Highly Granular Calorimeters: Technologies and Results

Yong Liu
Johannes Gutenberg-Universität Mainz

on behalf of the CALICE Collaboration

Instrumentation for Colliding Beam Physics (INSTR17)
Mar. 1, 2017, BINP Novosibirsk
Highly granular calorimeters: motivations

• Highly granular calorimeters
  – Motivated by requirements from precision physics programs at future lepton colliders
  – Prerequisite for Particle Flow reconstruction

• Particle Flow
  – Separate energy depositions from close-by particles: high granularity is essential
  – Connecting information from all sub-detectors
    • Charged particles measured in Tracker
    • Photons measured in Electromagnetic Calorimeter (ECAL)
    • Neutral hadrons measured in Hadronic Calorimeter (HCAL)

• To achieve excellent jet energy resolution
  – Goal at ILC: \( \lesssim 30\% / \sqrt{E(\text{GeV})} \) for di-jet energies in the order of \(~100\ \text{GeV}\)
The CALICE collaboration

- **CALICE collaboration today**
  - 55 institutes in 19 countries (4 continents)
  - ~350 members

- **Goal**
  - Research and development of highly granular calorimeters for future lepton colliders

- **Technologies**
  - A rich program exploring full spectrum of imaging calorimeter technologies

---

**Selected examples in the technology tree**

- **PFA Calorimeter**
  - ECAL
    - Tungsten
      - analog
        - Silicon
        - Scintillator
      - digital
        - MAPS
    - Scintillator
    - RPC
    - GEM
    - Micro megas
  - HCAL
    - Tungsten
    - Iron
      - analog
      - digital

- **Scintillator Tile**
  - 30x30x3 mm²

---

https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome
The CALICE physics prototypes

- **Si-W ECAL**
  - 30 layers, 1x1 cm² cells

- **Sc-AHCAL, Fe&W**
  - 38 layers, 3x3 cm² cells

- **GRPC-SDHCAL, Fe**
  - 48 layers, 1x1 cm² cells

- **Sc-W ECAL**
  - 30 layers, 1x4.5 cm² cells

- **RPC-DHCAL, Fe&W**
  - 54 layers, 1x1 cm² cells

- Various beam tests
- Detector concepts validated with physics prototypes
- Large data sets for precision shower studies
Performance of CALICE Physics Prototypes

- Sizeable experimental data for different calorimeter technologies
  - Performance info e.g. linearity, resolution, calibration, etc.
  - Only show a few selected examples

Fe-AHCAL: Energy Reconstruction
Performance of CALICE Physics Prototypes

- Sizeable experimental data for different calorimeter technologies
  - Performance info e.g. linearity, resolution, calibration, etc.
  - Only show a few selected examples

Fe-AHCAL: Energy Reconstruction

- Linearity of energy response within $\pm 1.5\%$ (AHCAL+TCMT)
- High granularity allows software compensation
  - Use shower density to correct for different responses to EM and purely hadronic showers

Fe-AHCAL: Energy Reconstruction

JINST 7, P09017 (2012)
Performance of CALICE Physics Prototypes

• Sizeable experimental data for different calorimeter technologies
  – Performance info e.g. linearity, resolution, calibration, etc.
  – Only show a few selected examples

Fe-AHCAL: Energy Reconstruction

• Linearity of energy response within ±1.5% (AHCAL+TCMT)
• High granularity allows software compensation
  – Use shower density to correct for different responses to EM and purely hadronic showers

Excellent energy resolution achieved: 45%/\sqrt{E(\text{GeV})} \oplus 1.8%

JINST 7, P09017 (2012)
Performance of CALICE Physics Prototypes

- Sizeable experimental data for different calorimeter technologies
  - Performance info e.g. linearity, resolution, calibration, etc.
  - Only show a few selected examples

Excellent energy resolution achieved:
\[ 45\% / \sqrt{E\,(\text{GeV})} \oplus 1.8\% \]

Similar energy resolution achieved in 2 combined calorimeter setups: only different with ECAL technologies (Silicon vs Scintillator)
CALICE data: understanding better hadronic showers

First interactions

\[ \langle E_{\text{res, event}}/\text{pseudolayer} \rangle \text{ [MIP]} \]

- 10 GeV
- \( \pi \) FNAL 2008
- FTFP_BERT
- FTFP_BERT_HP

\[ \text{CALICE SI-W ECAL} \]

\[ \text{NIM A 794, 240 (2015)} \]

Shower depth [pseudolayer]
CALICE data: understanding better hadronic showers

First interactions

MIP-like tracks (within hadronic showers)
CALICE data: understanding better hadronic showers

First interactions

MIP-like tracks (within hadronic showers)

Timing behavior of components
CALICE data: understanding better hadronic showers

First interactions

MIP-like tracks (within hadronic showers)

