Status Report

Felix Sefkow

Kick-off Meeting of the ECFA Detector Panel
DESY, Hamburg, May 2, 2012
Outline

- Introduction: Particle Flow and CALICE
- Detector technology projects
- Physics results
- Future plans
LC jet energies

- $e^+e^-$ physics: exclusive final states
  - Q-Qbar events are boring
  - $E_{\text{jet}} = \sqrt{s}/2$ is rare
- Mostly 4-, 6-fermion final states
  - e.g. $e^+e^- \rightarrow t\bar{t}H \rightarrow 8-10$ jets
- At ILC 500: $E_{\text{jet}} = 50...150$ GeV
  - Mean pion energy 10 GeV
- At ILC 1 TeV: $E_{\text{jet}} < ~ 300$ GeV
- At CLIC (3 TeV) < ~ 600 GeV
- Resolution matters!
Challenge: W Z separation

- Future precision physics with W and Z signals as Belle and LHCb do with D⁺ and Dˢ
- Jet energy resolution has to improve by factor 2
- Radiation hardness and rate capabilities at LC not critical w.r.t. LHC
In a typical jet:
- 60% of jet energy in charged hadrons
- 30% in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- 10% in neutral hadrons (mainly $n$ and $K_L$

Traditional calorimetric approach:
- Measure all components of jet energy in ECAL/HCAL!
- $\sim 70\%$ of energy measured in HCAL: $\sigma_E/E \approx 60\%/\sqrt{E(\text{GeV})}$
- Intrinsically “poor” HCAL resolution limits jet energy resolution

Particle Flow Calorimetry paradigm:
- Charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_E/E < 20\%/\sqrt{E(\text{GeV})}$
- Neutral hadrons (ONLY) in HCAL
- Only 10% of jet energy from HCAL $\rightarrow$ much improved resolution
Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:
★ Avoid double counting of energy from same particle
★ Separate energy deposits from different particles

e.g.

If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, “confusion”, determines jet energy resolution not the intrinsic calorimetric performance of ECAL/HCAL

Three types of confusion:
i) Photons
ii) Neutral Hadrons
iii) Fragments

Failure to resolve photon
Failure to resolve neutral hadron
Reconstruct fragment as separate neutral hadron
Understand particle flow performance

\[ \frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left( \frac{E}{100} \right)^{+0.3} \%
\]

- Particle flow is always better
  - even at high jet energies
- HCAL resolution does matter
  - also for confusion term
- Leakage plays a role, too
The different confusion terms correspond to: (i) hits from photons which are lost in charged hadrons; (ii) hits from neutral hadrons that are lost in charged hadron clusters.

The contributions to the PFlow jet energy resolution obtained with this parameterisation are shown in Fig. 10. It is worth noting that the predicted jet energy leakage plays a role, too. For a significant range of the jet energies relevant for the ILC, the predicted jet energy leakage significantly from the ILD Calorimetric only curve at high energies.

Table 5: Jets energy resolutions:

<table>
<thead>
<tr>
<th>Leakage (%)</th>
<th>i) Photons</th>
<th>ii) Neutral hadrons</th>
<th>iii) Charged hadrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.3 %</td>
<td>1.8 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>0.5</td>
<td>1.7 %</td>
<td>1.8 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>0.8</td>
<td>1.7 %</td>
<td>1.8 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>1.0</td>
<td>1.8 %</td>
<td>1.8 %</td>
<td>0.2 %</td>
</tr>
</tbody>
</table>

The empirical functional form of the jet energy resolution obtained from the total calorimetric approach. The performance of PFlow calorimetry also significantly improves the resolution compared to the purely traditional calorimetric approach. This parameterisation effectively shows a parameterisation of the jet energy resolution obtained from a simple sum of the total calorimetric approach. The parameterisation is intended to give an empirical parameterisation of the jet energy resolution:

$$\sigma_E/E = 21/\sqrt{E} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left( \frac{E}{100} \right) + 0.3\%$$

The results of the above studies rely on the accuracy of the MC simulation in describing EM and hadronic showers. The Geant4 simulation provides a good description of EM showers as has been shown previously in Ref. 8. Dependence on hadron shower modelling significantly from the ILD Calorimetric only curve at high energies.

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  - also for confusion term
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The different confusion terms correspond to: (i) hits from photons which are lost in charged hadrons; (ii) hits from neutral hadrons that are lost in charged hadron clusters; (iii) neutral hadrons being lost within charged hadron showers. For all jet energies considered, fragments from charged hadrons, which significantly from the effect of leakage (which is why it deviates even at high jet energies).

The empirical functional form of the jet energy resolution obtained from a simple sum of the total calorimetric resolution, respectively, represent: the intrinsic calorimetric resolution; the high granularity resolution. The performance of PFlow calorimetry also using a traditional calorimetric approach. This parameterisation effectively assumes an infinitely deep HCAL as it does not correctly account for the effect of leakage (which is why it deviates significantly from the ILD Calorimetric only curve at high jet energies).

