Calorimetry for a Linear Collider Experiment

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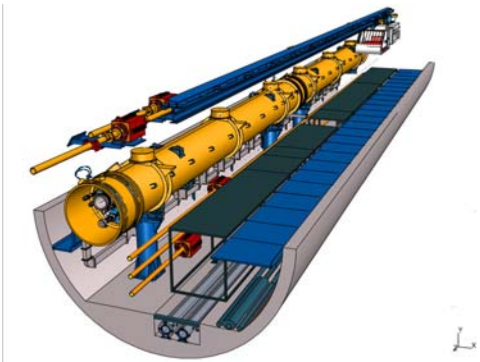
Imperial College London

Overview

- The International Linear Collider
- Jet reconstruction
- The CALICE collaboration
- CALICE-UK responsibilities
- First look at data
- CALICE-UK long-term R&D
- New opportunities

The International Linear Collider

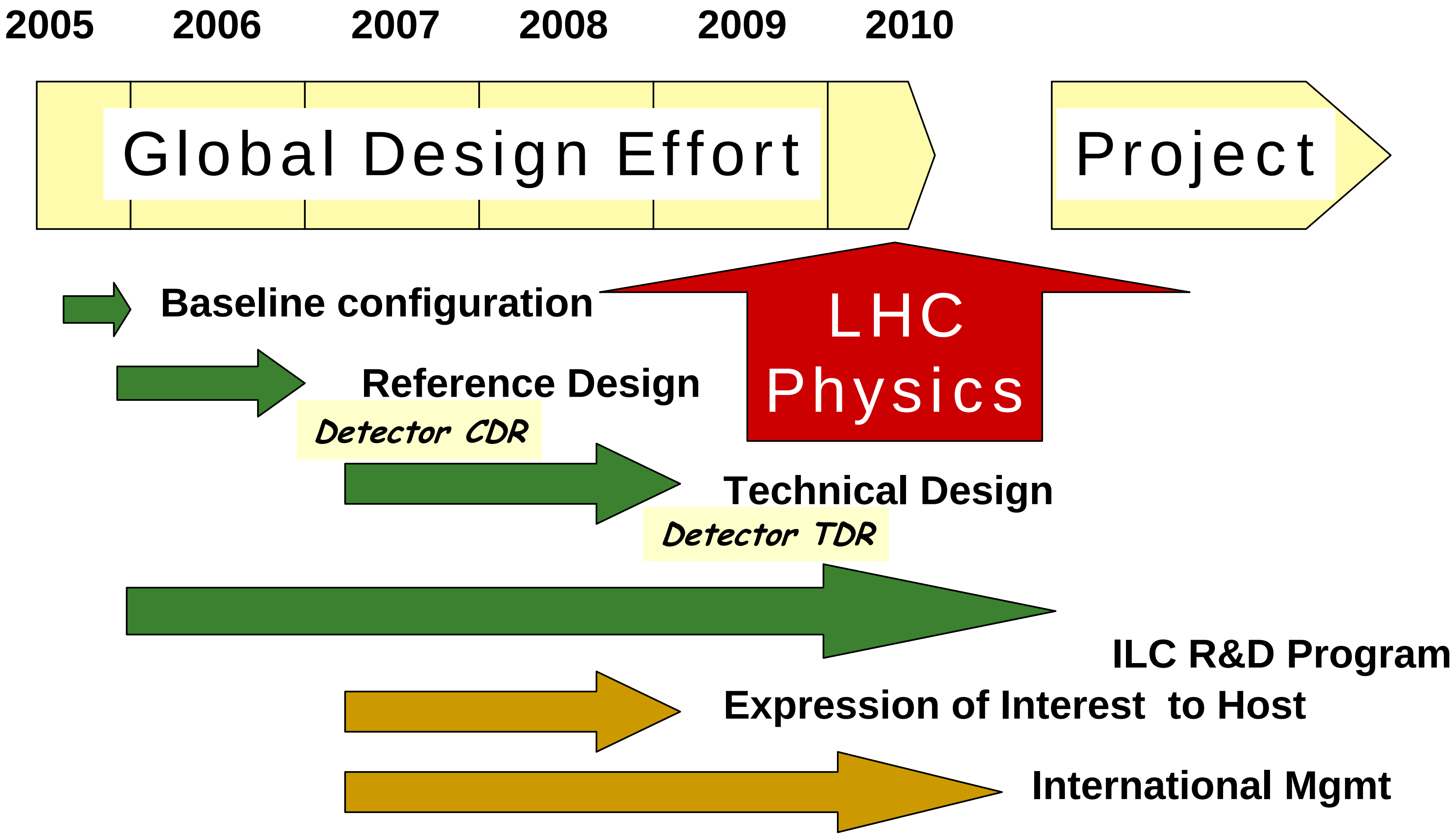
- The ILC means a 0.5-1.0 TeV e^+e^- collider
  - Will be superconducting linac; chosen as safer technology
  - Distant future; CLIC (CERN) 3-4 TeV but huge amount of R&D needed



- ILC could proceed now…
  - …if we were given the ~£2 billion needed
  - International level negotiations ongoing; hope to converge within five years

- Where also yet to be decided
  - Assumed all groups will collaborate on one global ILC
  - The "Global Design Effort" is coordinating the worldwide work
- Timescale to build ILC ~8 years
  - E.g. approval and funding granted in 2008 leads to first physics data in 2016

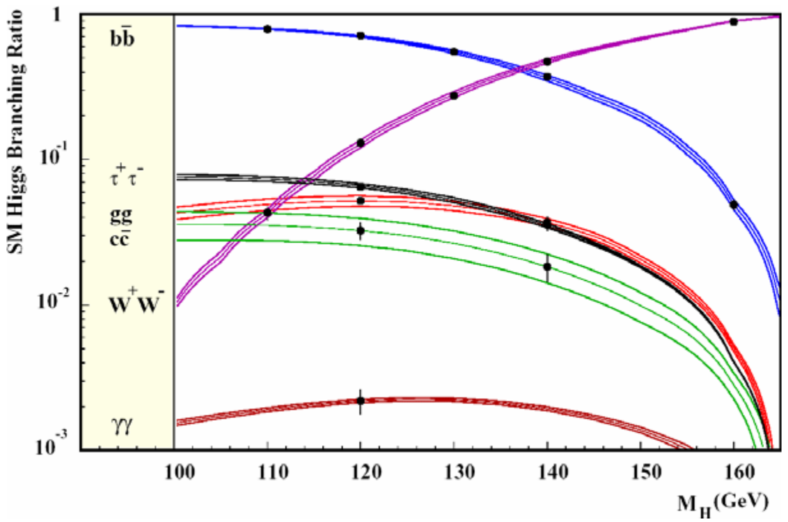
The GDE schedule



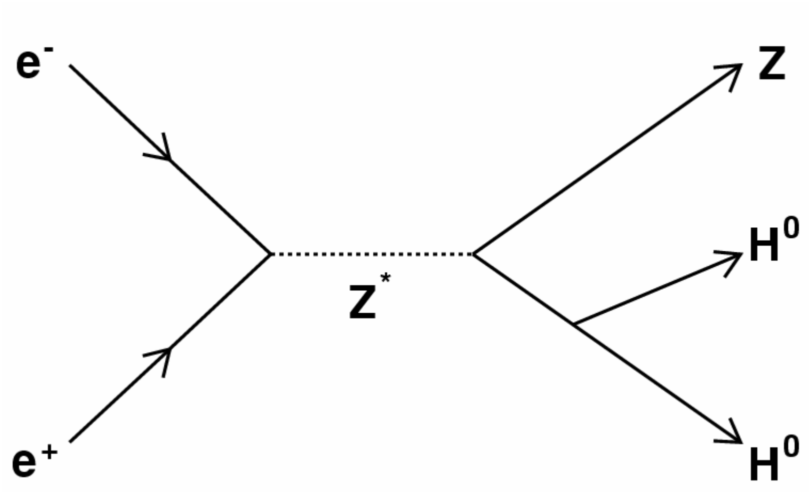
B.Barish, GDE

Physics at the ILC

- Doing the real science after the LHC discoveries
  - Precision measurements to test theories
  - If Higgs discovered at LHC; know mass
    - ILC can measure SM predictions
    - Many BFs to check mass^2 dependence, N.B. W^+W^- vs Z^0Z^0
    - Spin, width, self-coupling, N.B. ZHH
  - If SUSY discovered at LHC; only know relative masses accurately
    - ILC can measure absolute masses
    - Also many more BFs, spins, etc.

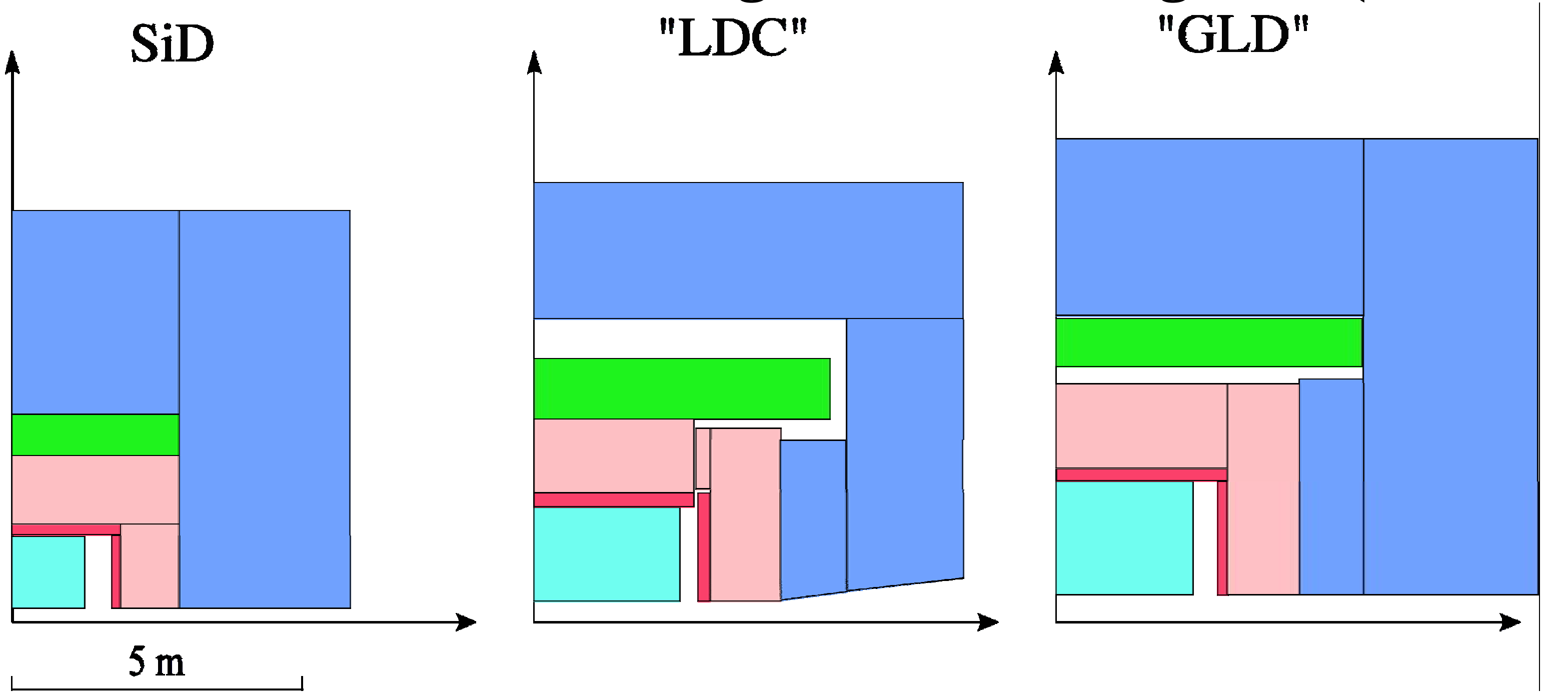


- Other physics
  - Top quark; mass to 50 MeV
  - EW symmetry; N.B. $\nu\bar{\nu}W^+W^-$
  - Weakly interacting new particles
  - Extra dimensions, etc, etc…



ILC detector concepts

- Sizes: “small” “large” “giant” (< CMS!)



- 5T
- Si Tracker
- SiW ECAL
- Gas or Scint HCAL

- 4T
- Gasous Tracker (+Si?)
- SiW ECAL
- Gas or Scint HCAL

- 3T
- Gasous Tracker
- Hybrid or Scint ECAL
- Scint HCAL

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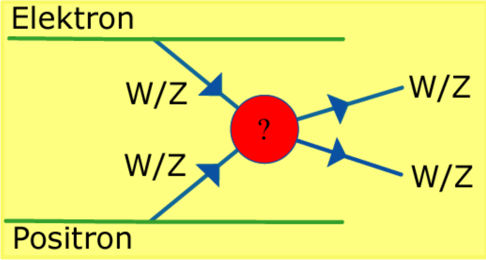
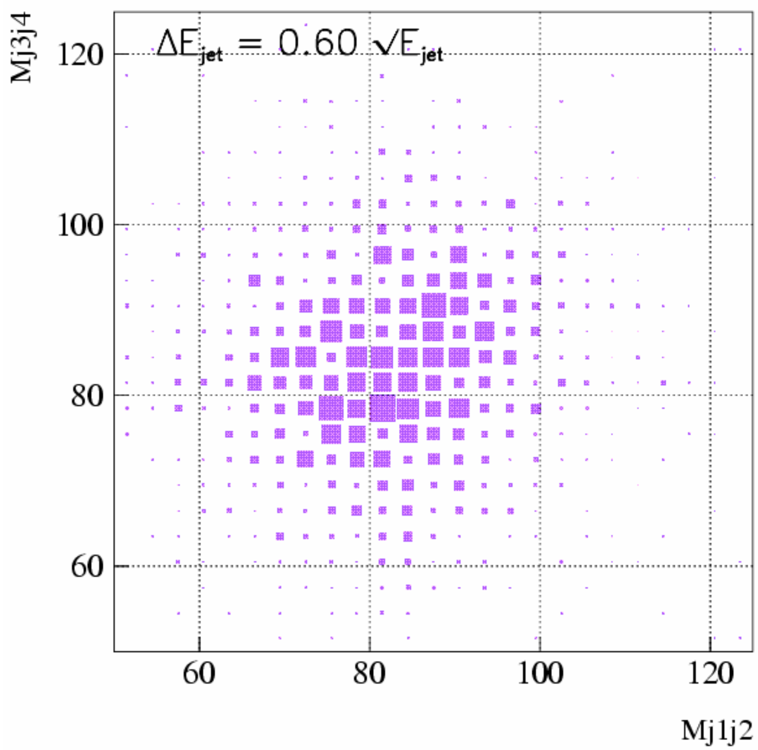
Detector needs high performance calorimetry

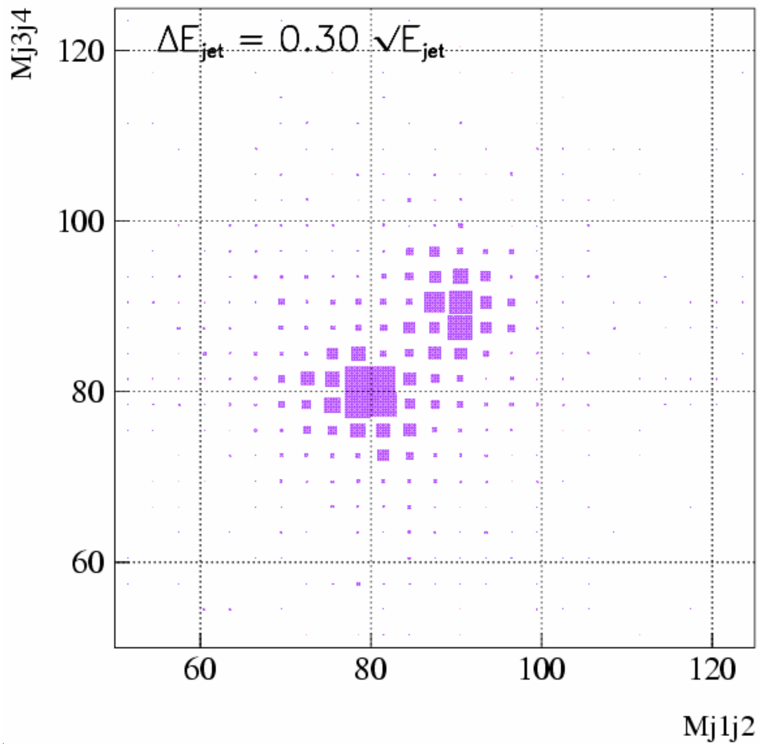
- Need to distinguish between W and Z and also reconstruct H
  - Majority of their decays are to quarks and hence jets
  - Need excellent hadronic jet resolution to tell them apart





