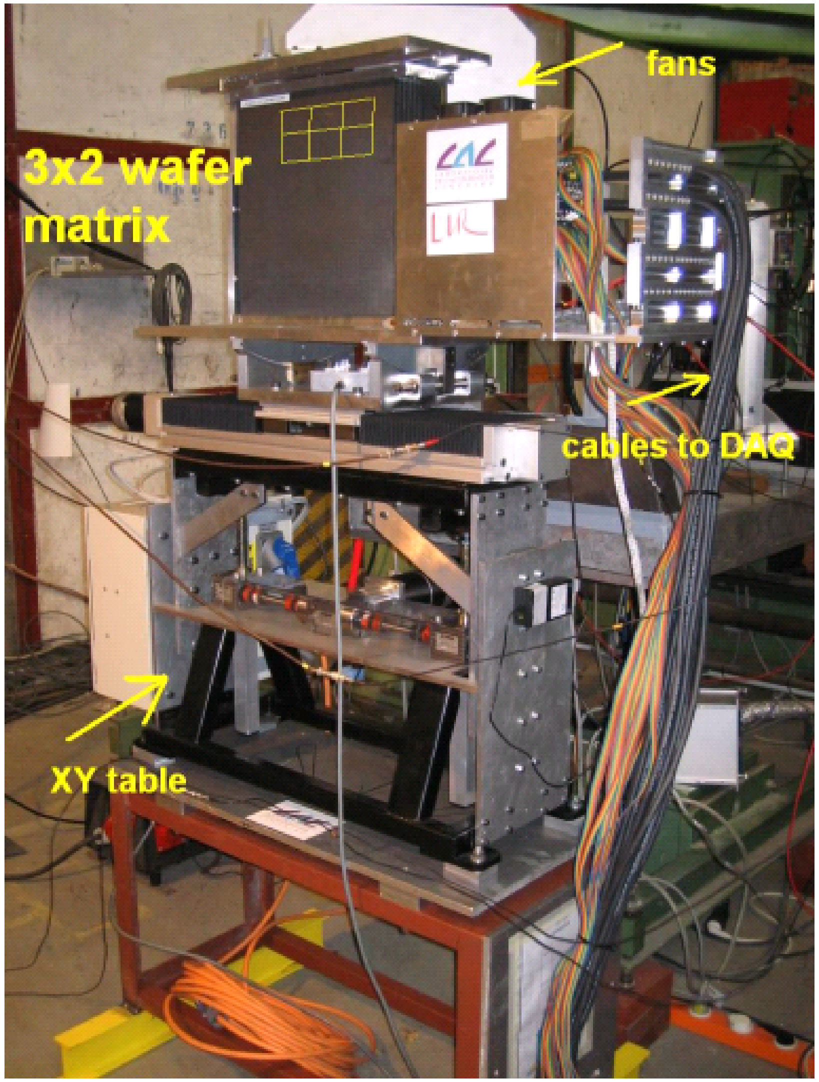
  ▷ useful for planning and guiding the next testbeam

  ▷ results indicative of detector characteristics

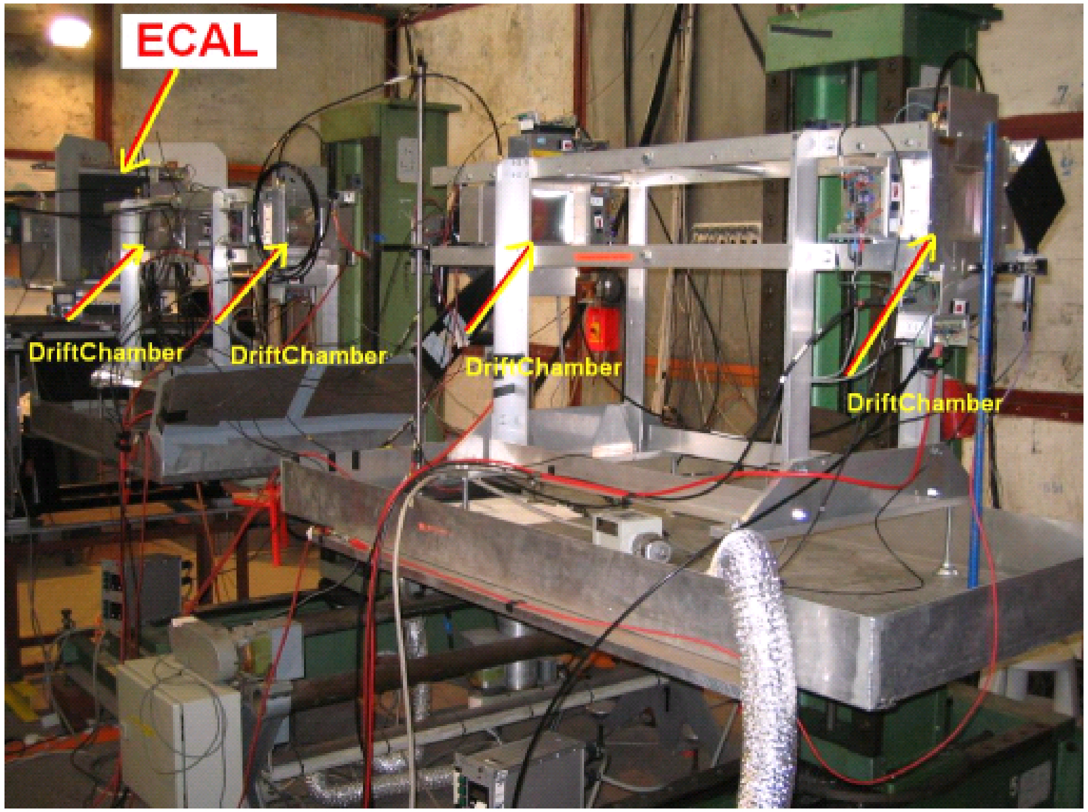
  ▷ pilot-reference studies to be repeated as detector grows