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### Table 5

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<th>Component</th>
<th>Resolution (%)</th>
<th>Tracking (%)</th>
<th>Leakage (%)</th>
<th>Confusion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3.1</td>
<td>2.0</td>
<td>3.0</td>
<td>3.1</td>
</tr>
<tr>
<td>i) Photons</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.2</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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- HCAL resolution does matter – also for confusion term
- Leakage plays a role, too

\[
\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left( \frac{E}{100} \right) + 0.3 \%
\]
Particle flow detectors

- large radius, large field, fine 3D calorimeter granularity, compact
  - Typ 1X0 long, transv: 0.5cm ECAL, 1cm gas HCAL, 3cm scint.
- optimized in full simulations and particle flow reconstruction

ILD: large TPC, B=3.5T
SiD: all-Si tracker, 5T
CLIC-ILD, CLIC-SiD: tungsten barrel HCAL
Calorimeter technology tree

- ILD, SiD
- ILC, CLIC

or semi-digital
We are more than 300 physicists and engineers from 57 institutes in Africa, America, Europe and Asia.

Our goal: develop highly granular calorimeter options based on the particle flow approach for an e+e- linear collider.

Twofold approach:
- Physics prototypes and test beam
  - Proof of principle, test of shower simulation models, development of reconstruction algorithms with real data
- Technical prototypes
  - Realistic, scalable design (and costing)
Particle flow calorimeters:

- Particle Flow concept proven in detailed simulations: provides required resolution up to CLIC jet energies

- Extremely fine calorimeter segmentation - 100M read-out cells - demands novel read-out technologies and poses new system integration challenges
  - remain compact: Moliere radius, stay inside coil
  - embed electronics, minimize power

- CALICE: collaborative R&D and test beam effort to
  - develop the technologies
  - establish the performance
  - validate the physics models
  - test the algorithms
  - demonstrate the scalability
Technologies for High Granularity

Si W ECAL
Sci W ECAL

not reported this time:
MAPS DECAL
Physics prototype 2005-2011: demonstrate SiW ECAL technique

18x18cm² active area, 30 layers
1x1cm² segmentation
~10000 readout channels

5-year test beam campaign
muons, electrons, hadrons
detector calibration, EM response
validation of simulation, hadronisation models
Physics prototype results

Response to electrons

Linear energy response to ~1%

Good description by simulation

Excellent imaging
Technical prototype under development

Higher readout granularity

Embedded low power FE electronics

Move towards industrial techniques modular construction

~2/3 scale mechanical module
carbon fibre, tungsten completed

Will be partially instrumented over next years, testing different technological solutions
Some examples

PCB with embedded ASICs
Low-volume interconnections
Water-based leakless cooling

Recent beam test of “technological” detector slab at DESY
Test of new ASIC, DAQ system, power/DAQ adapter board for technological prototype

Second round of beam tests planned for summer: larger scale with ~10 layers
Scintillator ECAL overview and perspectives

- PFA requires highly granular ECAL
to accommodate within reasonable cost
- scintillator strip ECAL with orthogonal directions to achieve fine segmentation
- very thin and novel photon sensor is developed

![Diagram of scintillator sensor with dimensions 1.9mm x 2.4mm]
prototype & performance

- 45mmx10mm strips
- 72 strips/layer
- 30 layer prototype

Beam momentum (GeV/c)

Deposit energy in ECAL (MIP)

Slope = 145.28 ± 0.01 (combined)
Slope = 147.83 ± 0.01 (center)
Slope = 142.37 ± 0.01 (uniform)

pi-0 recons

good linearity
current development

- finer granularity up to 5mm
  more than 8 p.e. & uniform ±5%
- electronics integration
- Beam test 2012 fall
- with Silicon W ECAL

small-area version of scint HCAL read-out
Technologies for High Granularity

Sci Fe HCAL
Sci W HCAL
Fe Scint tile AHCAL

- 38 layers steel sandwich
- World’s first large device with SiPMs: 7600 tiles / sensors
- Now used in CMS, T2K, medical imaging ,...

SiPM: MEPHI / PULSAR

- Extremely robust: 6 years of data taking without problems
- Many trips with dis-and re-assembly of the HCAL – DESY CERN DESY FNAL DESY CERN-PS CERN-SPS
Scint AHCAL calibration and electromagnetic performance

- SiPM gain monitoring: self-calibrating
- Cell equalization: MIPs
- Temperature correction: ~4%/K
- Validation of calibration and simulation with electrons

Published in JINST 6, P04003 (2011)
AHCAL technological prototype

- integrated readout (ADC & TDC), auto-trigger and LED system
- 12x12 tiles / board

New HCAL Base Unit (HBU2)
- 4 new HBUs in DESY lab
- 70 channels equipped with scintillator tiles, LEDs, SiPM readout, 4 ASICs
- 1 HBU2 connected to DAQ modules for first tests
- So far fully functioning!
- 1 HBU2 in DESY test beam
- We ordered 6 new HBU2s for full slab test:
  - Quality of electrical signals
  - Mechanics, temperature
  - DAQ

LED calibration system
- Wuppertal solution: Light directly coupled into tile by 1 integrated LED per channel
- Light output equalization via C1 – C3 (default: 150pF, plus: 22pF, 82pF)
- New design implemented in HBU2 and is currently tested extensively

Prague solution: Light coupled into tile by notched fiber
- Mechanical integration difficult
- First tests performed in DESY lab with new electronics and new tiles

Scintillating tiles
- Signal sampled by scintillating tiles → 3x3x0.3cm
- 3, 2592 tiles per layer
- 450 tiles from ITEP tested
- Gain: 500k – 2000k
- Light Yield = 15 ± 2
- Sample of 150 tiles in Heidelberg for characterisation of temperature dependence
- New batch of 470 tiles arrived at DESY last Thursday
- Equipment of several new HBUs
- Important step to multi-HBU-setup now possible!

