Imaging Analog Hadron Calorimetry with Scintillators and SiPMs

Frank Simon
Max-Planck-Institut für Physik
Excellence Cluster ‘Universe’

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Why do we care?

- Hadronic calorimeters are mainly used to measure jets: The final product of quarks and gluons created in elementary particle reactions

Every modern high energy physics detector has one - Why are we not satisfied with what we have? Why do we want to do better?
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“Forscher rätseln über neue Naturkraft”
- Spiegel Online, April 7, 2011

http://www.spiegel.de/wissenschaft/natur/0,1518,755597,00.html

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... imagine you had a factor 2 to 3 better resolution: could make the difference between puzzling observations and hard answers!

Hadronic Calorimetry in Particle Physics

• Calorimeters measure the energy of particles by total absorption

• Hadrons are challenging: Large volumes & dense materials needed
  • Characteristic length scale given by interaction length: typically $\sim 100 \, \text{g/cm}^2$:
    ‣ Hadron calorimeters are always sampling calorimeters:
      Alternating layers of dense absorbers and active elements

• Hadronic showers have a rich structure: Needs a versatile detection medium
• Tower-wise readout: light from many layers of plastic scintillators is collected in one photon detector (typically PMT)
O(10k) channels for full detectors
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• Extreme granularity to see shower substructure: small detector cells with individual readout for Particle Flow \( O(10M) \) channels for full detectors
Present Hadron Calorimeters ... And Dreams

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With PFA, this provides the factor 2 to 3 improvement we are looking for!
Overview

- The first Imaging Calorimeter: The CALICE analog HCAL
  - Making it possible: Scintillator cells with SiPM readout
  - Performance & Results

- Under the Hood
  - Calibration techniques
  - New ideas for scintillator tiles with SiPMs

- Pushing further: The 4\textsuperscript{th} Dimension
  - The T3B Experiment: First glimpse at the time structure of showers
The First Imaging Calorimeter
Photodetectors for Imaging Calorimeters

- Bringing the light from many small cells out of the detector is prohibitive: Fibers use up way too much space!

  - Need a light detector directly on the scintillator cell
    - Compact device with low power consumption
    - Insensitive to magnetic fields (the calorimeter usually sits inside a multi-T field!)

The tool of choice: Silicon Photomultipliers

Array of small APDs operated in Geiger mode:
Gain $10^5 - 10^6$

All pixels combined into one signal line:
Output proportional to number of fired pixels

Single photon detector capability
Combining SiPMs with Plastic

- Active medium of choice: Plastic scintillator
  - Cheap, easy to machine, sensitive to charged particles and neutrons, ...

Typical emission spectrum of plastic scintillator:
Maximum in the violet / blue spectral region 400 nm - 450 nm
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Sensitivity maximum
~ 550 nm (green)

NIM A563, 368 (2006)
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Wavelength-shifter needed!

NIM A563, 368 (2006)
Adding Scintillators

- Plastic scintillator tile, with a wavelength shifting fiber in a machined groove
  5 mm thick, 3 x 3 cm$^2$
- Photon detector (Silicon Photomultiplier)
  coupled to the WLS fiber
Adding Scintillators

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- Photon detector (Silicon Photomultiplier) coupled to the WLS fiber

- ~ 200 cells (larger size on the outside for cost reason) make up one 1 m$^2$ layer
Turning it into a Calorimeter

- Put active elements between passive absorbers
  - ~ 20 mm steel in total per layer
  - 38 layers total: 7602 channels
- Add readout electronics, data acquisition, calibration system ...
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absorbers with active layers
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absorbers with active layers
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data acquisition
 calibration system
... and putting it into Beam!

- CALICE AHCAL constructed in 2005/2006, beam tests in various configurations at DESY, CERN and Fermilab every year since then
CALICE Analog HCAL: Beautiful Performance

• The first large-scale use of silicon photomultipliers - and the first imaging hadronic calorimeter!