# CALICE-ECAL testbeam at DESY

## ECAL

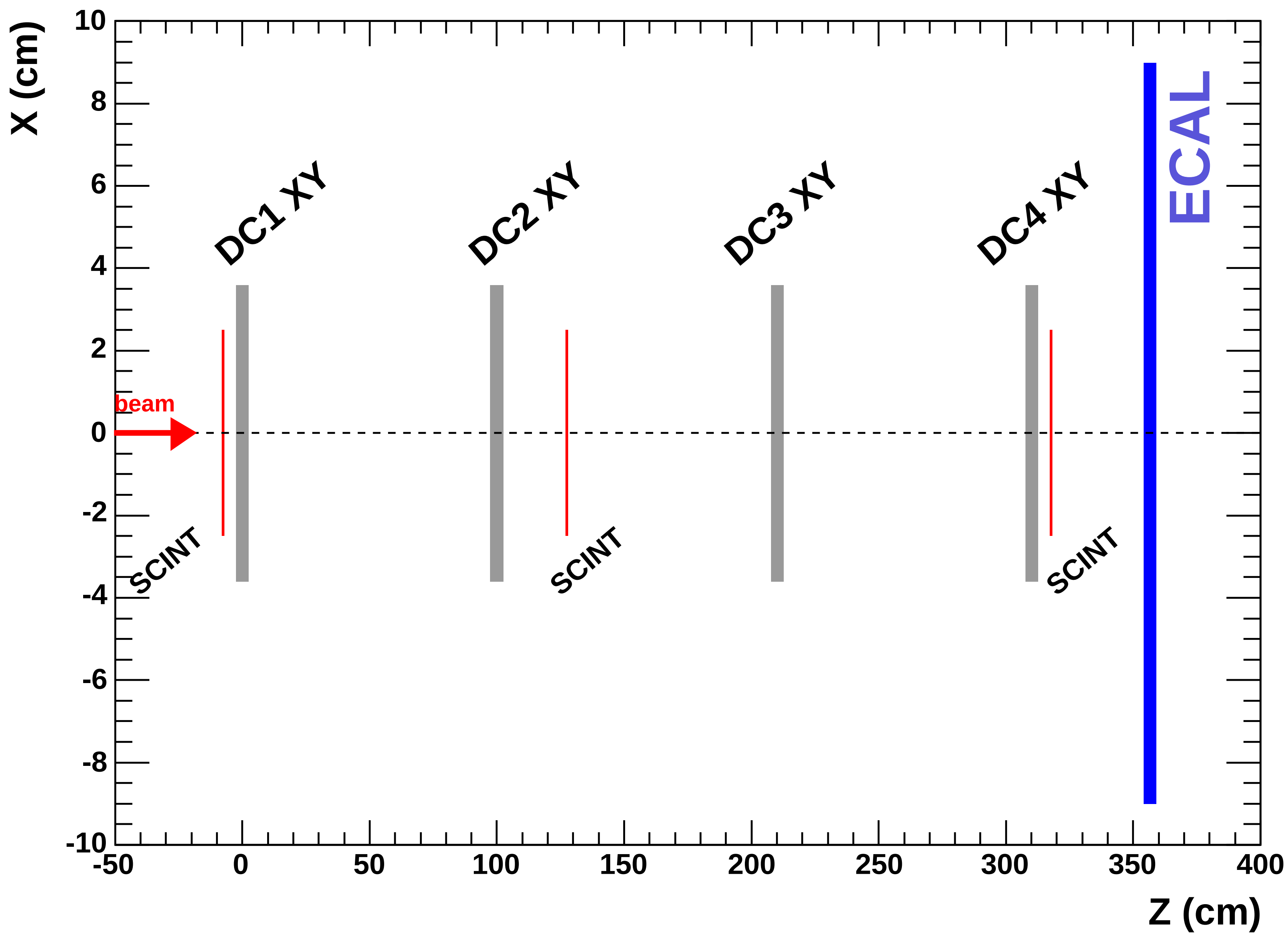



## layout at DESY T21

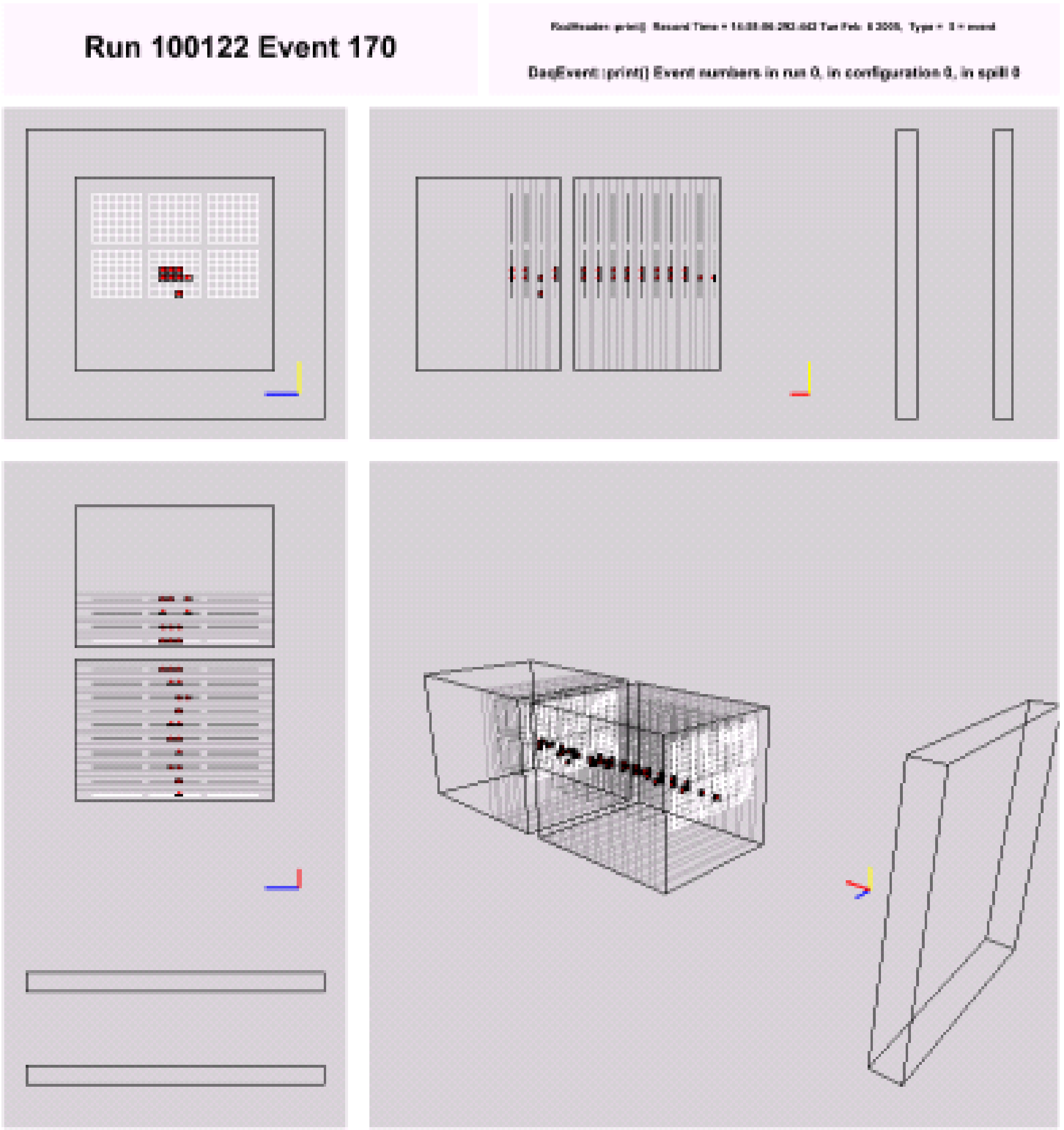



**DriftChambers and installation courtesy of Tsukuba Univ. and Kobe Univ.**

# Testbeam layout



# "Tracking Calorimetry"

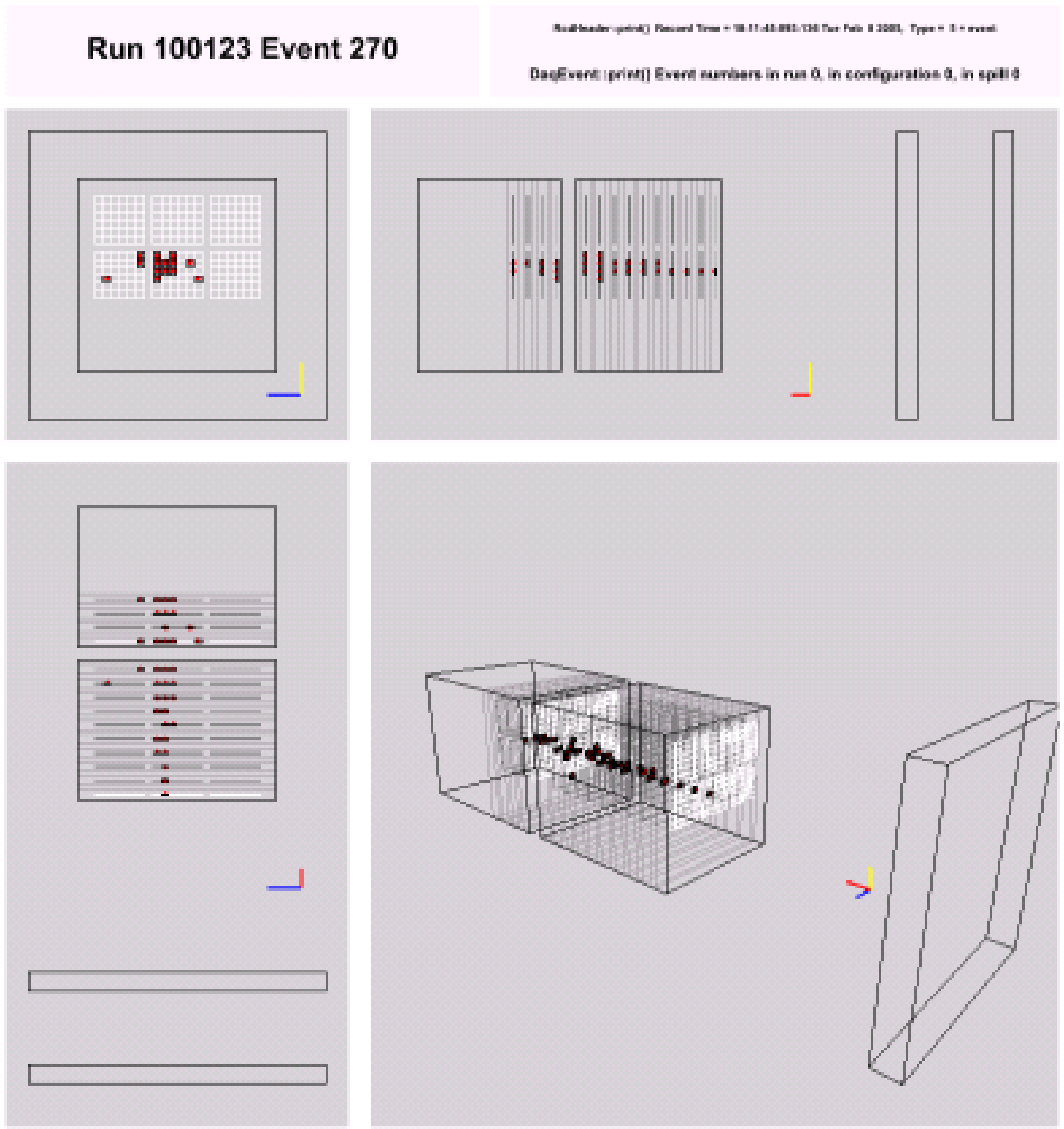



(not to scale)