Mechanics:
- 1mm flatness over 2m w/o machining

First test beam results
SiPMs and tiles

- Options for direct - fibre-less - coupling
- Uniformity problems solved
- Industrialized injection molding process
  - First tests
- Several types of blue-sensitive SiPMs available
- Much reduced noise and occupancy
Tungsten AHCAL prototype

Main purpose: Validation of Geant4 simulation for hadronic showers in tungsten

Data taken 2010/11 at CERN-PS/SPS, mixed beams 1 – 300 GeV

Scintillator tiles 3x3 cm² (in centre)
Read out by SiPM
**SiPM analog HCAL testbeam**

**T3B**: Time structure of shower: one row of 15 tiles with pico-scope read-out
Digital glass RPC tungsten HCAL

- 2012: test tungsten HCAL with gaseous readout.
  - Due to slow neutrons from $W$, energy resolution of a $W$-HCAL with gas detectors might not be the same as with scintillators. This needs testing.
  - Have two independent data sets to validate tungsten Geant4 simulations.

- Infrastructure has been adjusted to accommodate the new equipment

  Electronics rack

  Frame made to be transportable

  RPC version of T3B in preparation, too

  Tungsten stack (38 plates)
Technologies for High Granularity

(Semi-) Digital HCAL
RPC, GEM, Micromegas
The Digital Hadron Calorimeter - DHCAL

RPC – based imaging calorimeter

DHCAL = First large scale calorimeter prototype with

- Embedded front-end electronics
- Digital (= 1 – bit) readout
- Pad readout of RPCs (RPCs usually read out with strips)
- Extremely fine segmentation with 1 x 1 cm² pads

DHCAL = World record channel count for calorimetry
World record channel count for RPC-based systems

479,232 readout channels

DHCAL construction

- Started in fall 2008
- Completed in winter 2011

Test beam activities

- 10 Million muon events
- 25 Million secondary beam events
  Collected in 5 periods at FNAL
- Tests with Tungsten absorber ← starting now at CERN
Some nice DHCAL events

Configuration with minimal absorber

- 50 GeV π⁺
- 8 GeV e⁺
- 16 GeV π⁺
**Muons in the DHCAL**

**Broadband muons**

Obtained from +32 GeV beam with beam blocker

**Reconstruct**

Tracks in the DHCAL → Software alignment of layers

**Measure**

Efficiency, average pad multiplicity...

**Tune**

Monte Carlo simulation

---

**Figure:**

- **Residual** graph showing RMS 265 → 21 μm.
- **Efficiency** graph with data and simulation.
- **Multiplicity** graph showing track segments.
- **Calibration factors** graph with layer number.
Secondary beam in the DHCAL

Results so far similar to expectations based on GEANT4 simulation

Hadron response (before calibration)

Hadron resolution \( \frac{\hat{\phi}}{E} = \frac{\hat{a}}{\sqrt{E}} \cdot C \)

With containment cut
Assembling procedure
6mm (active area) + 5mm (steel) = 11 mm thickness

Construction of one unit of the SDHCAL prototype: 2-bit 3-threshold r/o

144 ASICs = 9216 channels/1m²

6mm (active area) + 5mm (steel) = 11 mm thickness
The homogeneity of the detector and its readout electronics were studied.

Power-Pulsing mode was tested in a magnetic field of 3 Tesla.

The Power-Pulsing mode was applied on a GRPC in a 3 Tesla field at H2-CERN (2ms every 10ms). No effect on the detector performance.
Construction of the SDHCAL prototype
460800 electronic channels
and self-supporting mechanical structure
with planarity requirements fulfilled

10500 ASIC
Were tested and calibrated

52 units produced
First technological prototype
50 units (>6 \( \lambda \)) working with power-pulsing

Currently in TB

10 GeV Pion
Cosmic hadronic shower

Power-pulsed

Colors corresponding to the 3 thresholds
GEM Test Beam with KPiX: Efficiencies, Hit multiplicities

95% efficiency at 10fC threshold for operating HV of 1950V w/ low noise

$g \approx 11000$
GEM Test Beam with KPiX: Efficiencies, Hit multiplicities

95% efficiency at 10fC threshold for operating HV of 1950V w/ low noise

\[ g \approx 11000 \]
Each of the GEM 100cmx100cm planes will consist of three 33cmx100cm unit chambers. Qualification of five 33cmx100cm GEM foils completed!!
Two 33cmx100cm chamber parts delivered
Class 10,000 clean room (12’x8’) construction completed
Jig for 33cmx100cm chamber being procured
MICROMEGAS for a SDHCAL