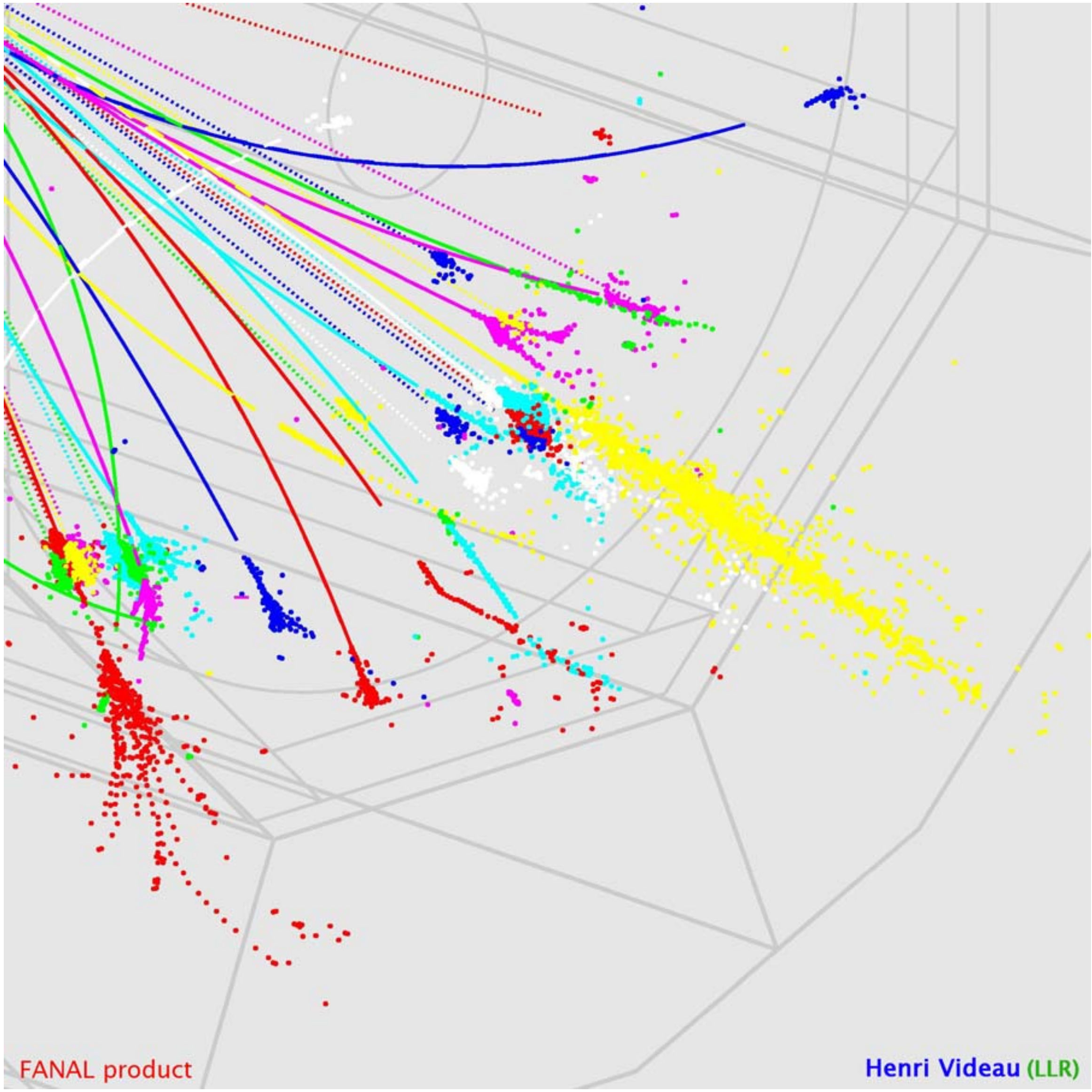
- ZZ vs WW jets
- Best LEP detector (Aleph)

- ZZ vs WW jets
- Projected ILC detector



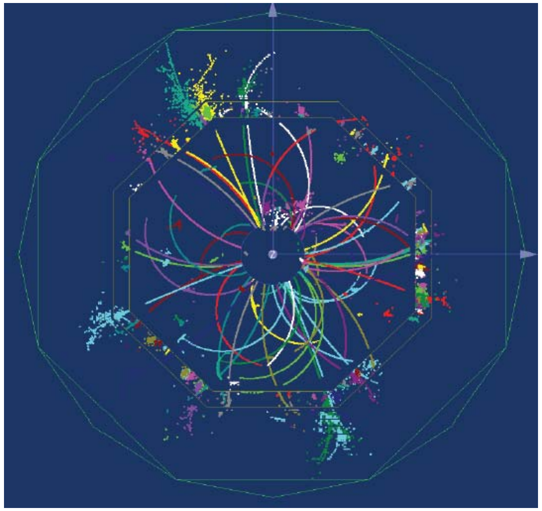
Jet resolution

- Determined by ability to separate
  - Charged and neutral particles
  - Electromagnetic and hadronic showers
- Need calorimeter with
  - Narrow showers
  - Small X_0, large λ
- Need good pattern recognition software to separate particles
  - "Tracking calorimeter"
  - Novel reconstruction; particle flow (PFLOW)



Particle flow algorithms

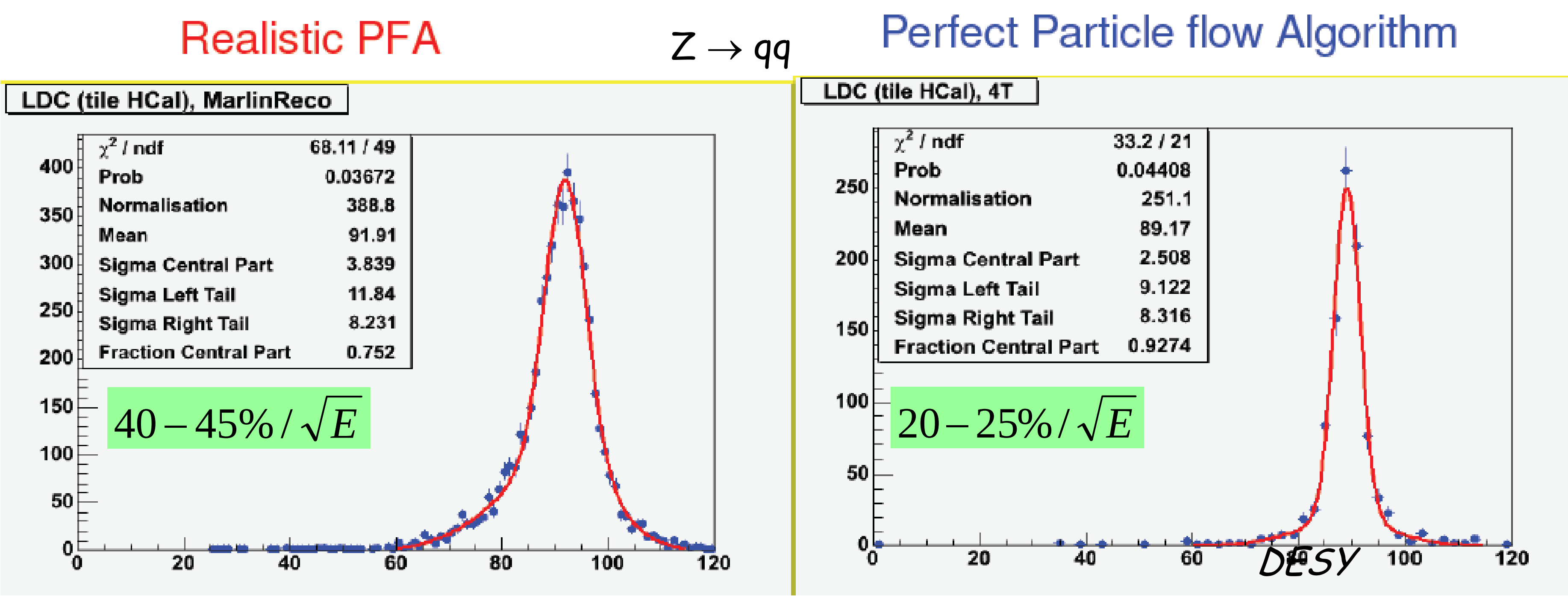
- Optimise jet energy resolution
  - Reconstruct each particle individually
  - Use the best possible detector component
- Tracking detectors for charged particles
  - **~65%** of the typical jet energy
  - Negligible resolution
- EM calorimeter for photons
  - **~25%** of the typical jet energy
  - Resolution ~10%/√E
- Hadron calorimeter for neutral hadrons
  - **~10%** of the typical jet energy
  - Resolution ~40%/√E



$Naively :\sim 15\% / \sqrt{E}$

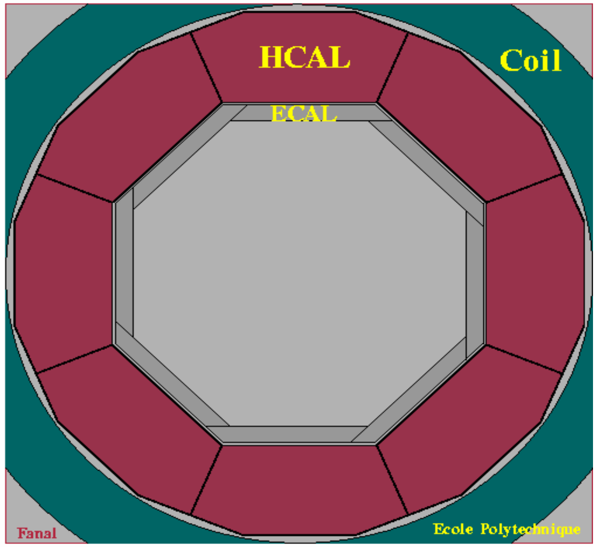
PFLOW state of the art

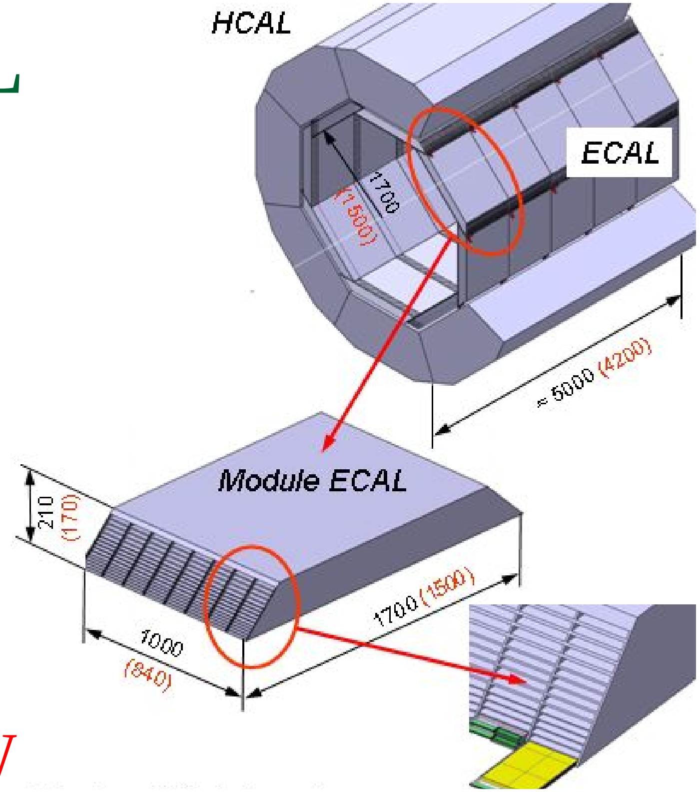
- **Perfect**: True MC tracks + true MC clusters + perfect linking + smearing
  - The real limit: includes resolution and neutrinos
- **Realistic**: Finite imaging quality and algorithm development
  - Full simulation, reconstruction, solid angle losses, loopers, etc.
  - Association "confusion" term dominates resolution
  - Cleverer algorithm could improved resolution



TESLA/LDC-type ECAL

For PFLOW, must have ECAL and HCAL within coil





Best performance seems to be from Si-W

- Tungsten to cause e/γ conversions, 40 sheets deep
  - Small $X_0 \sim 3.5$ mm
  - Small Moliere radius ~ 9 mm (measure of transverse shower size)
- Silicon diodes to detect shower charged particles
  - Small diode pads ~ $1\times1\text{cm}^2$; stable, compact, well-understood technology
  - Results in 3000m^2 of silicon, 38 million channels, ~£80M!

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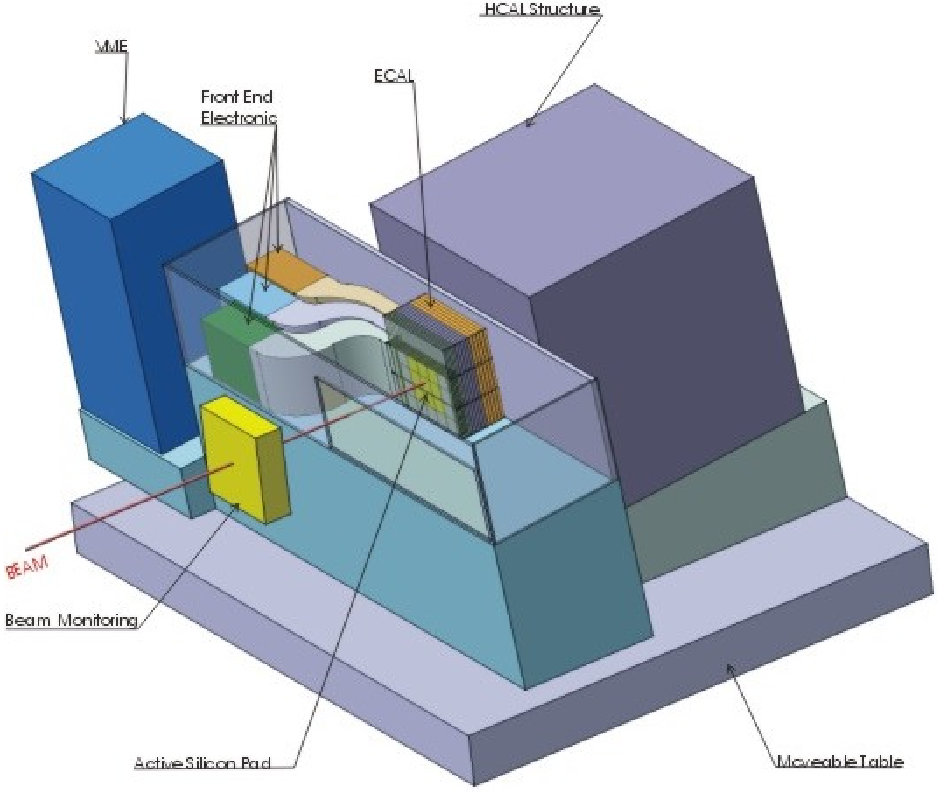
The CALICE Collaboration

CAlorimetry for a LInear Collider Experiment

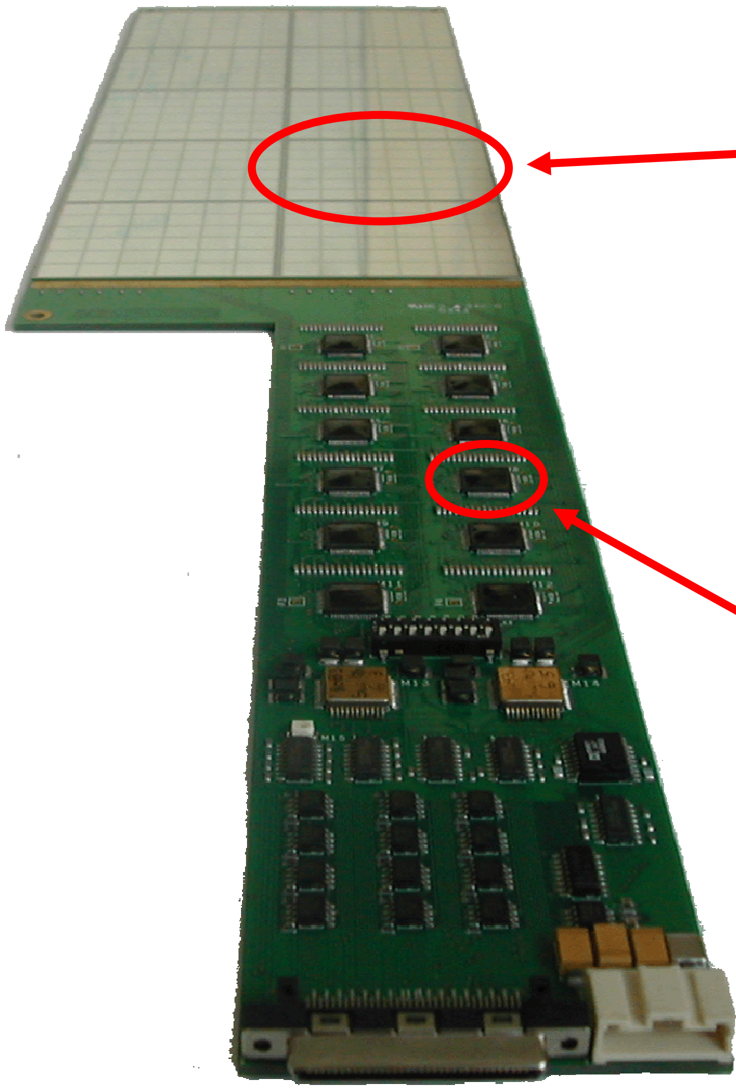
- Main aims
  - Tune (or verify) simulation to level it can be trusted to design the calorimeters for a ILC detector
  - Get realistic experience of calorimeter operations with novel technologies
  - Design the calorimeters in detail, particularly to reduce cost
- Expected that this leads directly into ILC detector
  - The schedule calls for detector TDRs in 2008/9
  - Must have calorimeter (and whole detector) design finalised by then
  - This sets timescale for CALICE

Pre-prototype beam test detectors

- Tuning simulation requires real data
  - Build "pre-prototype" segment of calorimeter and test in beams
    - Silicon-tungsten sampling electromagnetic calorimeter (ECAL); ~10k channels
    - Scintillating tile-iron analogue hadronic calorimeter (AHCAL); ~8k channels
    - RPC/GEM-iron digital hadronic calorimeter (DHCAL); ~380k channels
    - Three year timescale; beam tests scheduled for 2005-7 (maybe 2008)
  - Not a trivial number of channels; an experiment in its own right
  - Final data set: 10^8 events, 5TBytes