**$e^-$ 1 GeV**

**cell threshold = 0.5 mip**

# "Tracking Calorimetry"

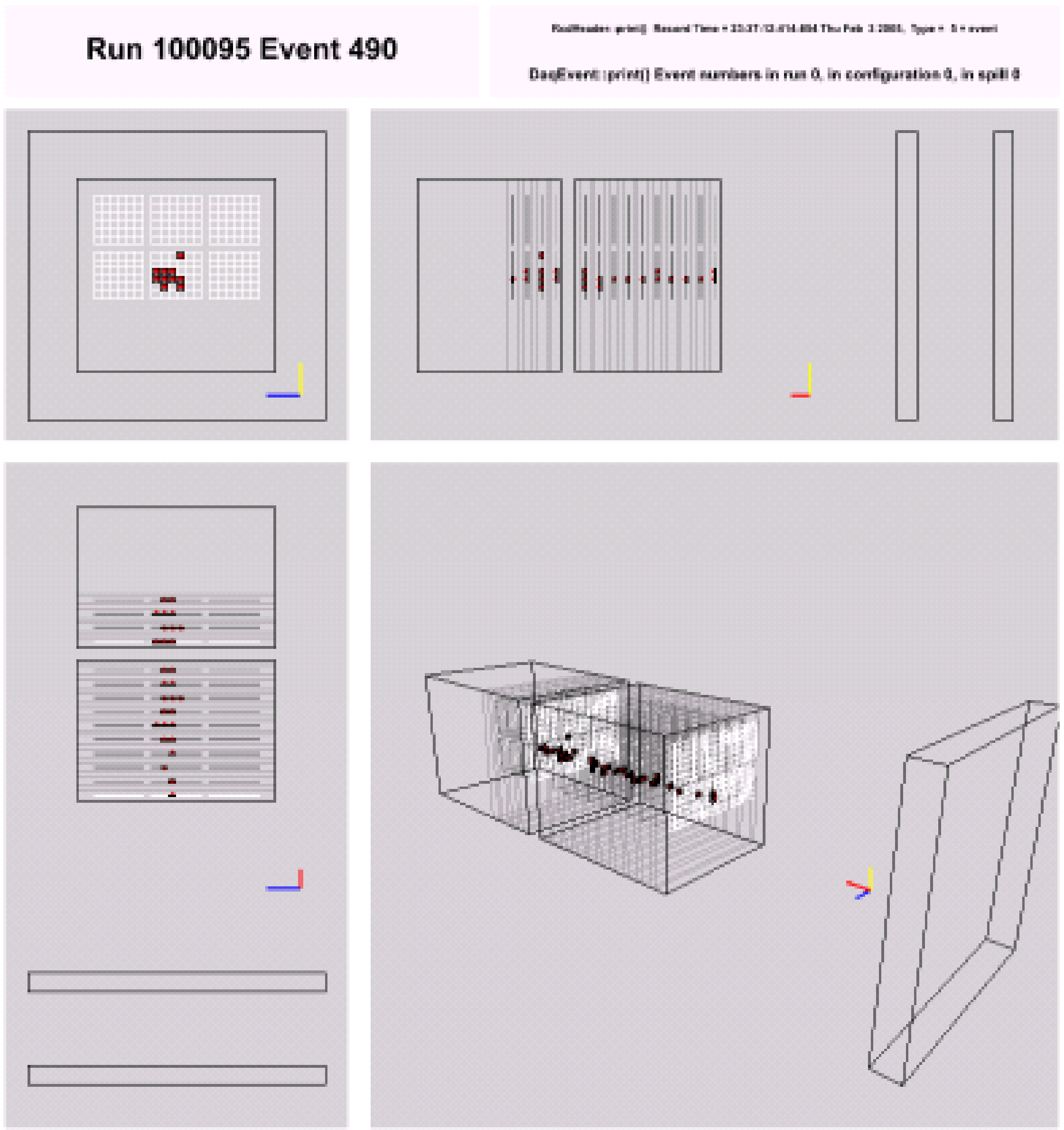



(not to scale)

**$e^{-}$ 2 GeV**

**cell threshold = 0.5 mip**

# "Tracking Calorimetry"

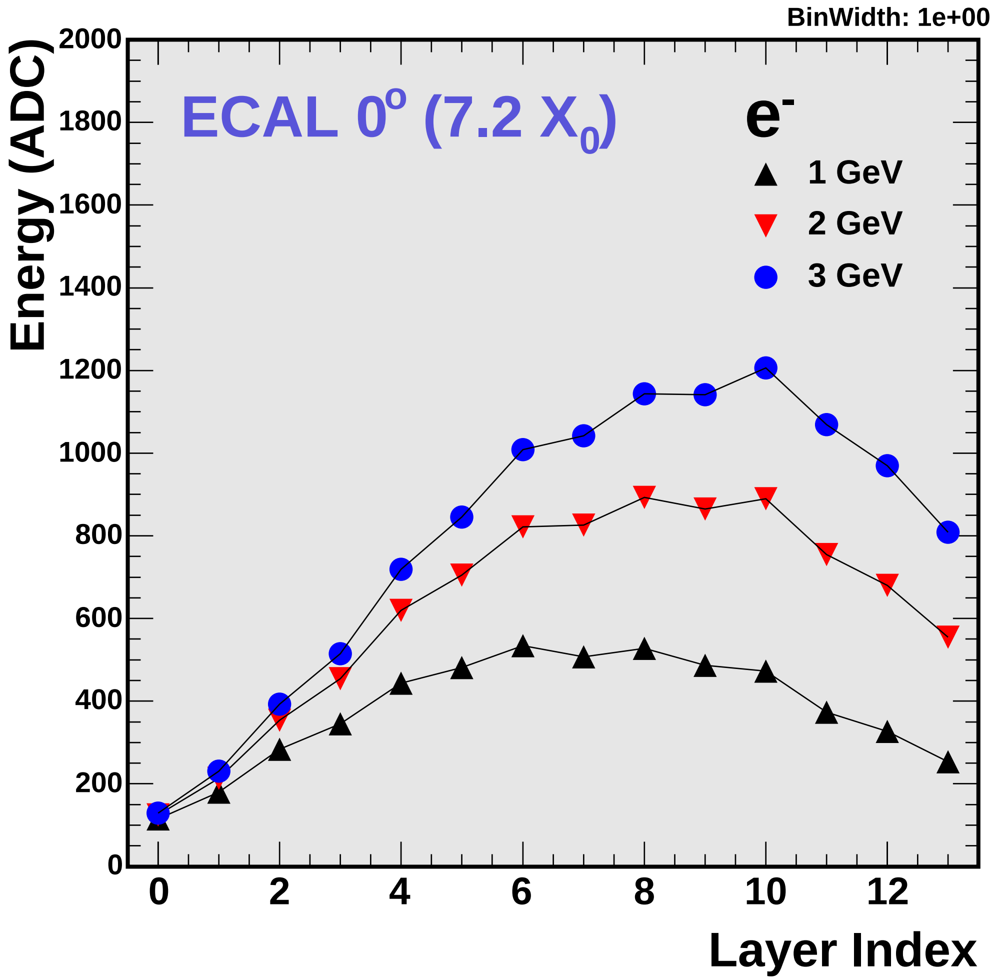


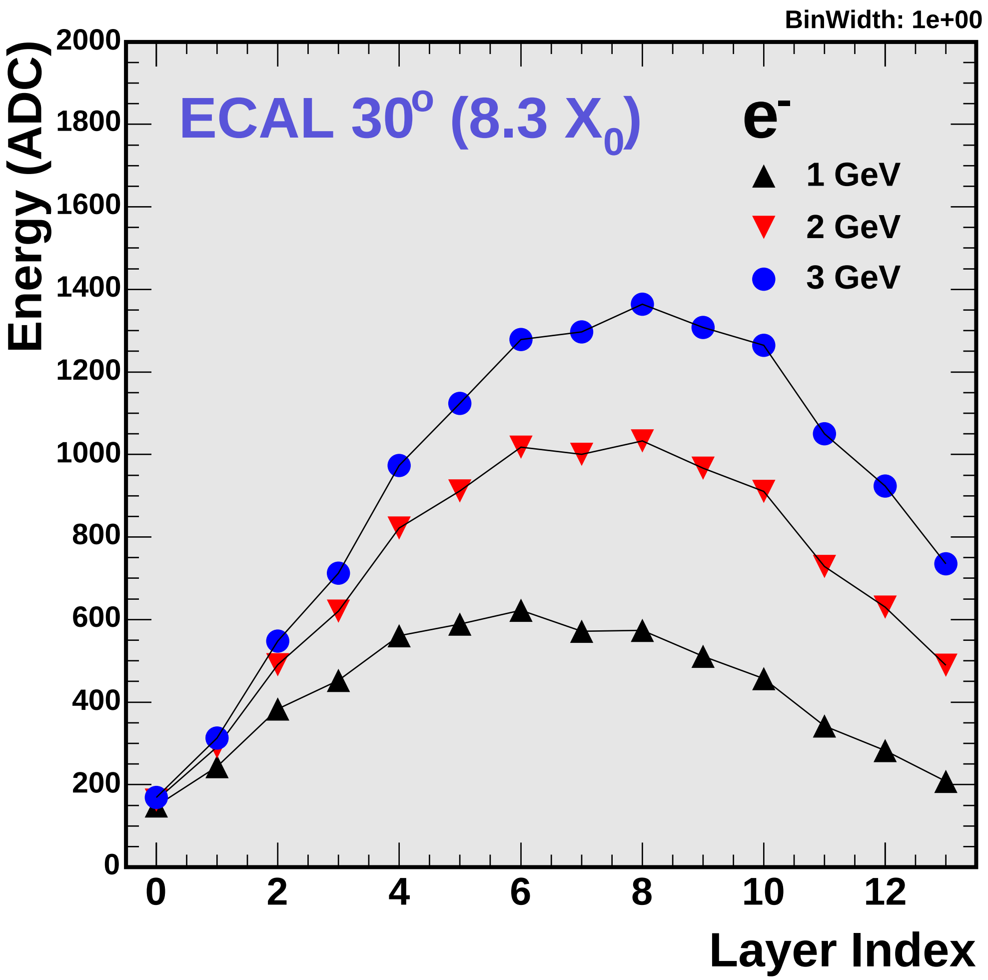

(not to scale)