Characteristics:
- Proportional mode
- Bulk-MICROMEGAS
- 1cm² pad readout
- Embedded readout electronics (3 thresholds)
- Operating at low voltage < 500 V
- High detection rate
- Robust, cheap (industrial process)
- Thickness: down to 6 mm

Prototype basic performances
- MIP most probable value: ~20 fC
- At 1.5 fC threshold:
  - Efficiency > 97%, channel disparity < 1%
  - Multiplicity < 1.1
- Excellent behaviour in electromagnetic and hadronic showers
MICROMEGAS for a SDHCAL

1m² MICROMEGAS layer:
- 9216 pads of 1 cm² (2% dead areas)
- 6 independent bulks
- 7 mm total thickness
  + 2 mm stainless steel (SS)
- fits in SS and W CALICE structures.
- Prototype with MICROROC chip
  - Non-flammable mixture Ar/CF4/iC4H10 95/3/2
  - 2 weeks operation in August 2011 (SPS) with less than 10 HV trips, no dead channels (~ 6 millions of recorded triggers: 150 GeV µ and π)
  - 10 days in GRPC-DHCAL in October 2011 (SPS) (~ 1 millions of recorded hadron triggers: 60 to 180 GeV)
  - Efficiency = 98 %, hit multiplicity = 1.15 ,
  Noise = 0.1 Hz for the complete 1m²
  - Response in hadronic showers, triggerless mode
- 4 MICROMEGAS layers expected for 2012 beam tests in GRPC-HCAL with common DAQ!
MICROMEGAS for a SDHCAL

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Common developments

Front end electronics

DAQ

not reported here: test beam infrastructure, software and computing
ILC Challenges for electronics

• Requirements for electronics
  – Large dynamic range (15 bits)
  – Auto-trigger on $\frac{1}{2}$ MIP
  – On chip zero suppress
  – Front-end embedded in detector
  – $10^8$ channels
  – Ultra-low power : (25$\mu$W/ch)
  – Compactness

• « Tracker electronics with calorimetric performance »

it’s gonna heat !
$\Rightarrow$ Power pulse
ASICS for ILC prototypes

- 1st generation ASICS: FLC-PHY3 and FLC_SiPM (2003) for physics prototypes
  - 36 ch. 32mm²
  - June 07, June 08, March 10

- 2nd generation ASICS: ROC chips for technological prototypes
  - Address integration issues
  - Auto-trigger, analog storage, internal digitization and token-ring readout
  - Include power pulsing: < 1 % duty cycle
  - Optimize commonalities within CALICE (readout, DAQ...)
  - 64 ch. 16mm²
  - Sept 06, June 08, March 10

- 3rd generation ASICS (AIDA funded):
  - Independent channels to perform Zero suppress
  - 64 ch. 70mm²
  - March 10
Readout architecture **common to all calorimeters** and minimization of data lines & power

- Daisy chain using token ring mode
- Open collector, low voltage signals
- Low capacitance lines

**Data bus**

<table>
<thead>
<tr>
<th>Chip 0</th>
<th>Chip 1</th>
<th>Chip 2</th>
<th>Chip 3</th>
<th>Chip 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acquisition</strong></td>
<td>A/D conv.</td>
<td>DAQ</td>
<td><strong>IDLE MODE</strong></td>
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<td><strong>IDLE MODE</strong></td>
</tr>
</tbody>
</table>

- 1ms (.5%) 
- .5ms (.25%) 
- 199ms (99%) 

1% duty cycle 
99% duty cycle

**Time between 2 bunch crossings:** 337 ns

**Train length:** 2820x337ns=950μs

**Time between 2 trains:** 200 ms
CALICE DAQ2 scheme

Original ideas and R&D from CALICE-UK (UCL, Cambridge U., Manchester U., RHUL)

ODR = Off Detector Receiver  
LDA = Link Data Aggregator  
DCC = Data Concentrator Card  
CCC = Clock & Control Card  

Machine clock (5 MHz)  
External Trigger, Spill

50 MHz  
Clk ~ 100 MHz  
(N×MClk)

LDA-DIF on HDMI (Config, Control, Data, Clock, Trig, Busy, Sync)  
Clock, Trig, Busy & Sync on HDMI (compatible LDA-DIF)  
Optique (alt. Cable) GigE  
Debug USB  
External Trigger
CALICE DAQ2 scheme

Implementation & debug made by CALICE-France: LLR, IPNL, LAPP

ODR = Off Detector Receiver
LDA = Link Data Agregator
DCC = Data Concentrator Card
CCC = Clock & Control Card
DIF = Detector InterFace

Machine clock (5 MHz)
External Trigger, Spill

Data ↔ Config

HCAL
ECAL

LDA-DIF on HDMI (Config, Control, Data, Clock, Trig, Busy, Sync)
Clock, Trig, Busy & Sync on HDMI (compatible LDA-DIF)
Optique (alt. Cable) GigE
Debug USB
External Trigger