ECAL sensitive layer; very front end PCB

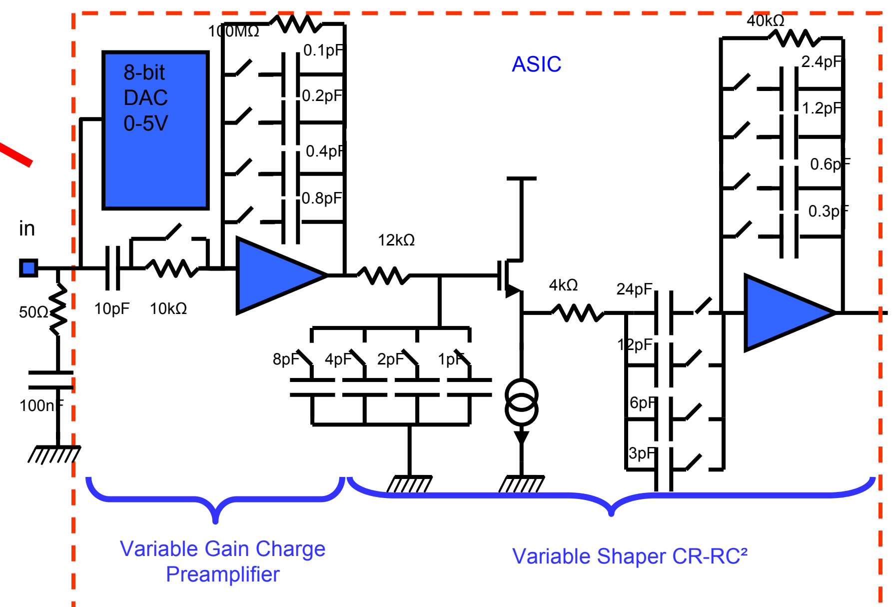


6x6 pads/wafer

LLR/EP

- Silicon diode pads 1×1cm^2
- Each layer 18×18 array

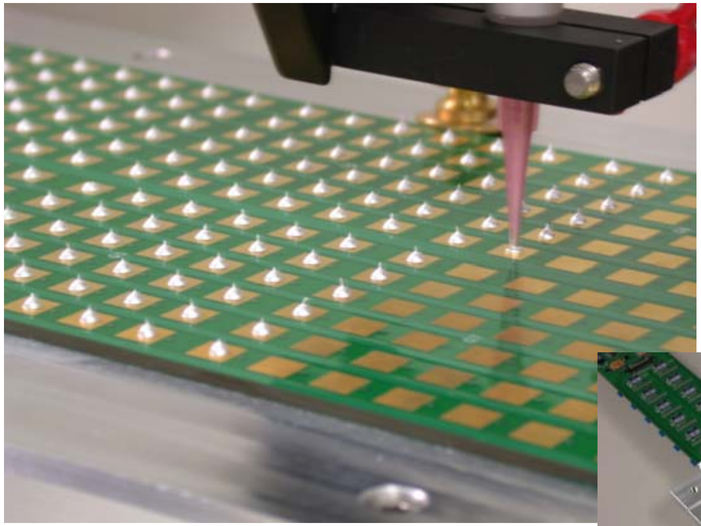
- Preamp ASIC; 18 channels
- Shaper and S&H; multiplexed output

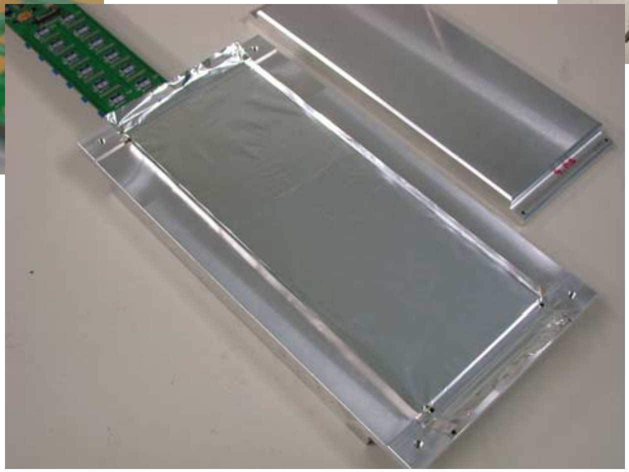


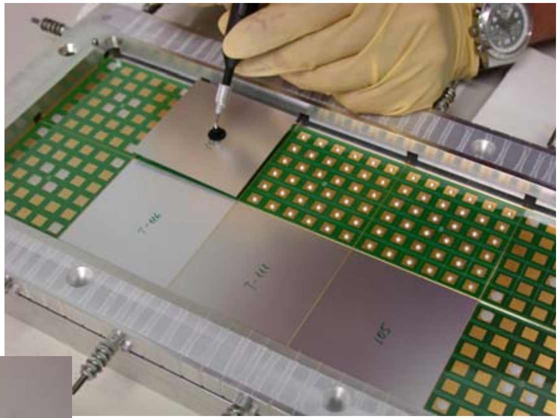
LAL/Orsay

VFE PCB construction

- Diode pads attached directly to PCB using conductive glue; ground contact to outer side of wafer using aluminium foil
  - Glue deposition automated
  - Wafer positioning and substrate foil attachment done by hand

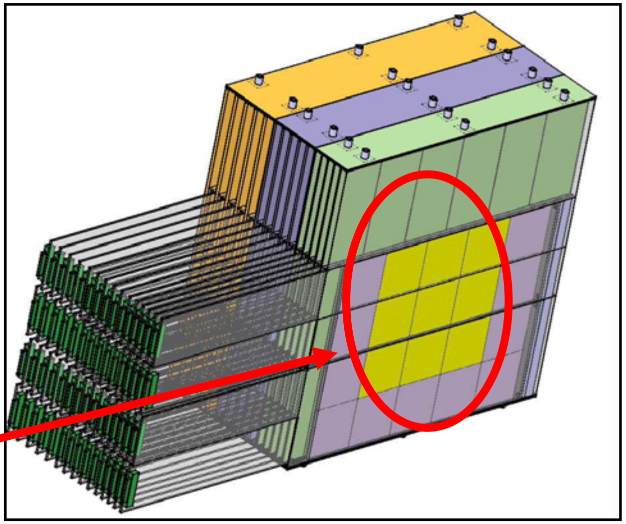




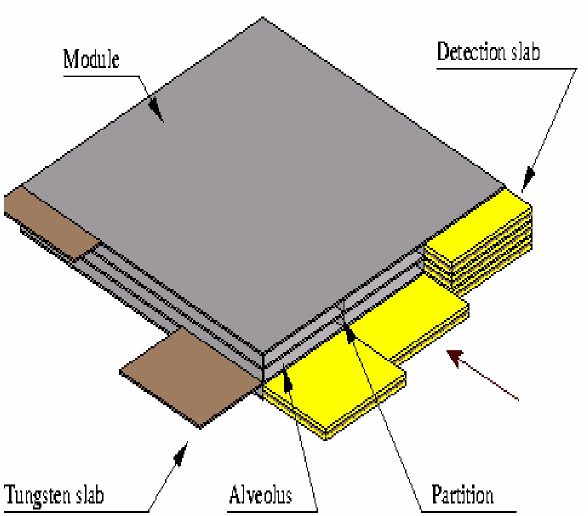


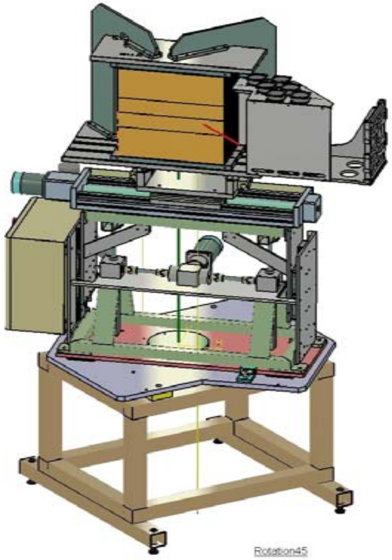
LLR/EP

ECAL mechanics



- Two VFE PCBs sandwiched to one tungsten sheet to make "slab"
- Slabs inserted into carbon fibre-tungsten mechanical structure
- $18\times18\times20$ cm^3 active area

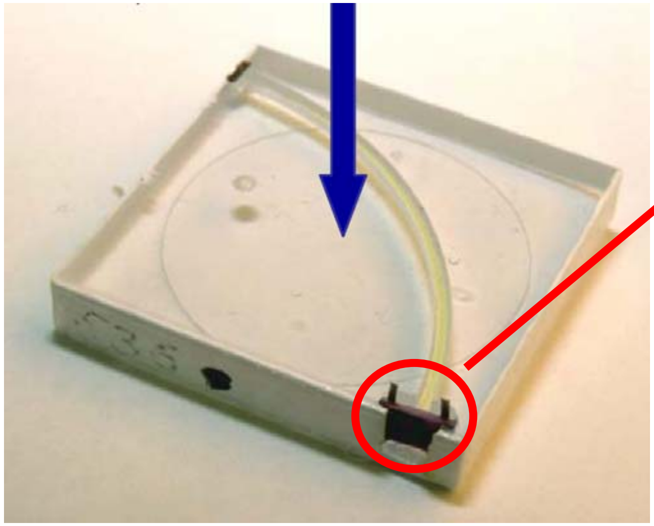




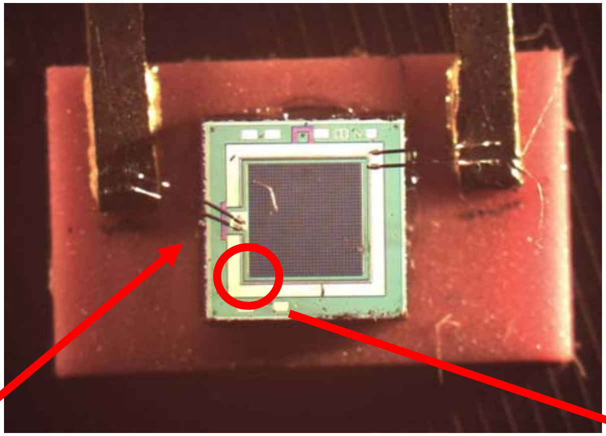
Whole ECAL mounted on movable stage

AHCAL scintillating tiles and SiPMs

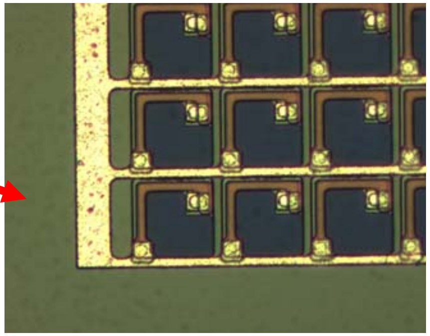
- 3×3 cm^2 scintillator tile
- Wavelength shifting fibre
- Coupled directly to SiPM



ITEP

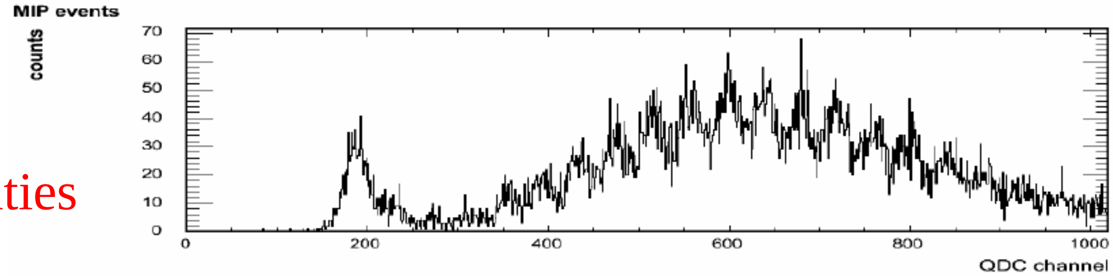


MEPHI / PULSAR



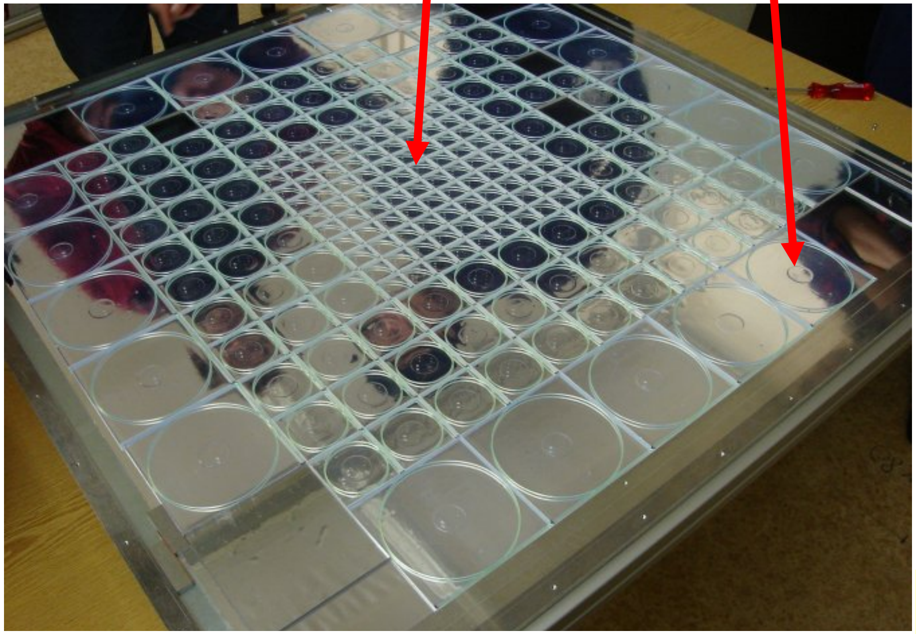
- Silicon PM: multipixel Geiger mode APDs; 1156 pixels
- Gain 10^6, bias ~ 50V, size 1 mm^2

- Single pixel peaks allow autocalibration
- Saturation gives non-linearities



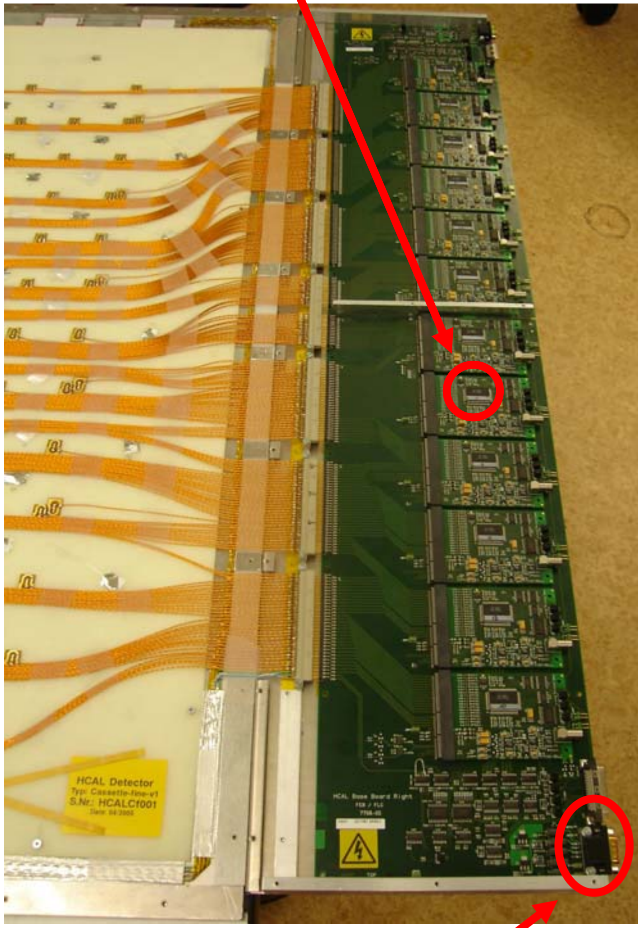
AHCAL sensitive layers

- 1 cubic metre
- 38 layers, 2cm steel plates
- 8000 tiles, each with SiPMs
- Tiles sizes: 3×3 cm^2 to 12×12 cm^2



DESY

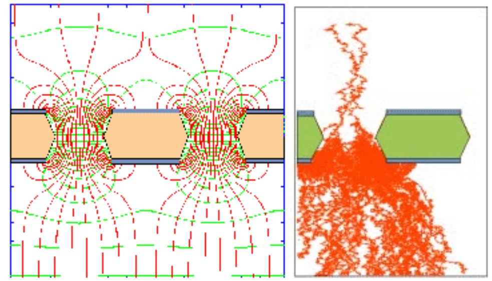
Modified version of ECAL ASIC

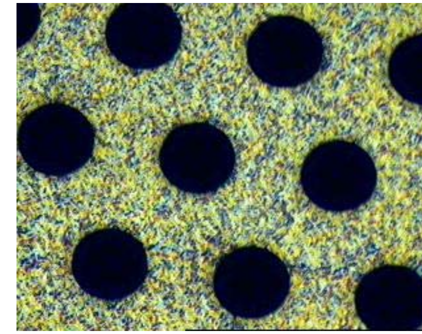


Same connector as ECAL

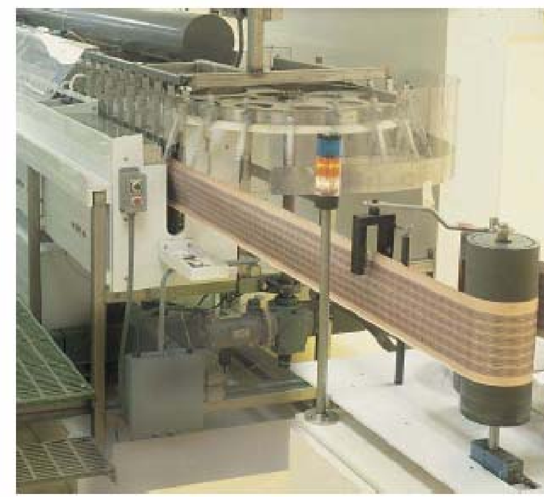
DHCAL technologies

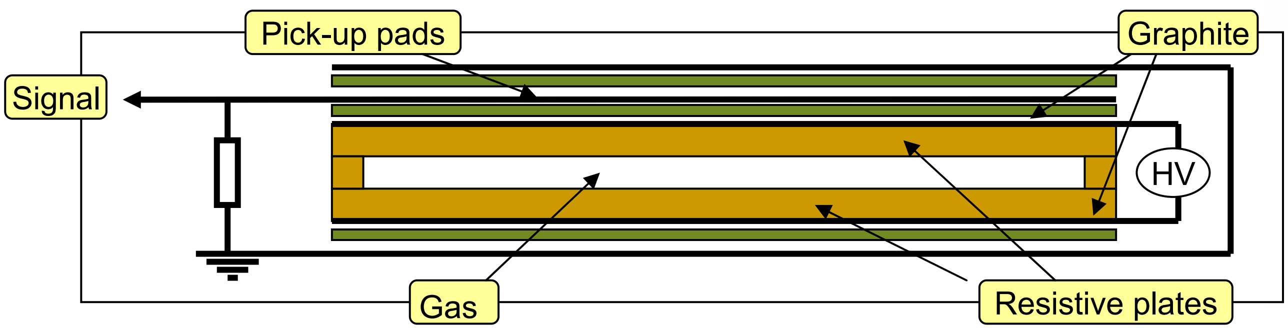
- Small cells ~ 1×1cm^2
- Binary readout
- Two technology options
  - GEMs: lower operation voltage, flexible technology
  - RPCs: robustness and larger signals