A rich data set for detailed studies of hadronic showers: Validation of simulations, better understanding of underlying physics

Unprecedented possibilities!
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→ Shower start point: Study shower properties without fluctuations of initial interaction

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- Transverse shower profile: Crucial for shower separation in PFA
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- Longitudinal shower profile: Depth of calorimeter, leakage at high energies,...

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⇒ Transverse shower profile: Crucial for shower separation in PFA
⇒ Longitudinal shower profile: Depth of calorimeter, leakage at high energies,...
⇒ Shower substructure: Detailed information about hadronic interactions
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- Transverse shower profile: Crucial for shower separation in PFA
- Longitudinal shower profile: Depth of calorimeter, leakage at high energies, ...
- Shower substructure: Detailed information about hadronic interactions
- Energy and energy density: Improved resolution with software compensation
The Things you can do... Comparisons to MC

- Comparisons to MC: Understanding shower components

- Provides insight into inner workings of simulations: Which parts work well, which need improvement?
The Things you can do: Shower Substructure

- Unprecedented resolution provides a look deep into the substructure of hadronic showers:
  - Resolution of individual MIP-like particles
- Newer simulation codes can reproduce the observations: Builds trust in the Geant4 approach... and in PFA performance studies!
The Things you can do: Energy Resolution

- The primary performance criterion for a calorimeter: Energy resolution
- For hadrons, it is a tough business:

![Diagram of energy resolution in calorimetry with scintillators and SiPMs](image-url)
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  EM component: energy (almost) completely converted into charged particles, no losses due to particle mass, ...
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  had. component: energy losses due to particle mass, binding energy, delayed emission, ...

  absorber

  

  electromagnetic component

  

  heavy frac
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  - EM component: energy (almost) completely converted into charged particles, no losses due to particle mass, ...
  - had. component: energy losses due to particle mass, binding energy, delayed emission, ...

• The challenge:
  
  - Typically, the response to the em component is larger than to the hadronic component (missing energy in hadronic case), “non-compensation”
  
  - Large event to event fluctuations between the components

- Limited energy resolution of hadronic calorimeters!
The Things you can do: Energy Resolution

• Ways to improve the resolution:

• Increase response to hadronic component:
  Sensitivity to neutrons provided by hydrogenous detection medium
  but: strict requirements on absorber to active medium ratios, longitudinal uniformity,...
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  - Increase response to hadronic component:
    Sensitivity to neutrons provided by hydrogenous detection medium
    but: strict requirements on absorber to active medium ratios, longitudinal uniformity,…
  
  - Software compensation:
    Exploit detector granularity to detect topological differences between components
    Weight energy deposits according to local energy density or overall shower density
Energy Reconstruction & Software Compensation

- Software compensation in the CALICE analog HCAL: Two techniques
  - Local: use energy content of each cell
  - Global: use shower properties - number of cells above and below thresholds

Resolution of $45\%/\sqrt{E}$ with small constant term for pions **in data**
Linear energy reconstruction within 1.5% over the full energy range from 10 GeV to 80 GeV

20% improvement of resolution with software compensation
Energy Reconstruction & Software Compensation

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20% improvement of resolution with software compensation

PFA calorimeters can also be pretty good hadronic calorimeters!
Under the Hood:
Calibration, Scintillator Tiles & New Ideas
From Signals to Results

• Several calibration levels applied
  • Pushing far beyond the needs of a hadronic calorimeter to fully understand imaging calorimeters with SiPM readout
From Signals to Results

- Several calibration levels applied
  - Pushing far beyond the needs of a hadronic calorimeter to fully understand imaging calorimeters with SiPM readout

- Auto-calibration feature of SiPMs: Response to individual photons can be clearly identified: Simple gain determination possible
  - In CALICE: Low-intensity LED light coupled to every cell, high gain of front-end electronics

Knowing the gain allows to convert an observed signal into a number of photons: Crucial for saturation corrections
From Signal to Results

- Calibrating the response of each cell to particles:
  - Setting the overall calibration scale
  - Cell-to-cell intercalibration
Correcting Saturation

- The number of pixels on the SiPMs is finite: The number of photons that can be detected simultaneously (meaning within a few ns) is limited
- Leads to saturation for high-amplitude signals

![Graph showing saturation correction](image)
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Mostly an issue for electromagnetic showers...
Correcting Saturation

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- Leads to saturation for high-amplitude signals.

