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This work is part of AIDA Work Package 9: Advanced infrastructures for detector R&D.
The Time Structure of Hadronic Showers in Analog and Digital Calorimeters confronted with Simulations
Outline

• Time structure in hadronic showers

• CALICE T3B and FastRPC - Experiments for timing measurements

• The time structure of hadronic showers
  • In tungsten and steel
  • With plastic scintillator and RPC active elements

• Confronting simulations with data

• Summary
Exploring Hadronic Showers in Time

- Hadronic showers have a complex structure - also in time!

**Instantaneous Component:**
- Detected via energy loss of electrons and positrons in active medium

**Delayed Component:**
- Neutrons from evaporation and spallation
- Photons, neutrons, protons from nuclear de-excitation following neutron capture
- Momentum transfer to protons in hydrogenous active medium from slow neutrons

**Diagram:**
- Illustration of the components of a hadronic shower, including charged and electromagnetic components.
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  **delayed component:**
  - neutrons from evaporation and spallation
  - photons, neutrons, protons from nuclear de-excitation following neutron capture
  - momentum transfer to protons in hydrogenous active medium from slow neutrons

  **Importance of delayed component strongly depends on target nucleus**
  **Sensitivity to time structure depends on the choice of active medium**
T3B - The Study of the Time Structure of Showers

- The CALICE Scintillator-Tungsten HCAL - A CLIC physics prototype
  - 38 layers with 10 mm Tungsten (93% W, 5% Ni, 2% Cu, density 17.6 g/cm³) absorber
  - 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
  - Record signal over long time window: ~ 2 µs to sample the full shower development
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⇨ First information on time structure, possibility for comparisons to Geant4, but: no complete “4D” shower reconstruction!
The T3B Setup - Tungsten

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

beam axis through cell 0

44.9 cm
**The T3B Setup - Tungsten**

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

  ![Diagram of T3B Setup](image)

  beam axis through cell 0

  0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

  44.9 cm

**Stand-alone system:**
- Installed downstream of CALICE WHCAL, depth ~ 5 λ
- Each cell read out with 1.25 GS oscilloscope, 2.4 µs sampling time per event
- Calibration triggers on dark noise between spills

**Synchronization with CALICE**
- Triggered by CALICE trigger - common analysis possible
The T3B Setup - Steel

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

Stand-alone system only:
• Installed downstream of CALICE SDHCAL (Glass RPCs between steel absorbers), depth ~ 6 λ
• Identical readout for T3B
• No correlation of T3B and SDHCAL data streams
  • Different DAQ version
  • Data taken during SDHCAL commissioning: Low data rate, insufficient for timing measurements
  ▸ Standalone trigger for T3B
Alternative Readout: Glass RPCs - Tungsten Only

- Provide a direct comparison of scintillator and gaseous readout: FastRPC - A 1 to 1 copy of T3B, but with a glass RPC instead of scintillators
  - identical granularity: 3 x 3 cm$^2$, one strip behind the CALICE WDHCAL
  - identical data acquisition: 2.4 µs acquisition window with 800 ps readout
  - identical analysis strategy - reconstruction of time of first hit

CALICE WDHCAL, \( \sim 5\lambda \)
tungsten & RPC active layers

RPC (produced at ANL)

FastRPC readout board, connected to oscilloscopes
Data Analysis

**Cell-wise reconstruction**

- With scintillator / SiPM readout:
  - Reconstruction of time of each photon
  - Reconstruct hits by clustering in time - require at least ~ 0.3 MIP equivalents within 9.6 ns
- With RPC readout:
  - Analogous to SiPM readout, but based on waveform integral

**Further analysis:**

- For robustness: Use only the first hit in each cell in an event - avoids uncertainties from hit separation, afterpulsing, … High granularity ensures multiple real hits are rare (at the %-level)
- Main observable: “Time of first hit” - Timing given by the second reconstructed photon (SiPM) / start of signal waveform (RPC)
The Time Structure: Tungsten vs Steel

- Hadronic showers characterized by a main prompt signal and a long tail

\[ f(t) = A_{\text{fast}} e^{-\frac{t}{\tau_{\text{fast}}}} + A_{\text{slow}} e^{-\frac{t}{\tau_{\text{slow}}}} + C \]

- 60 GeV hadrons - tungsten
  \( \tau_{\text{fast}} = 8.7 \text{ ns} \), \( \tau_{\text{slow}} = 480 \text{ ns} \), \( C = 5.5 \times 10^{-6} \)

- 60 GeV hadrons - steel
  \( \tau_{\text{fast}} = 7.7 \text{ ns} \), \( \tau_{\text{slow}} = 76 \text{ ns} \), \( C = 3.1 \times 10^{-6} \)

- 180 GeV muons
  \( C = 1.2 \times 10^{-6} \)