Timing behavior of components

Timing structure: scintillator vs gas
CALICE ECAL technological prototypes

**Scintillator-Tungsten ECAL**

New Scintillator strips
No WLS

Side-surface readout

Strip with bottom readout

- **Towards a full Sc-W ECAL detector**
  - Scintillator strips $45 \times 5 \times 2$ mm$^3$ per layer, with direct SMD-SiPM readout
    - Crossed layers to achieve effective granularity $5 \times 5$ mm$^2$
  - Front-end electronics fully integrated into each active layer
  - New bottom readout to reduce dead area; new SiPM with 10k pixels on 1x1 mm$^2$
  - Combined beam tests with Sc-Fe AHCAL at CERN/DESY: working smoothly

**Silicon-Tungsten ECAL**

Details in Vladislav Balagura’s talk in the same session
AHCAL overview

HCAL inside magnet: compact design

Technological Prototype: fully scalable

Magnet
AHCAL Cabling

H=110cm
W=82cm
L=230cm
AHCAL overview

HCAL inside magnet: compact design

Technological Prototype: fully scalable

Magnet

AHCAL Cabling

H=110cm

L=230cm

W=82cm

216cm

Electronics fully integrated into active layers
(6 readout boards in a slab)
AHCAL overview

HCAL inside magnet: **compact design**

Technological Prototype: **fully scalable**

- Magnet
- AHCAL Cabling

**HCAL Base Unit (HBU)**

- 144 scintillator tiles
- 30x30x3 mm³ scintillator tile
- SMD-SiPM

Electronics fully integrated into active layers (6 readout boards in a slab)

Dimensions:
- H = 110 cm
- W = 82 cm
- L = 230 cm
- 216 cm
AHCAL overview

HCAL inside magnet: **compact design**

Technological Prototype: **fully scalable**

High-granularity Calorimeter optimized by PFA:
**challenge of ~ 8 million channels** in final design

- Magnet
- AHCAL Cabling
- HCAL inside magnet: **compact design**
- Technological Prototype: **fully scalable**
- Magnet: 216cm
- W = 82cm
- H = 110cm
- L = 230cm

144 scintillator tiles

HCAL Base Unit (HBU)

Electronics fully integrated into active layers
(6 readout boards in a slab)
AHCal mass assembly: from design to reality

- **Surface-mount tile design**
  - Electronics for surface-mounted SiPMs established (SMD-HBU)
  - Scintillator tiles individually wrapped
  - 1st prototype board (144 channels) successfully built in 2014

Reflective foil cut by laser

Achieved excellent uniformity
AHCAL mass assembly: from design to reality

- **Surface-mount tile design**
  - Electronics for surface-mounted SiPMs established (SMD-HBU)
  - Scintillator tiles individually wrapped
  - 1st prototype board (144 channels) successfully built in 2014

- Mass assembly with a pick-and-place machine

  - Reflective foil cut by laser
  - Achieved excellent uniformity
AHCAL: latest mass assembly activities

- **Surface-mount tile design**
  - Adopted as a baseline design for the tech. prototype
  - 6 new SMD-HBUs assembled in 2016
    - New SiPMs with updated tile design
  - 2017: ~170 new boards will be fully assembled and tested
    - Collaboration-wide efforts ongoing
AHCAL: latest mass assembly activities

- Surface-mount tile design
  - Adopted as a baseline design for the tech. prototype
  - 6 new SMD-HBUs assembled in 2016
    - New SiPMs with updated tile design
  - 2017: ~170 new boards will be fully assembled and tested
    - Collaboration-wide efforts ongoing

- New generation of SiPMs
  - Reduced DCR and low inter-pixel crosstalk
  - Noise free in AHCAL
  - Improved uniformity (SiPMs, also pixels)
AHCAL: latest mass assembly activities

- **Surface-mount tile design**
  - Adopted as a baseline design for the tech. prototype
  - 6 new SMD-HBU assemblies in 2016
    - New SiPMs with updated tile design
  - 2017: ~170 new boards will be fully assembled and tested
    - Collaboration-wide efforts ongoing

- **New generation of SiPMs**
  - Reduced DCR and low inter-pixel crosstalk
  - Noise free in AHCAL
  - Improved uniformity (SiPMs, also pixels)
AHCAL: a new small prototype

• A small prototype for electromagnetic showers with high-quality SiPMs
  – 15 layers, single HBU per layer;
    • 7 HBUs with SMD-SiPMs built via mass assembly (Hamamatsu MPPCs, 2 generations)
    • 8 HBUs with high-quality SiPMs, each coupled to a tile’s side-surface (SensL)
  – New interface boards for all layers
  – To demonstrate: achievable precision of EM showers, power-pulsing mode and temperature compensation for SiPM

• Tested in DESY testbeam in 2016
  – MIP calibration for all layers
  – EM shower data taken with and without power pulsing
AHCAL: a new small prototype

- A small prototype for electromagnetic showers with high-quality SiPMs
  - 15 layers, single HBU per layer;
    - 7 HBUs with SMD-SiPMs built via mass assembly (Hamamatsu MPPCs, 2 generations)
    - 8 HBUs with high-quality SiPMs, each coupled to a tile’s side-surface (SensL)
  - New interface boards for all layers
  - To demonstrate: achievable precision of EM showers, power-pulsing mode and temperature compensation for SiPM
- Tested in DESY testbeam in 2016
  - MIP calibration for all layers
  - EM shower data taken with and without power pulsing

![Image of AHCAL prototype]