Saturation correction works well for electromagnetic showers:
No performance reduction for hadrons!
Fine Details - Spreads & Variations

- Matching of fiber to SiPM is tricky: Slight misalignments lead to reduced number of effective pixels - Affects saturation correction
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- ~ 30% RMS variation of signal (here for penetrating electrons from $^{90}$Sr source): A variety of factors - Taken care of by MIP calibration
Do Cell-to-Cell Spreads Matter?

- High granularity here comes in in our favor: Typically 10 cells / GeV
  Variations average out

Study in full simulations with PFA event reconstruction:
It takes more than 50% RMS cell-to-cell variations to take a hit in jet energy resolution.
Requirement here is not set by resolution, but by possibility for calibrating in groups
Expected requirement: ~ ± 10%
New Ideas for the Next Generation

- The wavelength-shifting fiber in the scintillator cells comes at a price:
  - increased mechanical complexity: Fiber needs to be inserted into every tile
  - reduced tolerances: Alignment of fiber end to SiPM critical: Decides light yield of cell and saturation level
  - Slower response: Additional time constant from WLS
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♫ Ideally, we would like to get rid of the fiber - and we can, now that blue / near-UV sensitive SiPMs exist
Testing Scintillator Tiles in the Lab

- Crucial: Capability to test performance of scintillator cells with SiPMs on the bench
- Setup with $^{90}$Sr source, allows scanning over the active tile area

Performance criteria:
- Overall signal amplitude ("light yield")
- Uniformity of response over active area
- Key requirement: Select only penetrating electrons (close approximation of MIPs)
- Trigger scintillator below tile under study

GEANT4 simulations, 5 mm scintillator
Fiber Benefits: Uniformity

- The fiber does not only shift the wavelength - it also collects light and guides it to the SiPM by total internal reflection:
  Provides uniform response over the tile surface

For this test: tile read out with MPPC - sensitivity not well matched to fiber emission
Going Fiberless: A Challenge

• Just putting a SiPM to a piece of scintillator does not work:

- Strategy for improvement:
  - Reduce amount of scintillating material close to photon sensor
  - Diffuse light to reduce spatial dependence
  - Optimize light yield
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After many iterations:

NIM A620, 196 (2010)
Fiberless Coupling: Reproducibility

- Comparing performance of a small sample of tiles (16 tiles)
- Each tile read out with a MPPC-50C (thanks Erika!)

All photon sensors adjusted to the same gain (slightly higher than specs)
Spread likely due to (automated) measurement procedure
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Tile response measured with $^{90}\text{Sr}$ source, extracted with Landau + Gauss fit
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Tile response measured with $^{90}$Sr source, extracted with Landau + Gauss fit

10% RMS spread observed for sample: corresponds to expected precision requirement
Fiberless Coupling: Scalability?

- An open question: How can we produce millions of cells needed for a complete collider detector?
  - Clear advantage for fiberless design: Should be easier to fabricate

- Designs suited for molding show good uniformity and satisfactory signal amplitudes

- Next steps: Try it out!
  Need the right material, and a company who can do it... Ideas?
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- Additional issues: Coating of tiles
  - Possible solution: Al sputtering
    First tests revealed problems with oxidation due to discharged: needs further investigation
Pushing Further: The 4$^{\text{th}}$ Dimension
Setting the Stage: Hadron Calorimetry at CLIC

- CLIC: A 3 TeV $e^+e^-$ linear collider
  The key CLIC feature: High Energy!
- 3 TeV energy means in principle up to 1.5 TeV jets

