



Calorimetry for a Linear Collider Experiment

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Imperial College London

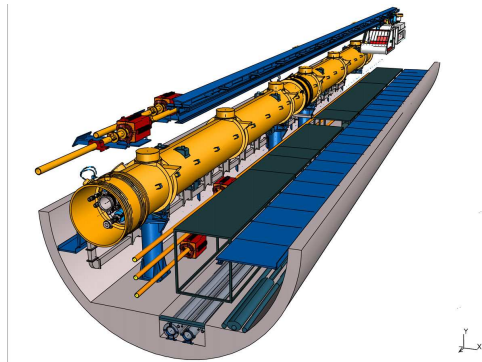
Overview

- **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

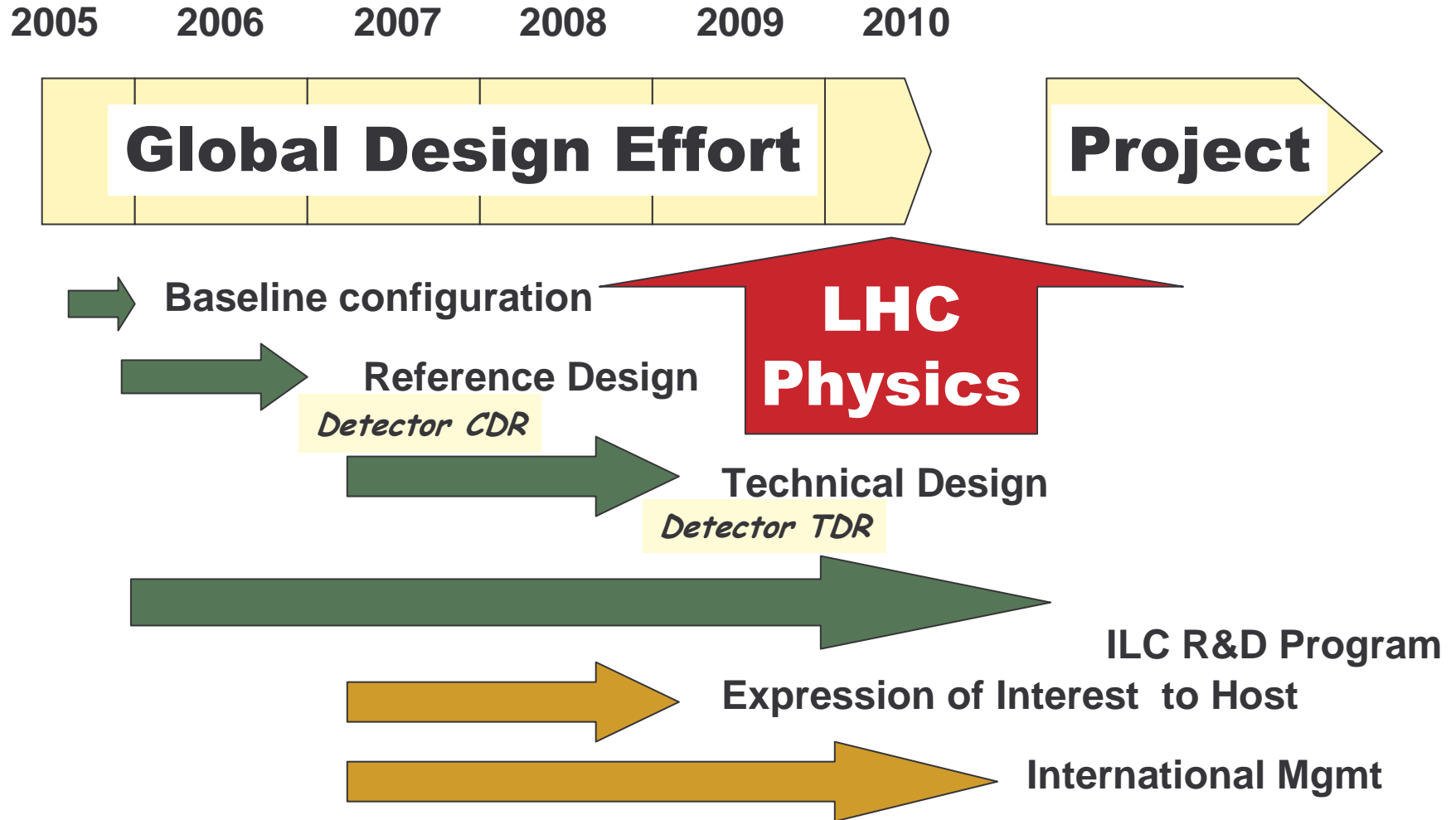


- ILC could proceed now...
 - ...if we were given the **~£2 billion** needed
 - International level negotiations ongoing; hope to converge within five years

- 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

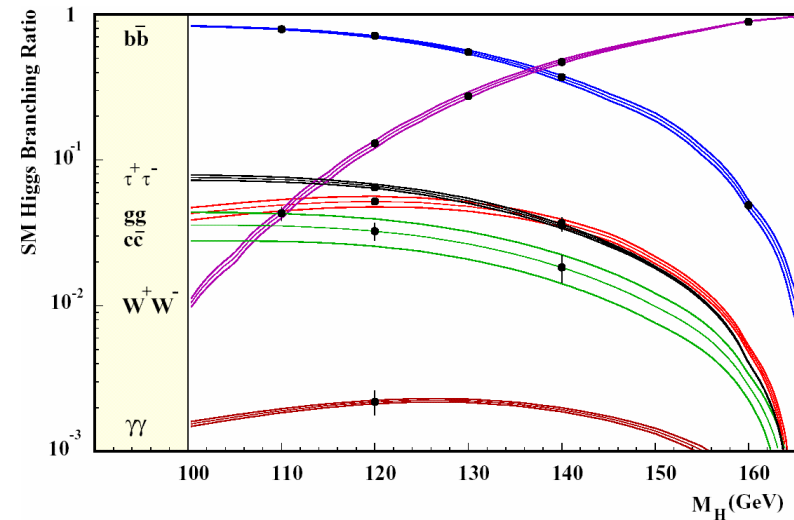


B.Barish, GDE

Physics at the ILC

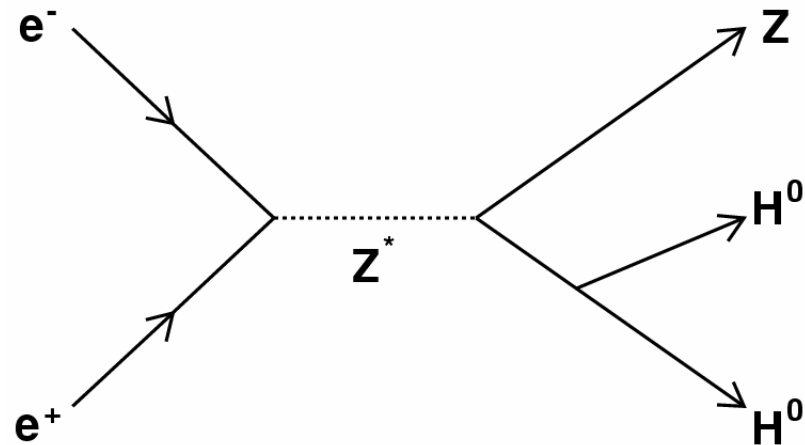
- Doing the **real science** after the LHC discoveries

- Precision measurements to test theories
- If **Higgs** discovered at LHC; know mass
 - ILC can measure SM predictions
 - Many BF's to check mass² 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 BF's, spins, etc.



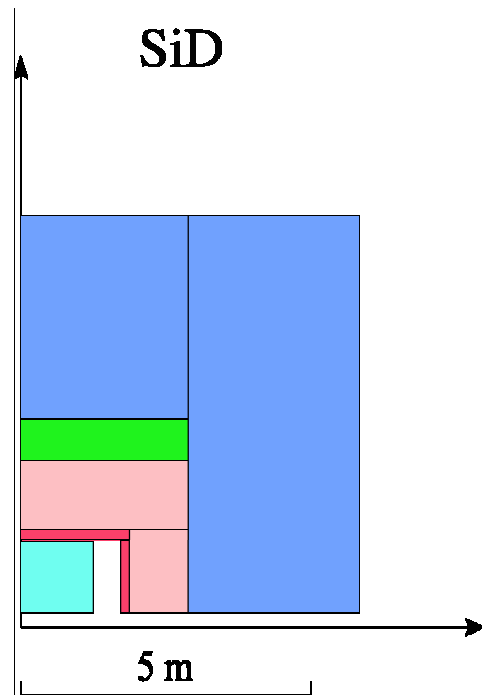
- Other physics

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



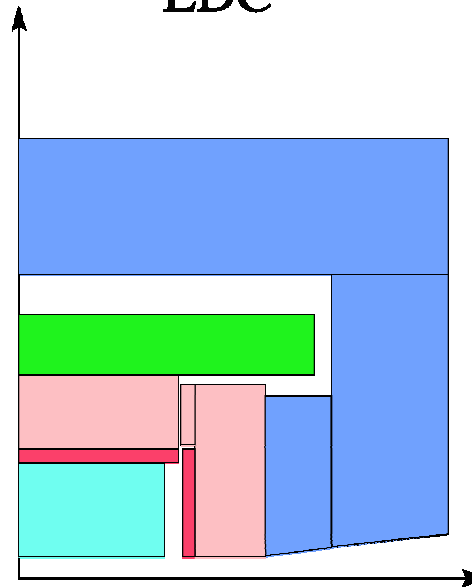
ILC detector concepts

- Sizes: “small”



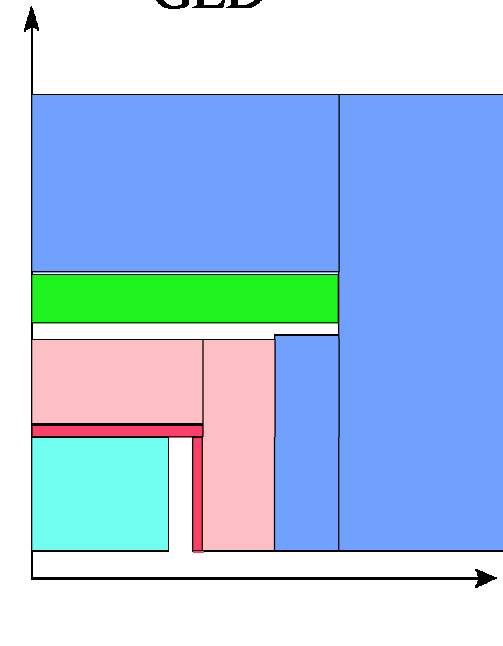
- 5T
- Si Tracker
- SiW ECAL
- Gas or Scint HCAL

- “large”
“LDC”



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

- “giant” (< CMS!)
“GLD”

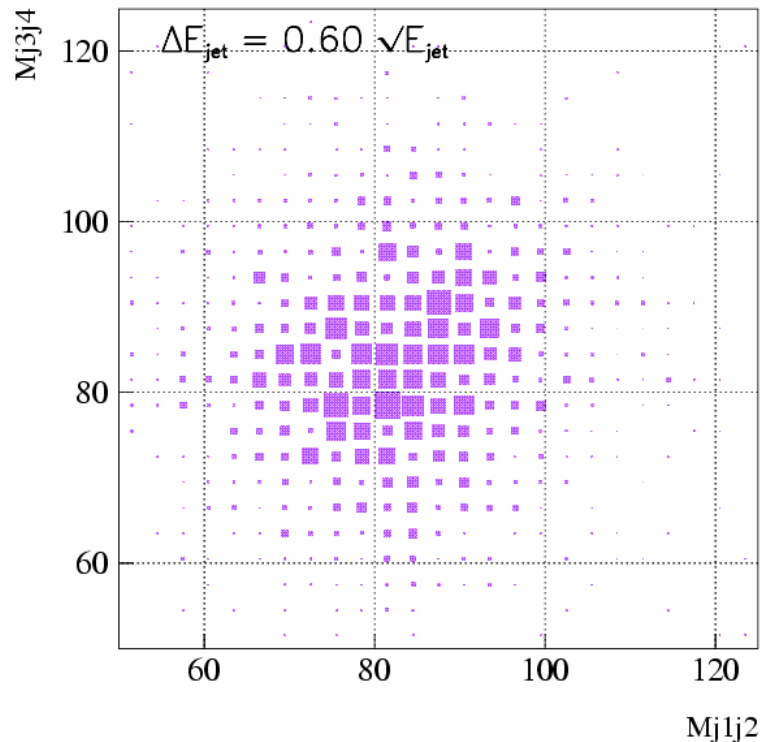
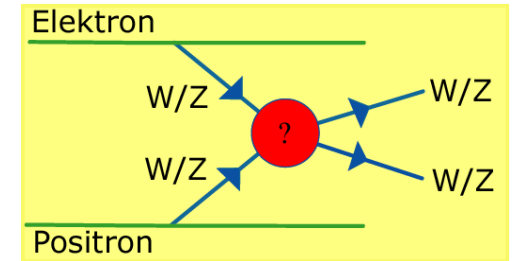


- 3T
- Gasous Tracker
- Hybrid or Scint ECAL
- Scint HCAL

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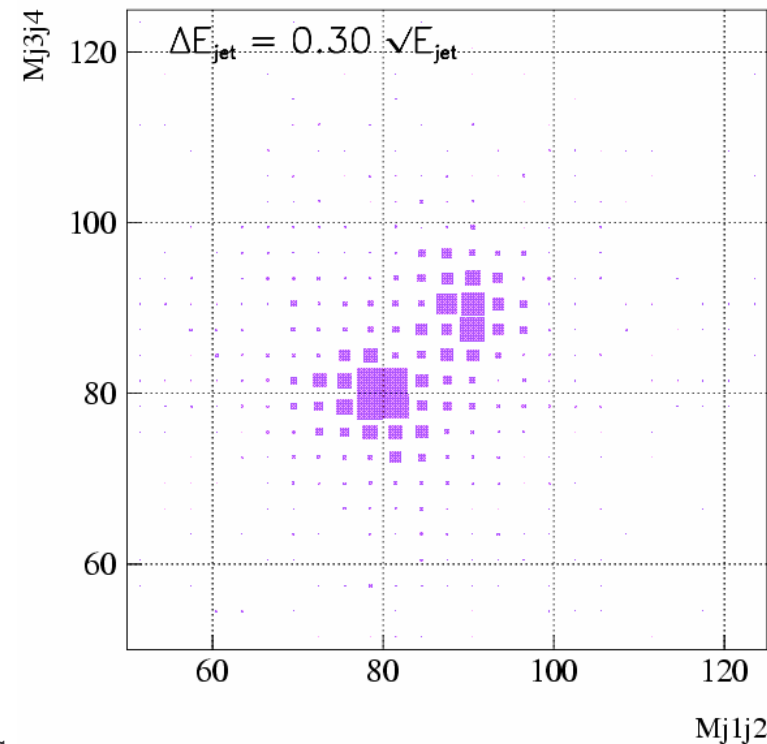
Detector needs high performance calorimetry