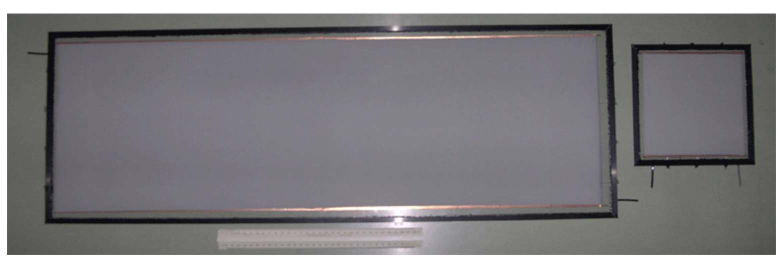


UTA



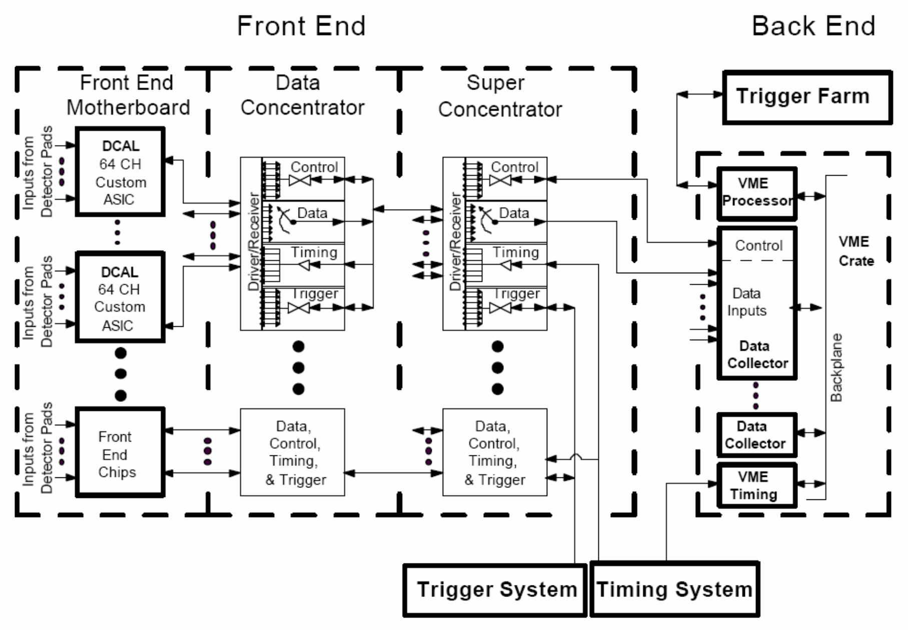


ANL

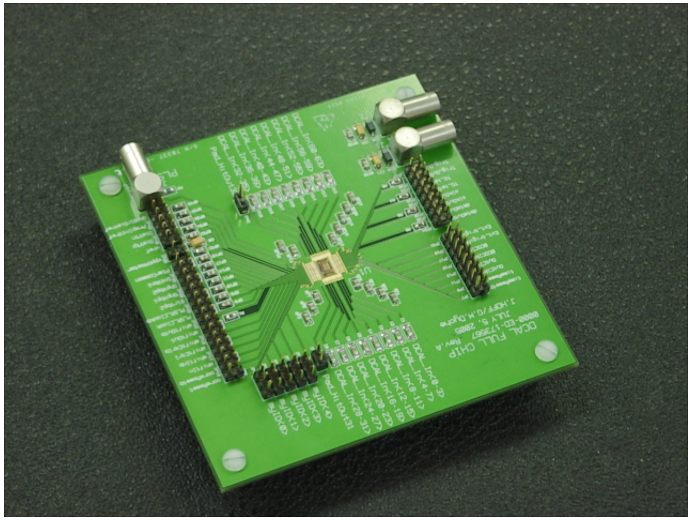


DHCAL electronics

- Same electronics for both options
  - Gain switch on preamplifier to handle smaller GEM signals
- Complete design exists
  - Although VME readout may use AHCAL readout



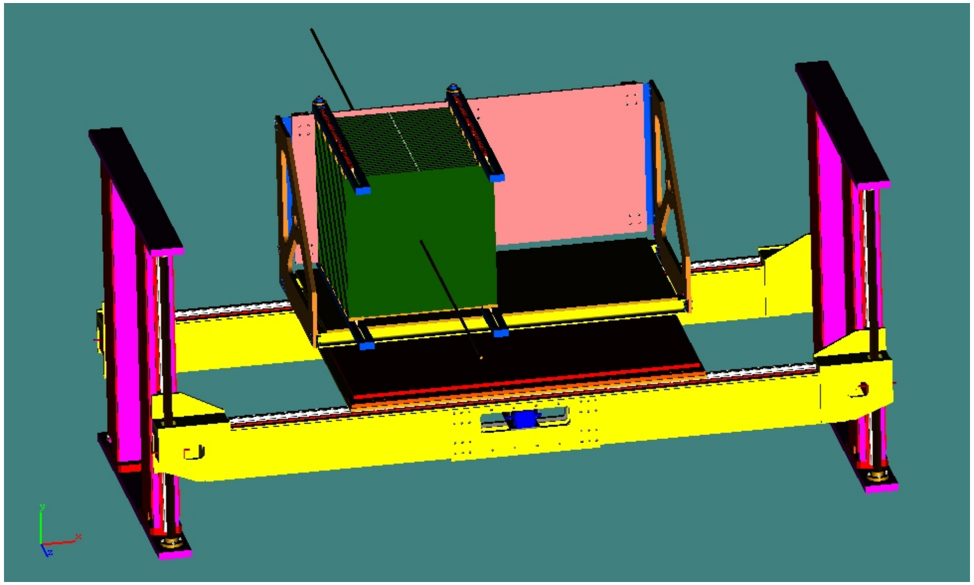
ANL/FNAL



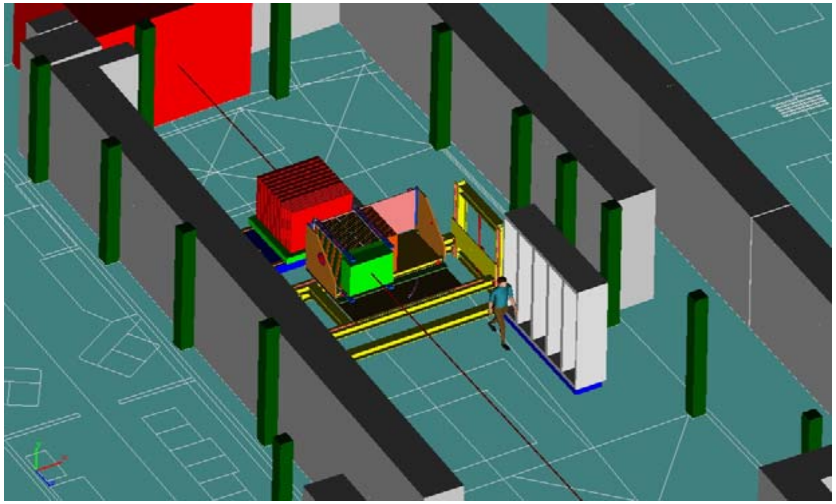
- Prototype front end boards under test
  - Schedule for production limited by US funding
- Hope to be ready for beam test in 2007/8

HCAL mechanics

- Use same converter layers and mechanical support for AHCAL and DHCAL
  - Comparisons easier
  - Only 4 interaction lengths
- Movable table design compatible with CERN and FNAL being finalized
- Allows rotation for non-normal incidence



DESY

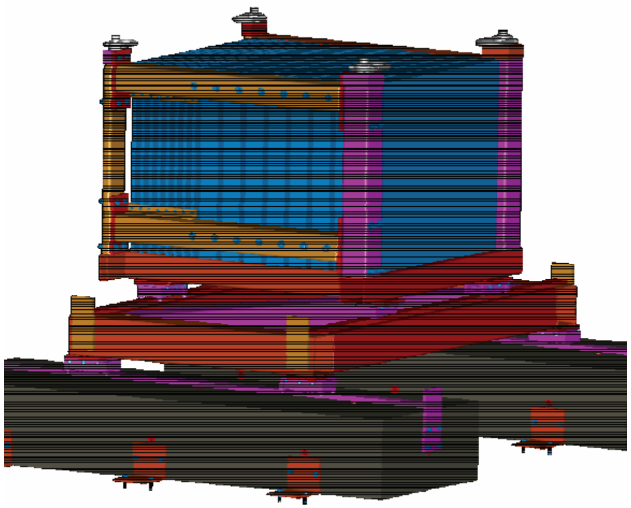


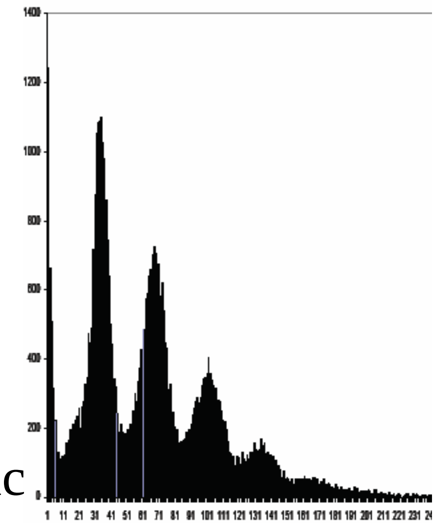
Tail catcher/muon tracker

- Scintillator strips; ~300 channels
- SiPM readout, reuse AHCAL electronics
- Stack; 8 layers × 2cm followed by 8 layers × 10cm of steel plates
- Start commissioning Jan06

NIU

All strips fabricated and QC'ed





Cosmic signals

19 cassettes assembled (w/o SiPM and LED driver)

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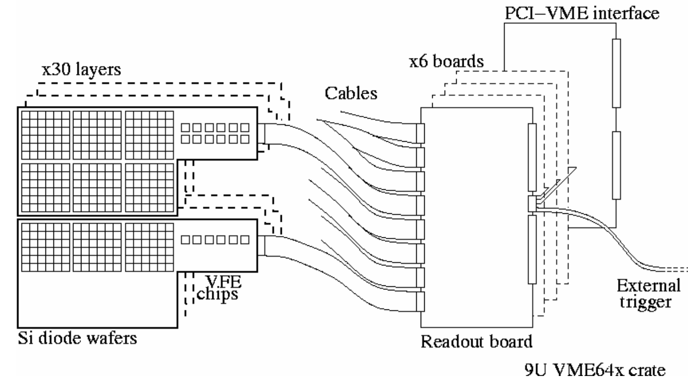
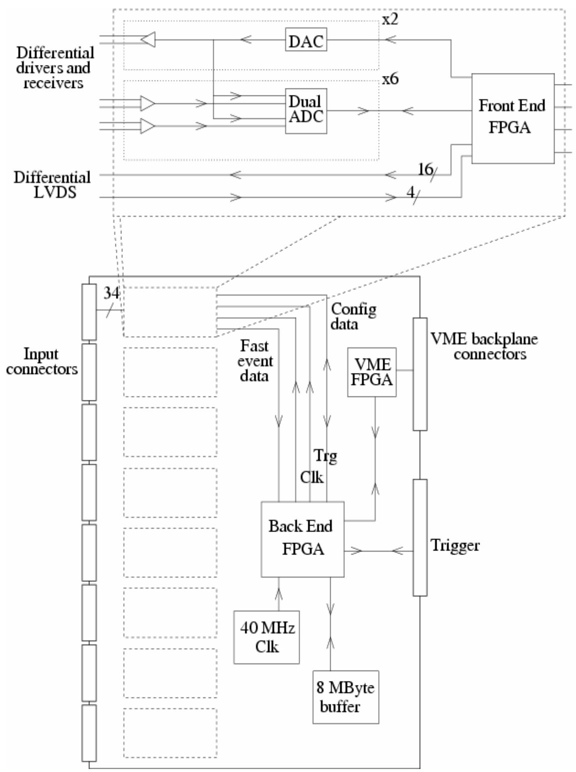
CALICE-UK contributions

- First round of funding approved Dec02
  - Covered activities for 2.3 years from Dec02-Mar05
- Six UK groups joined
  - Birmingham, Cambridge, Imperial, Manchester, RAL EID, UCL
- Funding to contribute to beam test program
  - ECAL VME readout
  - CALICE online system
  - Simulation/analysis studies
- ECAL readout boards now used by AHCAL and TCMT also
  - Potentially DHCAL readout also
  - UK now responsible for all CALICE VME readout

ECAL (and AHCAL) readout electronics

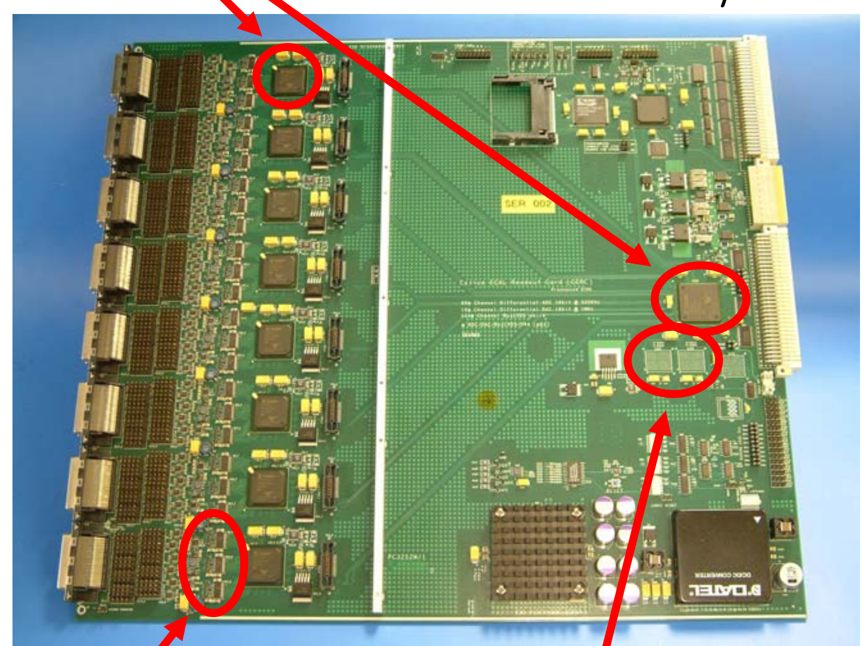
- Calice Readout Card (CRC) VME board
  - Modified CMS silicon tracker readout board
  - Does VFE PCB control, digitisation and data buffering
  - Also does trigger control





Virtex-II FPGAs

Imperial/RAL/UCL

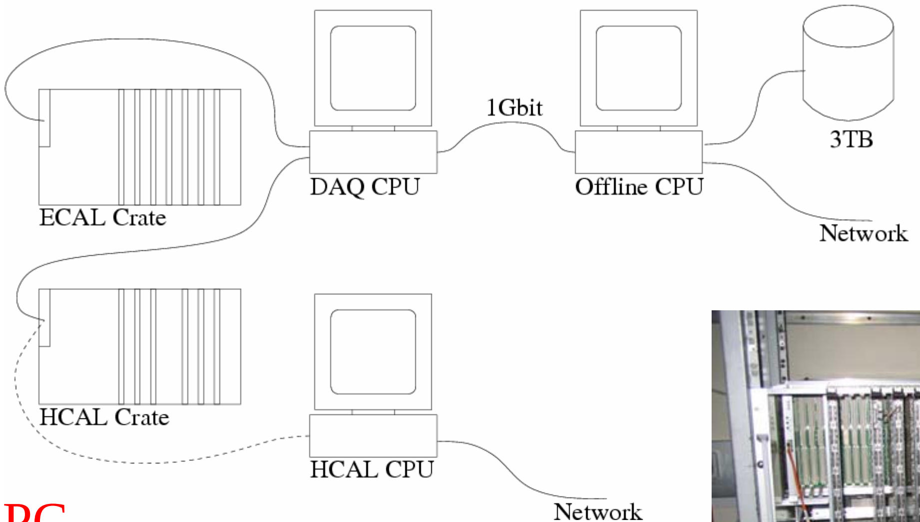


16-bit dual ADCs

8MByte buffer

DAQ online system

- DAQ CPU
  - Trigger/spill handling
  - VME and slow access
  - Data formatting
  - Send data via dedicated link to offline CPU
- Offline CPU
  - Write to disk array
  - Send to permanent storage
  - Online monitoring
  - Book-keeping



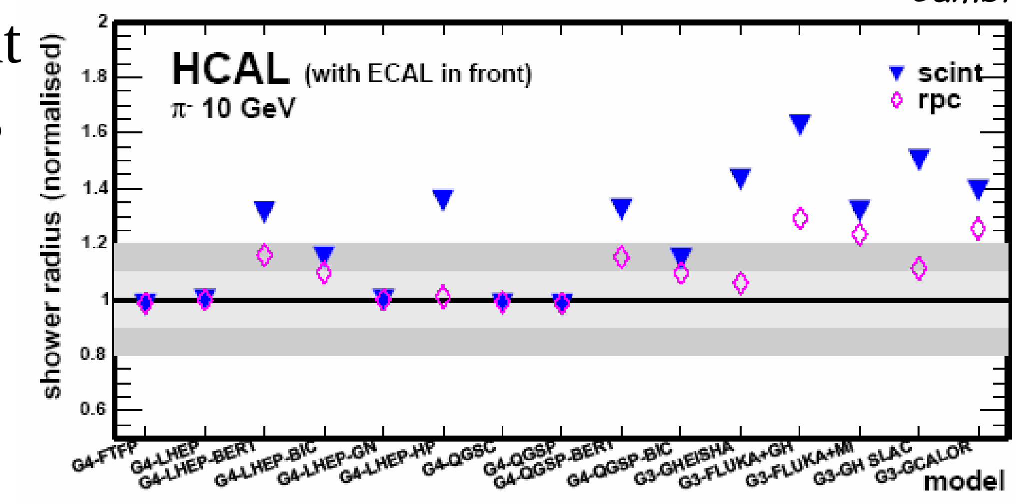
- HCAL PC
  - Partitioning
  - Alternative route to offline PC