Vincent.Boudry@in2p3.fr
CALICE DAQ2 scheme

ODR = Off Detector Receiver
LDA = Link Data Aggregator
DCC = Data Concentrator Card
CCC = Clock & Control Card
DIF = Detector Interface

LDA-DIF on HDMI (Config, Control, Data, Clock, Trig, Busy, Sync)
Clock, Trig, Busy & Sync on HDMI (compatible LDA-DIF)
Optique (alt. Cable) GigE
Debug USB
External Trigger

Vincent.Boudry@in2p3.fr
USB readout for SDHCAL

**USB: Config & data**

LDA
DCC

DAQ PC
ODR

Clk ~ 100 MHz
(N\times M\text{Clk})

Busy (RamFull) \iff Reset, Resume

(FastCommands)

LDA-DIF on HDMI (Config, Control, Data, Clock, Trig, Busy, Sync)

Clock, Trig, Busy & Sync on HDMI (compatible LDA-DIF)

Optique (alt. Cable) GigE

Debug USB

External Trigger

ODR = Off Detector Receiver

DCC = Data Concentrator Card

CCC = Clock & Control Card

LDA = Link Data Agregator

DIF = Detetcor InterFace

Vincent.Boudry@in2p3.f
SW framework

- XDAQ framework
  + Oracle DB for config.
  + LCIO for Data Output
- USB or HDMI readout

Running since 2010
constant improvement

L.Mirabito IPN Lyon
Technologies

• High granularity needs spur the use of novel detection techniques in calorimetry
  – Si pads at large scale, SiPMs, pad RPCs, MPGDs
  – ultra-low power mixed-circuit ASICs are key

• All major technologies have undergone or are undergoing extensive full-scale beam tests
• Si W ECAL and Sci Fe AHCAL analysis nearly complete
• Analysis of the more recent tests has just begun, but all results so far are encouraging and confirm the expectation

• Technological demonstrators of scalable systems start to provide first results
• No show stoppers seen, but more tests are necessary
Test beam experiments
Test beam experiments

DESY 2005
SiECAL

CERN 2006-2007
add Scint HCAL

FNAL 2008-09
Si -> Sci ECAL
Test beam experiments 2010+

DESY Testbeam Setup

CERN 2010-11
W abs. AHCAL

2012: DHCAL

FNAL 2010-11:
Scint AHCAL → RPC DHCAL

2012: m^3 SDHCAL

DESY
2nd generation scint HCAL

2nd generation scint HCAL

Status Report to ECFA-DP

Felix Sefkow       Hamburg, May 2, 2012
Summary of data taken

- Muon, LED and noise runs not included
- event size $\sim 50$kB -> 20 TB of physics data on the GRID
W-AHCAL Data taken at PS and SPS

W-HCAL energy sum [a.u.]

0 100 200 300 400

Normalised entries

0 0.005 0.01 0.015 0.02

CERN 2010, 3 GeV
4 GeV
5 GeV
6 GeV
7 GeV
8 GeV
9 GeV
10 GeV

W-HCAL energy sum [MIPs]

0 50 100 150 200 250

Normalized entries

0 0.1 0.2 0.3 0.4 0.5

W-AHCAL energy sum [MIPs]

0 50 100 150 200 250

Normalized entries

0 0.02 0.04 0.06 0.08 0.1

Positrons
1 GeV
2 GeV
3 GeV
4 GeV
5 GeV
6 GeV

Normalized entries

0 0.01 0.02 0.03

CERN 2010, e
1 GeV
2 GeV
3 GeV
4 GeV
5 GeV
6 GeV
7 GeV
8 GeV
9 GeV

1 - 250 GeV

W-AHCAL energy sum [MIPs]

0 200 400 600 800

Normalized entries

0 0.1 0.2 0.3 0.4 0.5

Pions
10 GeV
15 GeV
20 GeV
30 GeV
50 GeV
100 GeV
180 GeV
250 GeV

1 - 250 GeV
Physics results

Validation of Geant 4 simulations,
Tests of particle flow algorithm
Shower simulation in Geant 4

- Low energy: cascade models
- High energy: partonic models

minimize use of phenomenological parameterization

```
<table>
<thead>
<tr>
<th>BERT</th>
<th>LEP</th>
<th>QGSP</th>
<th>QGSP_BERT</th>
<th>QBBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>BERT</td>
<td>FTFP</td>
<td>QGSP</td>
<td>FTFP_BERT</td>
<td>FTF_BIC</td>
</tr>
<tr>
<td>BERT</td>
<td>FTFP</td>
<td></td>
<td></td>
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<tr>
<td>BIC</td>
<td>FTF</td>
<td></td>
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<tr>
<td>CHIPS</td>
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</tbody>
</table>
```

"legacy"
"linear combin."
"production"
"systematics"
"experimental"
SiW ECAL data

- Very precise information thanks to high granularity
- Shower decomposition very instructive

note zero suppression

showers wider in data than most lists, but FTFP_BERT does well at low energy reversed

12 GeV $\pi^-$ FTFP_BERT
- others
- protons
- electrons
- positrons
- mesons
- Monte Carlo : all
- CALICE

12 GeV $\pi^-$ QGSP_BERT

2010_JINST_5_P05007; Felix
CERN and FNAL Fe AHCAL data

- Test beam at FNAL used to explore lower energies
- Important new tests of GEANT4
- Many low energy particles in jets, even at high energy.
- Good agreement with CERN data