- 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



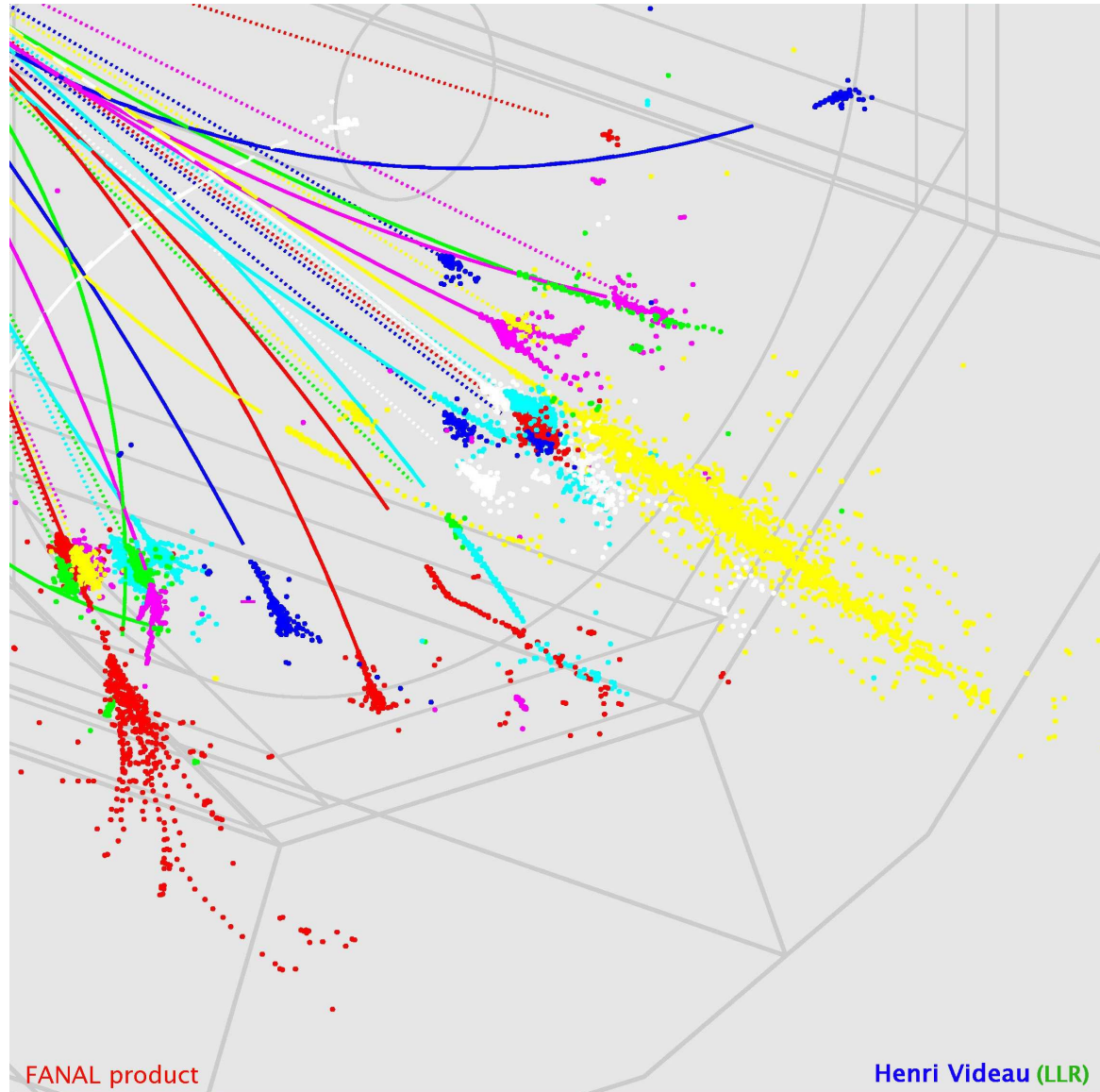
- **ZZ vs WW jets**
- Best LEP detector (Aleph)

- **ZZ vs WW jets**
- Projected ILC detector



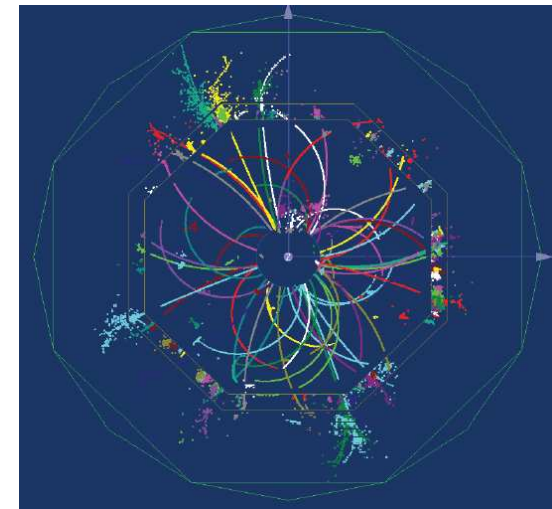
Jet resolution

- 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 $\sim 10\%/\sqrt{E}$
- Hadron calorimeter for neutral hadrons
 - **~10%** of the typical jet energy
 - Resolution $\sim 40\%/\sqrt{E}$



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

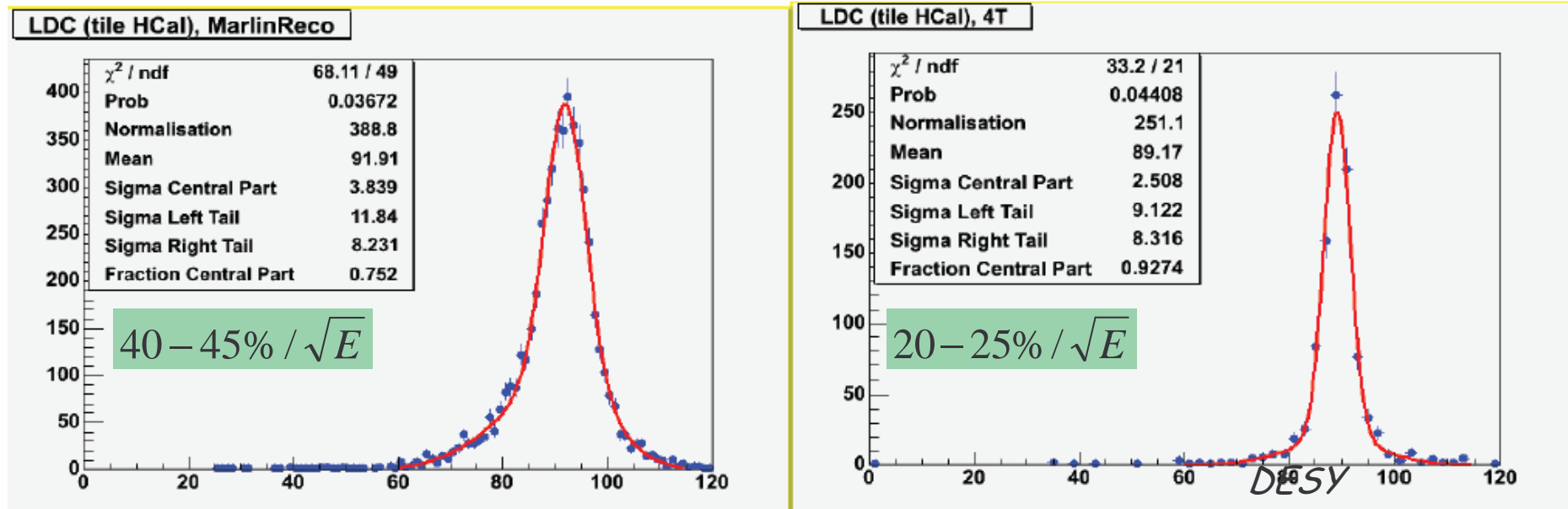
PFLOW state of the art

- **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

Realistic PFA

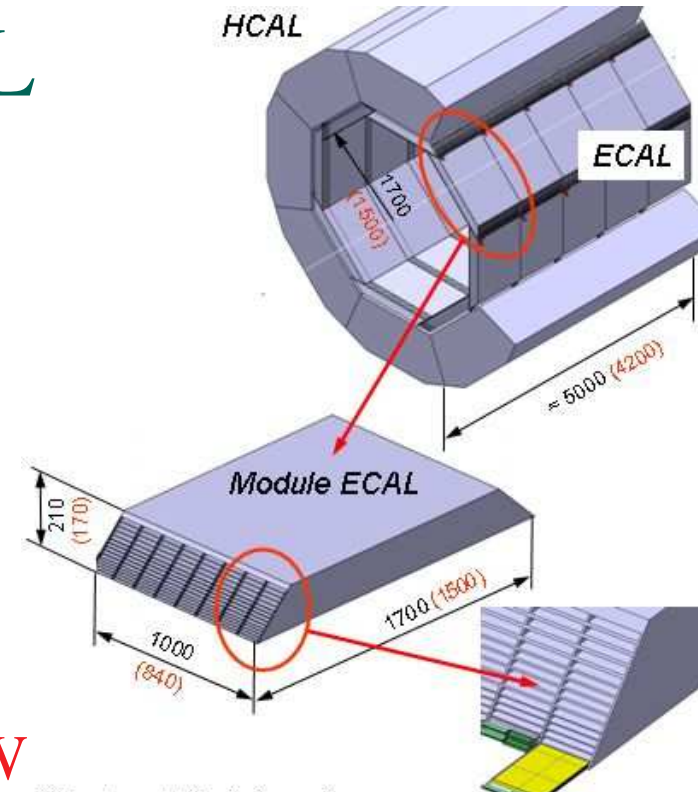
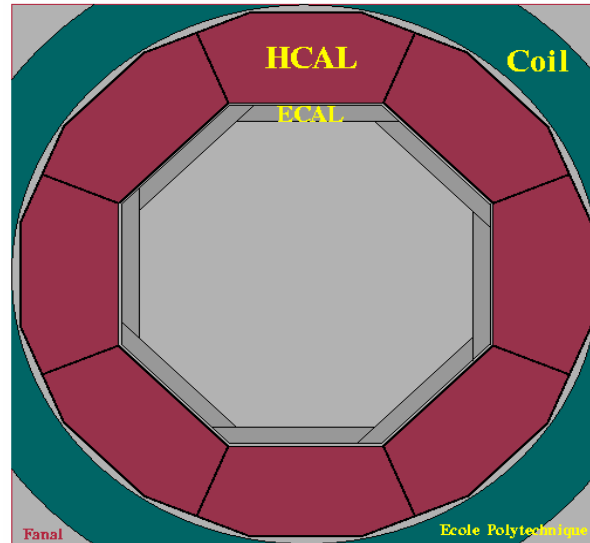
$Z \rightarrow qq$

Perfect Particle flow Algorithm



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 $\sim 1 \times 1 \text{cm}^2$; stable, compact, well-understood technology
 - Results in 3000m^2 of silicon, 38 million channels, $\sim \text{£}80\text{M}$!

-
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The CALICE Collaboration

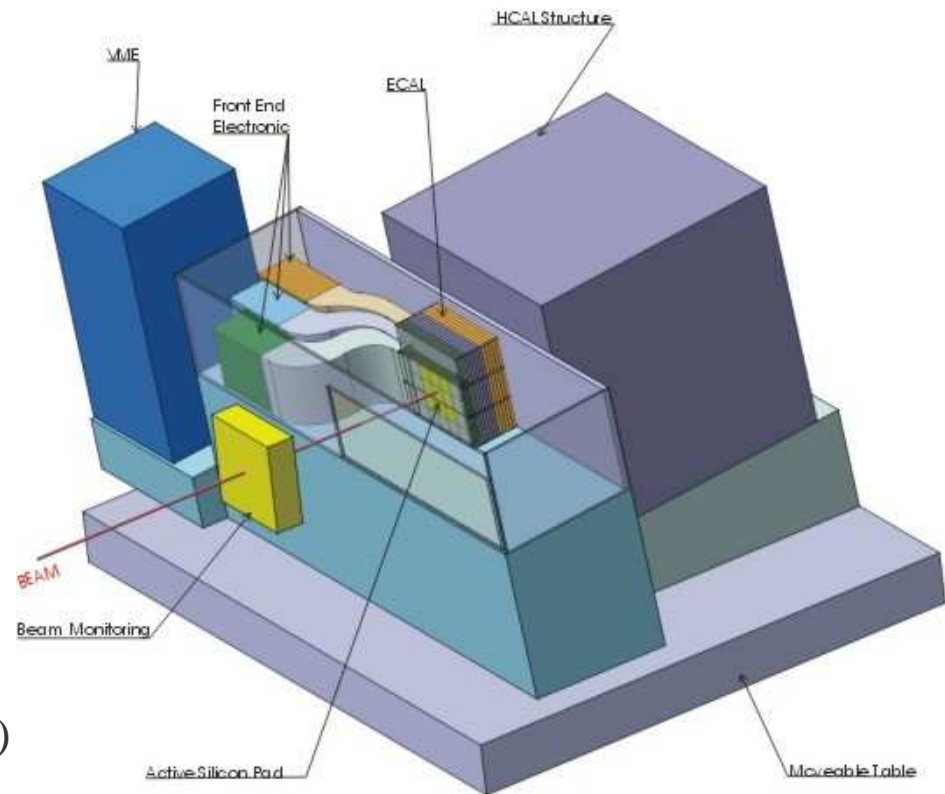
CAlorimetry for a LInear Collider Experiment



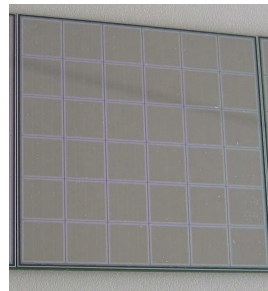
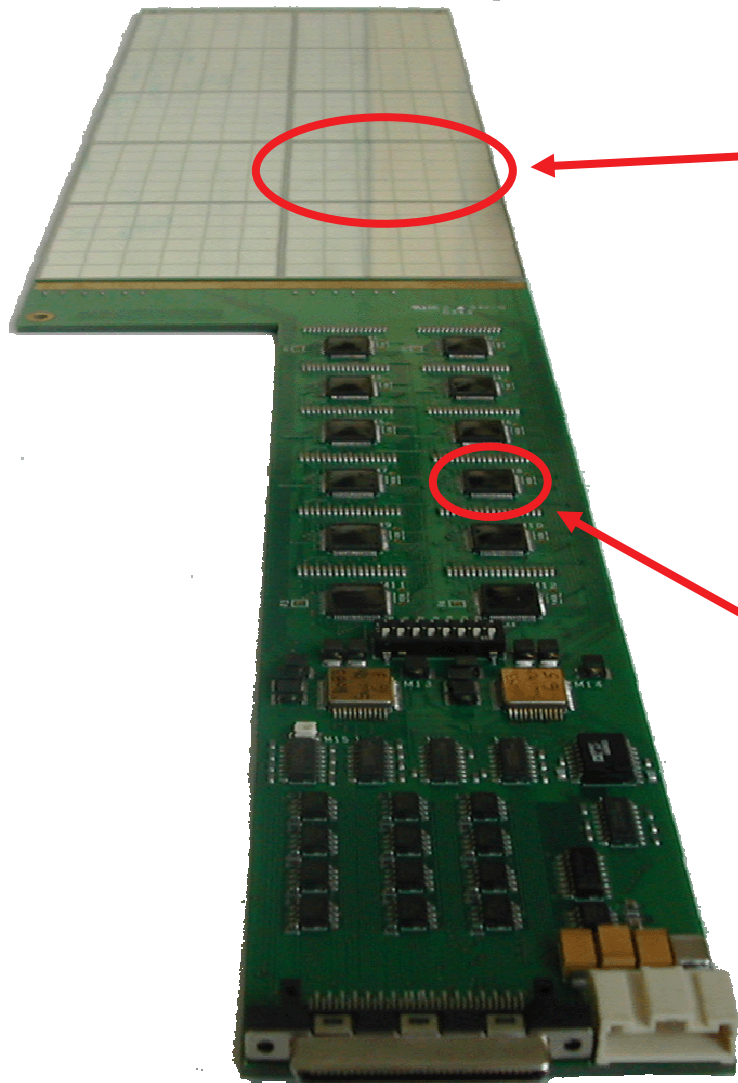
- Main aims
 - Tune (or verify) simulation to level it can be trusted to design the calorimeters for a ILC detector
 - Get realistic experience of calorimeter operations with novel technologies
 - Design the calorimeters in detail, particularly to reduce cost
- Expected that this leads directly into 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

