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 $\sim$£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 $\sim8$ years
  • E.g. approval and funding granted in 2008 leads to first physics data in 2016
The GDE schedule

2005 2006 2007 2008 2009 2010

Global Design Effort

Baseline configuration
Reference Design
Detector CDR
Technical Design
Detector TDR
LHC Physics
ILC R&D Program
Expression of Interest to Host
International Mgmt

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. \(\nu\nuW^+W^-\)
  - Weakly interacting new particles
  - Extra dimensions, etc, etc…
ILC detector concepts

- Sizes: “small”
  - SiD
  - 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
- Projected ILC detector

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

- Determined by ability to separate
  - Charged and neutral particles
  - Electromagnetic and hadronic showers

- Need calorimeter with
  - Narrow showers
  - Small $X_0$, large $\lambda$

- 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
  - $\sim 65\%$ of the typical jet energy
  - Negligible resolution
- EM calorimeter for photons
  - $\sim 25\%$ of the typical jet energy
  - Resolution $\sim 10\%/\sqrt{E}$
- Hadron calorimeter for neutral hadrons
  - $\sim 10\%$ 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 $Z \rightarrow q\bar{q}$  
Perfect Particle flow Algorithm

\[
\begin{align*}
\chi^2 / \text{ndf} & : 68.11 / 49 \\
\text{Prob} & : 0.03672 \\
\text{Normalisation} & : 338.8 \\
\text{Mean} & : 91.91 \\
\text{Sigma Central Part} & : 3.839 \\
\text{Sigma Left Tail} & : 11.84 \\
\text{Sigma Right Tail} & : 8.231 \\
\text{Fraction Central Part} & : 0.752
\end{align*}
\]

\[
\begin{align*}
\chi^2 / \text{ndf} & : 33.2 / 21 \\
\text{Prob} & : 0.04408 \\
\text{Normalisation} & : 251.1 \\
\text{Mean} & : 89.17 \\
\text{Sigma Central Part} & : 2.508 \\
\text{Sigma Left Tail} & : 9.122 \\
\text{Sigma Right Tail} & : 8.316 \\
\text{Fraction Central Part} & : 0.9274
\end{align*}
\]
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 $\sim 9$ mm (measure of transverse shower size)

- **Silicon** diodes to detect shower charged particles
  - Small diode pads $\sim 1 \times 1$ cm$^2$; stable, compact, well-understood technology
  - Results in 3000m$^2$ of silicon, 38 million channels, $\sim £80$M!
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The CALICE Collaboration

CAlorimetry for a LIinear Collider Experiment

190 physicists/engineers from 32 institutes and 9 countries
Coming from the 3 regions (America, Asia and Europe)

• 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

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

6x6 pads/wafer

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

- **Two** VFE PCBs sandwiched to **one** tungsten sheet to make “slab”
- Slabs inserted into carbon fibre-tungsten mechanical structure
- **18×18×20 cm³** active area

Whole ECAL mounted on movable stage
AHCAL scintillating tiles and SiPMs

- 3×3 cm² scintillator tile
- Wavelength shifting fibre
- Coupled directly to SiPM

- Silicon PM: multipixel Geiger mode APDs; 1156 pixels
- Gain $10^6$, bias ~ 50V, size 1 mm²

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

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AHCAL sensitive layers

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

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

![Diagram of DHCAL technology components]

**Components**
- Signal
- Pick-up pads
- Graphite
- Gas
- Resistive plates
- HV

*UTA*

[ANL Image]
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

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
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
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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

![Diagram of ECAL readout electronics]

- Virtex-II FPGAs
- 16-bit dual ADCs
- 8MByte buffer

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**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

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**Imperial**
Simulation and software development

- 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

Individual channel calibration to better than 1%

Cambridge

Cosmics

Typical channel
S/N ≈ 8.2
MIP ≈ 48

ADC value
**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**

Double $e^-$ events seen

Cambridge
Shower containment

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

- 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

Study of energy loss between wafers

Cambridge
Geant3/4 comparison

- 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

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13±2 px/MIP

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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
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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

**TESLA 500GeV**

- **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?

Signal transmission, readout and power dissipation are critical

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Off-detector dataflow

Patrick Le Du (LCWS04)
24 November 2005

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Investigating network topologies
Monolithic active pixel sensors

- Replace silicon diode pad wafers with MAPS
  - Contain readout electronics integrated into silicon wafer
  - Very fine pixels ~$50\times50\mu m^2$ (compared with $1\times1cm^2$ 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
Sensor simulation

- 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
Thermal and mechanical studies

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

- Mechanical stress over 1.6m
PFLOW clustering; $\pi^+/\gamma$ separation

True clusters

- Black cluster = 5 GeV/$c$ $\pi^+$.
- Red cluster = 5 GeV/$c$ $\gamma$.

Reconstructed clusters

- Black cluster matched to charged track.
- Red cluster left over as neutral $\Rightarrow \gamma$ energy well reconstructed.
π⁺/γ separability vs separation

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
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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!