Performance of the CALICE calorimeters

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On behalf of the CALICE collaboration
The CALICE Collaboration

- The CALICE is a collaboration of Calorimeter R&D for a future linear collider.
- ~330 physicists/engineers from 57 institutes and 17 countries.

**Final Goal:**
Construct fine granular calorimeter optimized for the Particle Flow measurement of multi-jets final state at a future linear collider.

**Intermediate task:**
Build prototype calorimeters in order to
- establish the technology
- collect hadronic showers data to tune clustering algorithm and validate existing MC models

2012/July/7

ICHEP 2012 @ Melbourne
Why fine granular? \(\rightarrow\) Particle Flow Calorimetry

- Most of the important physics processes to be studied at a future linear collider have multi-jets in final state.
  \(\rightarrow\) **Jet energy resolution plays an important role.**

- The best energy resolution is obtained by reconstructing momenta of individual particles avoiding double counting among Trackers and Calorimeters.
  - Charged particles (~60%) measured by Trackers.
  - Photons (30%) by electromagnetic calorimeter (ECAL).
  - Neutral hadrons (10%) by ECAL + hadron CAL (HCAL)

\[
E_{\text{TOT}} = p_{\text{Lepton}} + p_{\text{Charged Hadron}} + E_\gamma + E_{\text{Neutral Hadron}}
\]

\(\rightarrow\) Particle Flow Calorimetry

Separation of particles (showers) in the calorimeters is crucial for the particle flow, high granular calorimeters are therefore essential.
Calorimeter Technologies and Test Beam

- All calorimeters are designed for the Particle Flow = Fine granular.

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<th>HCAL</th>
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<td>Micro Megas</td>
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- A number of test beam have been carried out since 2006 at CERN, DESY, and FNAL.
Test Beam 2006~2009

CERN 2006-2007
add Scint HCAL

DESY 2005
SiECAL

FNAL 2008-09
Si -> Sci ECAL
Test Beam 2010~

CERN 2010-11
W abs.
AHCAL
2012:
DHCAL

FNAL2010-11:
Scint AHCAL → RPC DHCAL

2012: m$^3$ SDHCAL

DESY
2nd generation
scint HCAL

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Highlight from Test Beam Result

- Demonstration of Two particle separation
  - Si/W ECAL & Scint. AHCAL
  - Overlaid pion showers: 30GeV Charged hadron and 10GeV Neutral Hadron

Resolution degrades as second particle comes closer.
MC well reproduces the data.

⇒ Particle Flow works well with fine granular calorimeters!
Si/W ECAL

- **Physics Prototype**
  - Silicon-pad as sensitive layer $\rightarrow 24X_0$, 1 $\lambda_1$ (30 layers)
  - Tungsten as absorber layer
- **Test of new silicon sensors** (5mm x 5mm cell size) are ongoing at Ecole Polytechnique/Kyushu Univ.

- **Test beams**
  - 2006, ECAL 2/3 equipped, Low energy electrons (1-6 GeV at DESY), high energy electrons (6-50 GeV at CERN)
  - 2007, ECAL nearly completely equipped, High energy pions (6-120 GeV at CERN), Tests of embedded electronics
  - 2008, FNAL, ECAL completely equipped, Pions at small energy

Particle distance~ 5 cm $\rightarrow$ No confusion !!!

Transverse energy profile

These data are very fruitful for validation of GEANT4 models.

e.g.) For transverse shower radius, FTFP_BERT and FTF_BIC describe data well

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Scintillator Strip ECAL

- Sensor: **Scintillator strip + MPPC**
  - Scintillator strip: 45 x 5 x 2 mm³
  - MPPC: 1.4 x 1.4 x 0.6 mm³

- Scintillator strip in odd layers are **orthogonal** with respect to those in even layers.

→ **Effectively 5 x 5 mm² lateral granularity** (Same as the silicon pad). We can expect the **cost reduction** compared to the Si/W ECAL.

- Need to develop **special software algorithm** to extract the effective lateral granularity.