**$e^-$ 3 GeV**

**cell threshold = 0.5 mip**

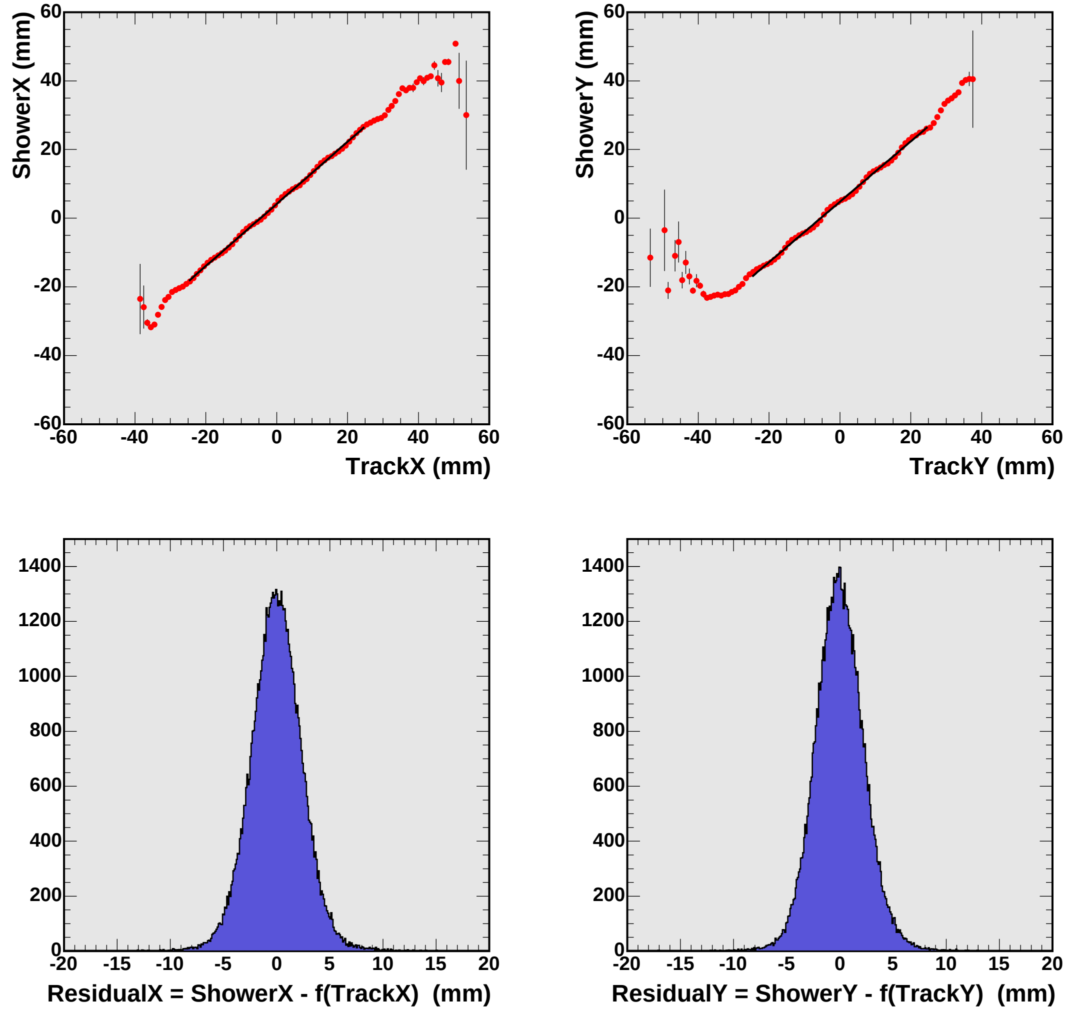
# Shower longitudinal profile



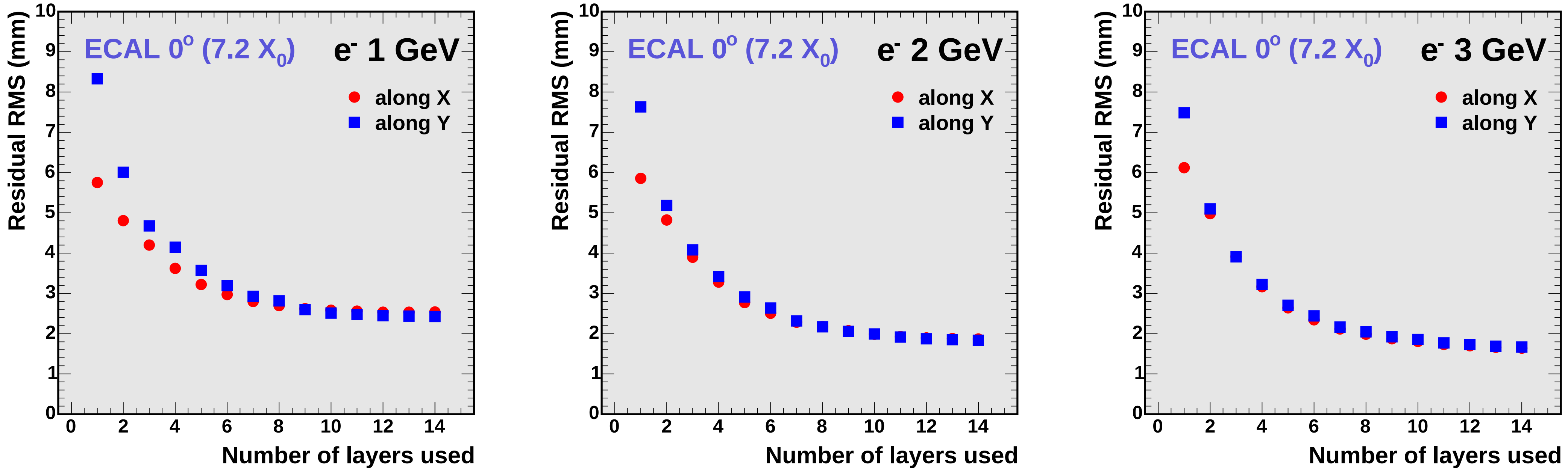

- **shower maximum is contained**
- **odd/even asymmetry of construction observed**
- **showers better contained at 30°**