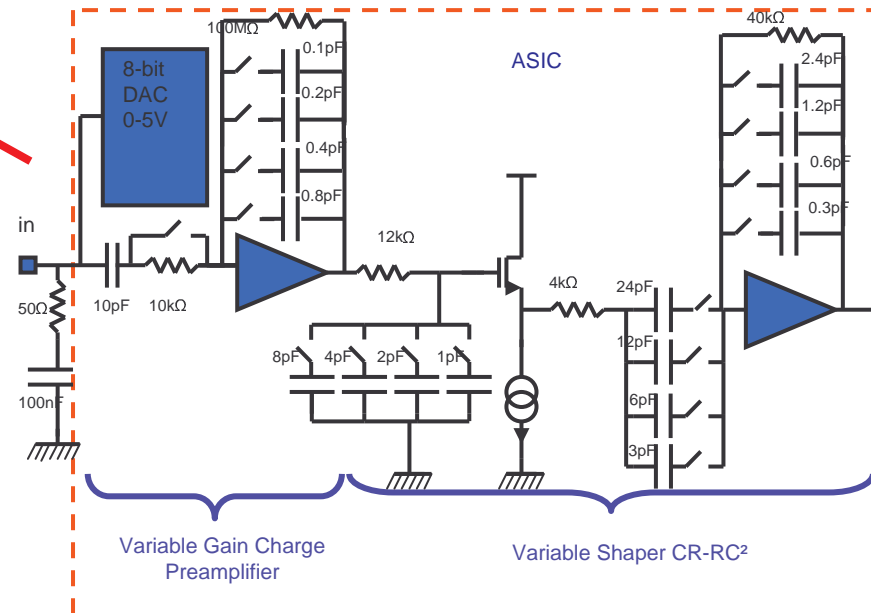


LLR/EP

6x6 pads/wafer

- Silicon diode pads $1 \times 1 \text{ cm}^2$
- Each layer 18×18 array

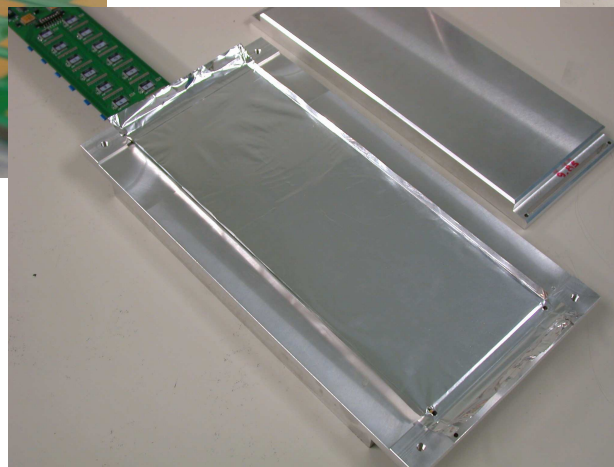
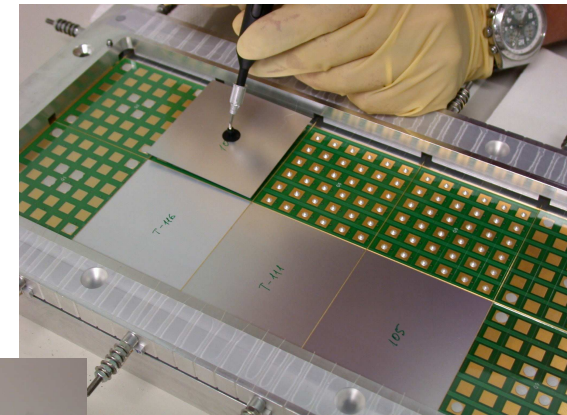
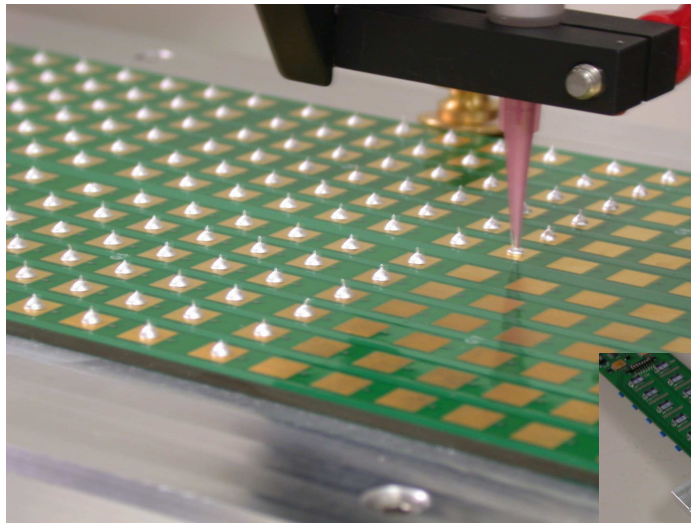
- Preamp ASIC; 18 channels
- Shaper and S&H; multiplexed output



LAL/Orsay

VFE PCB construction

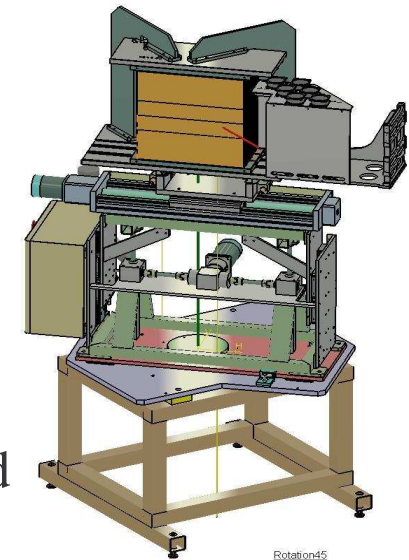
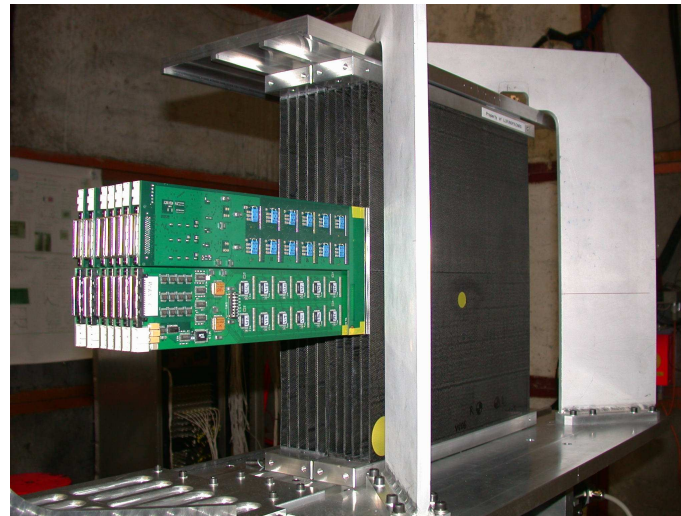
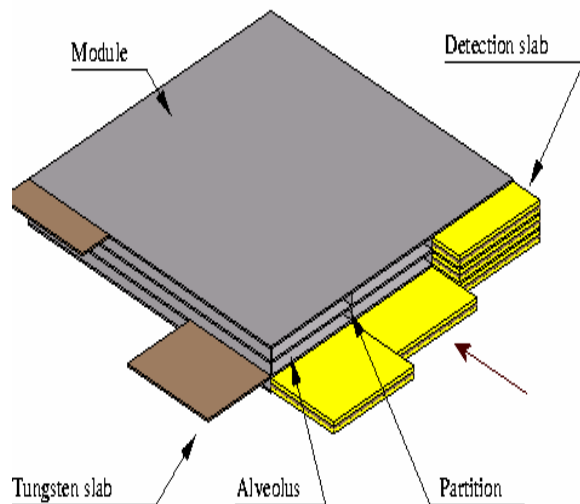
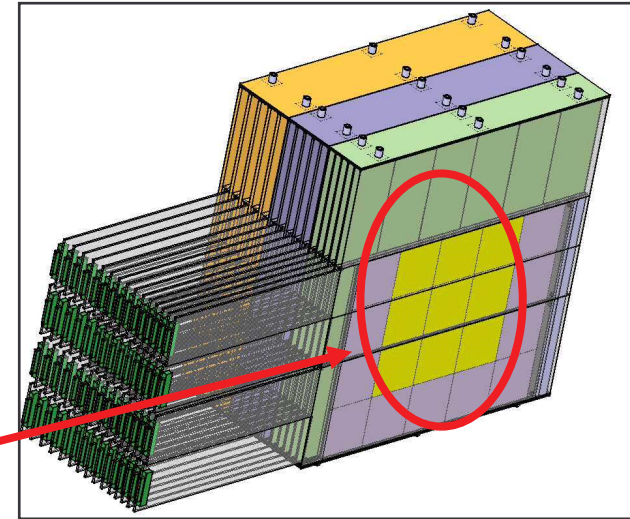
- Diode pads attached directly to PCB using conductive glue;
 - Glue deposition **automated**
 - Wafer positioning and substrate foil attachment done **by hand**



LLR/EP

ECAL mechanics

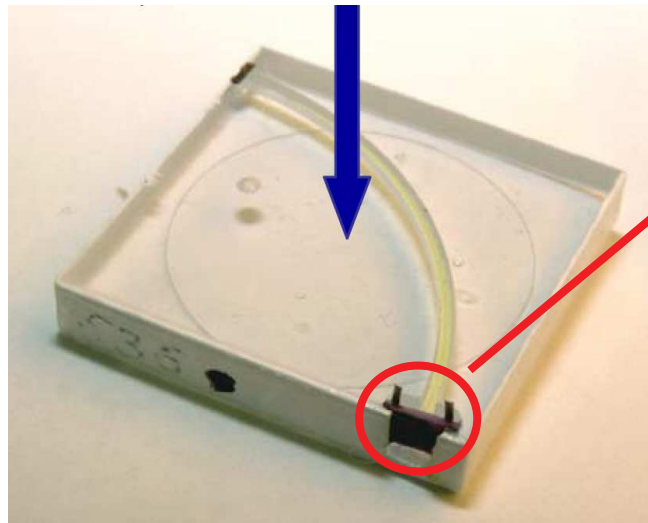
- Two VFE PCBs sandwiched to one tungsten sheet to make “slab”
- Slabs inserted into carbon fibre-tungsten mechanical structure
- $18 \times 18 \times 20 \text{ cm}^3$ active area



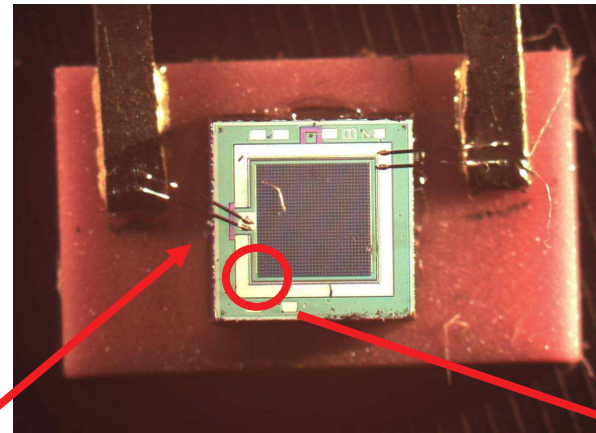
Whole ECAL mounted on movable stage

AHCAL scintillating tiles and SiPMs

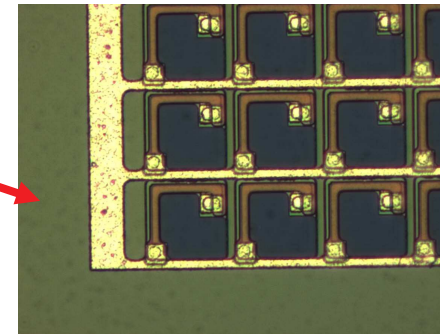
- $3 \times 3 \text{ cm}^2$ scintillator tile
- Wavelength shifting fibre
- Coupled directly to SiPM



ITEP

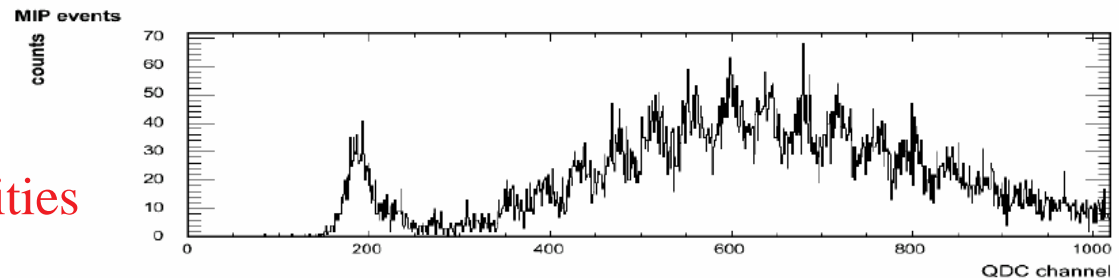


MEPHI / PULSAR



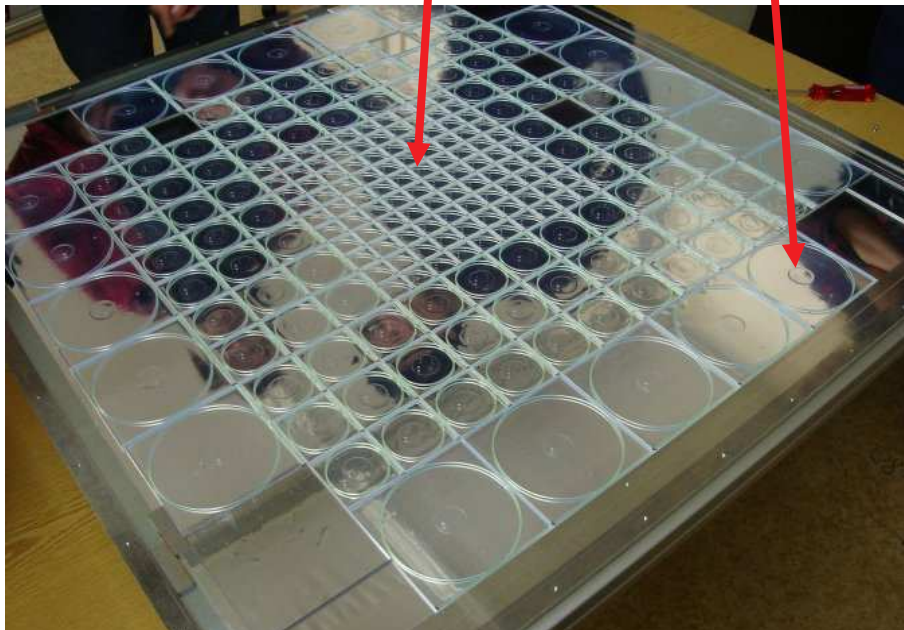
- Silicon PM: multipixel Geiger mode APDs; 1156 pixels
- Gain 10^6 , bias $\sim 50\text{V}$, size 1 mm^2

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



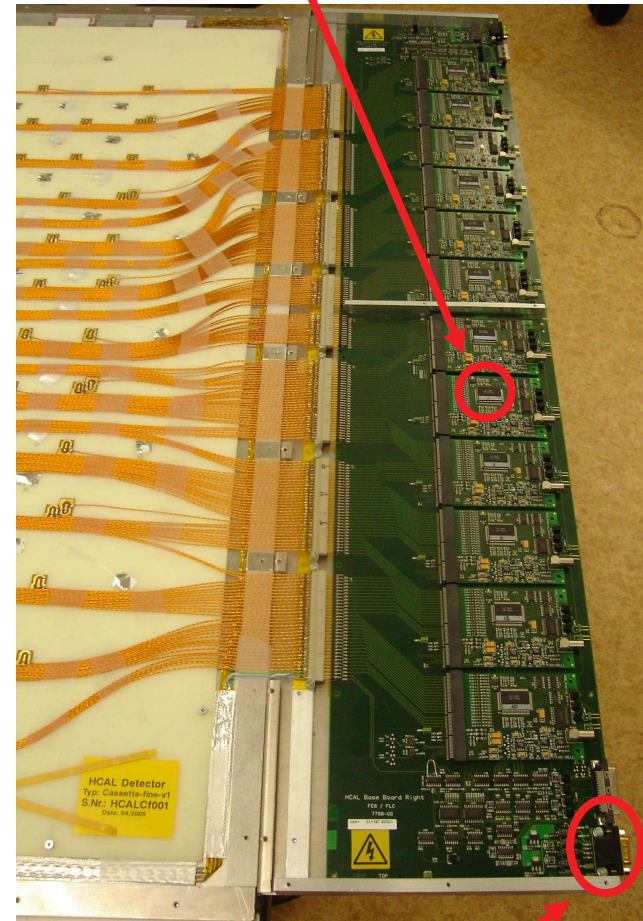
AHCAL sensitive layers

- 1 cubic metre
- 38 layers, 2cm steel plates
- 8000 tiles, each with SiPMs
- Tiles sizes: $3 \times 3 \text{ cm}^2$ to $12 \times 12 \text{ cm}^2$



DESY

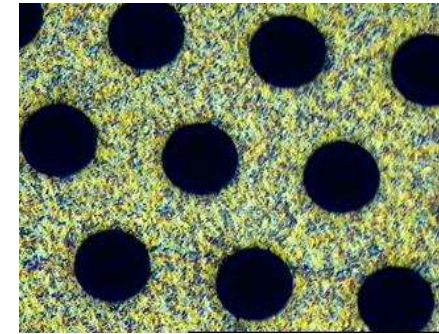
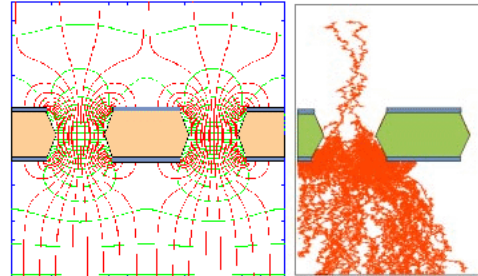
Modified version of ECAL
ASIC