Shower containment and leakage is a crucial issue

- A (very) deep hadron calorimeter is needed
- Use compact absorbers to limit the detector radius: Tungsten a natural choice
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- Key challenge (linked to high energy and machine-specific issues): Background
  - $\gamma\gamma \rightarrow$ hadrons substantial:
    - $\sim 12$ hadrons/bunch crossing in the barrel region
    - (4 GeV / bunch crossing) [up to 50 hadrons / 50 - 60 GeV barrel + endcap + plug calorimeters]
  - extreme bunch crossing rate: every 0.5 ns
  - Very good time resolution in all detectors important to limit impact of background!
Hadronic Showers: Complex (Time) Structure

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  - instantaneous, detected via energy loss of electrons and positrons in active medium
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  - Instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium
  - Delayed component: photons, neutrons, protons from nuclear de-excitation, detected via $e^+e^-$, momentum transfer to protons in hydrogenous active medium, energy loss, contributions from time of flight of low energy particles
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⚠ Importance of delayed component strongly depends on target nucleus
⚠ Sensitivity to time structure depends on the choice of active medium
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 Detector optimization and performance studies rely on Geant4: How well do the simulations reproduce the time structure of the response in the CLIC HCAL?

- Importance of delayed component strongly depends on target nucleus
- Sensitivity to time structure depends on the choice of active medium
T3B: An Experiment for a First Study of the Time Structure

- The CALICE Scintillator-Tungsten HCAL - A CLIC physics prototype
  - 30 layers with 10 mm Tungsten (93% W, 5% Ni, 2% Cu, density $17.6 \text{ g/cm}^3$) absorber (steel of AHCAL prototype replaced by Tungsten)
  - Active elements from CALICE AHCAL: 5 mm thick scintillator tiles, read out by SiPMs (no time information available)
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- T3B (Tungsten Timing Test Beam)
  - Goal: Measure the time structure of the signal within hadronic showers in a Tungsten calorimeter with scintillator readout
  - Use a (very) small number of scintillator cells, read those out with high time resolution
  - First test beam campaign: November 2010, CERN PS
  - Second campaign: Started this week at CERN SPS
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⇒ First information on time structure, possibility for comparisons to Geant4, but: no complete “4D” shower reconstruction!
T3B Technology

• Scintillators and photon sensors:
  • Fast response - Use fiberless scintillator tiles
  • High light yield to provide sensitivity to small energy deposits
    - Use photon sensors with high PDE, limited dynamic range: MPPC-50C (400 pixels)

• Data acquisition:
  • Fast sampling to allow for single photon resolution: 1 GHz or more
  • Long acquisition window to provide sensitivity to late shower components: 2+ μs
  • High trigger rate: faster than CALICE AHCAL trigger, > few kHz
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- Adopted solution for T3B: PicoScope 6403 (USB controlled oscilloscope)
  - 1.25 GHz sampling for 4 channels per unit
  - 1 GB buffer memory (shared between channels)
  - Burst trigger mode: Maximum rate determined by window length:
    ~ 500 kHz for 2µs acquisition window
The T3B Setup: Test Beams at CERN PS & SPS

- 15 3 x 3 cm² scintillator cells, sampling the radial extent of the shower beam axis through cell 0

435 mm
The T3B Setup: Test Beams at CERN PS & SPS

- 15 3 x 3 cm² scintillator cells, sampling the radial extent of the shower

Stand-alone system:
- Installed downstream of CALICE WHCAL, depth ~ 4 λ
- Calibration triggers on dark noise between spills
Synchronization with CALICE
- Triggered by CALICE trigger - common analysis possible in the future
Data Analysis - Technique

• For each channel, a complete waveform with 3000 samples (800 ps /sample) is saved
• Waveform decomposed into individual photon signals, using averaged 1 p.e. signals
  • Average 1 p.e. signal taken from calibration runs between spills, refreshed every 5 minutes: Continuous automatic gain calibration

• Reconstruction of the time of each photo-electron:
  Allows various different analyses

![Waveform Analysis](image-url)
First Results - Muons

- Energy of muons reconstructed in the central T3B tile
  - Full reconstruction with waveform decomposition
  - Response variations from cell to cell: 10% (from bench measurements)

- Two integration times: Short time window rejects a significant fraction of SiPM afterpulses (detailed investigations of other contributions ongoing)
First Results - Muon Timing