**Figure 1:** CERN data.

**Figure 2:** FNAL data.
- Test beam at FNAL used to explore lower energies
- Important new tests of GEANT4
- Many low energy particles in jets, even at high energy.
- Good agreement with CERN data
Timing in Tungsten HCAL

- For CLIC energies, containment becomes a major issue.
- Addressed using Tungsten HCAL – same scintillators with W absorber instead of Fe.
- Timing is also an issue at CLIC.
- Timing tests carried out using dedicated layer in the CALICE W-HCAL.
- (Overlapping) pulses can be resolved; examine time of first hit.
- Find detailed neutron tracking in GEANT4 is necessary to fit the observations.
Validate Geant4 with tungsten

- Neutron-rich absorber - independent tests
  - not many data available anyway
- Amazing agreement for a difficult material in a difficult range

<table>
<thead>
<tr>
<th>Simulation/Data</th>
<th>E_{\text{available}} [GeV]</th>
<th>\langle E_{\text{rec}} \rangle \text{ [MIPs]}</th>
<th>RMS [MIPs]</th>
<th>\langle z_{\text{cog}} \rangle \text{ [mm]}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>∑ entries \cdot 0.015</td>
<td>0.03</td>
<td>0.02</td>
<td>1.01</td>
</tr>
<tr>
<td>QGSP_BERT_HP</td>
<td>∑ entries \cdot 0.01</td>
<td>0.015</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>FTFP_BERT_HP</td>
<td>∑ entries \cdot 0.01</td>
<td>0.015</td>
<td>0.01</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Results still under internal review

Validate Geant4 with tungsten

- Neutron-rich absorber - independent tests
  - not many data available anyway
- Amazing agreement for a difficult material in a difficult range
Shower fine structure

- Could have had the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already - for more recent models

MC truth

Scint HCAL

Mean Track Multiplicity / event

Track multiplicity

CALICE preliminary

CALOR2010, Beijing, China

Particle Showers in a Highly Granular HCAL

Shower fine structure

- 8 GeV

π

π

π

π

π

- 25 GeV

Beam

ECAL upstream

➔

MC reco

→

# Tracks VS # Charged Particles in Geant4

# Charged Particles in Geant4 with E_{kin} > 500 MeV (w/o e⁻)

MC reco

MC reco

Entries (normalized to Integral = 1)

MC/Data

0.05

0.1

0.15

0.2

0.25

0.3

0.35

0.4

0.45

0.5

0.55

0.6

0.65

0.7

0.75

0.8

0.85

0.9

0.95

1

1.1

1.2

1.3

1.4

1.5

1.6

1.7

1.8

1.9

2

2.1

2.2

2.3

2.4

2.5

2.6

2.7

2.8

2.9

3

3.1

3.2

3.3

3.4

3.5

3.6

3.7

3.8

3.9

4

4.1

4.2

4.3

4.4

4.5

4.6

4.7

4.8

4.9

5

5.1

5.2

5.3

5.4

5.5

5.6

5.7

5.8

5.9

6

6.1

6.2

6.3

6.4

6.5

6.6

6.7

6.8

6.9

7

7.1

7.2

7.3

7.4

7.5

7.6

7.7

7.8

7.9

8

8.1

8.2

8.3

8.4

8.5

8.6

8.7

8.8

8.9

9

9.1

9.2

9.3

9.4

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9.6

9.7

9.8

9.9

10

10.1

10.2

10.3

10.4

10.5

10.6

10.7

10.8

10.9

11

11.1

11.2

11.3

11.4

11.5

11.6

11.7

11.8

11.9

12
Containment – use of Tail Catcher

- Tail catcher gives us information about tails of hadronic showers.
- Use ECAL+HCAL+TCMT to emulate the effect of coil by omitting layers in software, assuming shower after coil can be sampled.
- Significant improvement in resolution, especially at higher energies.
Dream: s/w compensation with fine segmentation
• Significantly improved resolution AND linearity
• High granularity - many possibilities, local and global
PFLOW with test beam data

- The "double-track resolution" of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- Test resolution degradation if second particle comes closer
- Important: agreement data - simulation

**Si W ECAL & Scint HCAL**

- ~18 cm separation of shower
- ~7 cm separation of shower

30 GeV charged hadron
10 GeV 'neutral' hadron

**Graph:**
- Probability of recovering within 3σ as a function of distance between shower axes [mm].
  - 10 GeV neutral + 10-GeV track
  - 30 GeV track
  - CALICE data
  - LHEP
  - QGSP_BERT

**Figure 6.12:** Probability of separating hadron showers: The figure shows the degradation of neutral hadron energy as a function of transverse separation from a second shower induced by a charged hadron.

**Figure 6.11:** ECAL plus AHCAL combined resolution for pions. The upper curve represents the resolution obtained with a single weight factor for each of the calorimeters, while the lower reflects a simple software compensation approach and uses weights for the hits that depend on the hit amplitude and on the hit position.

