# Measurements of the Time Structure of Hadronic Showers in a Scintillator-Tungsten HCAL

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Calorimeter for ILC

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# Outline

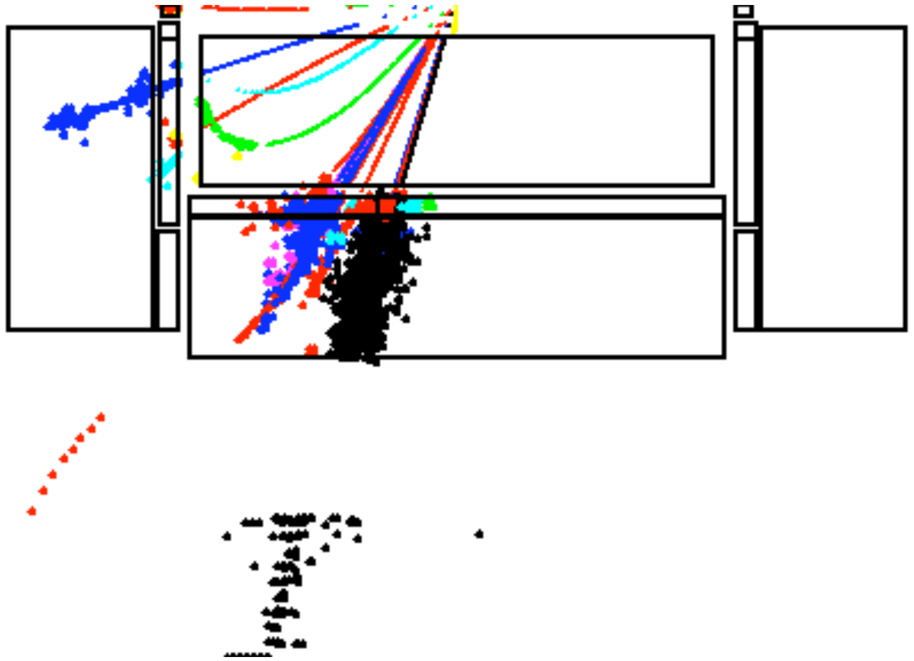
- Hadron Calorimetry at CLIC: Competing Requirements
- The Time Structure of Hadronic Showers
- First measurements in a Tungsten HCAL
  - The T3B Setup
  - First Results
- Summary & Outlook

# 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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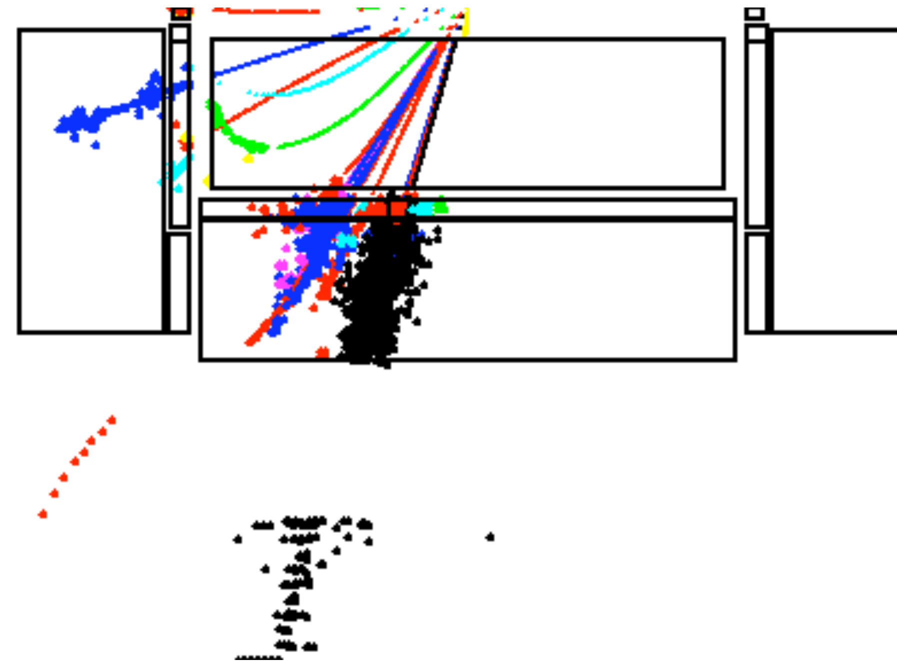