- Present analysis: determining the Time of First Hit
  - minimum of 8 p.e. (~ 0.4 MIP) within 9.6 ns

Time of First Hit for Muons:
- Response to instantaneous energy deposit

Muons from PS:
Energy a few GeV
First Results - Muon Timing

- Present analysis: determining the Time of First Hit
  - minimum of 8 p.e. (~ 0.4 MIP) within 9.6 ns

Time of First Hit for Muons:
- Response to instantaneous energy deposit
- Time resolution (including trigger): ~ 800 ps
- Consistent with simulations including time smearing

Muons from PS:
Energy a few GeV
First Results - Pion Data

- Data taken in CALICE WHCAL Testbeam at CERN PS
- Current analysis: Highest energy taken at PS - 10 GeV $\pi^-$
- Time of First Hit

Time of first hit:
Easy to define in data and MC without detailed treatment of
- afterpulsing
- time distribution of scintillator response
- photon travel
- ...

![Graph showing time of first hit data](Calice_T3B_Preliminary_Data_10GeV.png)
Time of First Hit in Simulations

- Simulations using smeared photon distributions
- Same analysis procedure as real data
- Two physics lists:
  - QGSP_BERT: LHC standard, used for CLIC detector studies
  - QGSP_BERT_HP: Variant with high precision neutron tracking
Data & Simulations - First Results

- QGSP_BERT shows a pronounced tail of late energy depositions
- Data agrees better with QGSP_BERT_HP - Reduced activity beyond 20 ns
Data & Simulations - First Results

Data consistently described by QGSP_BERT_HP
- QGSP_BERT deviates strongly

Compact Comparison:
Mean Time of First Hit
- calculated in a time window of 200 ns (-10 ns to 190 ns from maximum in tile 0)
Data & Simulations - First Results

- Data consistently described by QGSP_BERT_HP
  - QGSP_BERT deviates strongly

Compact Comparison:
Mean Time of First Hit
- calculated in a time window of 200 ns (-10 ns to 190 ns from maximum in tile 0)

- High precision neutron tracking or other means to suppress excessive late energy depositions necessary to describe observed time structure in T3B
Summary I

• For a new generation of colliders, we want a new generation of detectors:
  High granularity, paired with sophisticated algorithms promises unprecedented resolution

• Compact silicon-based photon sensors enable highly granular calorimeters with scintillators as active medium

• CALICE has 5 years of operational experience with a physics prototype
  • First large-scale use of SiPMs - Successful proof of concept
  • Good performance: A PFA calorimeter can be a very good HCAL as well!
  • Fantastic opportunities to study the details of hadronic showers:
    Unprecedented possibilities for the validation and improvement of simulation models
Summary II

• Detailed understanding of the characteristics of a SiPM calorimeter - often beyond what is needed to obtain good hadronic performance
  • Calibrations with muons & LEDs
  • Correction for saturation of photon sensors
  • Large sample studies of scintillator tiles and SiPMs

• Ideas for the next generation of detectors
  • Not discussed here: Technical prototype of CALICE: Compact, fully integrated readout electronics
  • Fiberless scintillator tiles: Fast response, good uniformity & reproducibility
    Need ideas for mass production!
Summary III / Outlook

- A versatile technology: With the right readout, the time structure of hadronic showers is accessible
  - First proof of concept measurements - Already a physics conclusion:
    The current default physics list in HEP, QGSP_BERT, has too much late energy deposit: Overestimation of needed integration time.
    High precision neutron tracking provides improved performance

- Upcoming opportunities:
  - Next generation electronics for the CALICE AHCAL:
    Time stamping for every channel - Potentially a full “4D-Calorimeter”
  - Currently taking data with Tungsten absorbers: A whole new game of shower model validations & detector studies
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• Upcoming opportunities:
  • Next generation electronics for the CALICE AHCAL: Time stamping for every channel - Potentially a full “4D-Calorimeter”
  • Currently taking data with Tungsten absorbers: A whole new game of shower model validations & detector studies

... and who knows what other exciting ideas and projects come next!