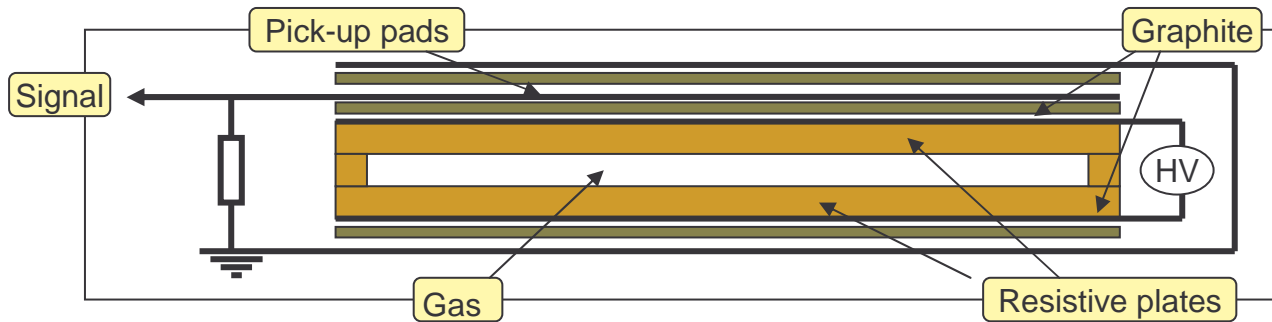
Same connector as ECAL

DHCAL technologies

- Small cells $\sim 1 \times 1 \text{cm}^2$
- Binary readout
- Two technology options
 - GEMs: lower operation voltage, flexible technology
 - RPCs: robustness and larger signals



UTA

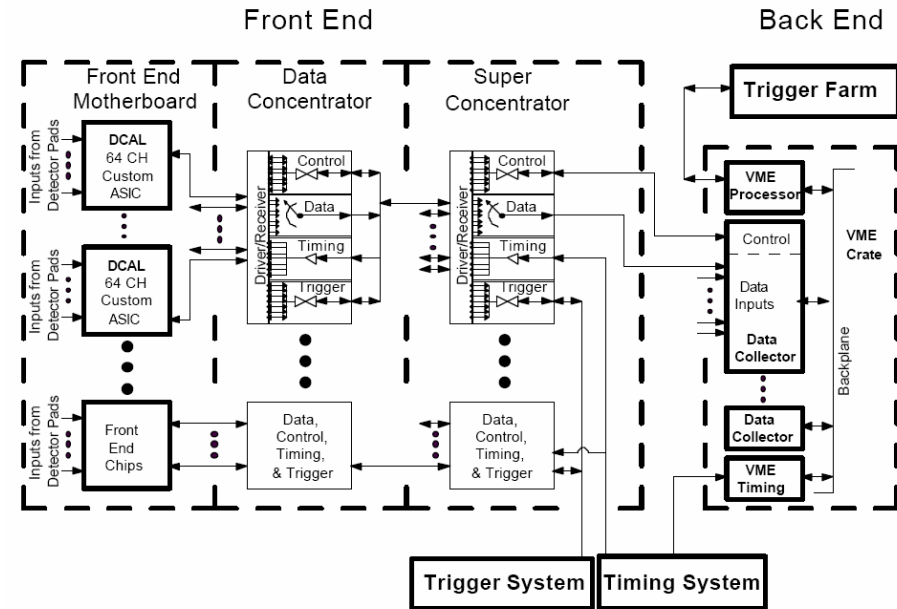


ANL

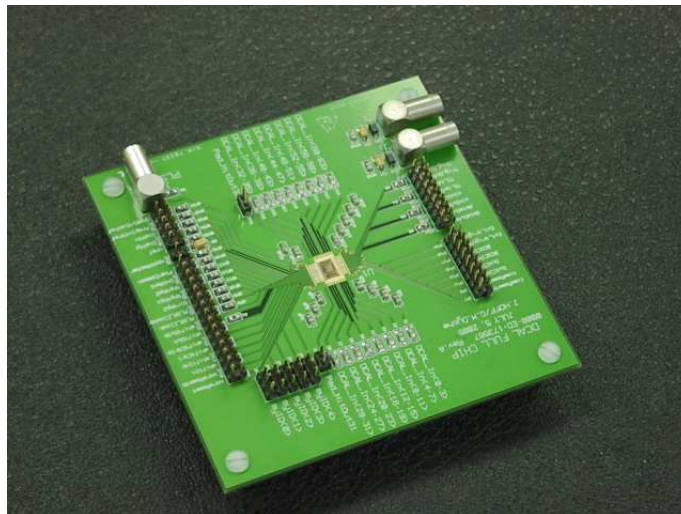


DHCAL electronics

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



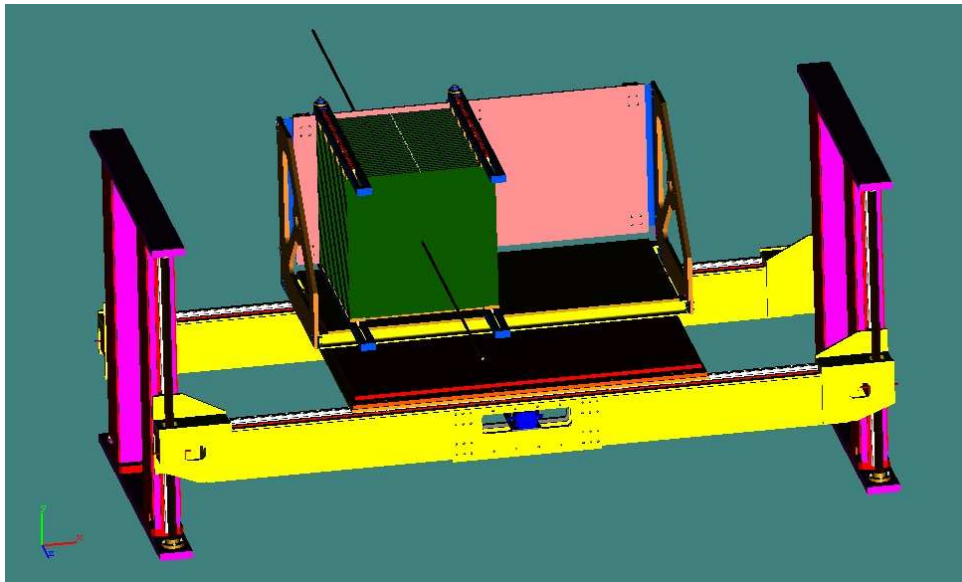
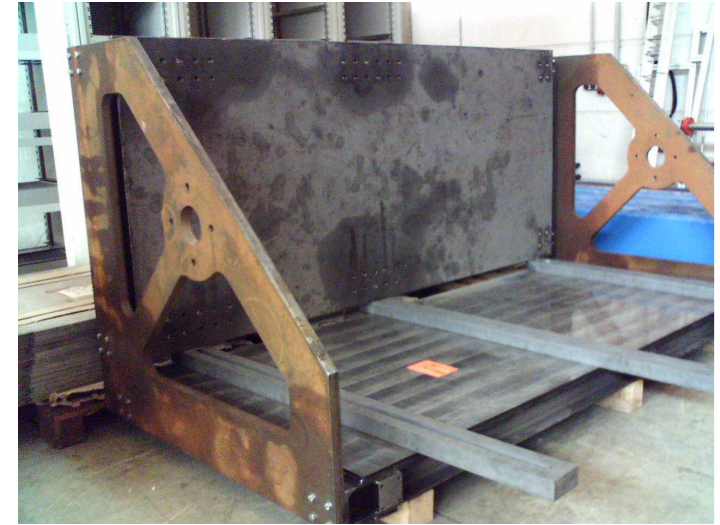
ANL/FNAL



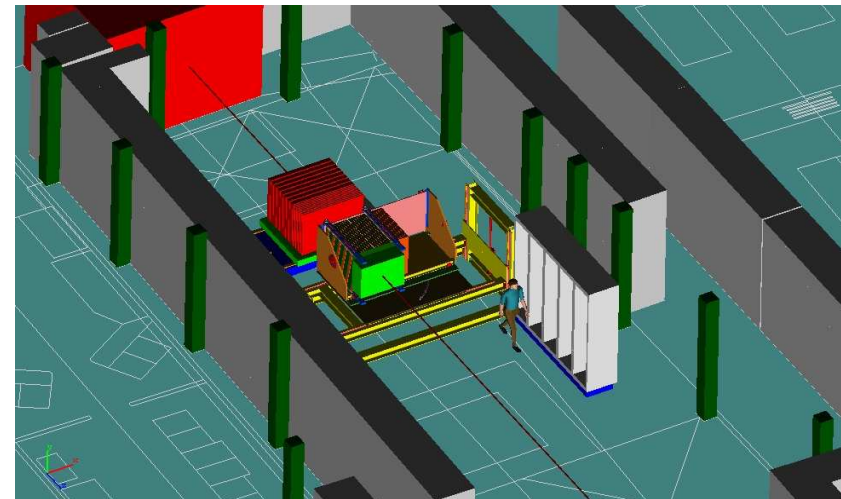
- Prototype front end boards under test
 - Schedule for production limited by US funding
- Hope to be ready for beam test in 2007/8

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



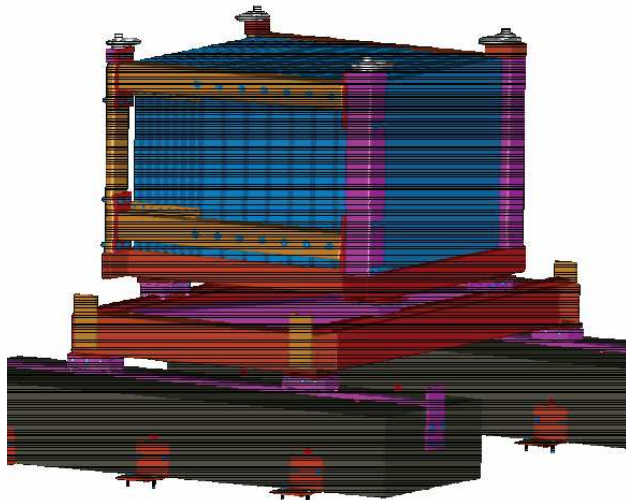
Tail catcher/muon tracker

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

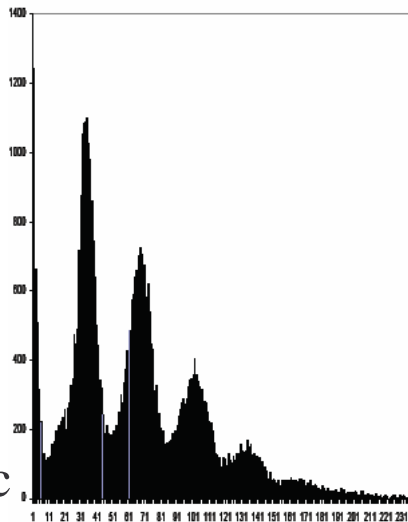
NIU



All strips fabricated and QC'ed



Cosmic signals



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

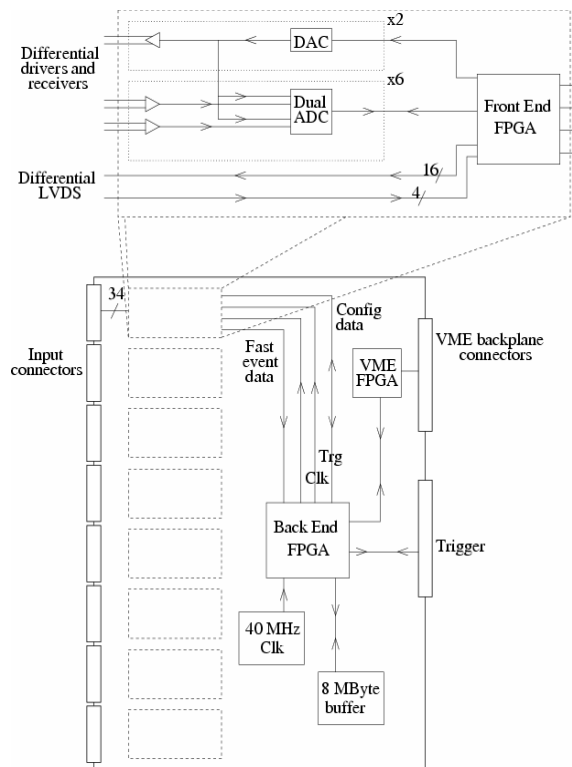
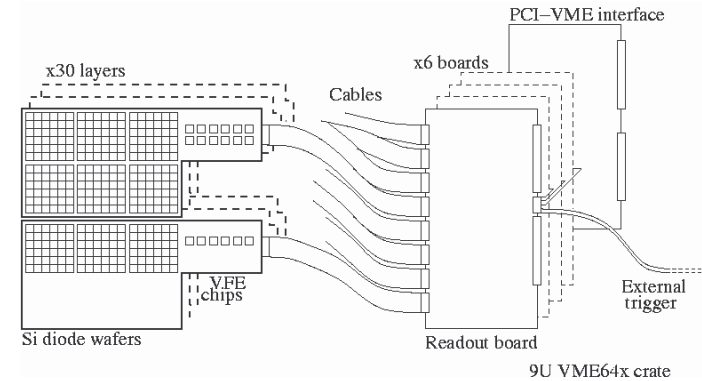
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CALICE-UK contributions

- 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**

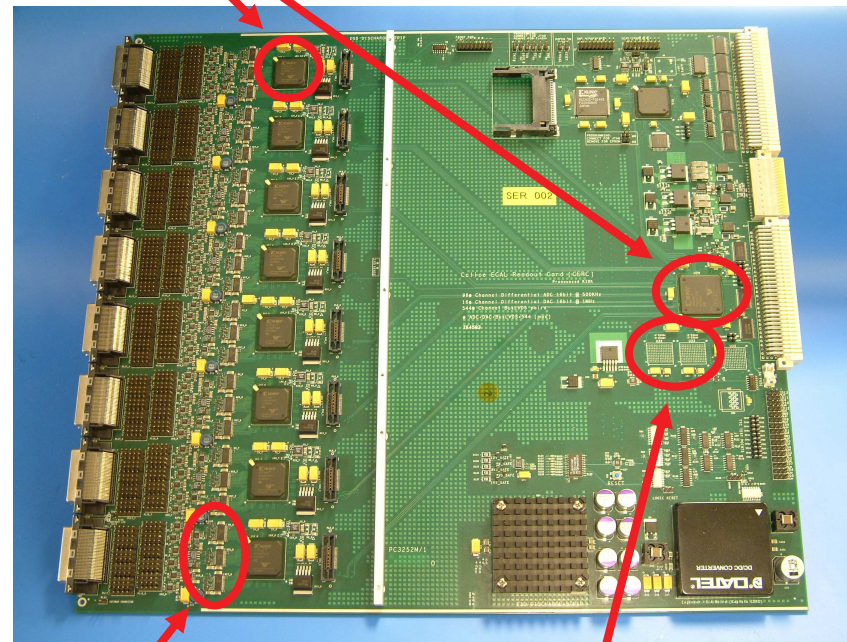
ECAL (and AHCAL) readout electronics

- 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



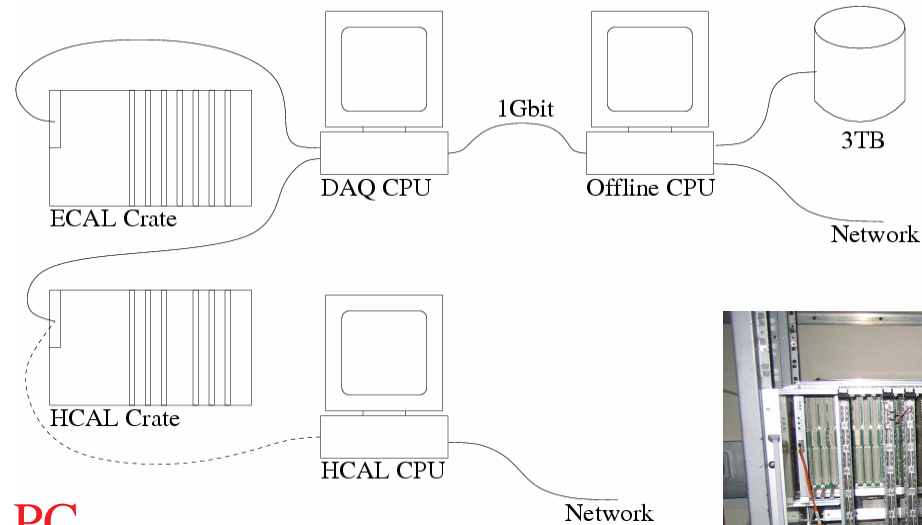
16-bit dual ADCs

8MByte buffer

DAQ online system

- **DAQ CPU**

- Trigger/spill handling
- VME and slow access
- Data formatting
- Send data via dedicated link to offline CPU