**Figure 6.14:** Shows the experimental ΔE/E energy resolution, as a function of transverse separation from a second shower induced by a charged hadron.
DHCAL first results: pions

**MC predictions for a large-size DHCAL based on the small-size prototype results.**

32 GeV data point is not included in the fit.

**Standard pion selection**

+ No hits in last two layers
Summary on analysis

- The high granularity and the wide energy range covered allow unprecedented tests of the Geant 4 physics lists.
- Altogether, the state of the art models yield a precise description up to a level of a few percent - of response, resolution and topology.
- New observables like track multiplicity or timing give novel input to model builders.

- The particle flow performance has been validated with test beam data.

- There is still a huge potential on tape or in-coming, in particular with gaseous digital read-out, with Fe and with W.
Future plans

• We must fully exploit the existing prototypes
  – more data taking after LS1

• We must fully exploit the existing data
  – physics analysis is involved, but rewarding

• We must proceed from single or few layer demonstrators to full-scale tests of the integration concepts

• New physics possibilities: 4x finer ECAL, timing in AHCAL

• There is lots to do on system level - powering, cooling, data concentration - before we can proceed to pre-production prototypes (module 0)
Conclusion

• Calorimetry is in revolutionary change - modern imaging calorimeters give insight
  – granularity - redundancy - modeling

• Particle flow detectors achieve W / Z separation, are experimentally validated in beams, and maturing in design

• Proof-of-principle test beam campaign to be completed for all technologies
  – Analysis partially completed, ongoing or just started

• Ready for the next phase

• Wealth of shower physics for the HEP community
Acknowledgments

• Thanks for providing me with material for this talk:
  – Catherine Adloff, Vincent Boudry, Daniel Jeans, Erik van der Kraaïj, Imad Laktineh, Shaojun Lu, Angela Lucaci-Timoce, Jose Repond, Nathalie Seguin-Moreau, Frank Simon, Tohru Takeshita, Mark Terwort, David Ward, Jae Yu

• Thanks to all my CALICE colleagues for continuous support

• Thank you for your attention!
Back-up slides
Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco.

1x1  3x3  5x5  10x10

M. Thomson (Cambridge)
Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco.

- Tile granularity:
  - 1x1: 50M
  - 3x3: 5M
  - 5x5: 2M
  - 10x10: 500k

M. Thomson (Cambridge)
Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco.
  - $1\times1$
  - $3\times3$
  - $5\times5$
  - $10\times10$
- Confirms earlier studies for test beam prototype
- $3\times3$ cm$^2$ nearly optimal

M. Thomson (Cambridge)
PFLOW under CLIC conditions

- Overlay $\gamma\gamma$ events from 60 BX (every 0.5 ns)
- take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- apply pt and timing cuts on cluster level (sub-ns accuracy)

Z @ 1 TeV + 1.4 TeV BG (reconstructed particles)
PFLOW under CLIC conditions

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Z @ 1 TeV
## Data taken

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Energy Points</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$:</td>
<td>16 energy points in range from 10 to 300 GeV, including ~400k Kaons at 60 and at 80 GeV</td>
<td>25.8 M</td>
<td></td>
</tr>
<tr>
<td>$e$:</td>
<td>6 energy points in range from 10 to 40 GeV</td>
<td>2.3 M</td>
<td></td>
</tr>
<tr>
<td>$\mu$:</td>
<td>for calibration over full surface</td>
<td>4.7 M</td>
<td></td>
</tr>
<tr>
<td>$\pi/e$:</td>
<td>10 energy points in range from 1 to 10 GeV</td>
<td>17.5 M</td>
<td></td>
</tr>
<tr>
<td>$\mu$:</td>
<td>for calibration, mostly inner region</td>
<td>10 M</td>
<td></td>
</tr>
</tbody>
</table>

**T3B:** A dedicated experiment to study shower time development. Took the same events in sync with AHCAL, plus standalone events.
GEM DHCAL Plans
GEM DHCAL Plans

Phase I (Through late 2011) ➔ Completion of 30cm x 30cm characterization and DCAL chip integration

- Performed beam tests @ FTBF with 30cm x 30cm double GEM chambers, one with KPiX9 and 3 with DCAL
- Completion of 33cmx100cm large foil evaluation
GEM DHCAL Plans

✓ Phase I (Through late 2011) ➔ Completion of 30cm x 30cm characterization and DCAL chip integration
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• Phase II (late 2011 – early 2013): 33cm x 100cm unit chamber development and characterization
  – Begin construction of 2 unit 100cmx33cm chambers, one with kPiX and one with DCAL
  – Bench test with sources and cosmic rays and beam tests
  – Construction of 100cmx100cm plane
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• Phase III (Early 2013 – mid 2014): 100cmx100cm plane construction
  – Construct 6 unit chambers with DCAL for two 100cmx100cm planes
  – Characterize 100cmx100cm planes with cosmic rays and beams
GEM DHCAL Plans

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- Phase III (Early 2013 – mid 2014): 100cmx100cm plane construction
  - Construct 6 unit chambers with DCAL for two 100cmx100cm planes
  - Characterize 100cmx100cm planes with cosmic rays and beams