01.03.2017
Highly Granular Calorimeters, INSTR17 (yong.liu@uni-mainz.de)
AHCAL technological prototype

- Goal: to instrument AHCAL technological prototype in a steel stack
  - Correspond to ~ 1% of barrel HCAL at ILC
  - Scalable to a full HCAL at ILC
  - 40 layers totally; 4 HBUs in each layer
  - Big step towards mass production & QA
    - Tile mass production via injection molding
    - Quality assurance: ASICs, SiPMs, HBUs
AHCAL technological prototype

• Goal: to instrument AHCAL technological prototype in a steel stack
  – Correspond to ~ 1% of barrel HCAL at ILC
  – Scalable to a full HCAL at ILC
  – 40 layers totally; 4 HBUs in each layer
  – Big step towards mass production & QA
    • Tile mass production via injection molding
    • Quality assurance: ASICs, SiPMs, HBUs
Semi-Digital HCAL

- SDHCAL technological prototype: GRPC-Fe
  - 1×1 cm² pads, 48 layers (6λ), 3 thresholds
    - Operated in avalanche mode
  - Compact self-supporting structure design
    - Negligible dead zones; eliminates projective cracks
- Promising results achieved in beam tests
  - Auto-triggering mode tested, with external trigger kept
  - Power pulsing tested for reducing power consumption
  - Threshold information improves the energy reconstruction
SDHCAL: road map to a full detector

- **SDHCAL 1m³ prototype**
  - Larger RPC (3×1 m²) under development
  - New electronics: for the final detector
    - DIF board: small dimensions to fit ILD small space
    - 1 DIF for 2 ASUs (Active Sensor Units) + PCB+ ASICs
    - 3 DIFs for a large GRPC layer (1m²)
    - ASIC: HARDROC3 (zero suppression, extended dynamic range, etc.)
  - New detector conception: gas distribution, cassette conception
  - Improved mechanical structure: excellent flatness (<1mm) for 3×1 m² plates

**New cassette to ensure better contact between the detector and electronics**

**New circulation system**

144 ASICs = 9216 channels/1m²

3072 channels on 2 ASUs (100cm×33cm)
Applications to LHC experiments

- LHC experiments: Phase II upgrades to cope with high luminosity
  - Many challenges: high pile-up, high-level radiation, etc.
  - Good spatial resolution → high granularity
  - Timing separation between vertices → good timing resolution
- Phase II upgrades of both ATLAS and CMS detectors involve technologies developed by CALICE

---

**CMS: High Granular Calorimeter (CMS-HGCAL)**

**ATLAS: High Granularity Timing Detector (ATLAS-HGTD)**
Summary and outlook

• CALICE collaboration is developing high-granularity calorimeters based on Particle-Flow paradigm

• Detector concepts have been validated with physics prototypes

• CALICE data with different active and passive media
  – Possibilities to study hadronic showers in unprecedented granularity
  – Contributing substantially to further development of hadronic models in Geant4

• Technological prototypes with various technologies
  – To prove design can be scalable to a full detector
    • Fully integrated electronics, scalable DAQ, mechanics, mass production, etc.
  – Ongoing developments to address remaining technological challenges

• CALICE technologies find applications in future HL-LHC experiments
  – Fruits of creative ideas, hard work and close collaboration
Summary and outlook

• CALICE collaboration is developing high-granularity calorimeters based on Particle-Flow paradigm

• Detector concepts have been validated with physics prototypes

• CALICE data with different active and passive media
  – Possibilities to study hadronic showers in unprecedented granularity
  – Contributing substantially to further development of hadronic models in Geant4

• Technological prototypes with various technologies
  – To prove design can be scalable to a full detector
    • Fully integrated electronics, scalable DAQ, mechanics, mass production, etc.
  – Ongoing developments to address remaining technological challenges

• CALICE technologies find applications in future HL-LHC experiments
  – Fruits of creative ideas, hard work and close collaboration

Thank you!
Backup
Calorimeter granularity optimization

- Jet energy resolution versus the number of HCAL cells
  - Towards cost optimization
  - $3 \times 3 \text{ cm}^2$ cell size is still a very reasonable choice: 8M cells
CALICE technology in CMS Phase-II upgrade

- CMS-HGCAL EE+FH: using technologies developed for Si-W ECAL
  - EE: 28 layers, Si+Brass, ~26\(X_0\) (1.5\(\lambda\))
  - FH: 12 layers, Si+Brass, 3.5\(\lambda\)
  - New readout chip (SKIROC2-CMS), 30 ps timing resolution
- CMS-HGCAL BH
  - Scintillator (with SiPM) + Steel: 12 layers (5\(\lambda\)), 450m² scintillator
CALICE technology in ATLAS Phase-II upgrade

- **ATLAS-HGTD**: using technologies developed for CALICE Si-W ECAL
  - Location: z around 3500mm, Δz=60~70mm, R=90~600mm, 2.5 < η < 5
  - Silicon detectors: 4~5 layers
  - Optionally Si-W pre-shower (3~4X₀)
  - Intrinsic timing resolution: o(10) ps
  - Precision position and time info, for pile-up subtraction