- **HCAL PC**

- Partitioning
- Alternative route to offline PC

- **Offline CPU**

- Write to disk array
- Send to permanent storage
- Online monitoring
- Book-keeping

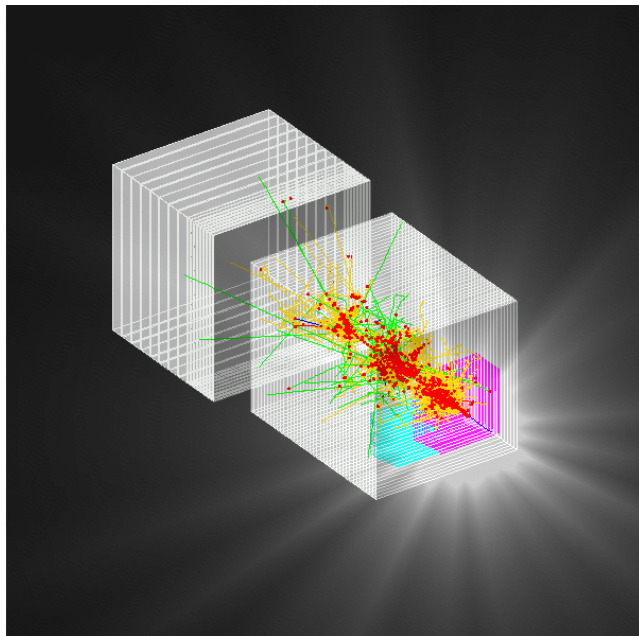
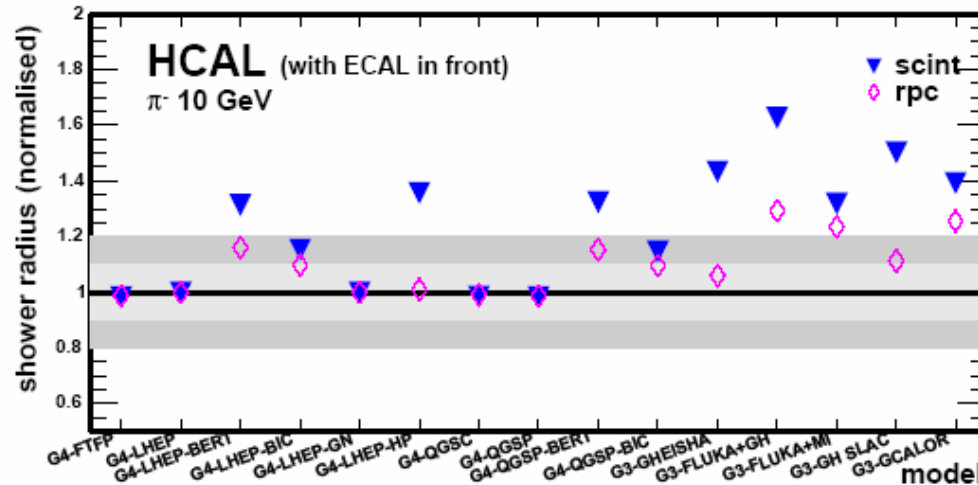


Imperial

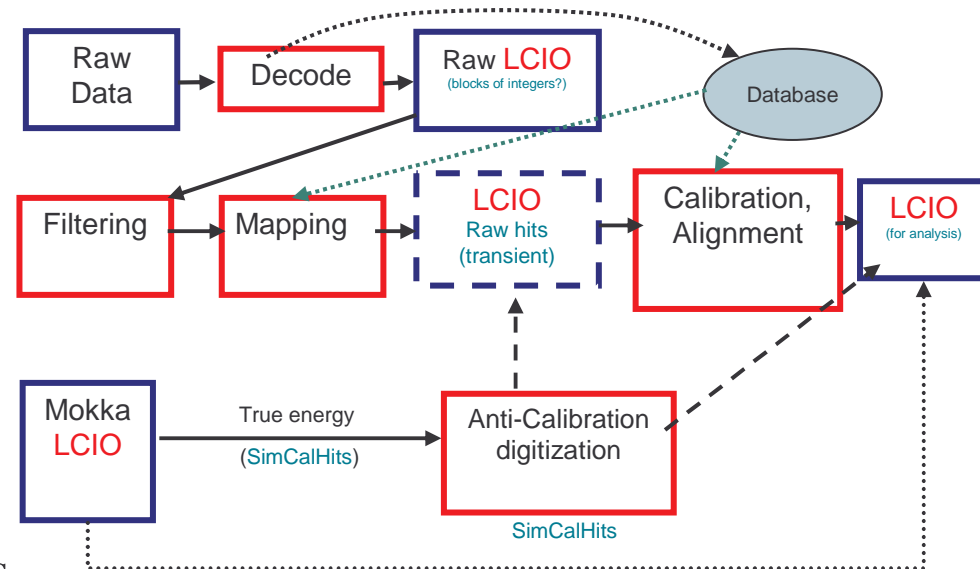
Simulation and software development

Cambridge

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



Full offline reconstruction and simulation chain exists



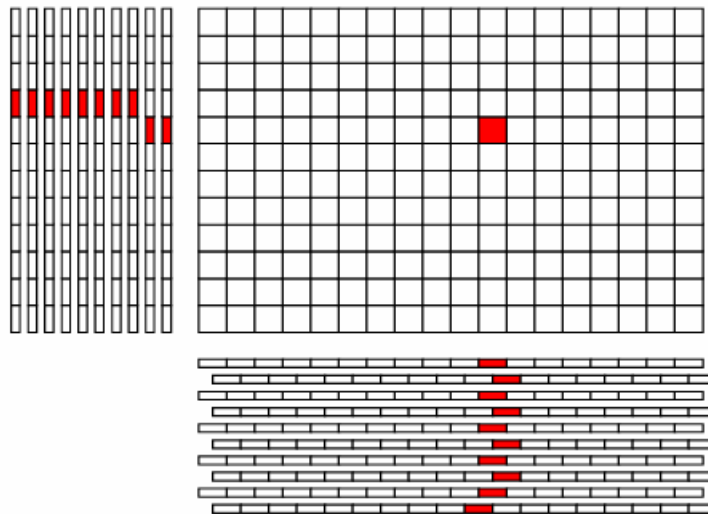
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ECAL cosmics at Ecole Polytechnique

Dec04/Jan05

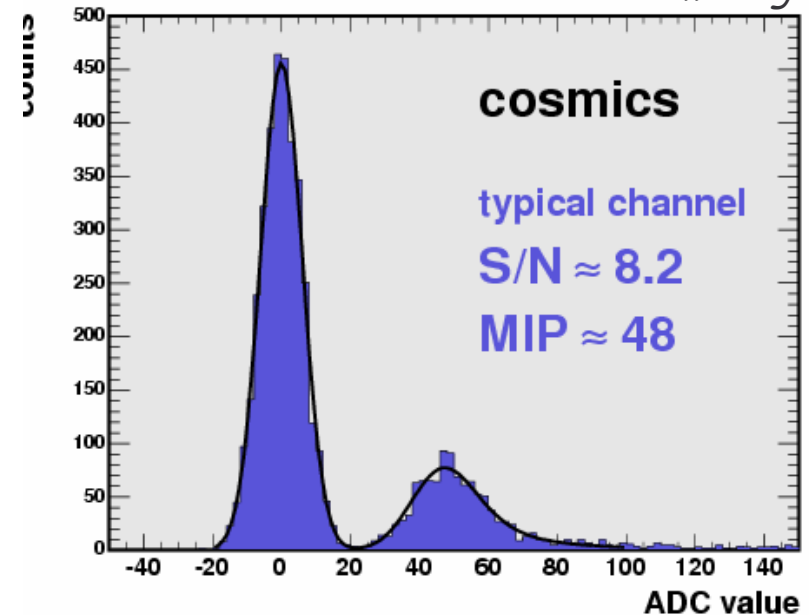
- Cosmic ray hodoscope
- 10 layers only; **2160** channels
- Prototype online system
- Two week run (over Christmas!)
- **1M events**, 10GBytes of data

Imperial



RodHeader::print() Record Time = 17:52:03:670:136 Tue Jan 4 2005, Type = 5 = event

Cambridge

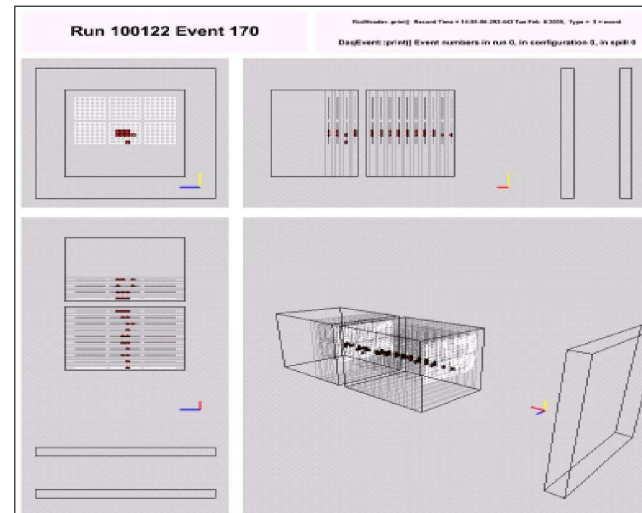
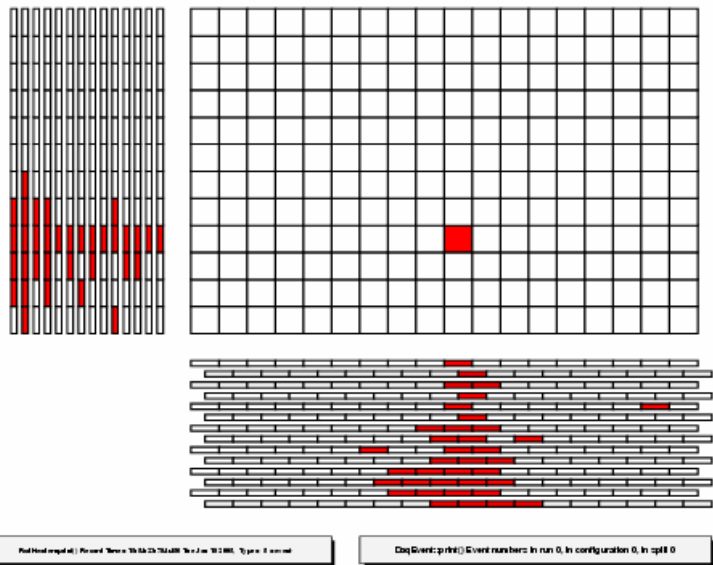


Individual channel
calibration to better than **1%**

ECAL beam test at DESY

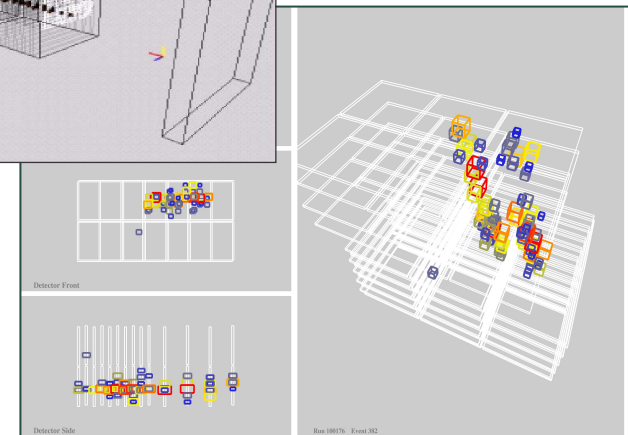
Jan/Feb 2005

- 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



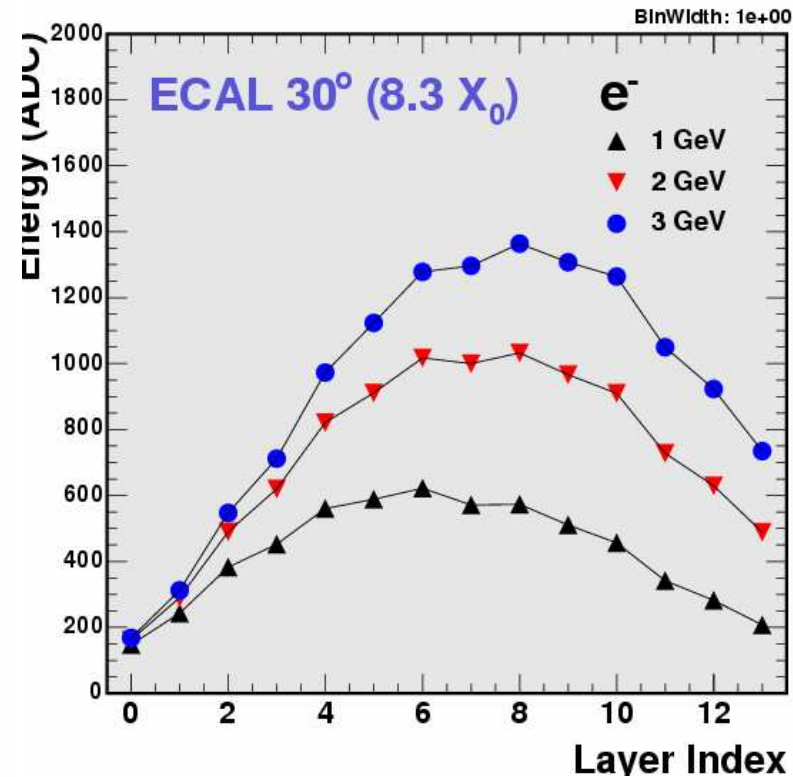
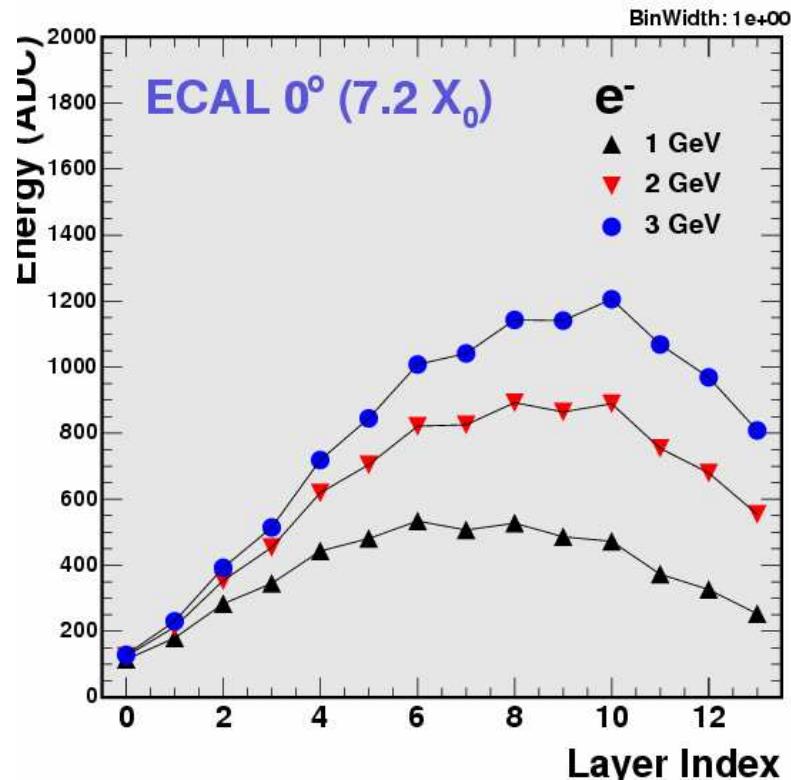
Cambridge