# Tracking - Residuals



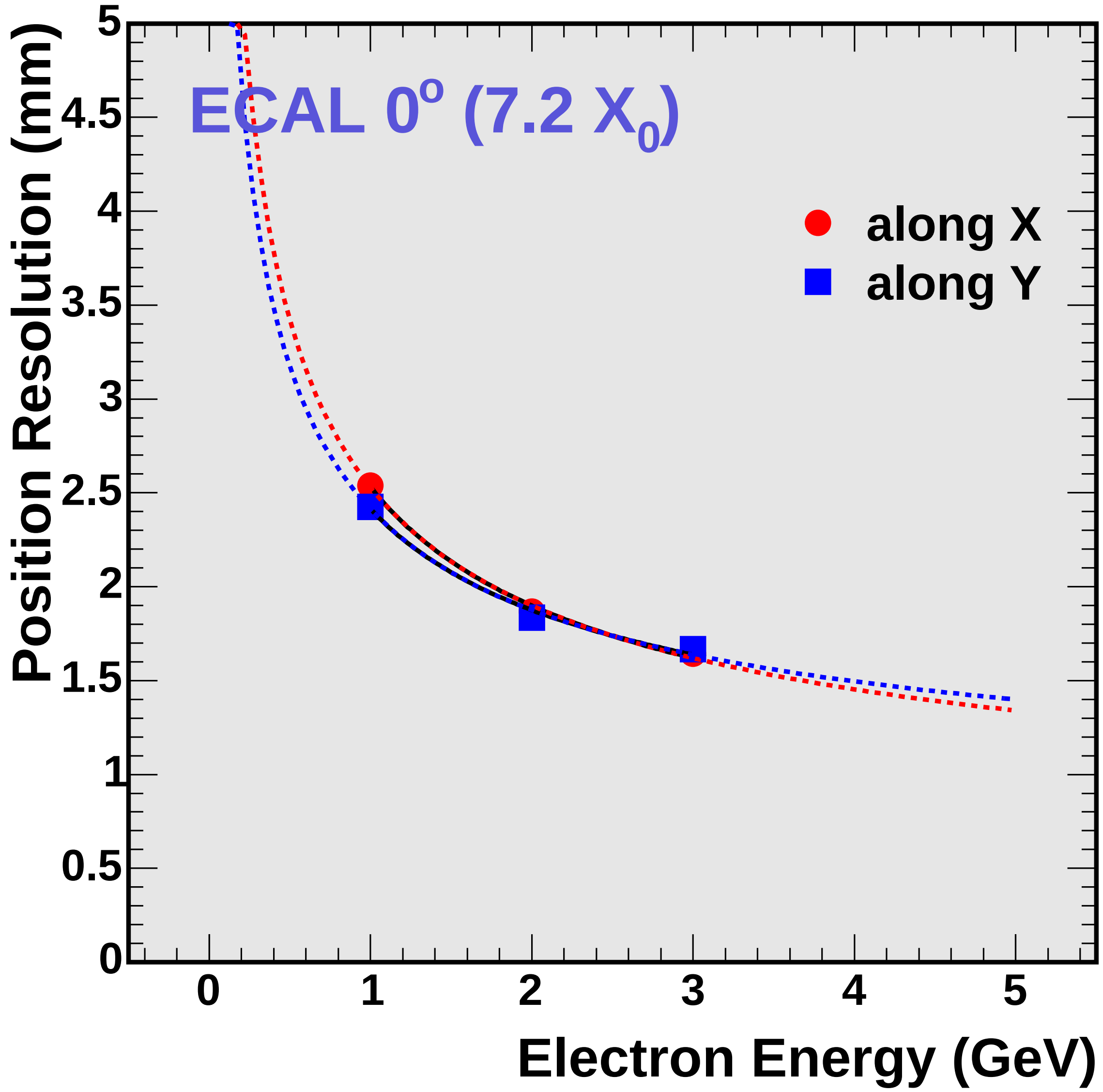

- ShowerX,Y from barycenter in ecal
- TrackX,Y from 4 drift chambers

# Position resolution



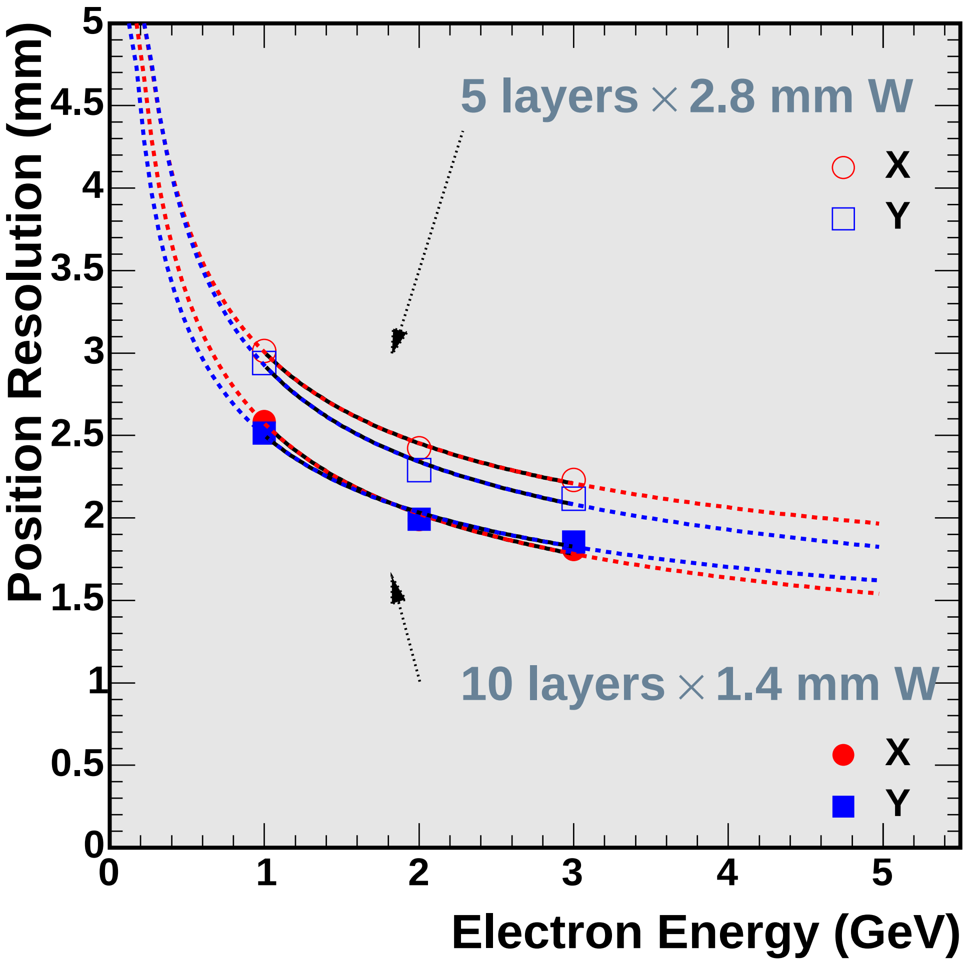

▷ **Residual RMS as a function of the number of ecal layers used**

# Position resolution



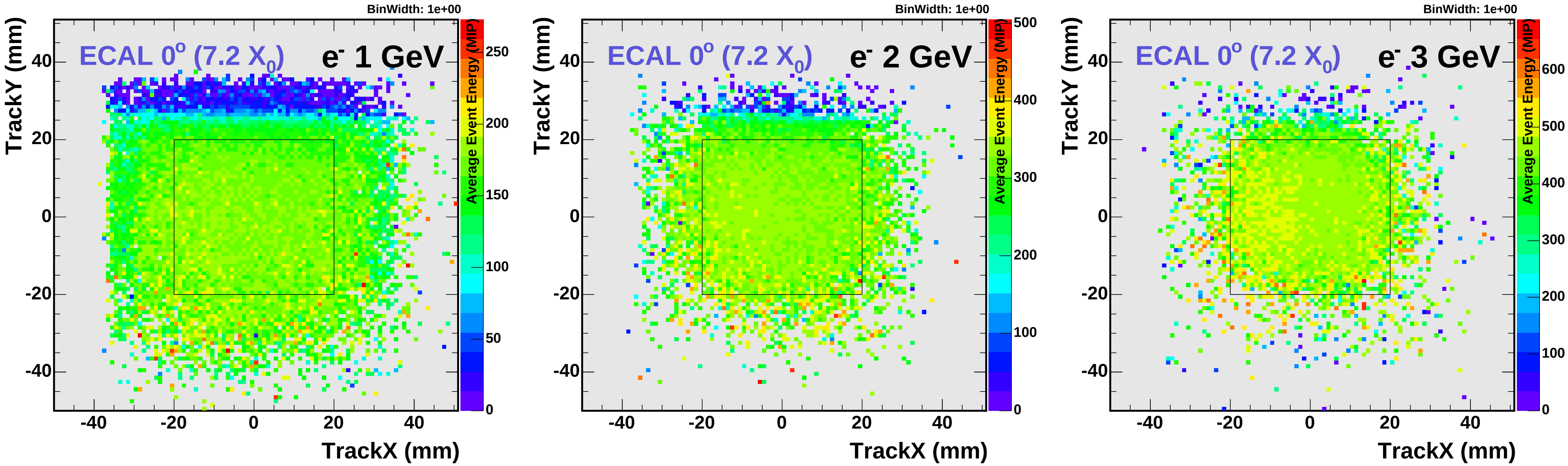

▷ **highly granular ECAL** ⟶ **excellent position resolution**

# Position resolution - undersampling

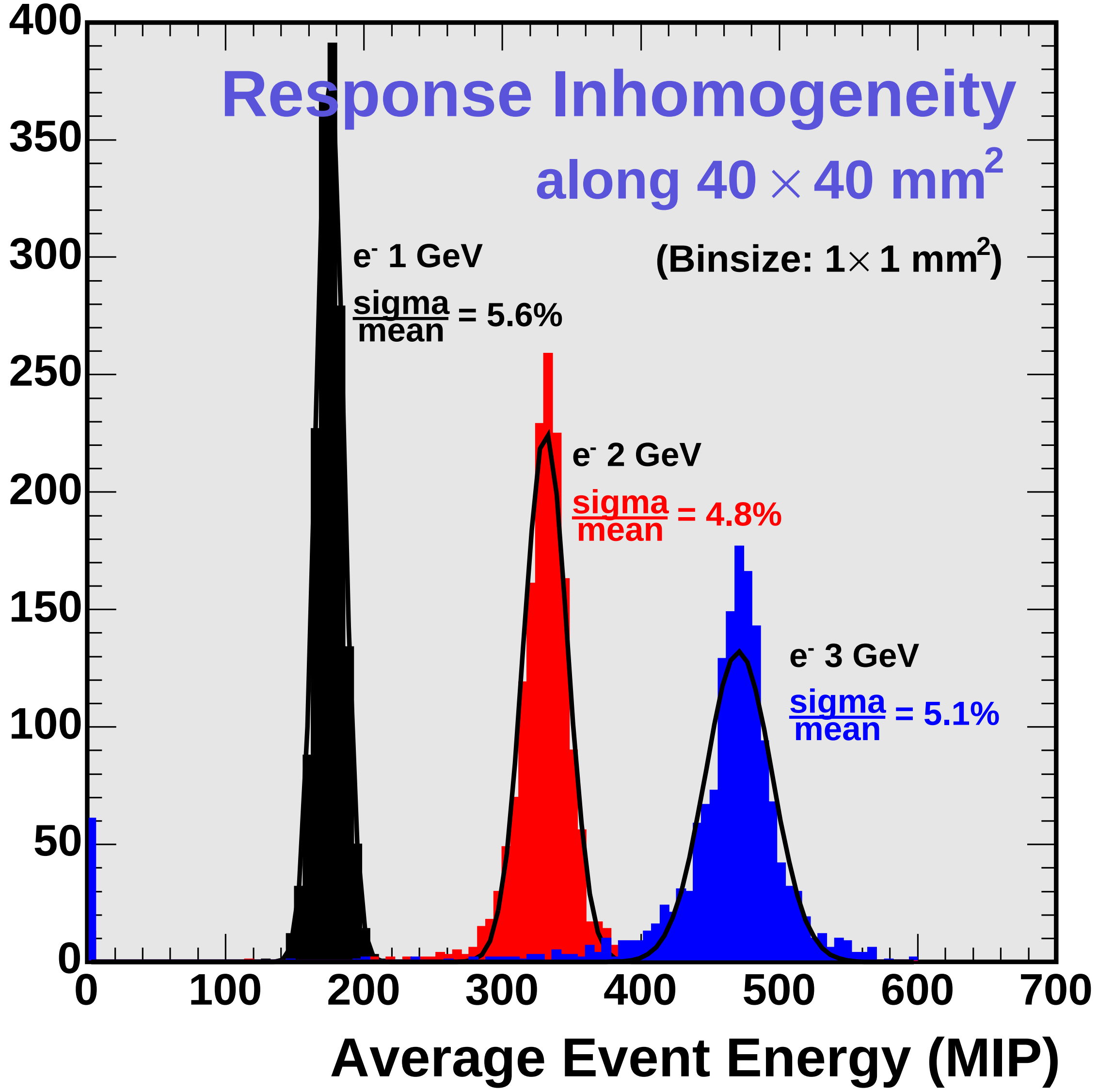



- do tracking by using only hits from every 2nd layer
- to investigate the tracking performance of an ecal with 5 layers × 2.8 mm W
  (instead of 10 layers × 1.4 mm W)
- expect position resolution to degrade by factor $\frac{\sigma_5}{\sigma_{10}} \approx \frac{\sqrt{10}}{\sqrt{5}}$