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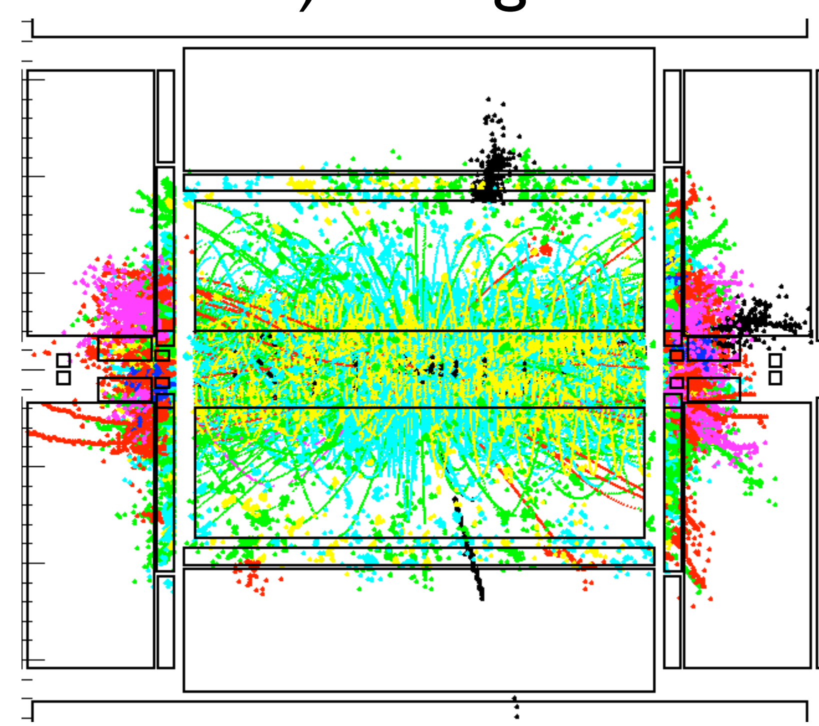
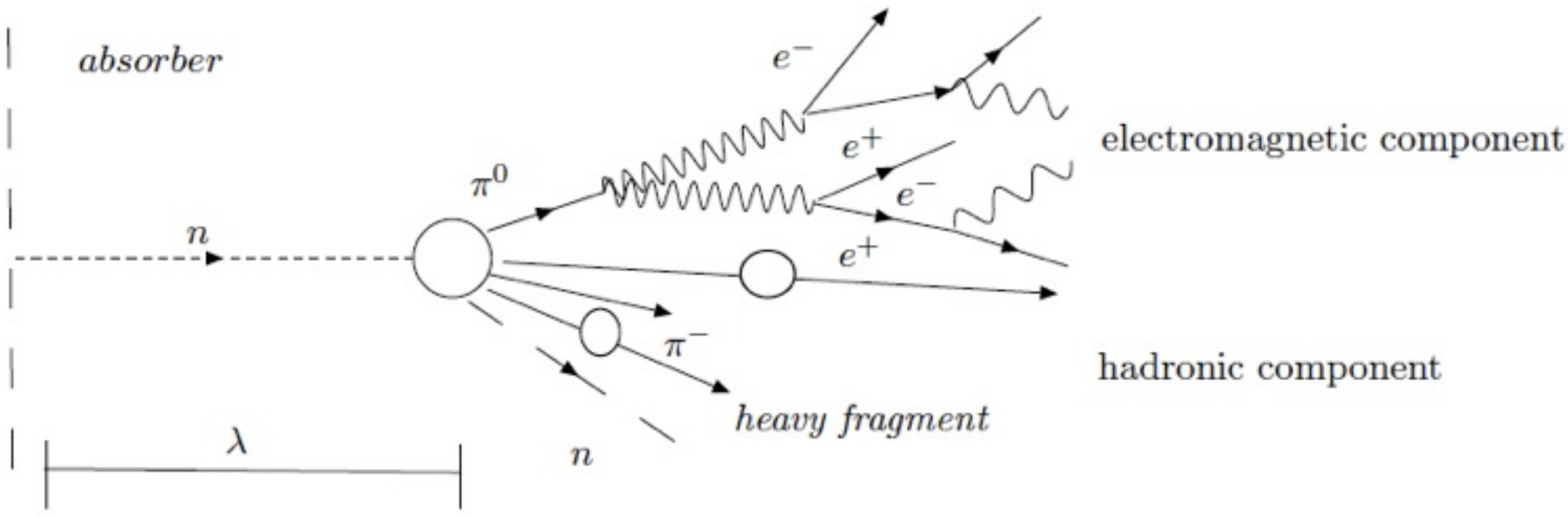
- Key challenge (linked to high energy and machine-specific issues): Background
  - $\gamma\gamma \rightarrow$ hadrons substantial:
    ~ 12 hadrons/bunch crossing in the barrel region
    (4 GeV / bunch crossing) [up to 50 hadrons /
    50 - 60 GeV barrel + endcap + plug calorimeters]
  - extreme bunch crossing rate: every 0.5 ns