Double e^- events seen



Shower containment

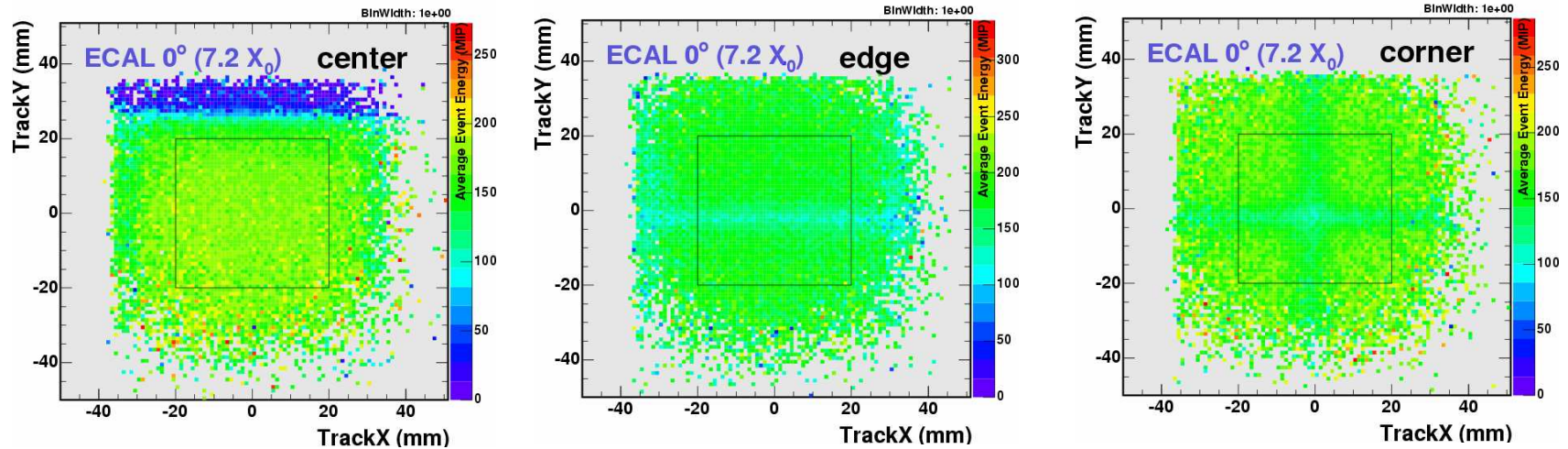
Cambridge



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

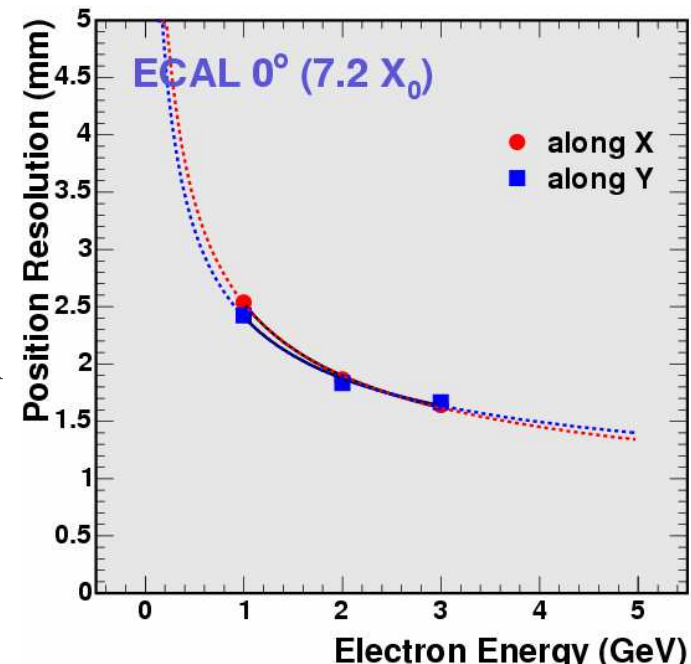
Position effects and resolution

Cambridge



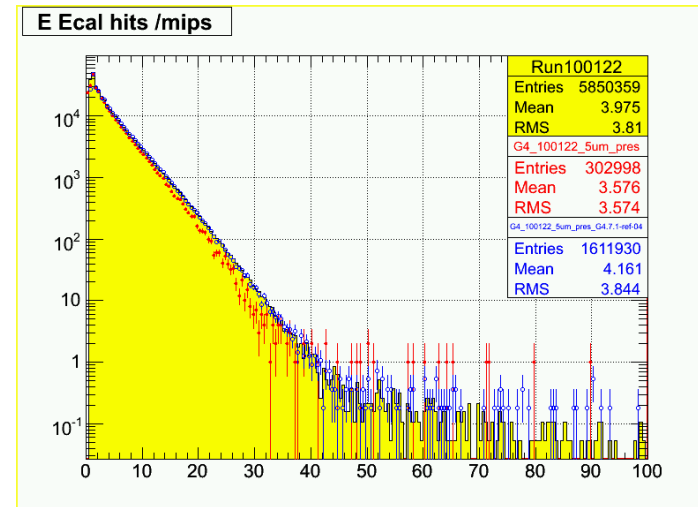
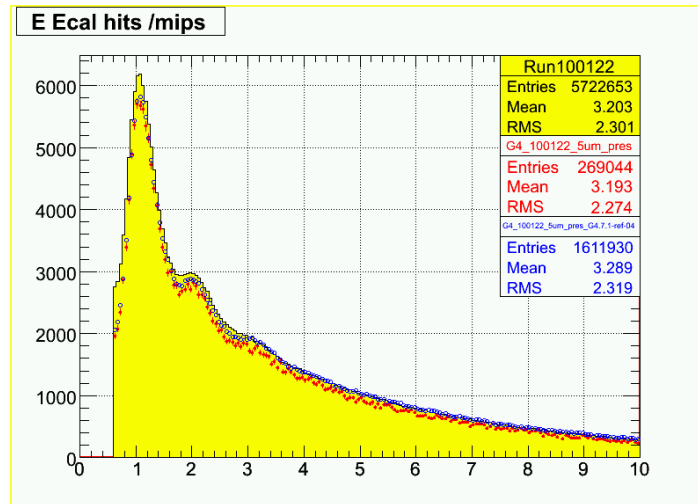
Study of energy loss between wafers

- 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



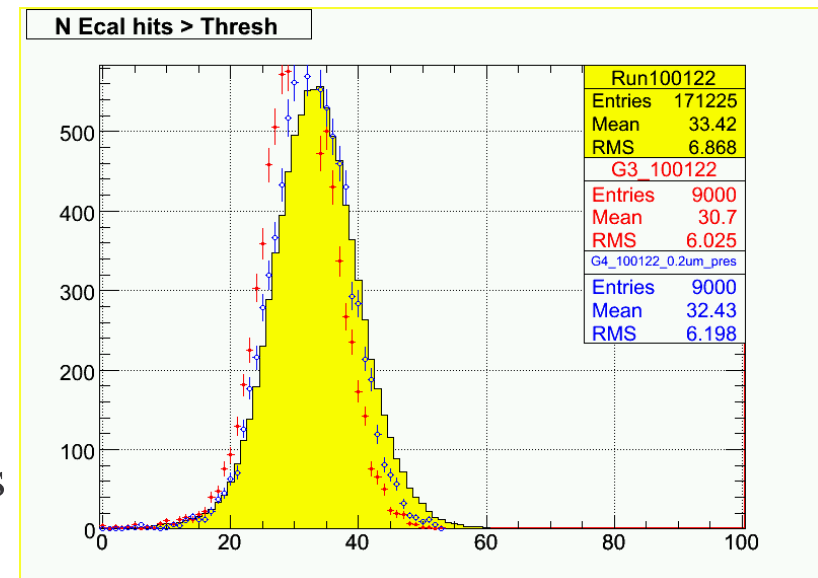
Geant3/4 comparison

Cambridge



- Geant4 requires adjustment of minimum step size cut-off → $0.2\mu\text{m}$!
- Takes factor ~ 20 times longer to run
- Fix in latest beta release

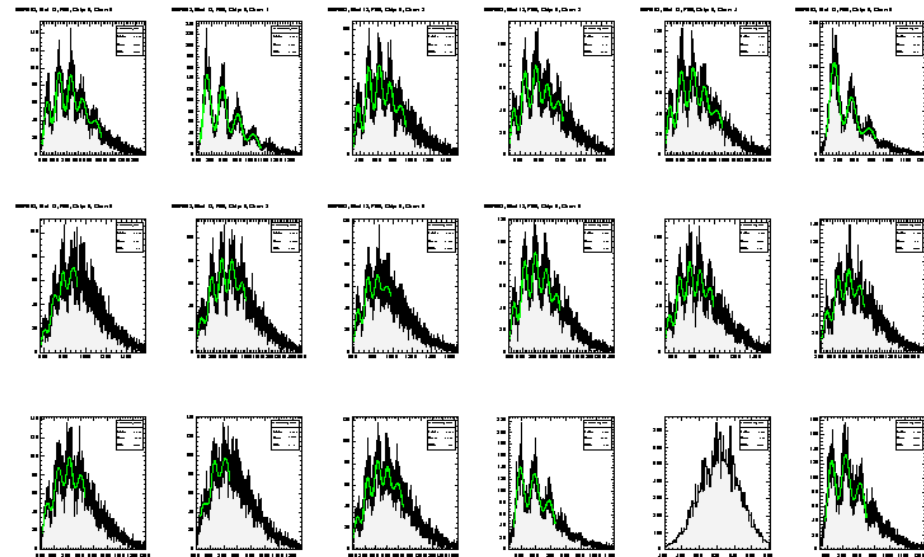
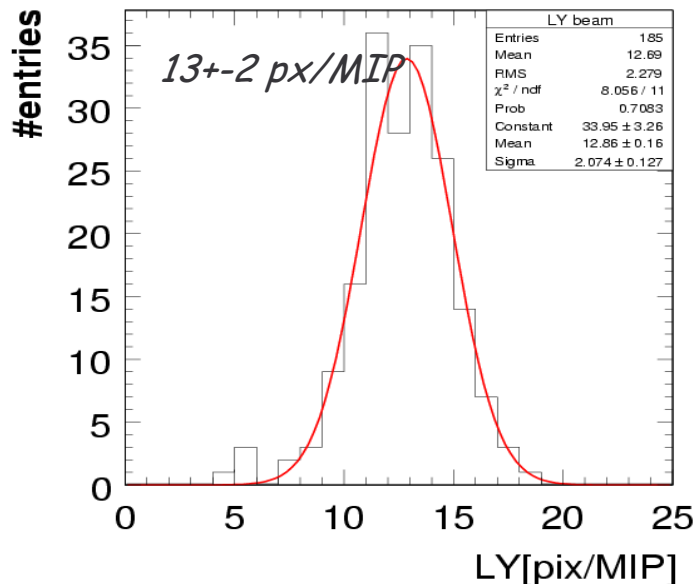
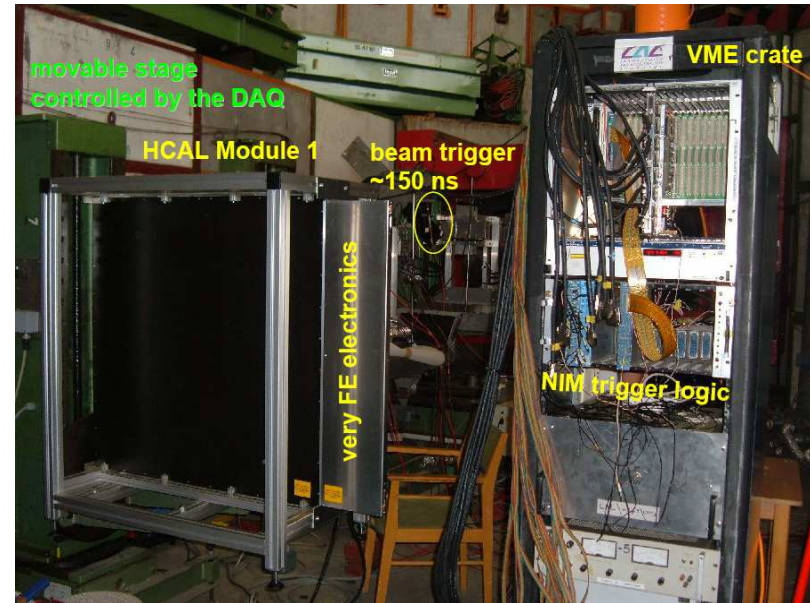
With adjustment, Geant4 gives better agreement than Geant3



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



DESY

Future beam tests: CALICE world tour

Ecole Poly 2004/5 – cosmics

DESY 2005/6 – e beam



FNAL 2007/8 – hadron beam

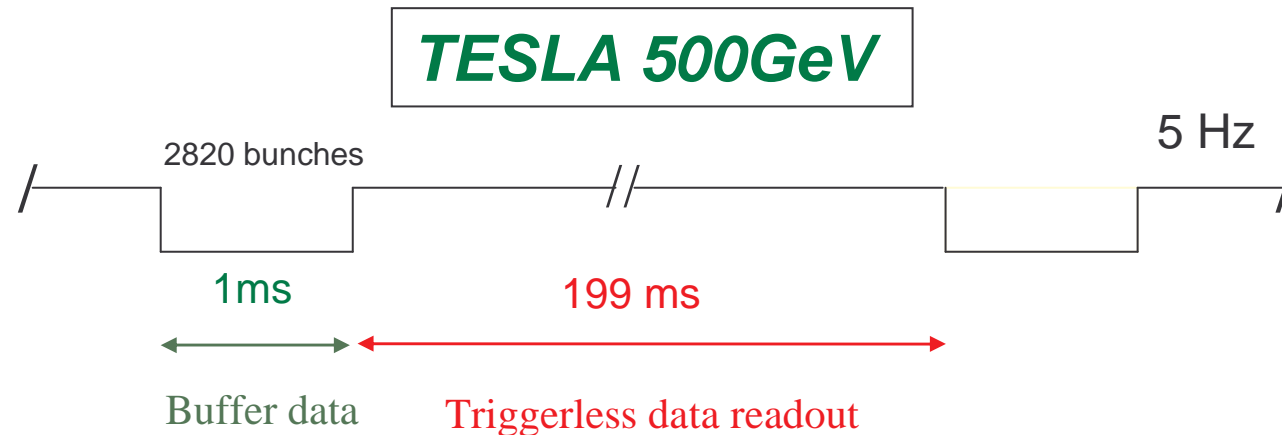
CERN 2006 – hadron beam

-
- 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

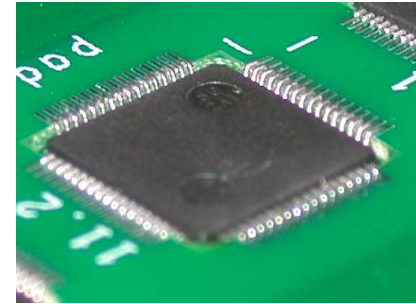


- **Three** parts to the DAQ system
 - Very Front End PCB
 - On-detector to off-detector networks
 - Off-detector: receivers
- Want to identify and study **bottlenecks**, not build DAQ system now
 - General ILC push towards “**backplaneless**” DAQ
 - (Almost) all off-detector hardware commercial; minimal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

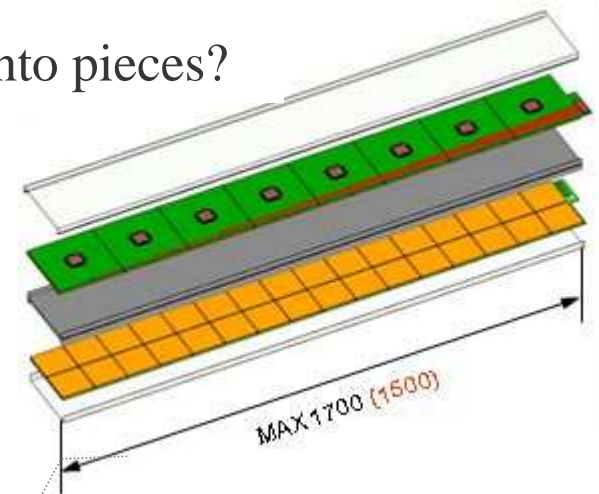
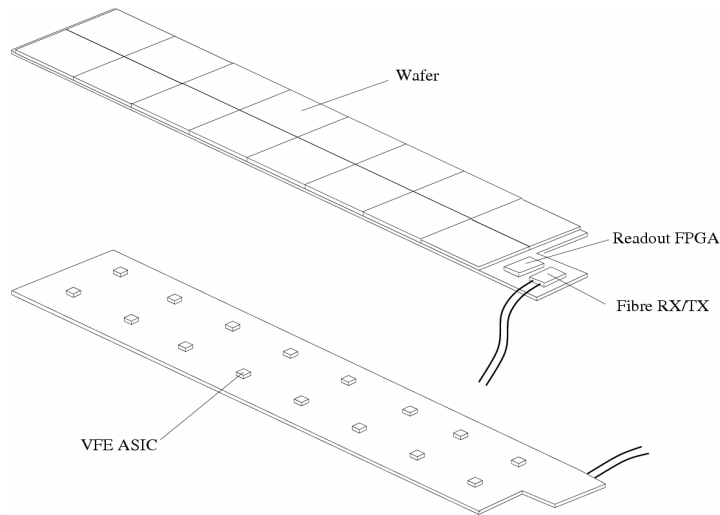
Very Front End PCB

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

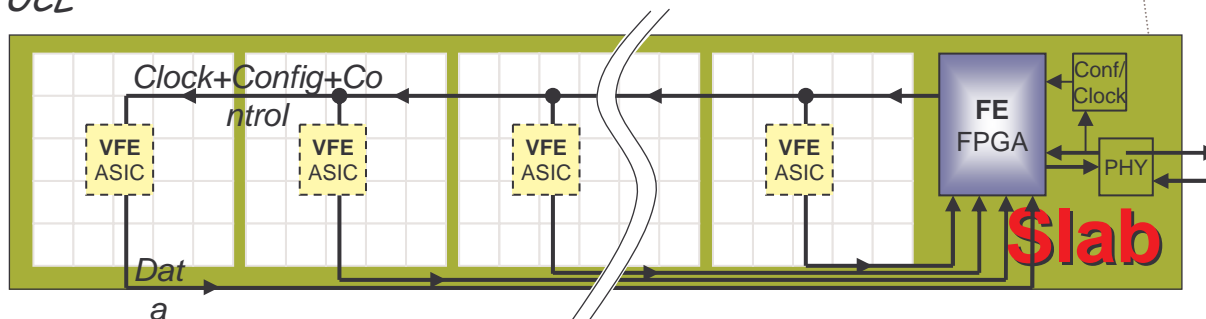
Embed components?