# Response map - center of wafer

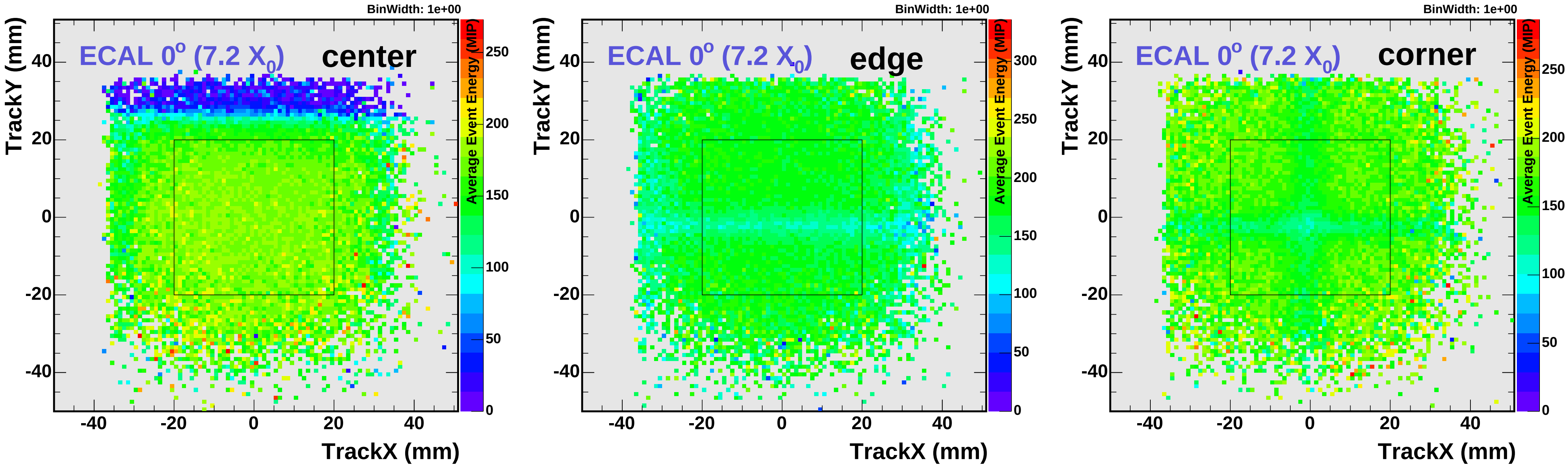


# Response Inhomogeneity

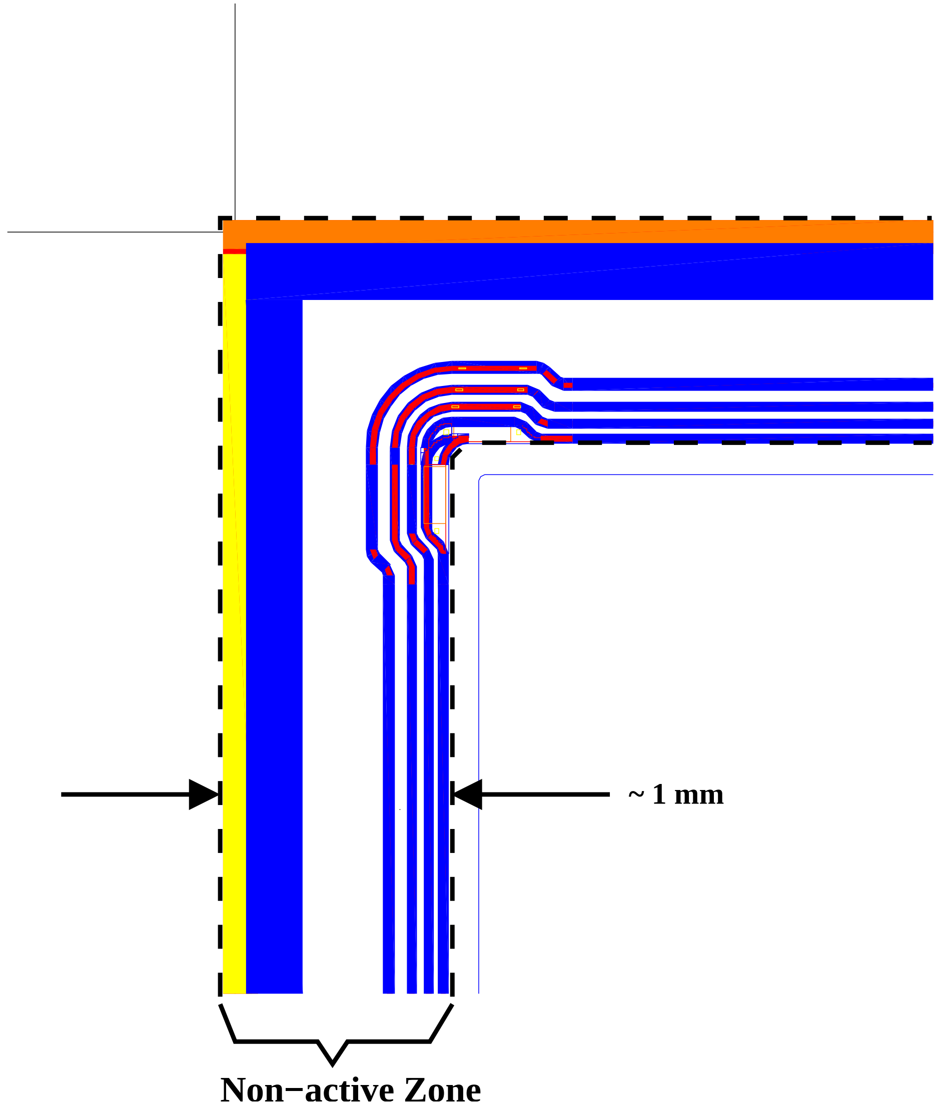



▷ **response variation around the center of wafer**

# Response map - center/edge/corner of wafer

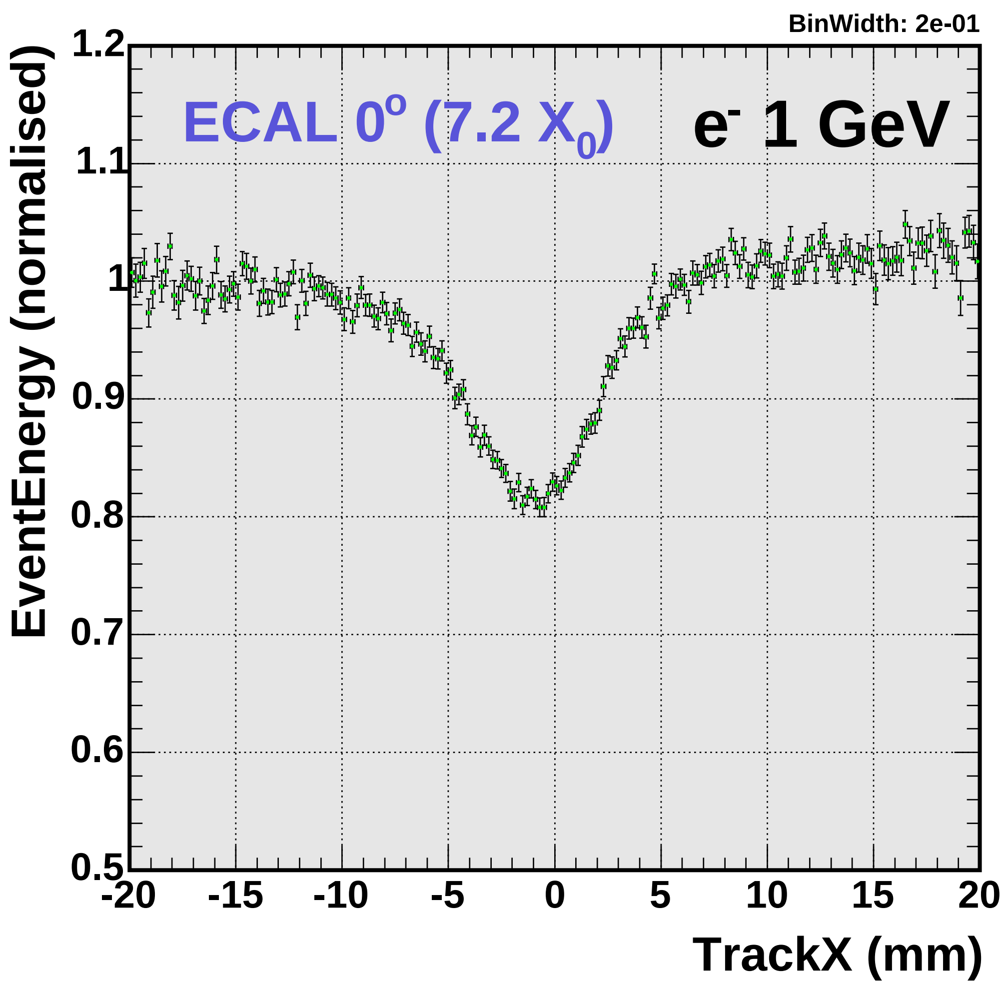


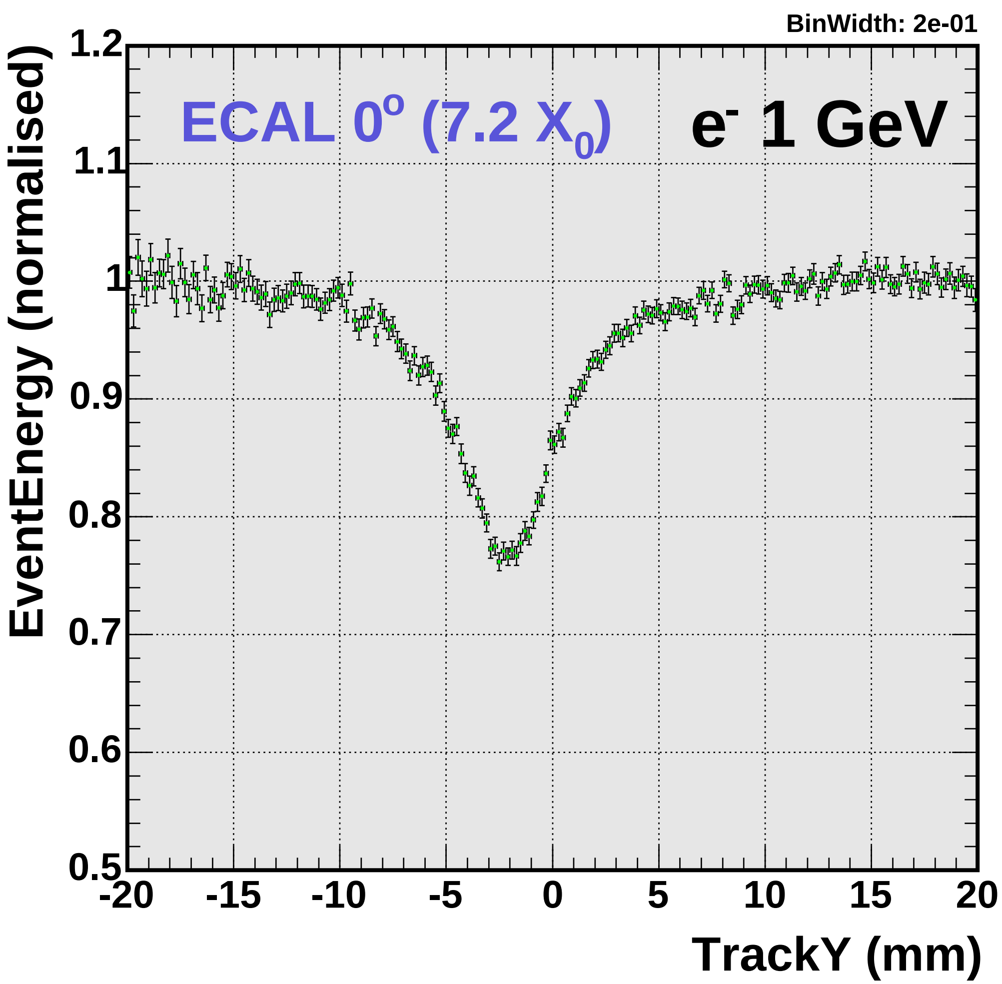