- Phase IV (Mid 2014 – late 2015): 100cm x 100cm plane GEM DHCAL performances in the CALICE stack
  - Complete construction of five 100cm x 100cm planes inserted into existing CALICE calorimeter stack and run with either Si/W or Sci/W ECALs, and RPC or other technology planes in the remaining HCAL
a DAQ for all technological prototypes

Requirements

- «Generic» DAQ extensible for large detectors usable
  - in Test Beams for CALICE protos
  - as prototype for ILC calorimeters
- Features (more on next slide)
  - Common interface for all protos: Detector InterFace (DIF) cards
  - 1 or 2 concentrator cards
  - all signals on 1 cable with secure communication protocol (8b/10b)

Acquisitions modes

- Standard mode (ext\textsuperscript{al} trigger): not used
- Triggered mode
  - ROC in auto-trigger; readout on external trigger (typical TB mode)
- «ILC like»:
  - bunch acquisition without trigger (optionally power pulsing): during a spill; readout on ROC full.

Calibration

- 3 CALICE prototypes en route:
  - SDHCAL: \( \approx 400.000 \) ch; Digital (2b/ch)
  - ECAL: \( \approx 22.000 \) ch; Energy (12b)
  - AHCAL: \( \approx 52.000 \) ch; Energy & time (2\times12b)

Key elements:

- Noise taming;
- huge configurations;
- Stability
History & Status

- **Genesis**
  - Most HW and FW blocks have been developed in UK; support vanished in 2011
    - Integration taken over @ LLR in 2010 → debug and dev (with DCC card)

- **Implementation**
  - First set-up on SDHCAL (LAPP) & ECAL (LLR); AHCAL just started (DESY)
  - SW started from scratch in 2010 @ IPNL on XDAQ (for SDHCAL) + Oracle

- **Test beams:**
  - SDHCAL with HDMI in 2011: too many instabilities... (mix of HW, FW, SW).
    - 2012: running 400 kCh / 50 planes / 150 DIFs on USB (perfs but now very stable...)
  - ECAL with full system (3 DIFs) in April

- **Work in progress:**
  - Deployment of SW for ECAL & AHCAL; later deployment of HDMI for SDHCAL
  - Replacement of HW: LDA → GigaDCC (LLR) and CCC → CCC2 (Mainz)...
  - Integration with AIDA DAQ (aka EUDAQ + beam interface)
ROC Chips performance (Testbench and at System level)

- **HARDROC2 (DHCAL, RPC):**
  - Semi digital readout with 3 thresholds
  - Auto trigger on 10fC up to 20 pC
  - Scalable readout scheme successfully tested
  - **Power pulsing in magnetic field successfully tested in 2010**
  - SDHCAL technological proto with 40 layers (5760 HR2 chips) built in 2010-2011.

- **MICROROC: (DHCAL, μMEGAS)**
  - Similar to HARDROC (semi digital readout) with charge preamp input (smaller signals)
  - Noise: 0.2fC (Cd=80 pF). Auto trigger on 1fC up to 500fC
  - Very good performance of the electronics and detector (Threshold set to 1fC on 1 m2 in TB)
ROC Chips performance

- **SPIROC2 (AHCAL, SiPM):**
  - Autotrigger on 1 spe (150 fC)
  - Charge measurement (up to 300 pC)
  - Time measurement (~ 1 ns)
  - 16 deep analog memory
  - Internal 12 bits ADC

- **SKIROC2 (AHCAL, SiPM):**
  - Similar to SPIROC2 but with Charge preamp input (1 MIP= 4fC)
  - Very good performance on testbench
  - First measurements performed in Test beam: very promising
Embedded electronics - Parasitic effects?
Exposure of front end electronics to electromagnetic showers

- No sizable influence on noise spectra by beam exposure
  $\Delta$Mean $< 0.01\%$ of MIP $\Delta$RMS $< 0.01\%$ of MIP
- No hit above 1 MIP observed
  $\Rightarrow$ Upper Limit on rate of faked MIPs: $\sim 7 \times 10^{-7}$

Possible Effects: Transient effects
Single event upsets

Comparison: Beam events
(Interleaved) Pedestal events

Chips placed in shower maximum of 70-90 GeV em. showers

NIM A 654 (2011) 97
Tests of GEANT4 physics lists

ECFA detector R&D Panel

Analysis Results
Tests of Particle Flow

- Ultimate aim is to design calorimeter optimised for particle flow.
- Test by overlaying charged and (fake-)neutral showers from data and reconstructing using PandoraPFA.
- Check simulation of performance as a function of separation between showers.
- CALICE calorimeters not compensating.
- But can use granularity to distinguish electromagnetic and hadronic energy deposits, and weight accordingly.
- Various techniques give similar results.
- Improve resolution by ~20% across wide energy range; also slightly improve linearity of response.
Correction of leakage using AHCAL alone?

- How well can we do using HCAL alone?
- Correction based on observables sensitive to leakage:
  - Shower start point
  - Fraction in last 5 layers
- Can achieve improvement in both linearity and resolution.
Digital HCAL

ECFA detector R&D Panel

Analysis Results