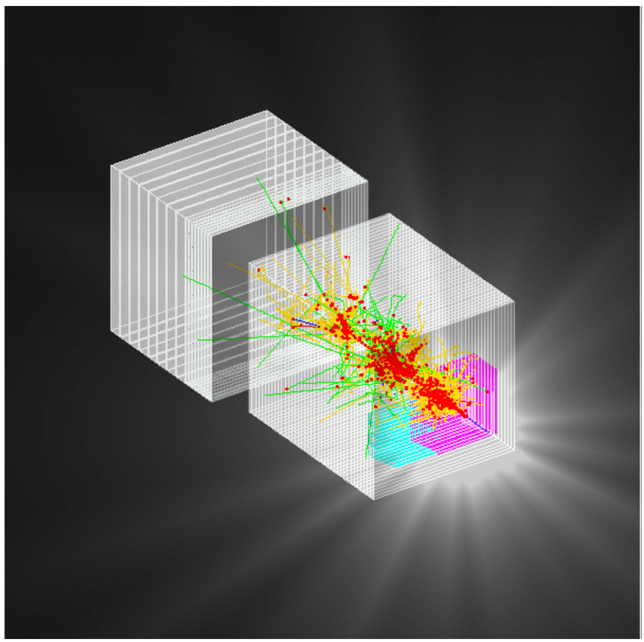
Imperial

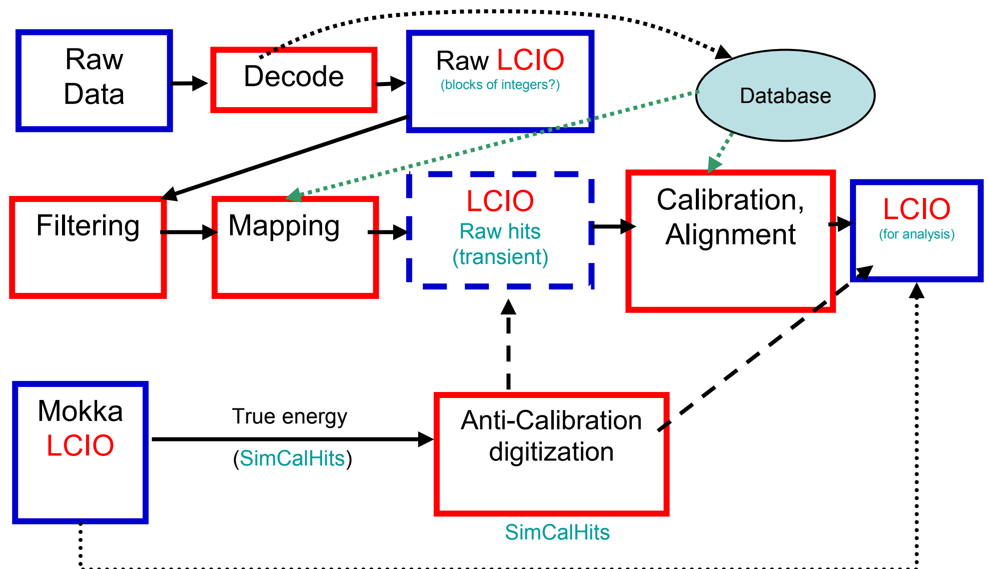
Simulation and software development

Cambridge

- Comparisons of different hadronic shower models
  - Differences up to 60%
  - Depends on HCAL type







Full offline reconstruction and simulation chain exists

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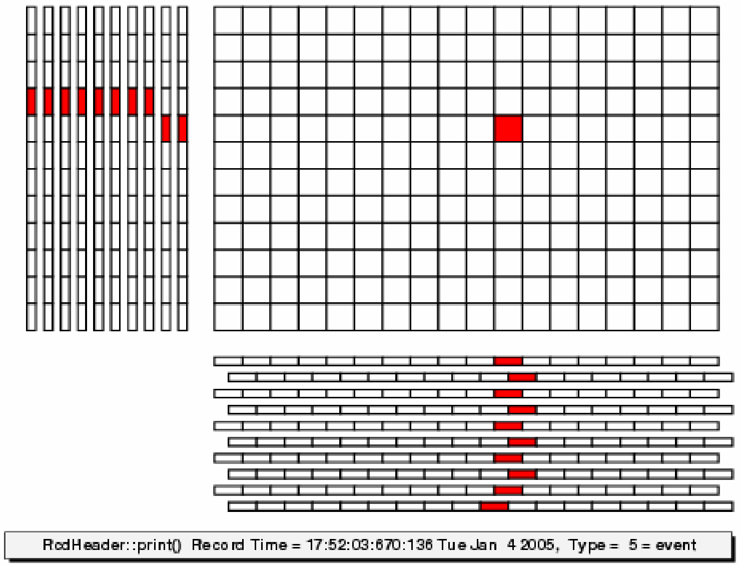
ECAL cosmics at Ecole Polytechnique

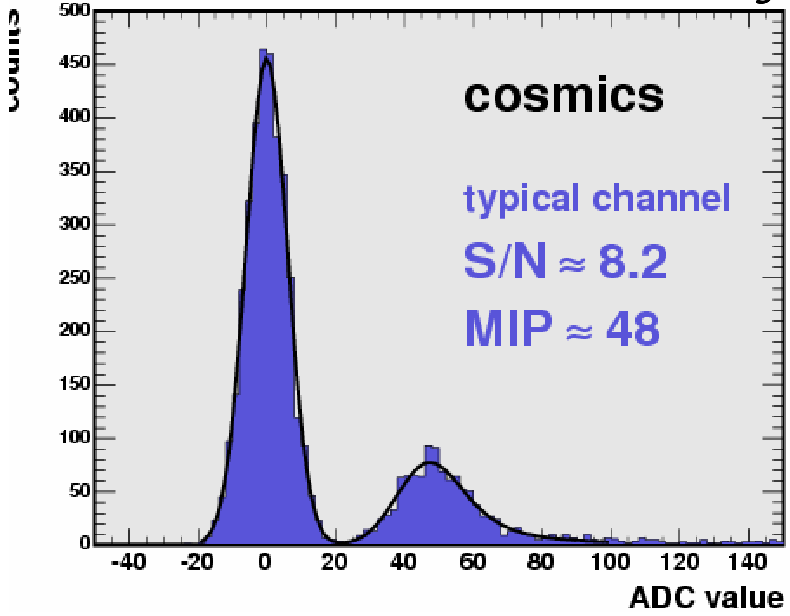
Dec04/Jan05

- Cosmic ray hodoscope
- 10 layers only; 2160 channels
- Prototype online system
- Two week run (over Christmas!)
- 1M events, 10GBytes of data

Imperial



Cambridge

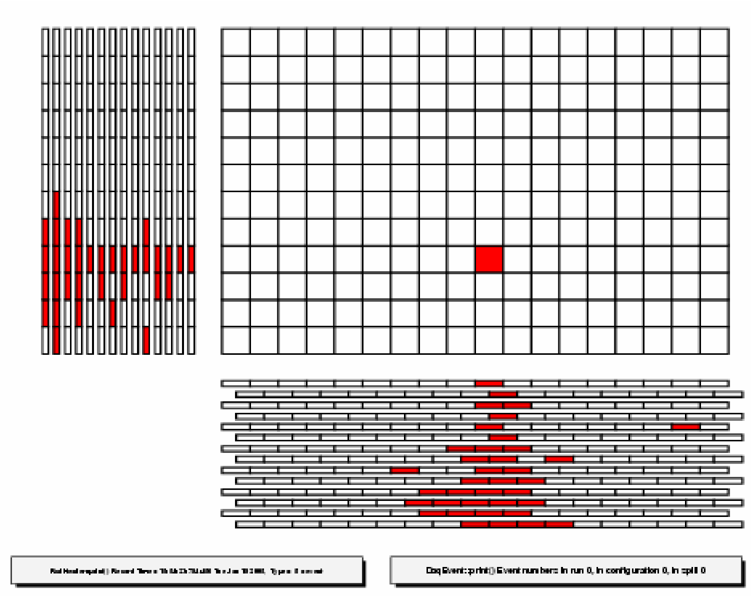


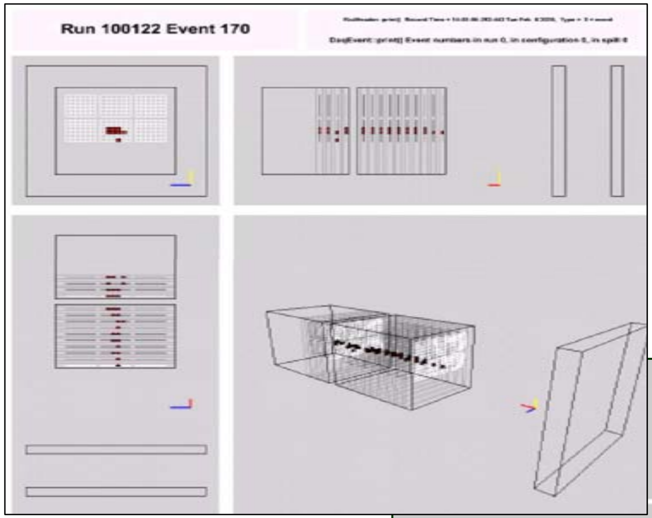
Individual channel calibration to better than 1%

ECAL beam test at DESY

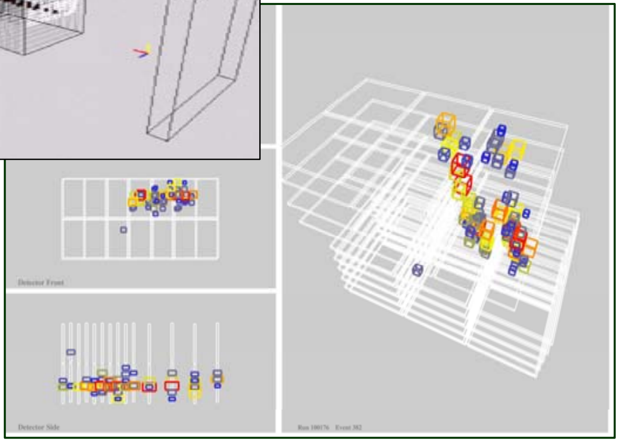
Jan/Feb 2005

- Low energy (1-3 GeV) electron beam
- 14 layers only; 3024 channels
- ~1/3 total pre-prototype ECAL
- Four week engineering run; all results preliminary
- 25M events, 300GBytes of data





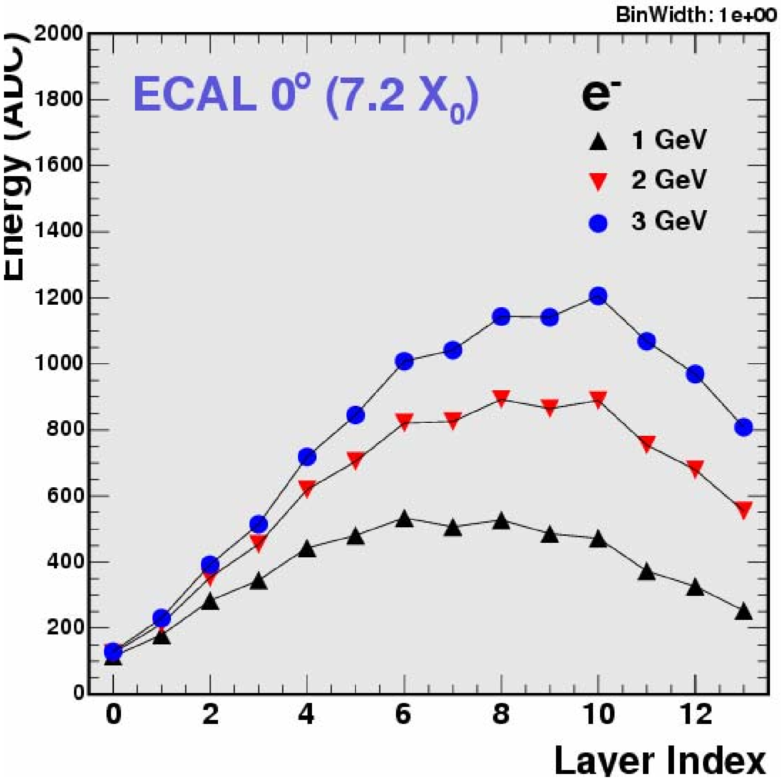
Cambridge

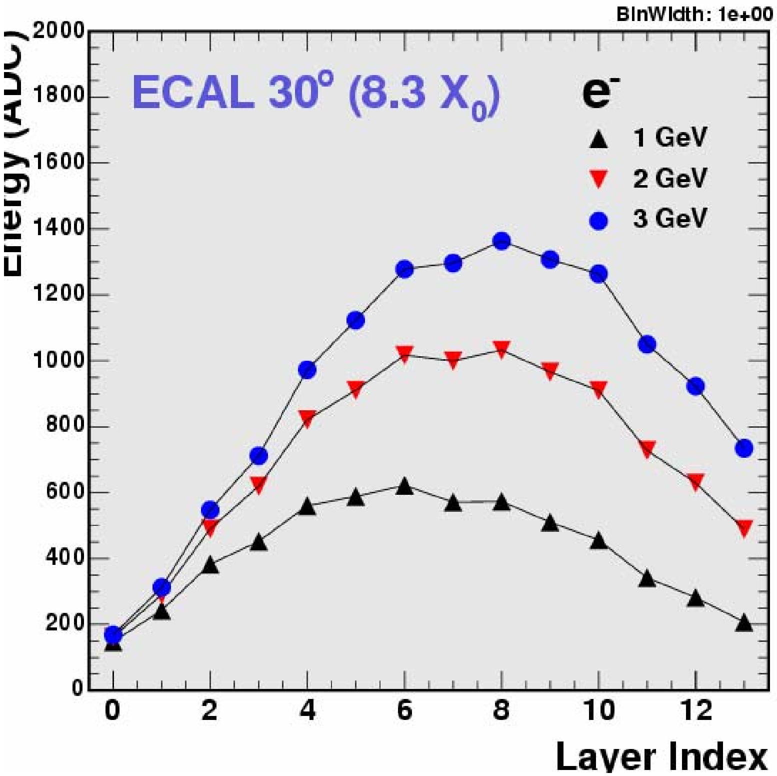


Double e$^-$ events seen

Shower containment

Cambridge

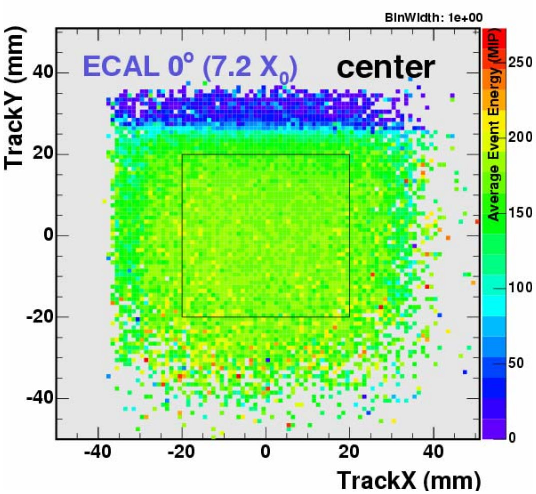


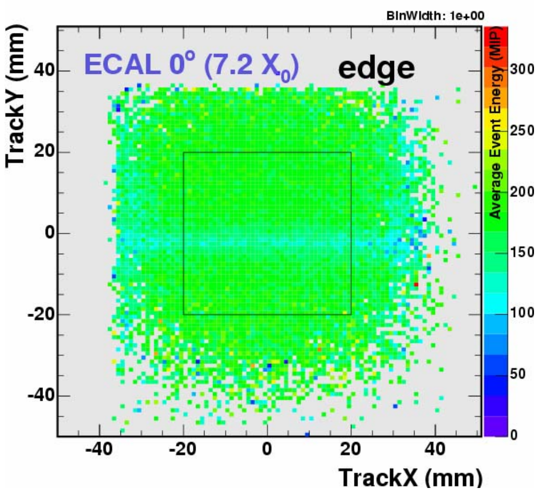


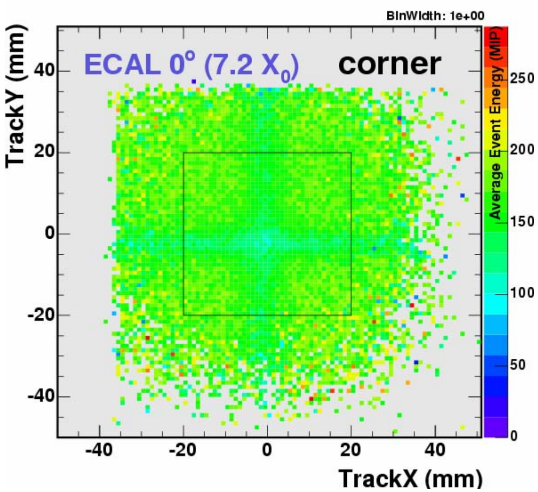
- 14 layers = $7.2X_0$ insufficient to contain even 1GeV electron showers
- 30^0 entrance angle gives $8.3X_0$; visibly better
- No meaningful energy resolution results possible with these data