# Wafer border




▷ **(C.LoBianco, LC-DET-2004-007)**

# Position scan along wafer borders

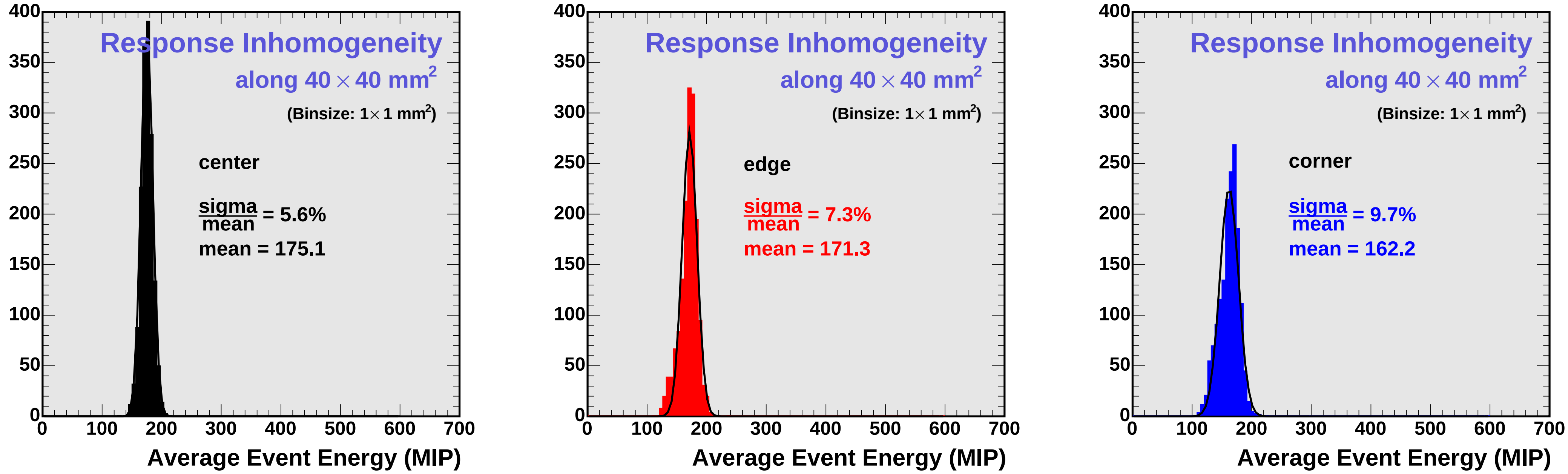



- ▷ **alternate layers staggered along X (by 2.5 mm)**
- ▷ **dip is shallower and wider**

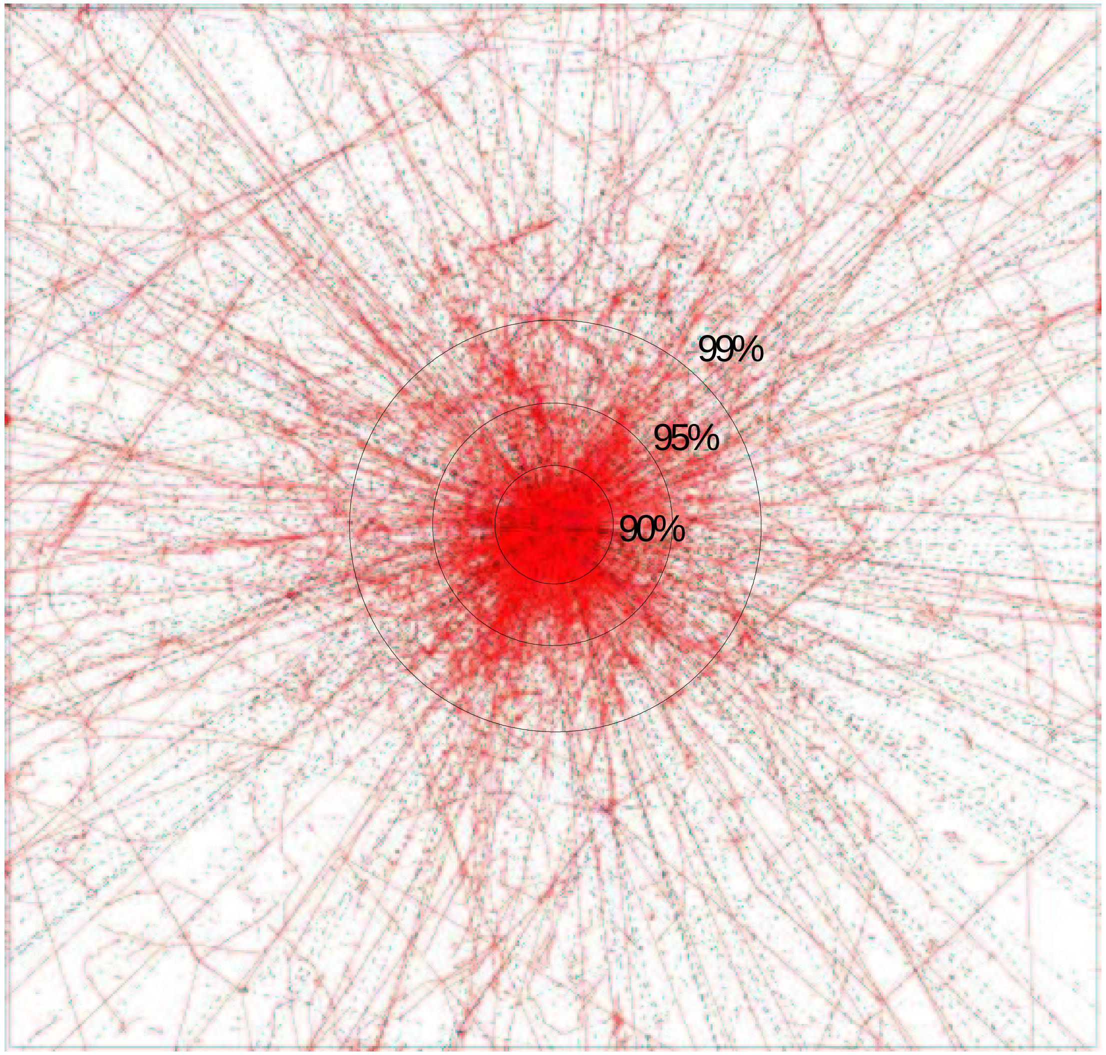
- ▷ **layers not staggered along Y**
- ▷ **dip is deeper and narrower**