- Test Beams since 2007~
  - Linearity Deviation: <1.5%
  - Stochastic Term: 13.16+-0.05 %
  - Constant Term: 2.32+-0.02 %

**CALICE PRELIMINARY**
**Analog HCAL**

- **Physics Prototype**
  - Sensitive layers: 212 scintillator tiles.
  - Light collection via WLS fiber and SiPM readout.
  - Iron as absorber layer.

- Test beam was performed in 2006-2011
  - Excellent electromagnetic performance

- The calorimeter is non-compensating. High granularity can be used to distinguish electromagnetic and hadronic energy deposit.
  → **Software compensation**

Resolution 57.6% → 45%
Linearity : < 1.5 %
**Study of Time Structure of Hadronic Shower**

- T3B (Tungsten Timing Test Beam) is first dedicated experiment to study the time structure of hadronic shower for CLIC HCAL.

- 15 3 x 3 cm² scintillator cells were installed downstream of CALICE Tungsten HCAL to study the radial extent of the hadronic shower.

- Beam axis through cell 0

- Mean time of first hit is compared to Geant4.

→ Data is consistent with the QGSP_BERT_HP.
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Digital HCAL

• Even finer granularity than analogue calorimeter. Binary (one-bit) readout is enough due to the large number of cells. → Digital Calorimeter

• **RPC/DHCAL**
  ✓ RPC layers are inserted in the existing CALICE AHCAL.
  → 480k channels (World record!)

• **GEM/DHCAL**
  ✓ Test beam was carried out with the 30 x 30 cm² GEM chambers in Aug. 2011. Analysis is ongoing.

CALICE PRELIMINARY

Standard pion selection
+ No hits in last two layers (No leakage)
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Analysis for Standard pion selection:
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Events:
- 32GeV Positoron
- 4 Muon Tracks
- 60GeV Pion
- Neutral Hadron
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**Semi-digital HCAL**

- Good energy resolution can be achieved by the digital calorimeter.
- However, the shower core is very dense at high energy and saturation will occur. Two-bits readout improves the resolution.

→ Semi-digital calorimeter

**GRPC/SDHCAL**

- 48 GRPC as active layers
- Iron as absorber layers
- $1 \times 1 \text{ m}^2$, $6\lambda_I$

First look at the TB of May 2012

- Front end electronics can be power pulsed
- Raw data
- No gain correction
- No selection except time hit clustering

100GeV pion, three thresholds
Semi-digital HCAL

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- However, the shower core is very dense at high energy and saturation will occur. Two-bits readout improves the resolution.

\[ \text{Semi-digital calorimeter} \]

- **Micromegas/SDHCAL**
  - 1 m\(^2\) micromegas layer at the back of SUS
  - 9216 pads of 1 cm\(^2\)
  - 8mm thickness
  - No space charge effect

- 2 weeks operation in August 2011
  - Efficiency = 98%
  - Hit multiplicity = 1.15
  - Front-end electronics can be power pulsed

- This allows comparison with MC
- Test beam of 4 micromegas layers is expected in this year.
Summary

• The CALICE collaboration is aiming to establish high granular calorimeter system optimized for the particle flow measurement of multi-jets final state at a future linear collider.

• A number of test beam have been intensively carried out since 2006 in order to prove the principle of each technologies.

→ Excellent performance has been shown, although some analyses are still ongoing or just started.

• We are now moving to next stage: Physics Prototype → Technological Prototype

Precise measurement tells us a lot!
Backup
Detectors optimized for Particle Flow

• Figure of Merit for PFA:

\[ \frac{BR^2}{\sqrt{\sigma^2 + R_M^2}} \]

→ Large inner radius, large B field and fine granular calorimeter are favored.

• ILD/SiD for ILC/CLIC

large TPC, B = 3.5 T

all Si tracker, B = 5T

B : Magnetic field
R : calorimeter inner radius
\( \sigma \) : calorimeter granularity
\( R_M \) : Moliere radius