Position effects and resolution

Cambridge

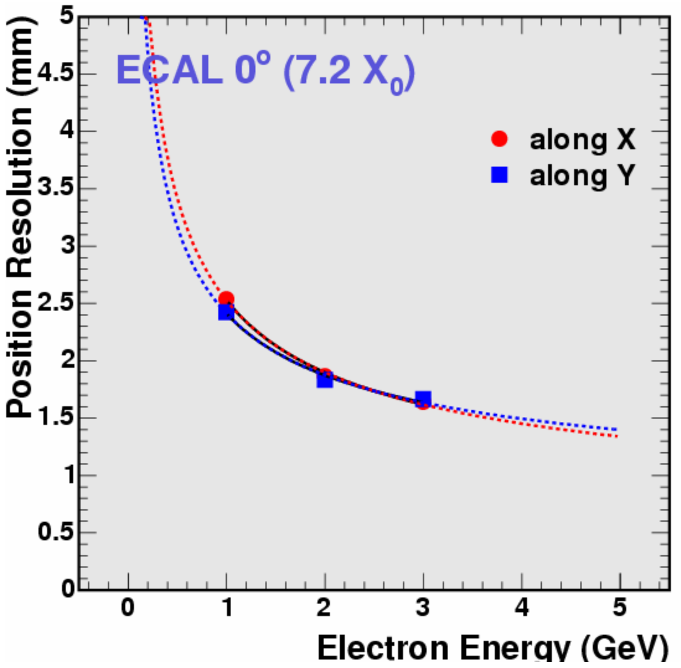






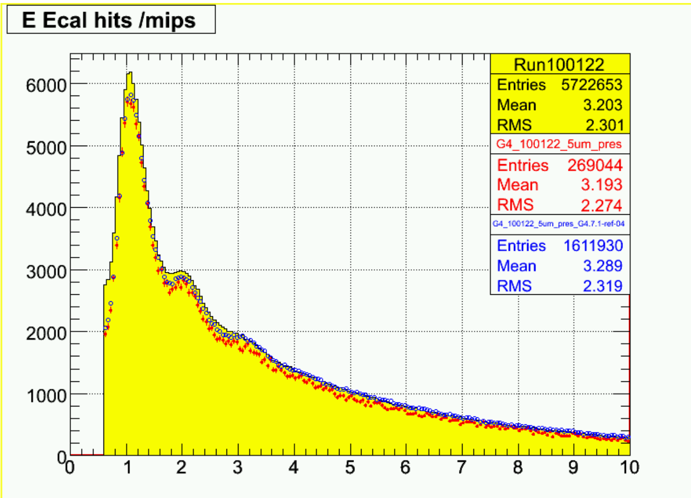
Study of energy loss between wafers

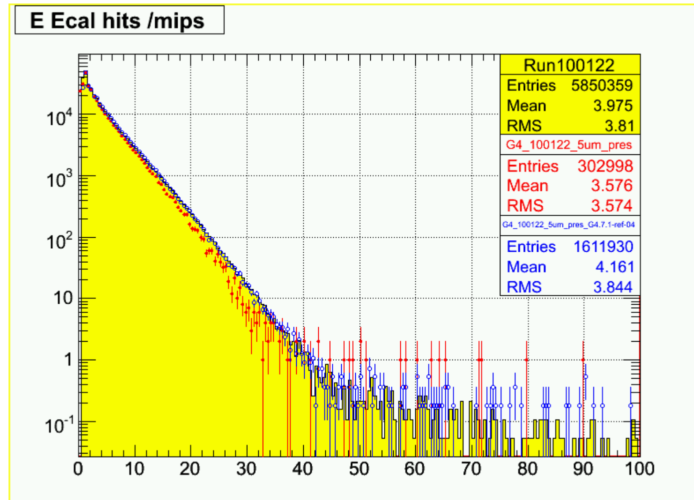
- Energy-weighted position per layer
- Use whole shower to give entrance position of electron into ECAL
- Compare with drift chamber tracking
- Resolutions of order a few mm



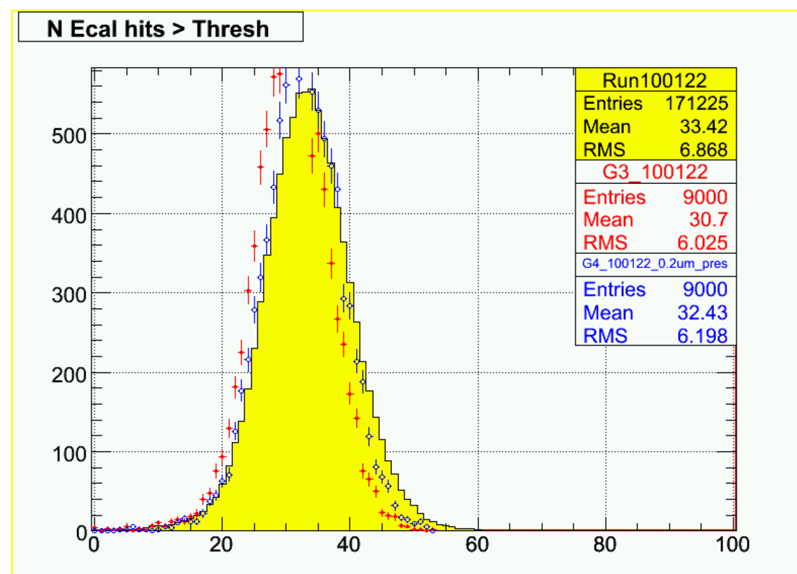
Geant3/4 comparison

Cambridge





- Geant4 requires adjustment of minimum step size cut-off → 0.2μm!
- Takes factor ~20 times longer to run
- Fix in latest beta release

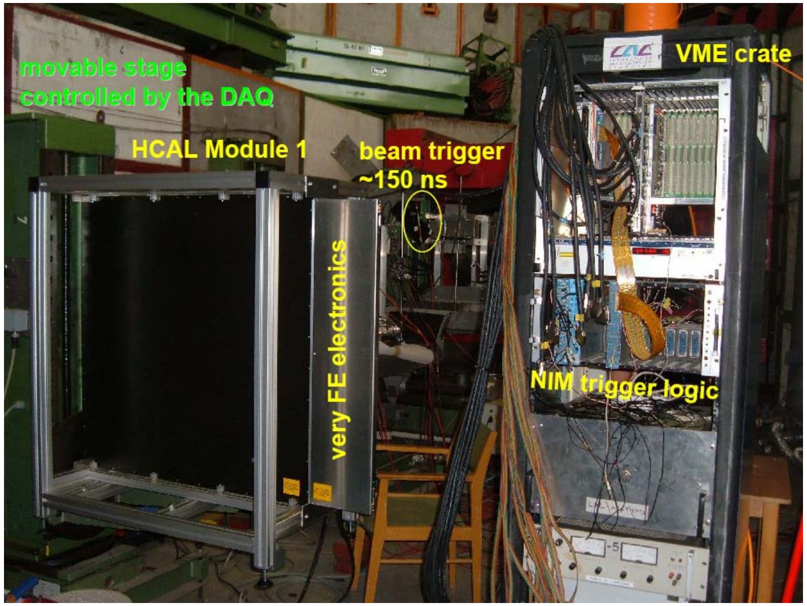


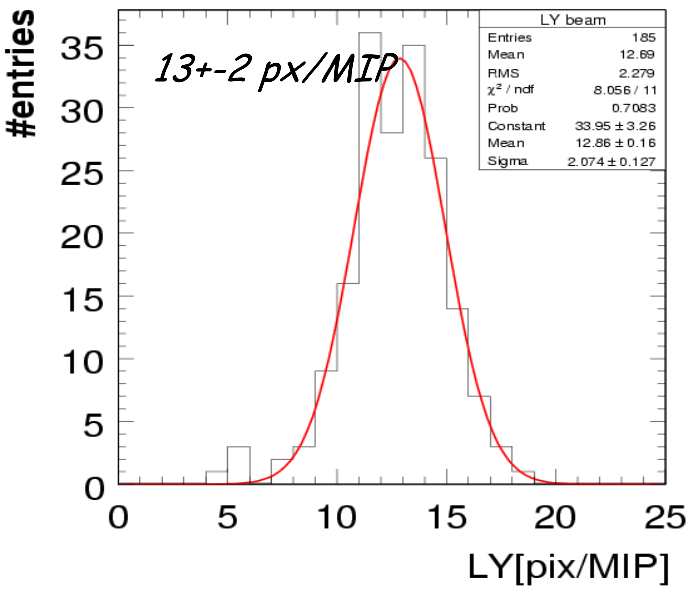
With adjustment, Geant4 gives better agreement than Geant3

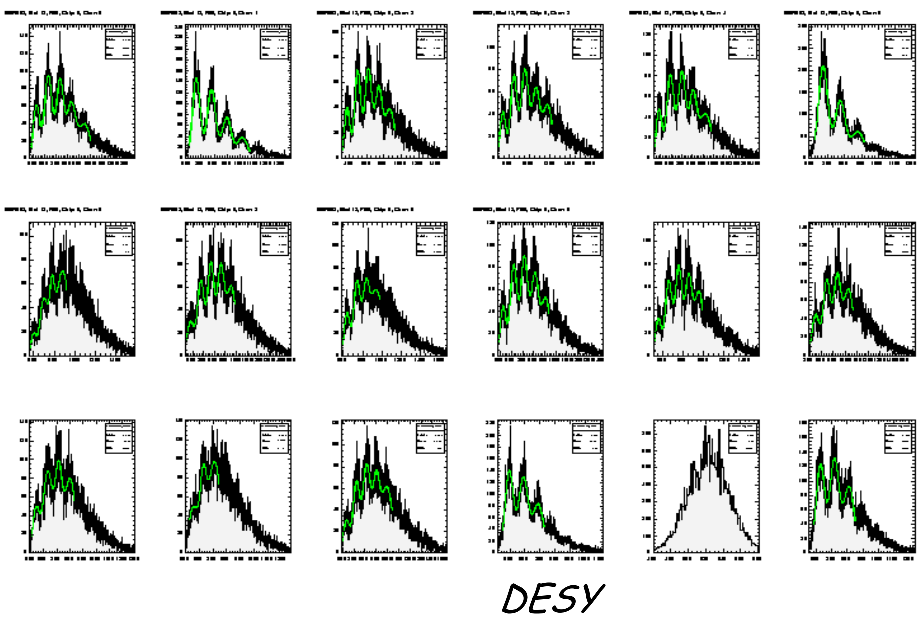
AHCAL beam tests

Sep/Nov05

- DESY electron beam
- Single AHCAL layer at a time
- Six modules scanned over whole surface; calibration of every tile
- Feb/Apr06 combined ECAL+AHCAL runs

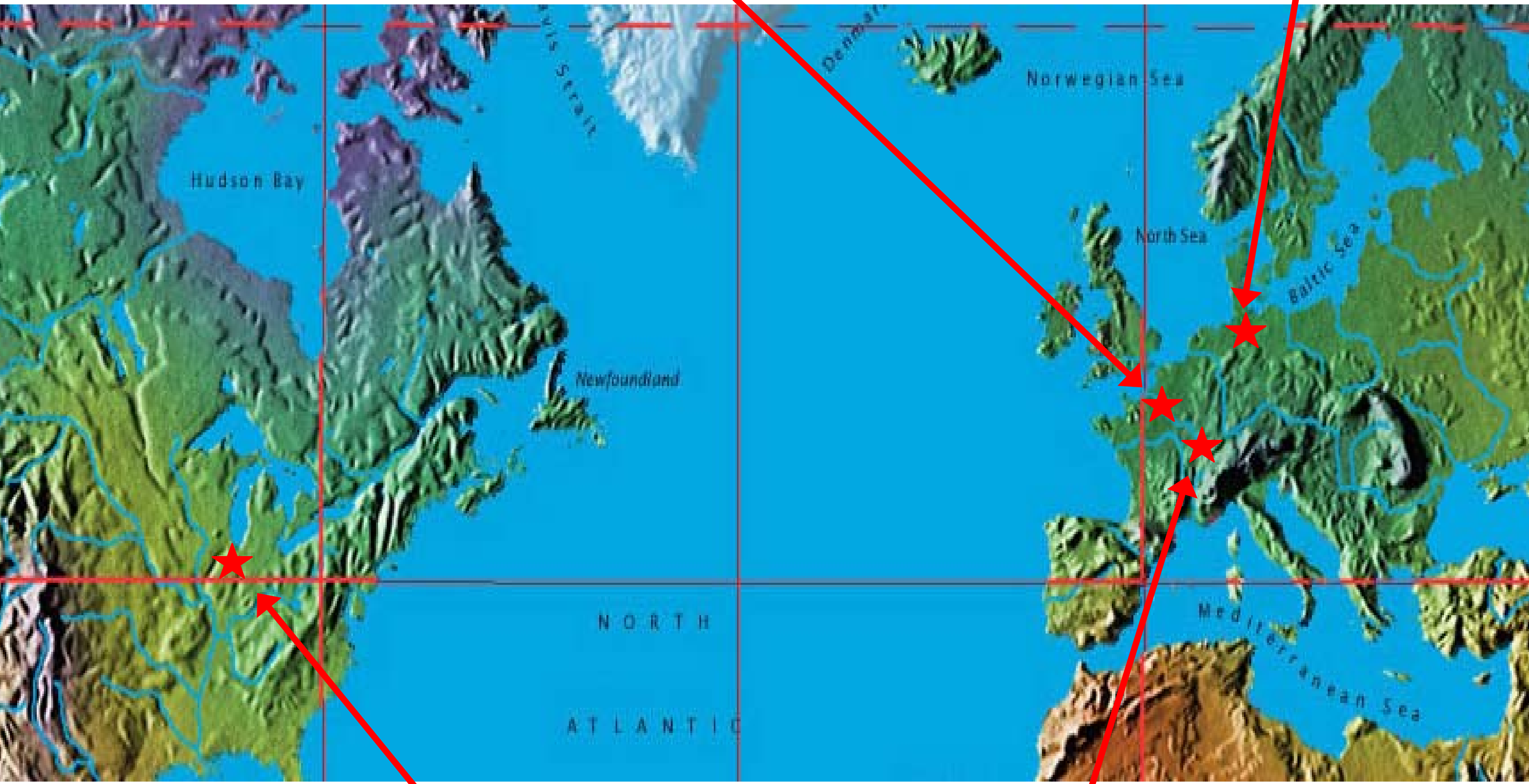






Future beam tests: CALICE world tour

Ecole Poly 2004/5 – cosmics
DESY 2005/6 – e beam



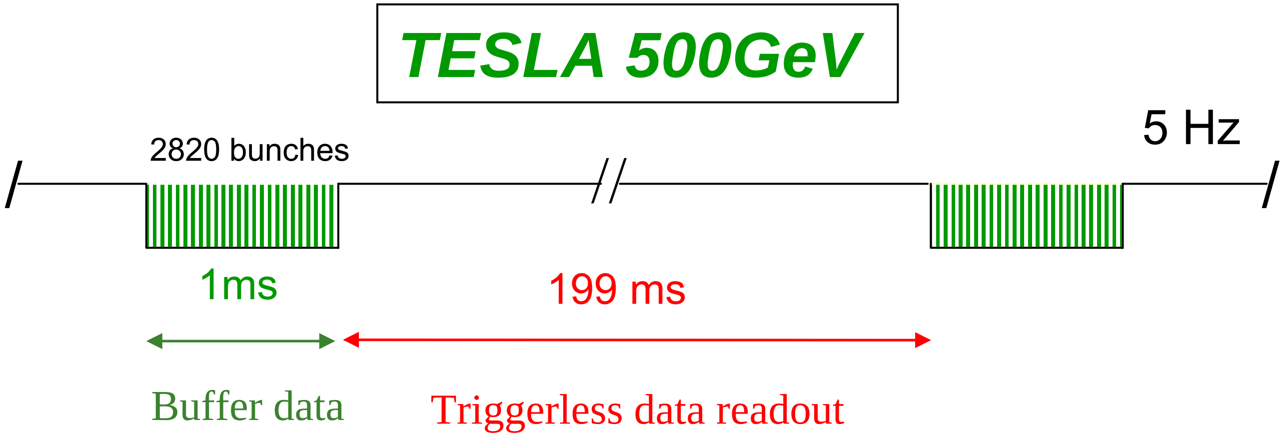
FNAL 2007/8 – hadron beam
CERN 2006 – hadron beam

- The International Linear Collider
- Jet reconstruction
- The CALICE collaboration
- CALICE-UK responsibilities
- First look at data
- CALICE-UK long-term R&D
- New opportunities

CALICE-UK long-term R&D

- Second round of funding approved this year
  - Covers activities for 3.5 years from Oct05-Mar09
  - Takes us up to time of TDRs
- New groups joined
  - RAL (PPD and EID), RHUL
- Funding to continue ongoing beam test program…
- …plus longer-term R&D in four areas
  - Generic DAQ studies
  - MAPS sensors for the ECAL
  - Thermal and mechanical ECAL studies
  - Simulation, both ECAL and global detector design
- Also members of EUDET collaboration
  - Applied for EU funding; covers many aspects of ILC detector R&D
  - If approved, cover DAQ and beam test activities from Jan06-Dec09

Generic long-term DAQ R&D

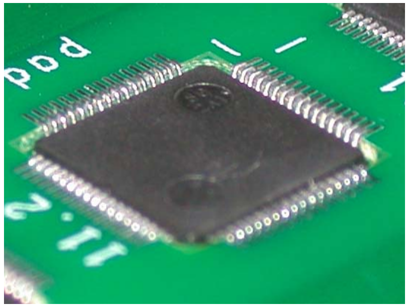


- Three parts to the DAQ system
  - Very Front End PCB
  - On-detector to off-detector networks
  - Off-detector: receivers
- Want to identify and study bottlenecks, not build DAQ system now
  - General ILC push towards "backplaneless" DAQ
  - (Almost) all off-detector hardware commercial; minimal customisation
  - Benefits for cost, upgrades and cross-subsystem compatibility (HCAL)

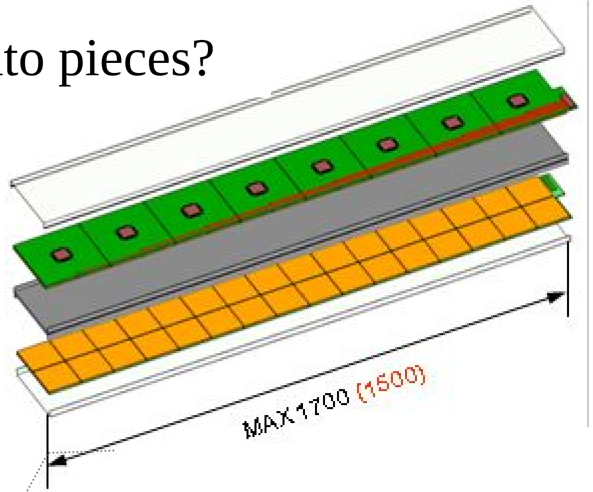
Very Front End PCB

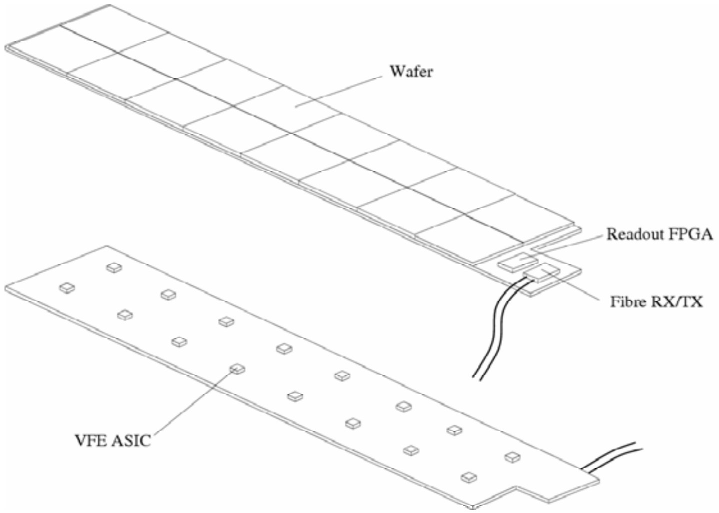
- VFE PCB slab must be
  - Around 1.6m long
  - As thin as possible

Embed components?