# Response Inhomogeneity

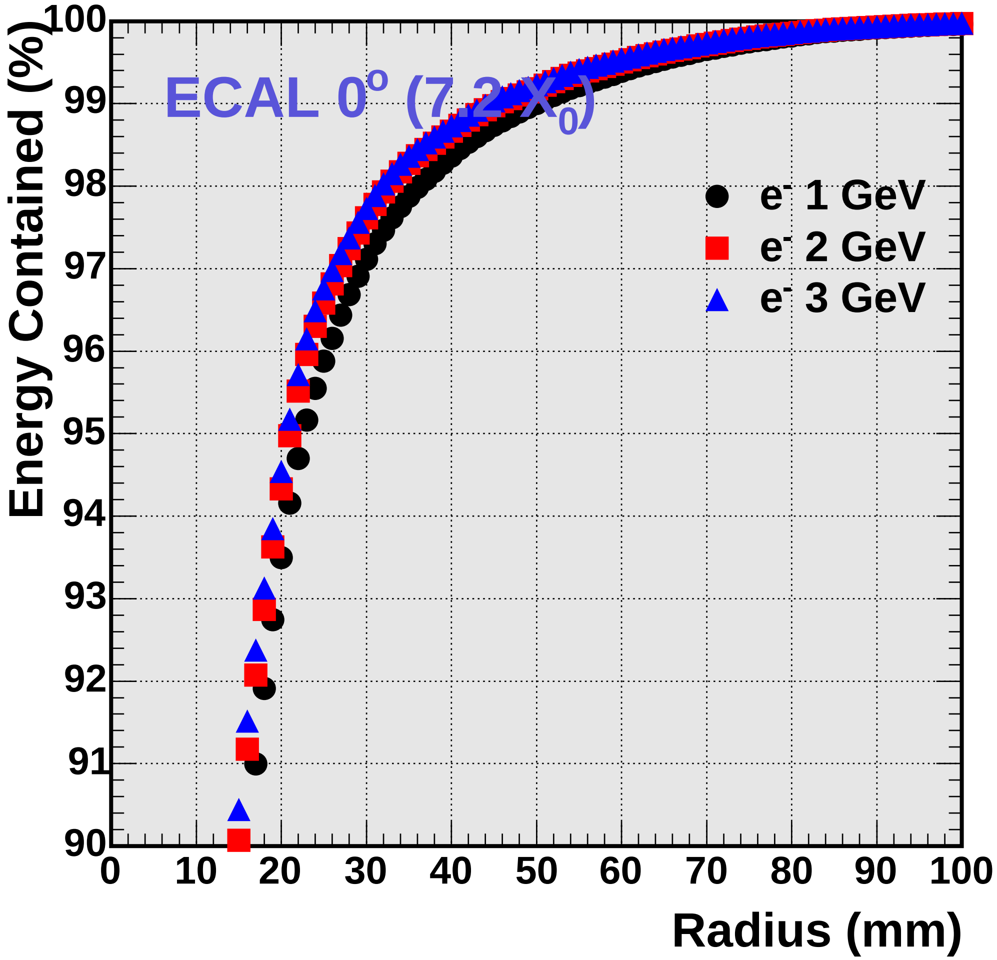


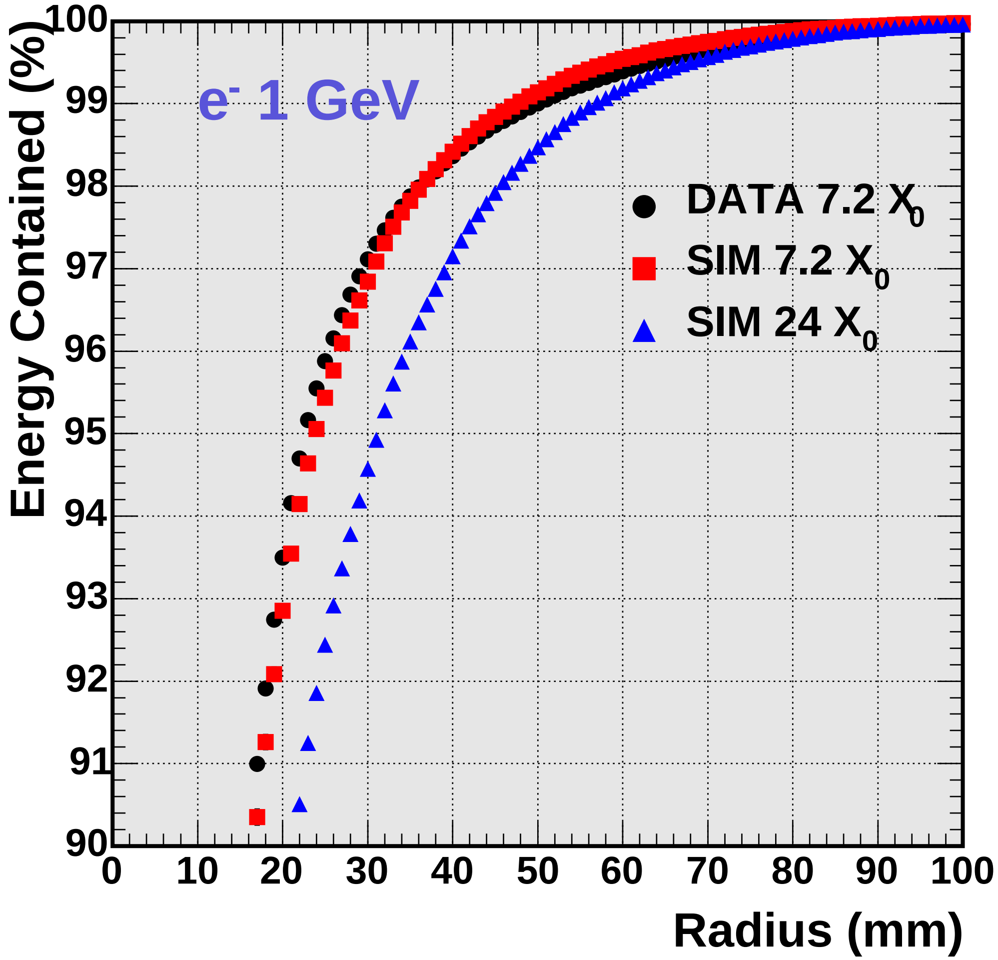

▷ **response variation around the center/edge/corner of wafer**

# Moliere radius



# Transverse containment (Moliere radius)




▷ **e.g. 1 GeV $e^-$ shower "contained" at**

| | | |
|---|---|---|
| : 90% | within radius | 16 mm |
| : 95% | | 23 mm |
| : 99% | | 50 mm |

▷ **data-simulation comparison**

▷ **results expected for the 24 $X_0$ prototype**

REMINDER: for an infinitely long and wide calorimeter

| | | |
|---|---|---|
| shower contained at | 90% | within radius $\sim 1\ R_M$ |
| | 95% | $\sim 2\ R_M$ |
| ( for solid W, $R_M \simeq 10$ mm ) | 99% | $\sim 3.5\ R_M$ |

# Status and Outlook

- **Si/W ECAL prototype**

  : first testbeam at DESY with $e^-$ (Jan/Feb05),
  a lot of data collected, analysis in progress

- **analogue HCAL**

  : in final stage of construction,
  first testbeam expected in summer 2006

- **digital HCALs**

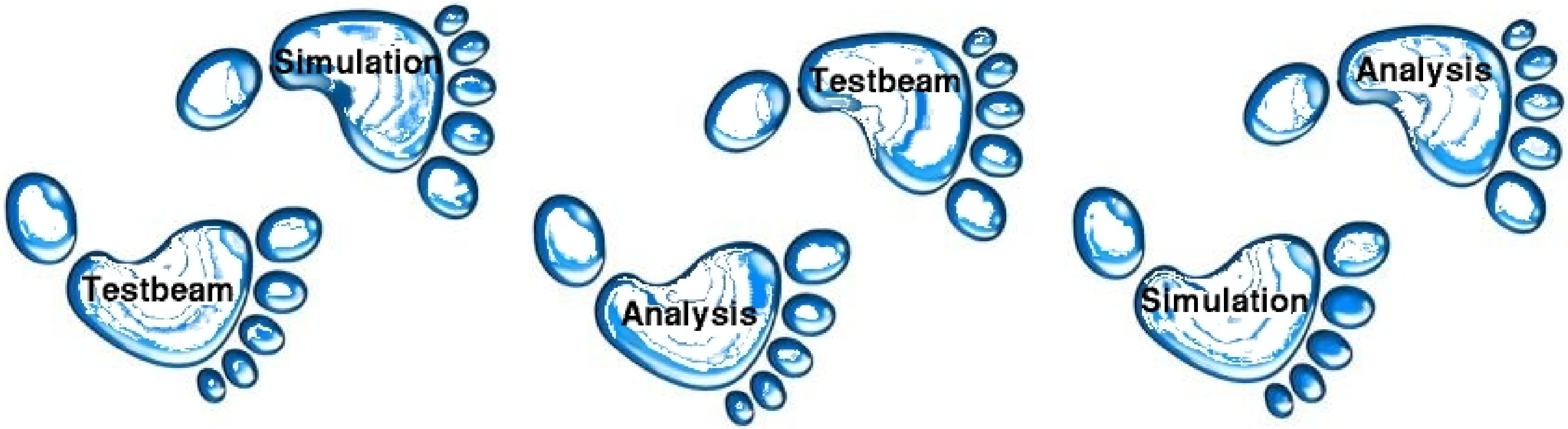
  : studies at single layer level,
  ready to scale-up construction (funding permitting)

- **years to come**

  : series of individual and combined testbeams at DESY, CERN, FNAL, ...

# Strategy ...

**from concepts+questions towards answers and a final design**



# CALICE world tour

Ecole Poly 2004/5 – cosmics

DESY 2005/6 – e beam


FNAL 2007/8 – hadron beam

CERN 2006 – hadron beam

**(P.Dauncey)**

# Summary

- **an experiment at a future LC**
  - strict requirements for vertex, tracking and calorimetric detectors
  - a lot of R&D effort needed (= money $\times$ time $\times$ bright manpower)

- **CALICE Collaboration**
  - to conduct the R&D for calorimetry
  - **the main goal**

    highly granular EM and HADR calorimeters to allow very efficient pattern recognition for excellent shower separation and pid within jets to provide excellent jet reconstruction efficiency

  - concepts-prototype studies
    - ▹ Si/W ECAL, scint analogue HCAL, gaseous digital HCALs
    - ▹ loop over simulation-testbeam-analysis chain started
    - ▹ a lot to come, a lot to learn