Subdivide into pieces?

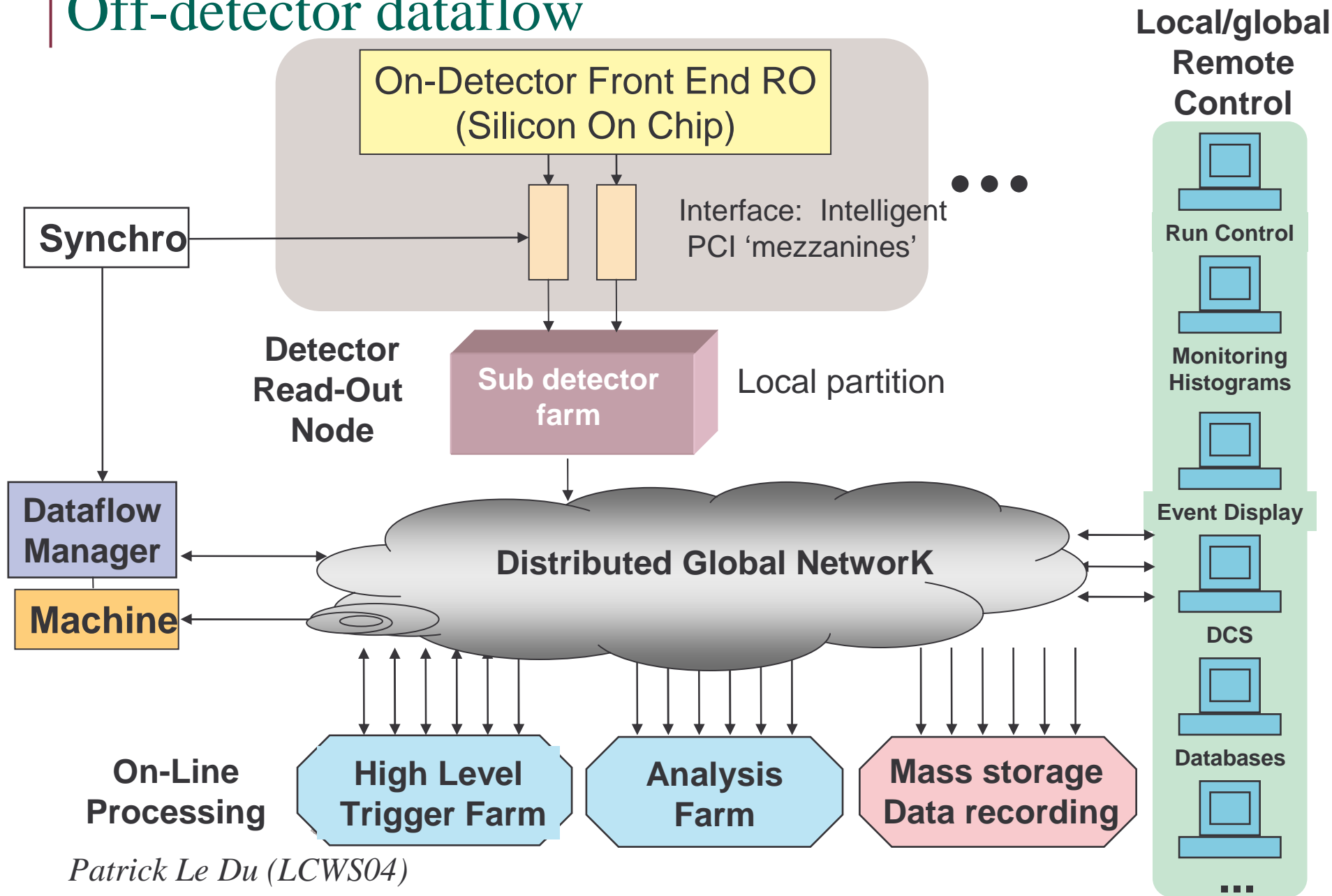


UCL



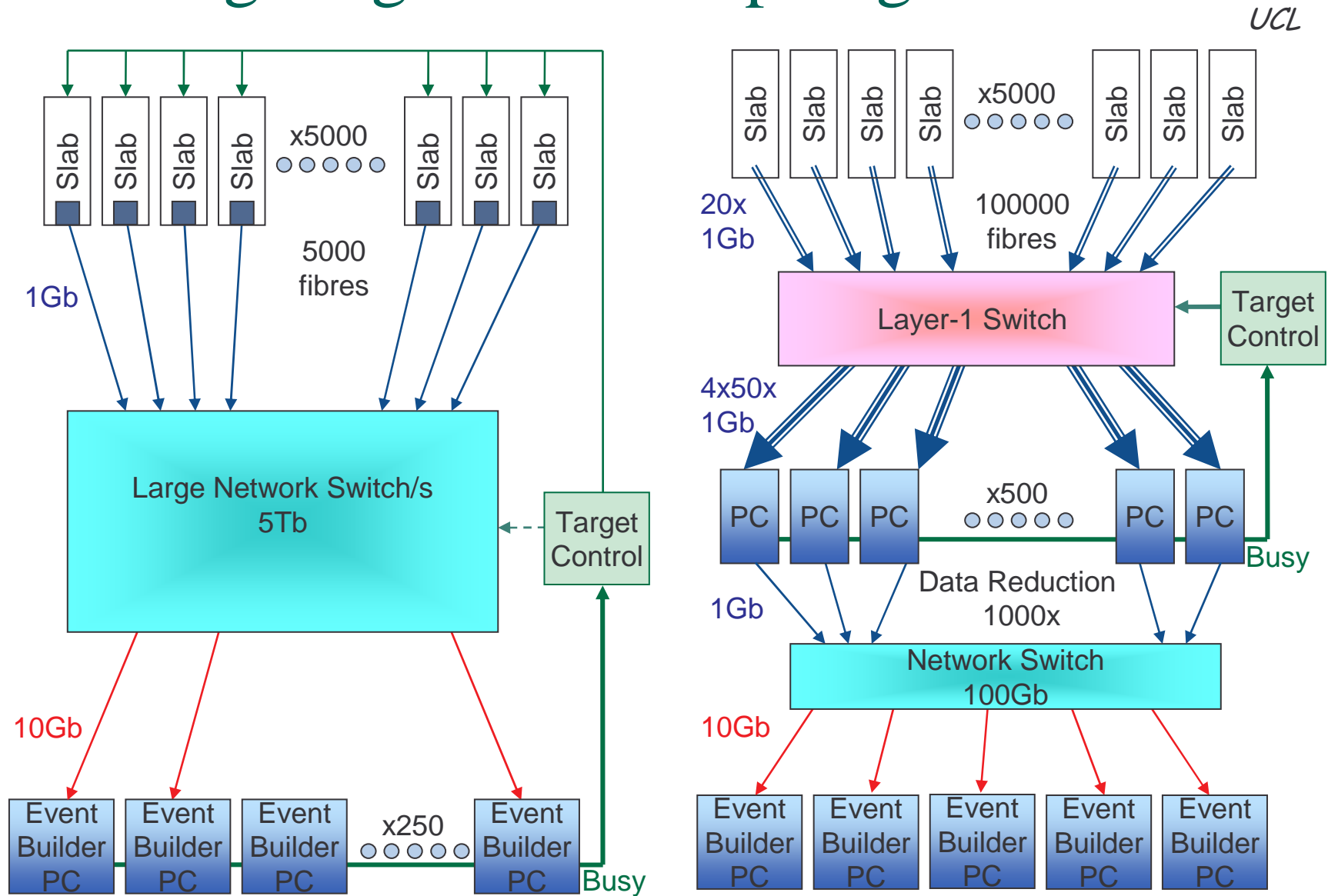
Signal transmission, readout and power dissipation are **critical**

Off-detector dataflow



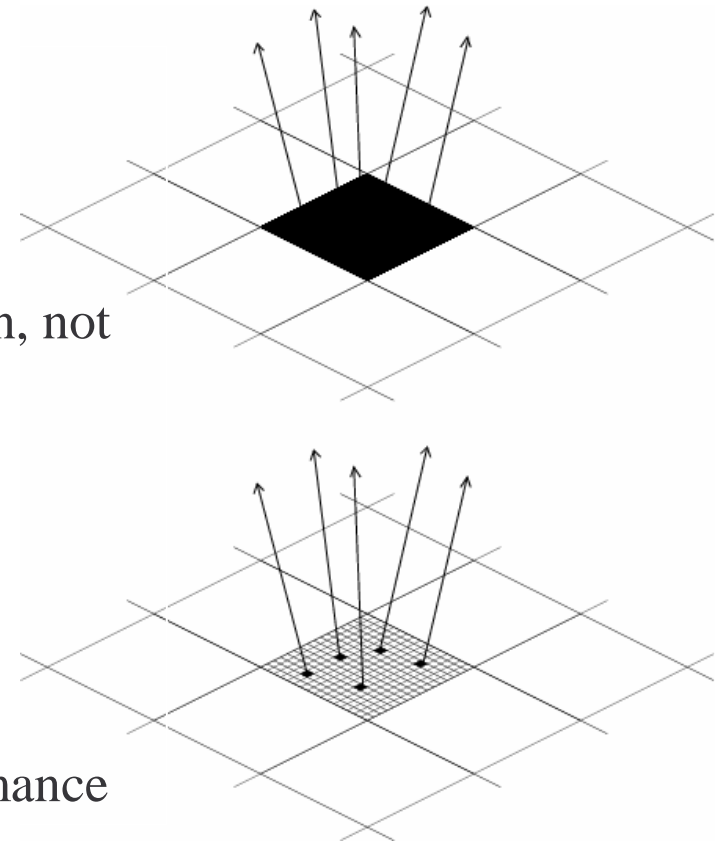
Patrick Le Du (LCWS04)

Investigating network topologies



Monolithic active pixel sensors

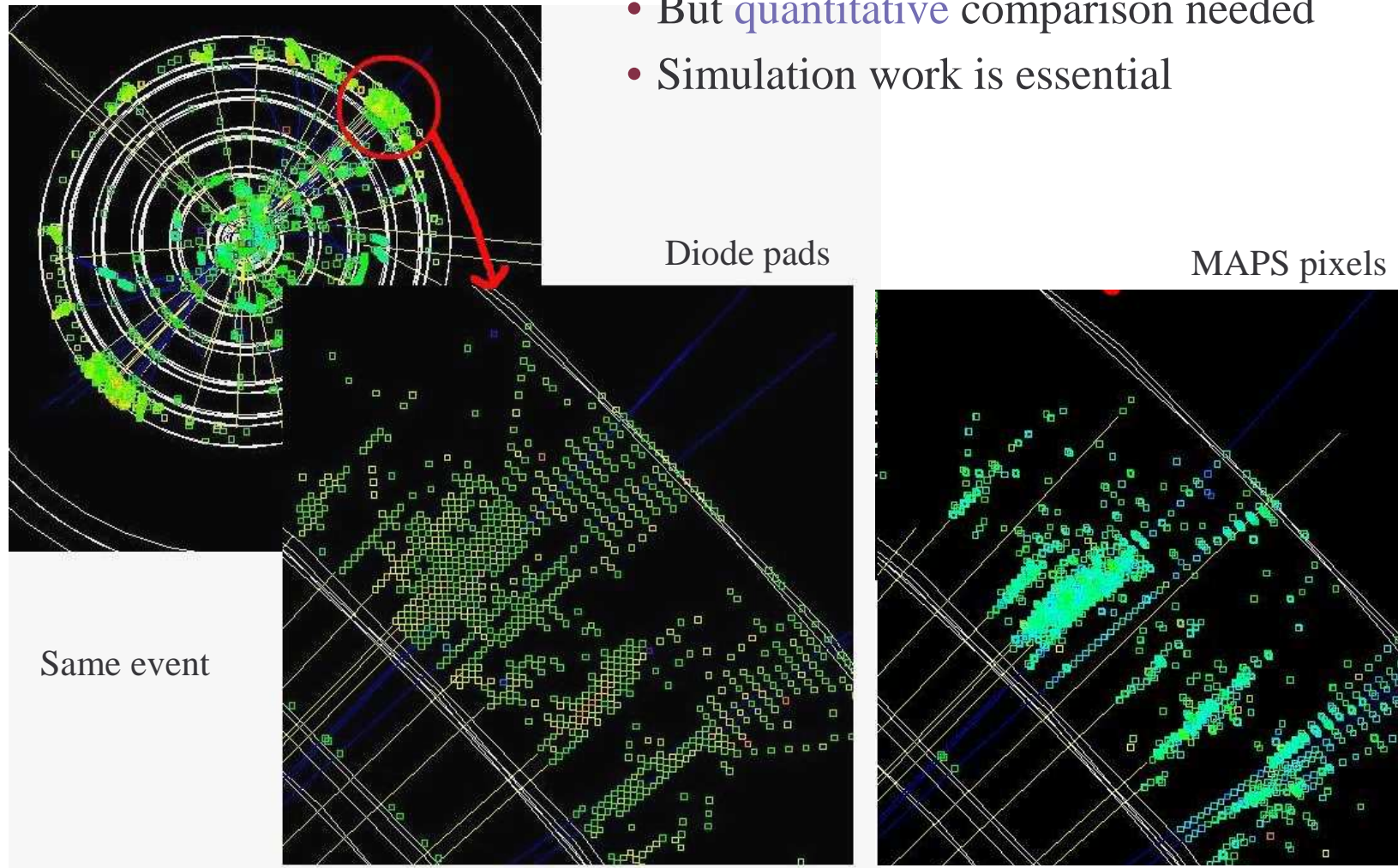
- Replace silicon diode pad wafers with **MAPS**
 - Contain readout electronics integrated into silicon wafer
 - Very fine pixels $\sim 50 \times 50 \mu\text{m}^2$ (compared with $1 \times 1 \text{cm}^2$ diode pads)
 - Allows binary (single bit) readout = DECAL
- Potential for
 - Better **spatial** resolution 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