CALICE T3B
The Time Structure: Tungsten vs Steel

- Hadronic showers characterized by a main prompt signal and a long tail

- Late components in tungsten substantially more pronounced than in steel
  - “fast” late component (~ 8 ns - ~ 50 ns) enhanced by a factor of ~ 2.3 in W
  - “slow” late component (> ~ 50 ns) enhanced by a factor of ~ 13 in W
The Impact of the Active Medium: Scintillator vs Gas

- Comparable behavior for prompt component
- Striking difference in intermediate range: ~ 8 ns to 50 ns

Absorber material: Tungsten
The Impact of the Active Medium: Scintillator vs Gas

Comparable behavior for prompt component

Striking difference in intermediate range:
~ 8 ns to 50 ns

- Further quantified:
  Factor 5 - 8 suppression of intermediate component in gaseous detectors: MeV - scale neutrons: High sensitivity of scintillators through elastic scattering on H

Absorber material: Tungsten
Impact of Time Structure on Shower Shape

- In the outer shower regions late hits are more important:
  Neutrons spread far, prompt component concentrated along shower axis
Impact of Time Structure on Shower Shape

- In the outer shower regions late hits are more important: Neutrons spread far, prompt component concentrated along shower axis.

- Effect less pronounced with RPC readout: Reduced sensitivity to MeV-scale neutrons.

![Graph showing the impact of time structure on shower shape](image-url)

The Time Structure of Hadronic Showers
TIPP, Amsterdam, June 2014

Frank Simon (fsimon@mpp.mpg.de)
Timing vs Hit Energy

- Late hits are predominantly of low energy - High energy deposits dominated by electromagnetic subshowers in the prompt part of the cascade
Comparison to Simulations

- In general good agreement of simulations with data for steel - slight underestimation of intermediate late component without HP neutron treatment.
Comparison to Simulations

In general good agreement of simulations with data for steel - slight underestimation of intermediate late component without HP neutron treatment.

HP neutron treatment crucial for tungsten: severe overestimation of very late component by QGSB_BERT.
Comparison to Simulations

- Radial dependence well modelled for steel - within a few 100 ps

GEANT4 9.4p03

60 GeV hadrons - steel
- Data
- QBBC
- QGSP_BERT_HP
- QGSP_BERT

CALICE T3B

Mean Time of First Hit [ns]

Shower Radius [cm]
Comparison to Simulations

- Radial dependence well modelled for steel - within a few 100 ps
- Radial dependence for tungsten needs HP neutron treatment
Summary

• Time structure of hadronic showers highly relevant for calorimetry at future colliders
  • Within CALICE dedicated experiments have been carried out to study it in tungsten and steel with scintillators (T3B) and gaseous detectors (FastRPC)

• In gaseous detectors, the sensitivity to the intermediate time component is reduced in particular the region from a few to a few 10 ns
  • Reduced sensitivity to MeV-scale spallation neutrons due to low hydrogen content of active medium

• The comparison of GEANT4 simulations to the data shows:
  • The time structure in steel is in general quite well described, but profits from high precision neutron models
  • For the simulation of showers in tungsten high precision neutron models are mandatory to reproduce the late components of the shower
  • Simulations to compare to the RPC data in preparation
Backup
The Life of a Pion in the WAHCAL

CALICE T3B Data

T = 0: Activity maximum in layer 39 (rear of calorimeter)

Shown: First hits in each cell only
The Life of a Pion in the WAHCAL

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Shower @ 2 to 4 ns

CALICE T3B Data

T = 0: Activity maximum in layer 39 (rear of calorimeter)

Shown: First hits in each cell only
**The Life of a Pion in the WAHCAL**

- **Shower @ 6 to 8 ns**

  - **CALICE T3B Data**

  - **T = 0**: Activity maximum in layer 39 (rear of calorimeter)

  - Shown: First hits in each cell only
The Life of a Pion in the WAHCAL

CALICE T3B Data

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The Life of a Pion in the WAHCAL

CALICE T3B Data

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The Life of a Pion in the WAHCAL

**Shower @ 30 to 40 ns**

**CALICE T3B Data**

T = 0: Activity maximum in layer 39 (rear of calorimeter)

Shown: First hits in each cell only
The Life of a Pion in the WAHCAL

T = 0: Activity maximum in layer 39 (rear of calorimeter)

Shown: First hits in each cell only
The Life of a Pion in the WAHCal

Shower @ 80 to 100 ns

CALICE T3B Data

T = 0: Activity maximum in layer 39 (rear of calorimeter)

Shown: First hits in each cell only
Time vs Energy of First Hits in T3B

• The “universal” T3B observable: Time of First Hit
  • Multiple hits per tile in one event are rare: < 3% at 30% amplitude of primary hit
The “universal” T3B observable: Time of First Hit

- Multiple hits per tile in one event are rare: < 3% at 30% amplitude of primary hit

- Substantial difference between showers in steel and tungsten: More pronounced late activity in W