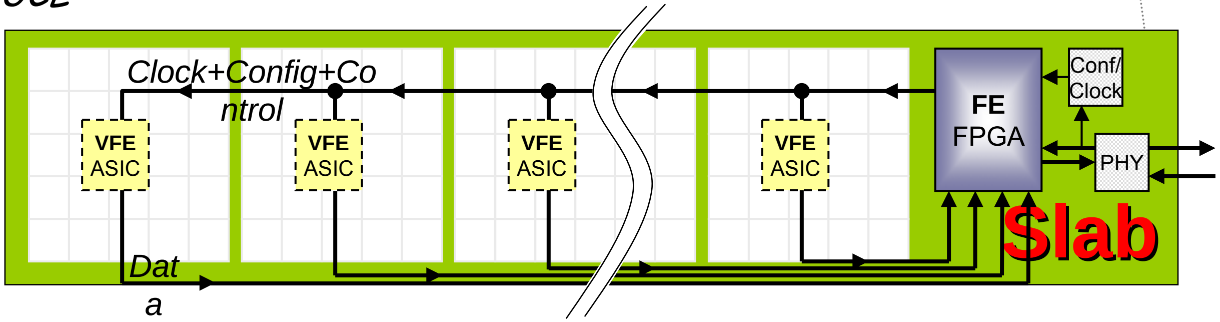


Subdivide into pieces?



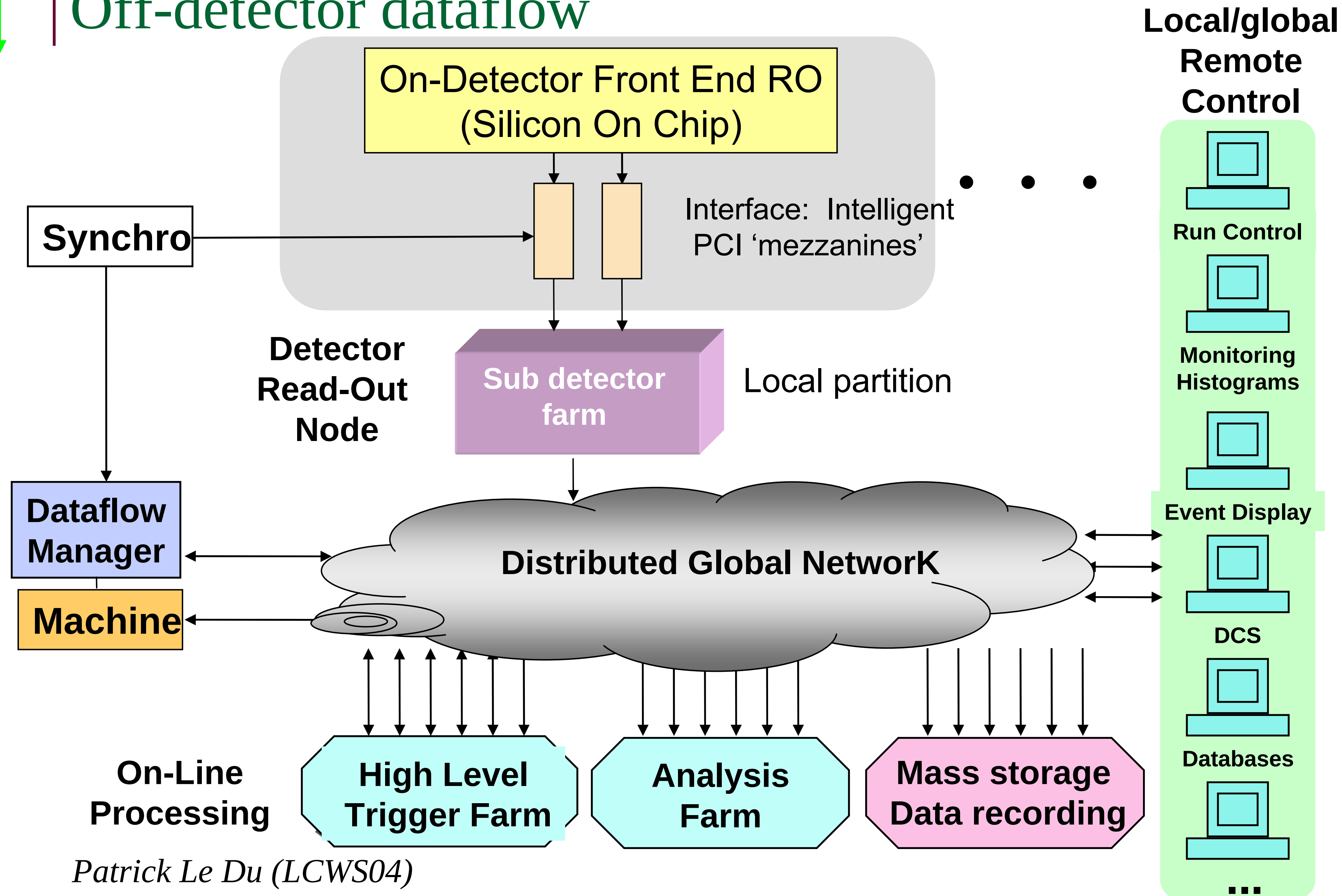


UCL



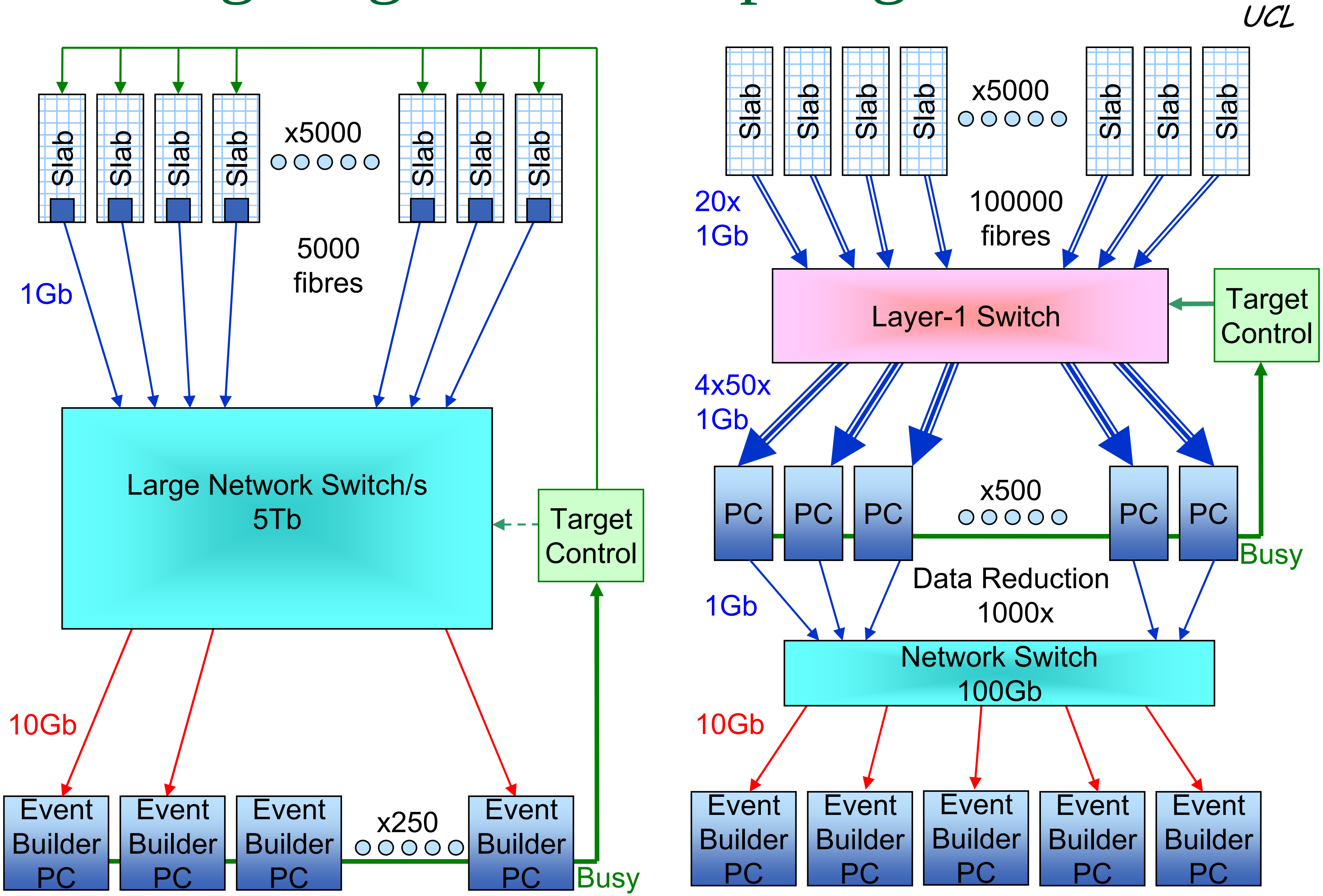
Signal transmission, readout and power dissipation are critical

Off-detector dataflow



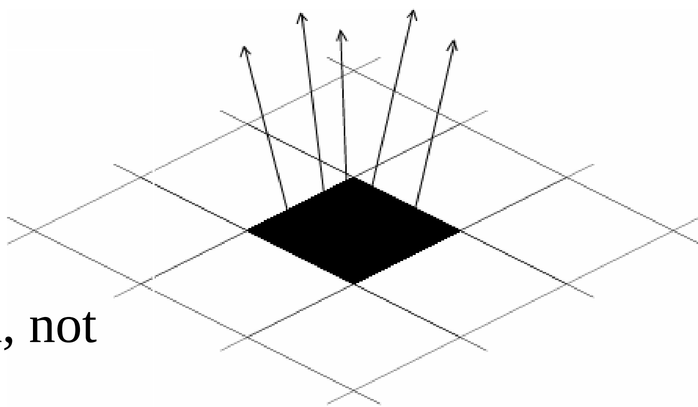
Patrick Le Du (LCWS04)

Investigating network topologies

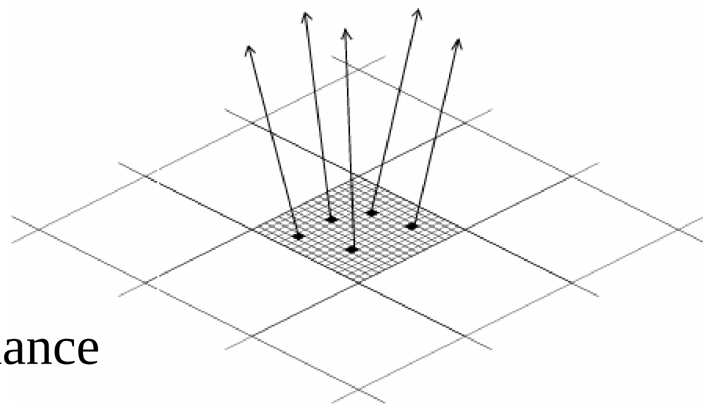


Monolithic active pixel sensors

- Replace silicon diode pad wafers with MAPS
  - Contain readout electronics integrated into silicon wafer
  - Very fine pixels ~50×50μm^2 (compared with 1×1cm^2 diode pads)
  - Allows binary (single bit) readout = DECAL
- Potential for
  - Better spatial resolution and hence pattern recognition
  - Much cheaper; requires standard CMOS silicon, not high resistivity diode quality wafers

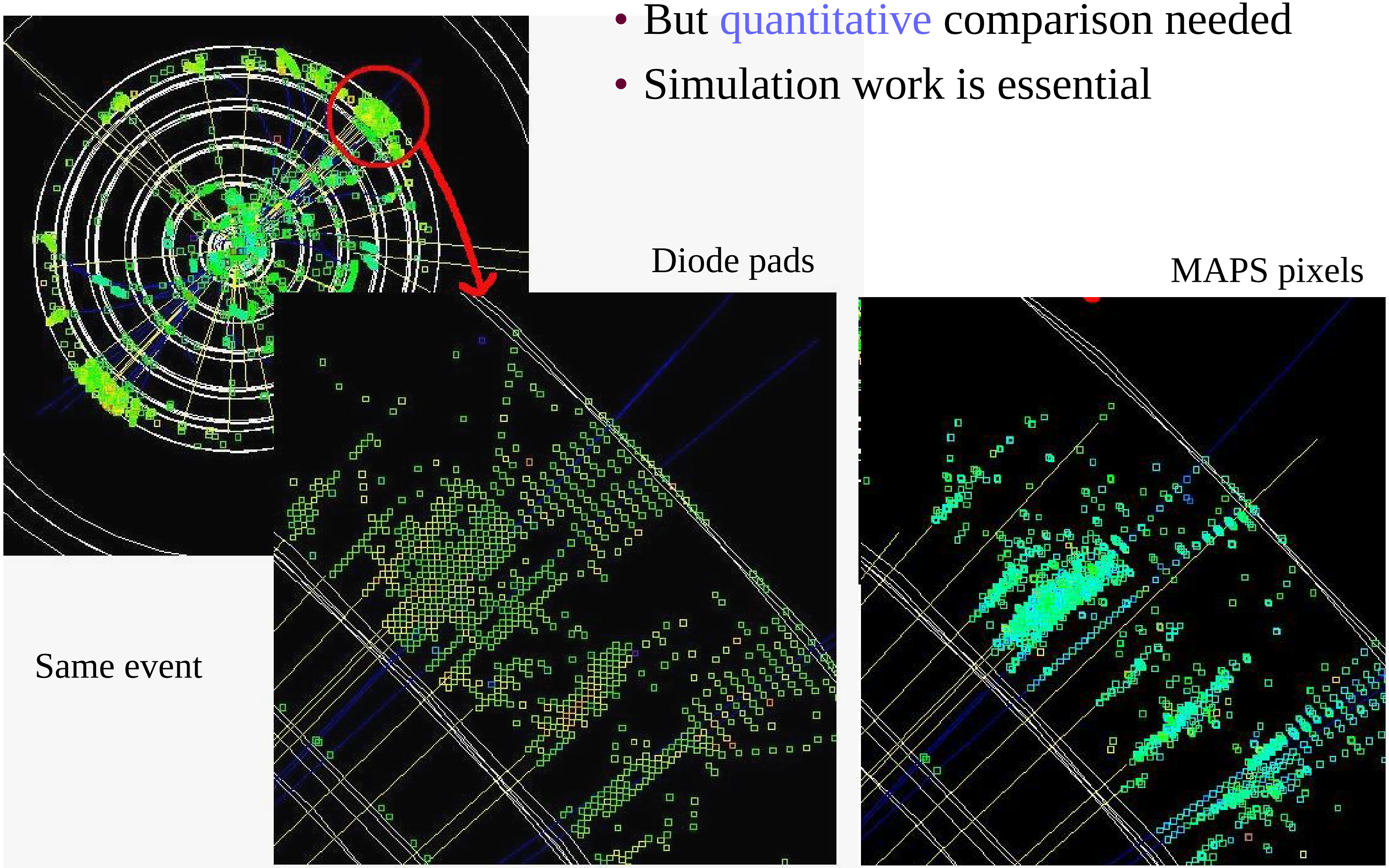


- Over next three years
  - Make prototype MAPS sensors
  - Test with radiation sources and cosmics here
  - Test in beam (at DESY) in ECAL structure
  - Allows direct comparison to diode pad performance



Simulation studies of MAPS

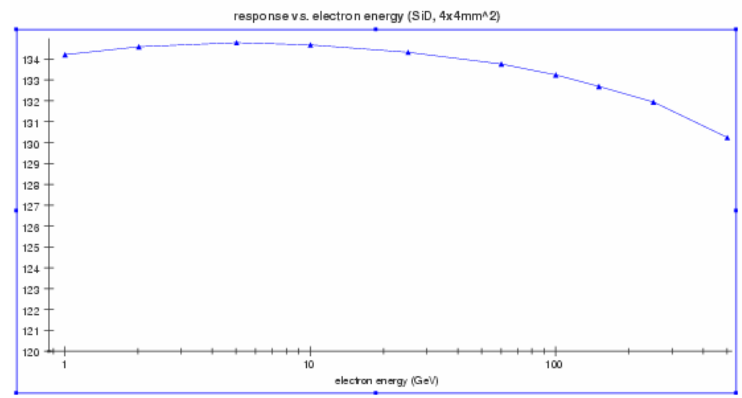
- By eye, pixels look very good compared with diodes
  - But quantitative comparison needed
  - Simulation work is essential