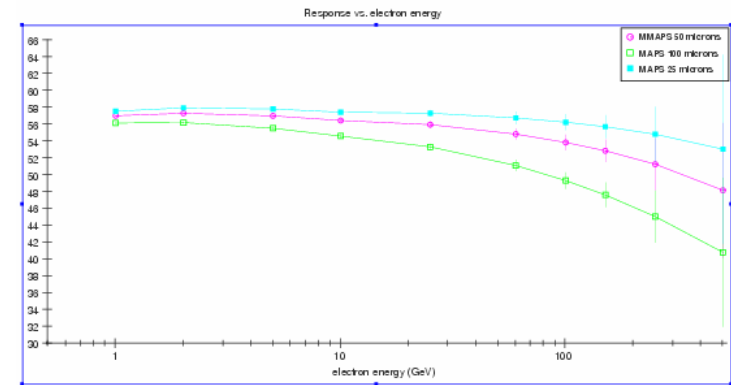
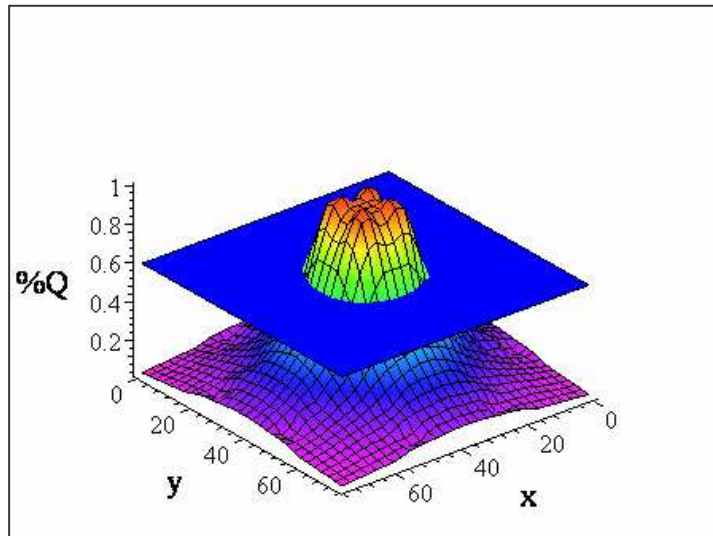
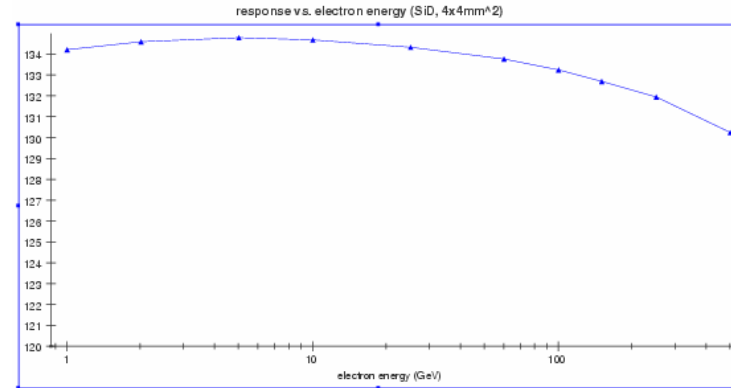


Birmingham

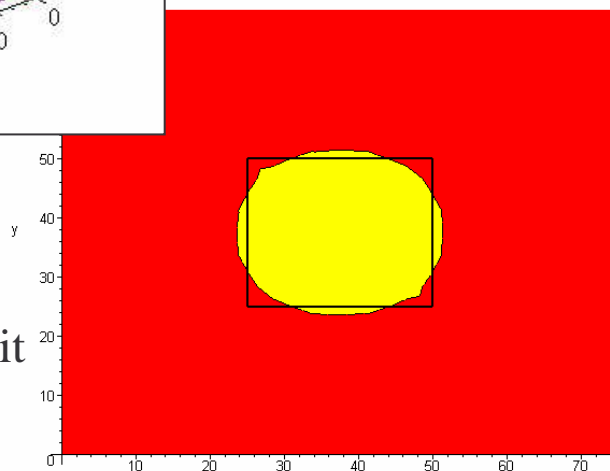
Sensor simulation

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 $25 \times 25 \mu\text{m}^2$ pixel area

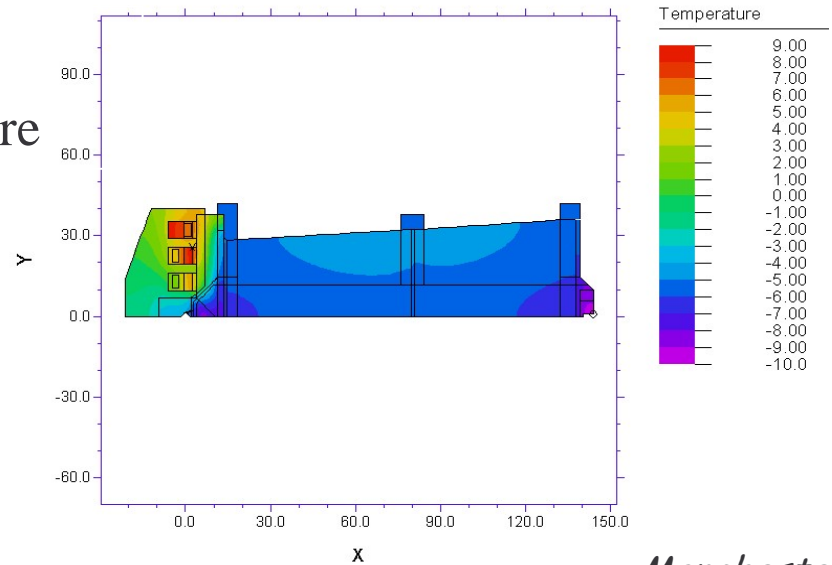
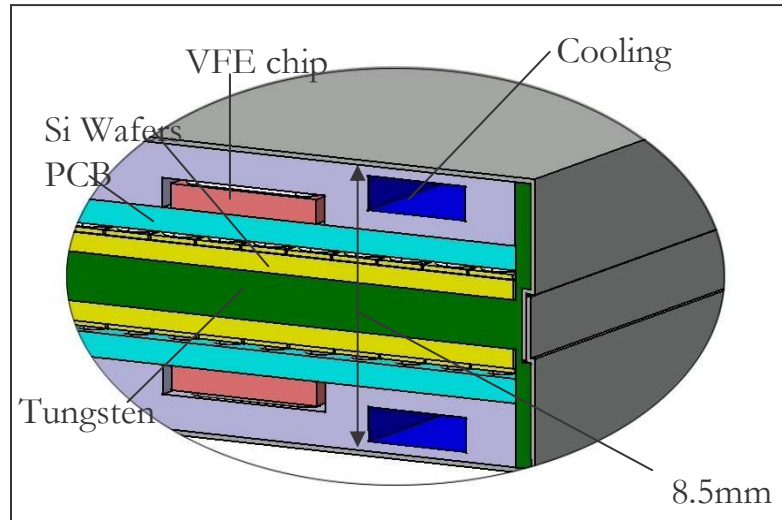


Comparison of energy response vs. shower energy for standard **SiD** ECAL and **MAPS** ECAL

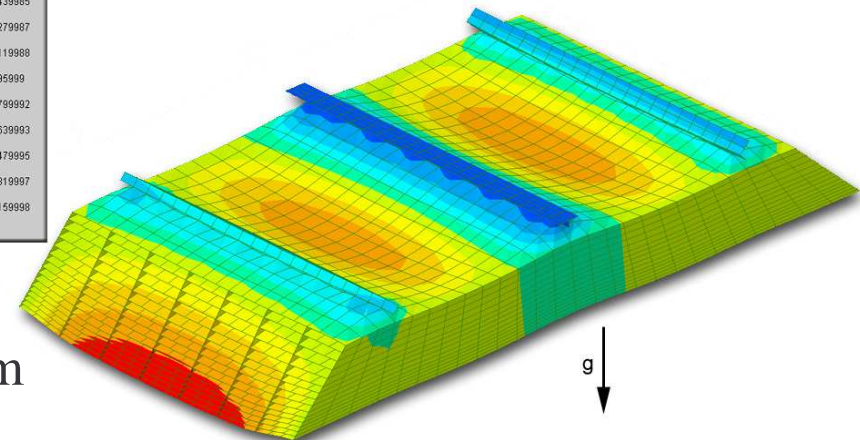
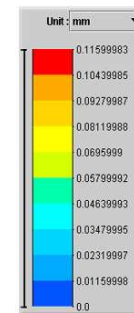
RAL

Thermal and mechanical studies

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



Manchester



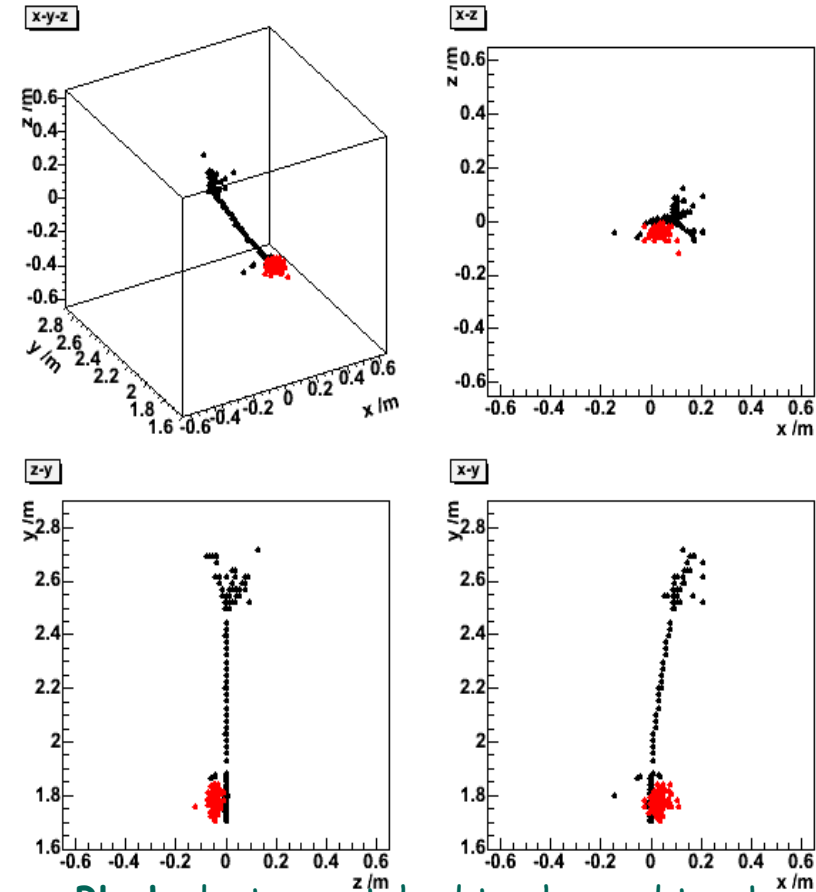
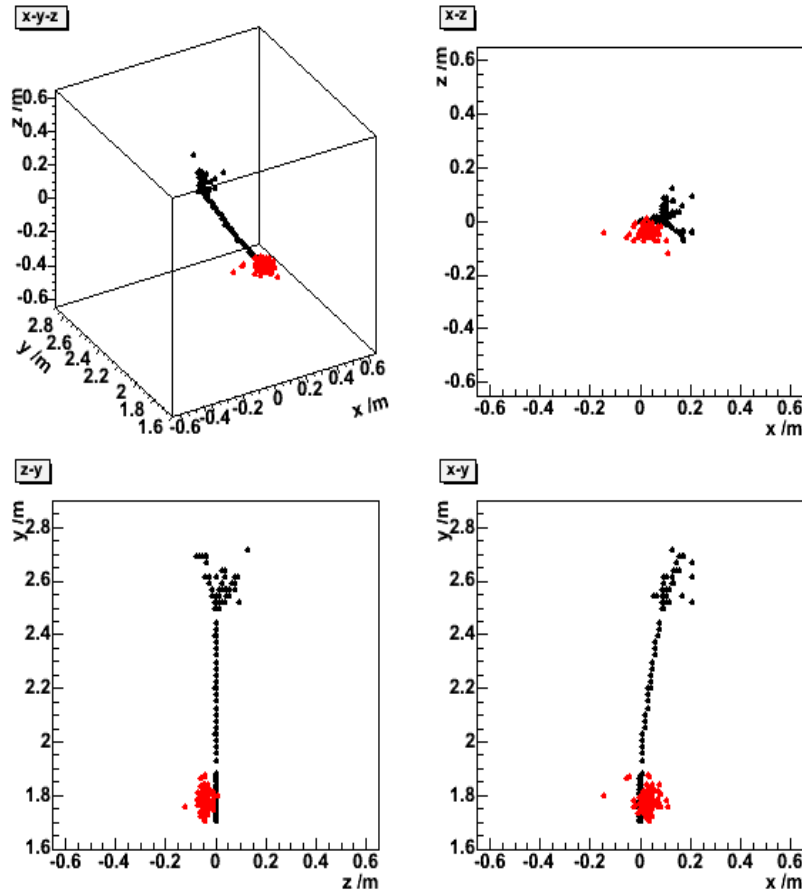
- Mechanical stress over 1.6m

PFLOW clustering; π^+/γ separation

Cambridge

True clusters

Reconstructed clusters

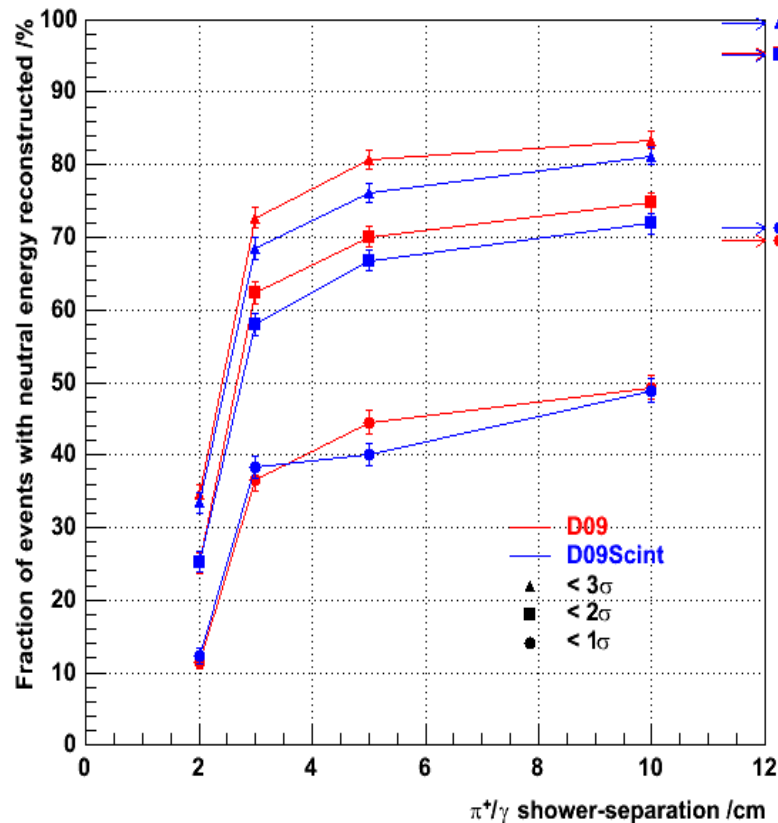


- **Black** cluster = 5 GeV/c π^+ .
- **Red** cluster = 5 GeV/c γ .

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

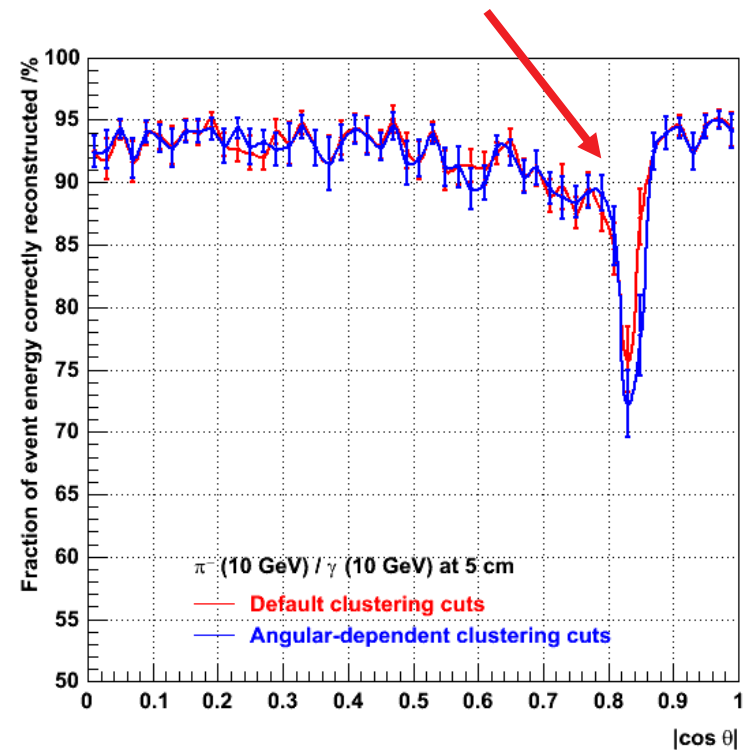
π^+/γ separability vs separation

5 GeV/c π^+/γ



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

- 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!