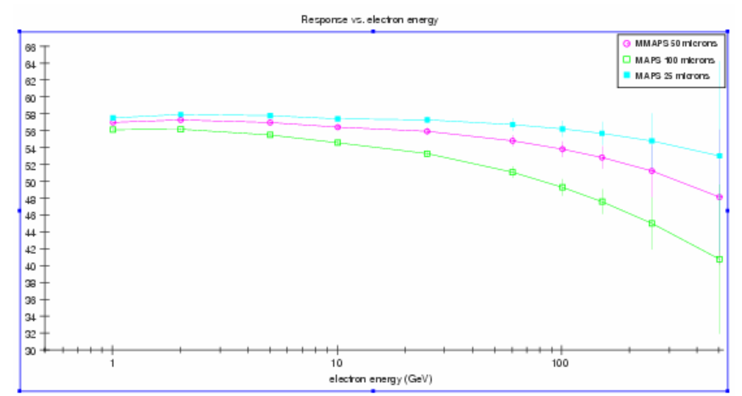
Birmingham

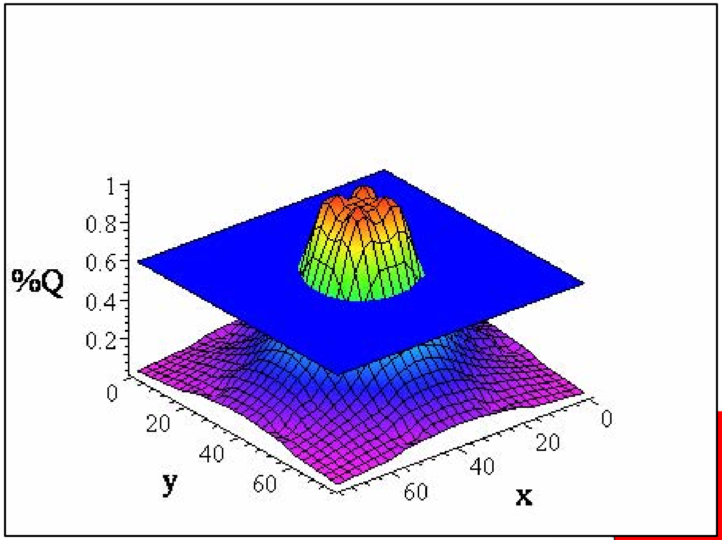
Sensor simulation

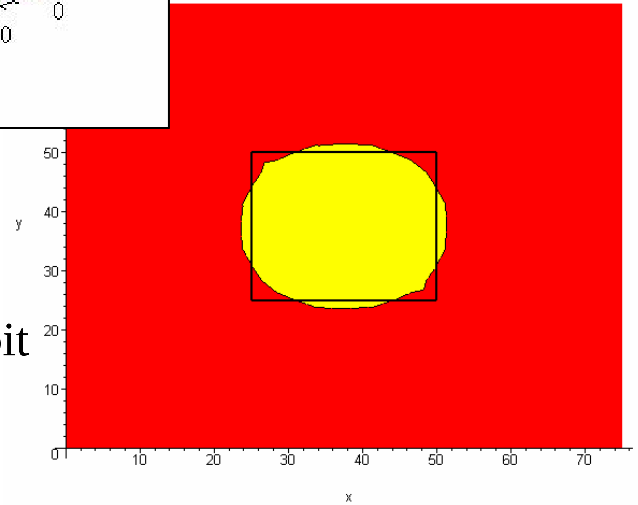
Birmingham



- Need to simulate details
  - Efficiency and crosstalk
  - Optimise 0-hit and 2-hit cases







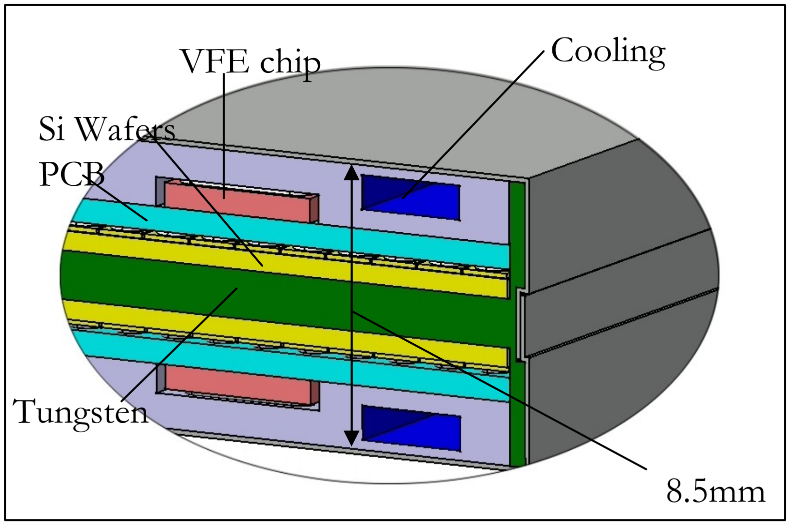
- Charge diffusion and 60% threshold cut
- Resulting efficiency to set bit over 25×25μm² pixel area

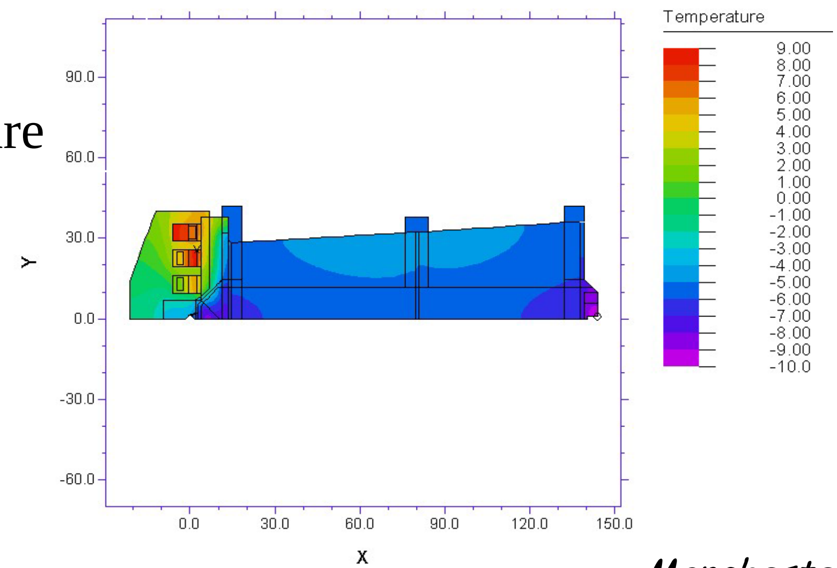
Comparison of energy response vs. shower energy for standard SiD ECAL and MAPS ECAL

RAL

Thermal and mechanical studies

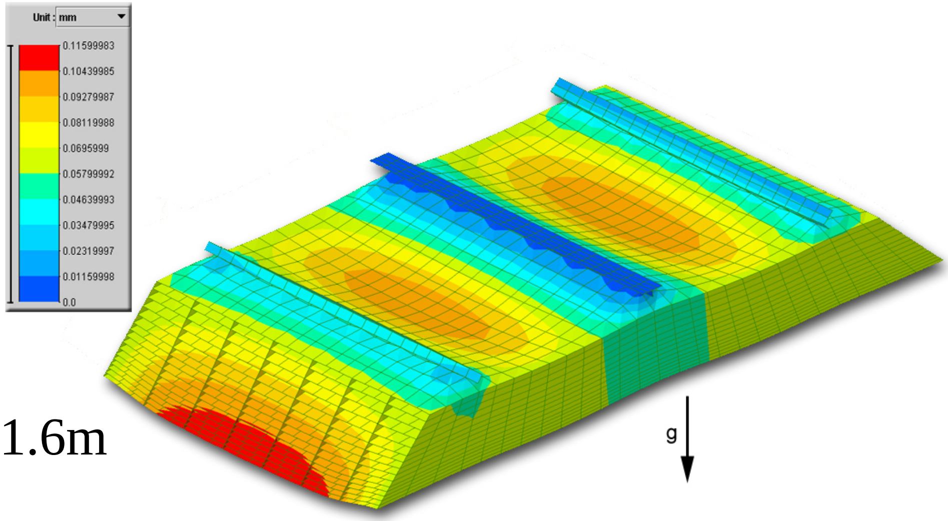
- Getting electronics heat out is critical
- Requires mechanically integrated structure





Manchester

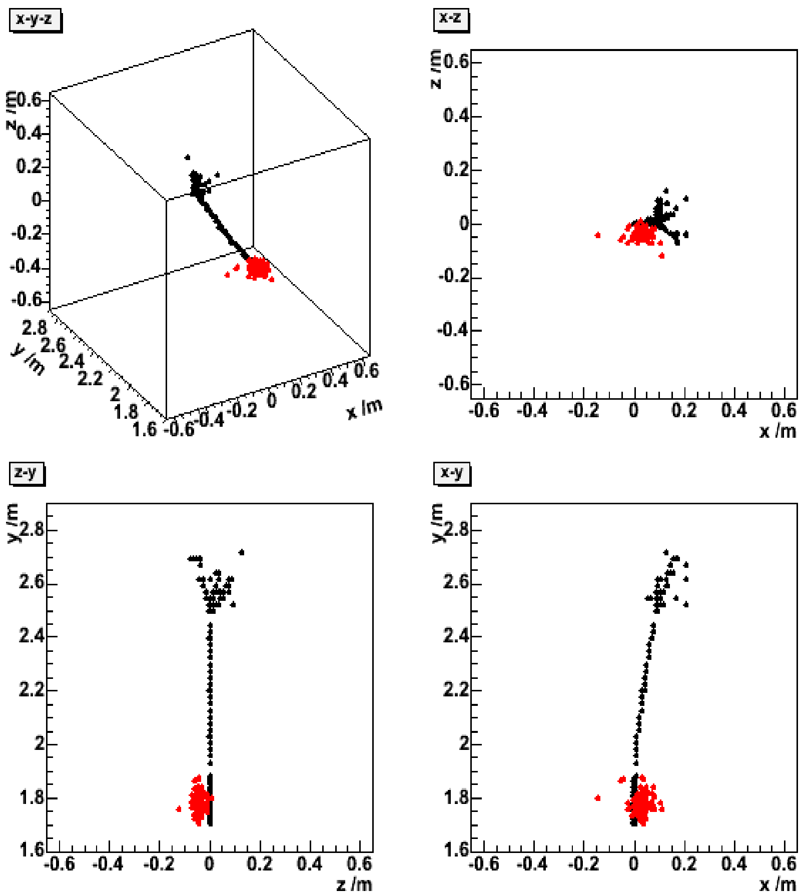
- Mechanical stress over 1.6m



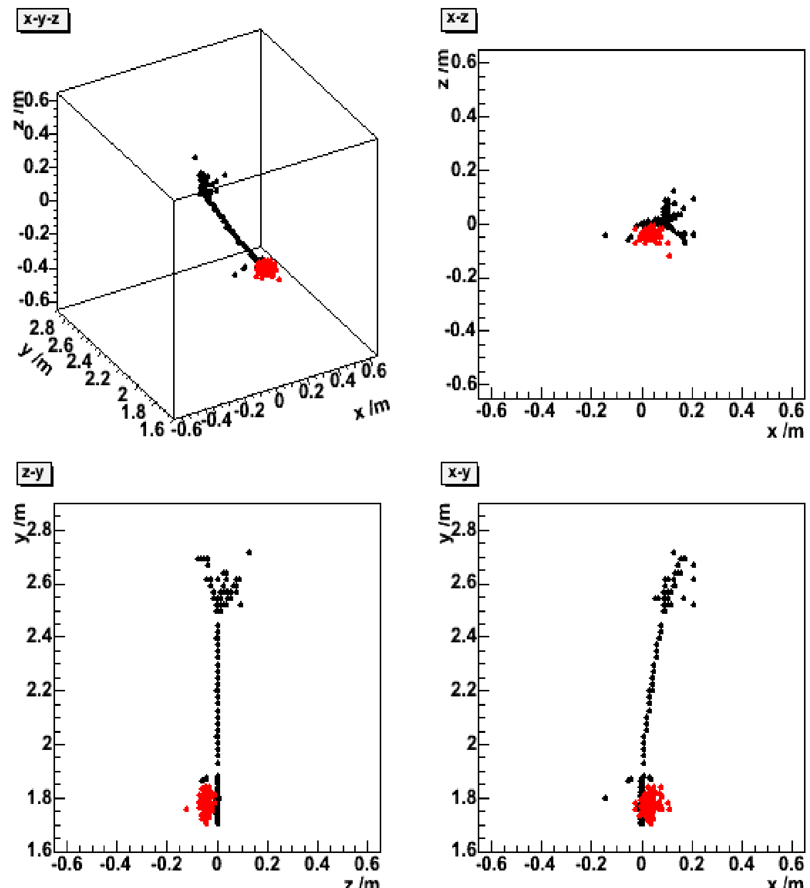
PFLOW clustering; π^+/γ separation

Cambridge

True clusters



Reconstructed clusters

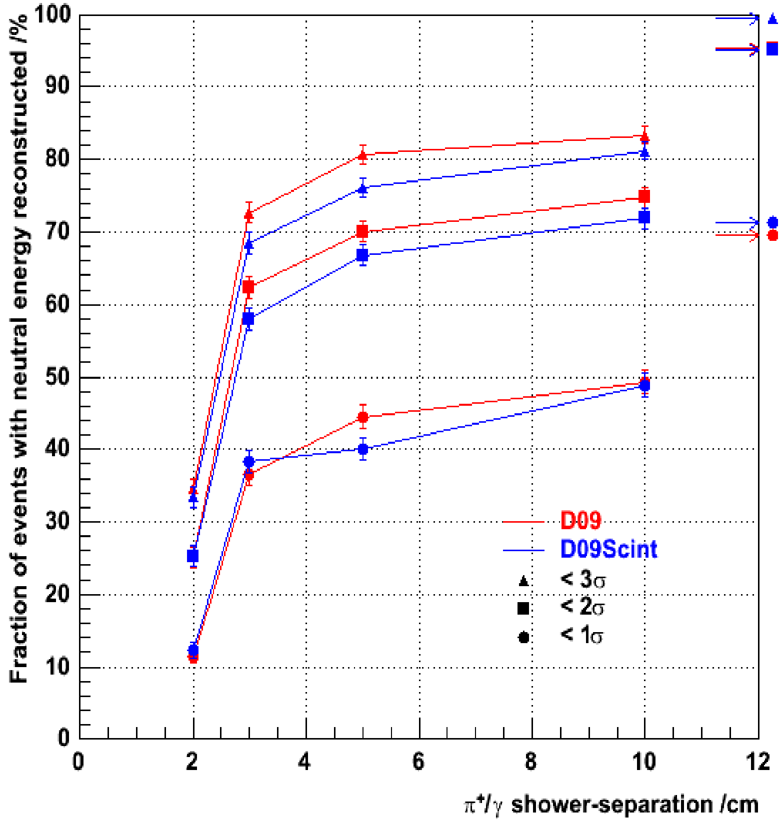


- **Black** cluster = 5 GeV/*c* π^+.
- **Red** cluster = 5 GeV/*c* γ.

- **Black** cluster matched to charged track.
- **Red** cluster left over as neutral $\Rightarrow \gamma$ energy well reconstructed.

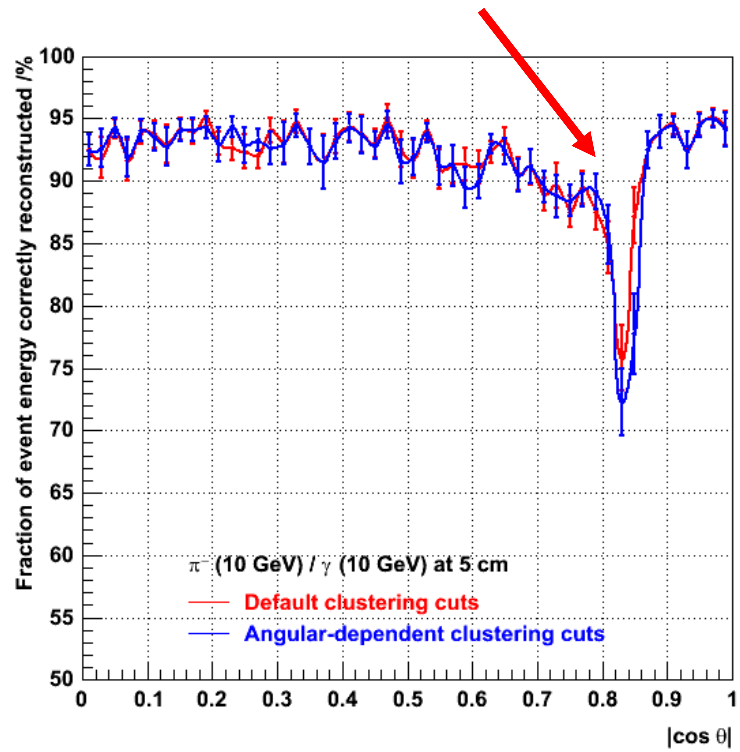
π^+/γ separability vs separation

5 GeV/c π^+/γ



Fraction of events with photon energy reconstructed within 1,2,3σ

- Reconstruction efficiency as a function of polar angle
  - Hard at barrel-endcap overlap



Cambridge

- The International Linear Collider
- Jet reconstruction
- The CALICE collaboration
- CALICE-UK responsibilities
- First look at data
- CALICE-UK long-term R&D
- New opportunities

New opportunities

- There is a huge amount which we could do with more effort!
  - Data analysis; particularly when we restart next year
  - Simulation of DAQ rates, MAPS, etc.
  - PFLOW, clustering algorithms, etc.
- Any new groups would be very welcome from our side
  - Would need approval by PPRP
  - PPARC would need to see some “value added”
- In terms of potential long-term projects
  - Gridify simulation, reconstruction and analysis?
  - Other aspects of long-term electronics/DAQ R&D?
  - Larger involvement with detector concept groups (particularly SiD and GLD)?
  - Something completely new???

CALICE is very open to new collaborators!