➯ Very good time resolution in all detectors important to limit impact of background!

# Hadronic Showers: Complex (Time) Structure

- Hadronic showers have a rich substructure:



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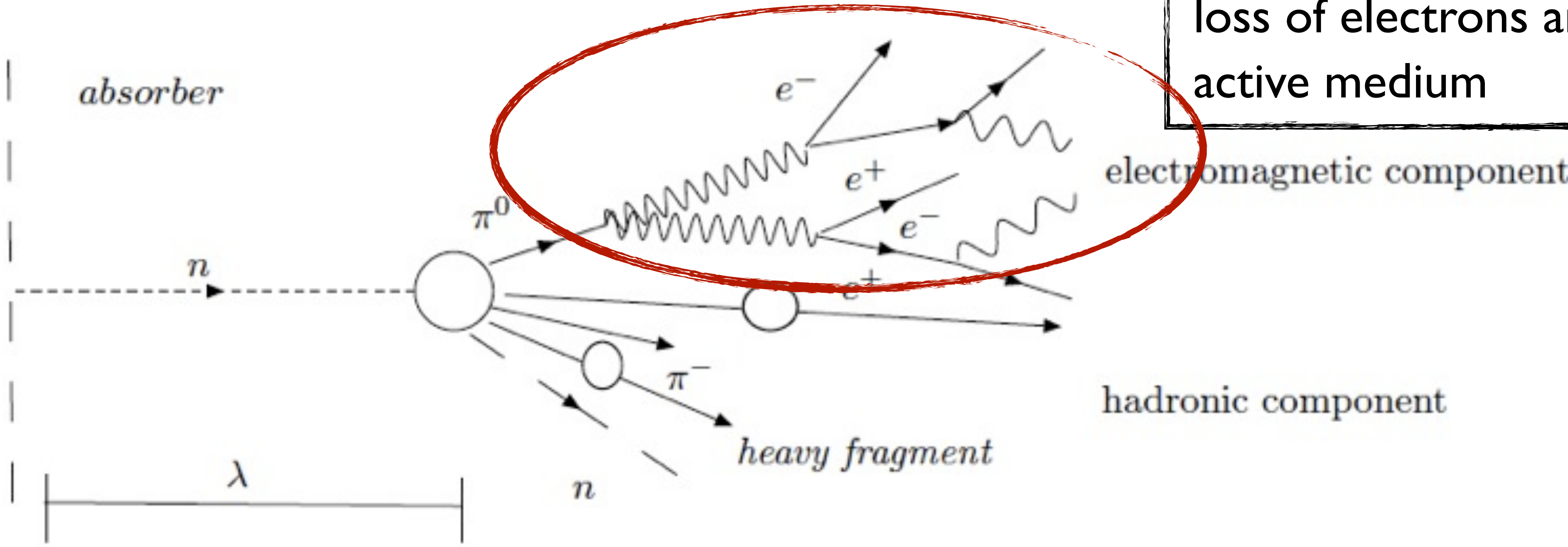

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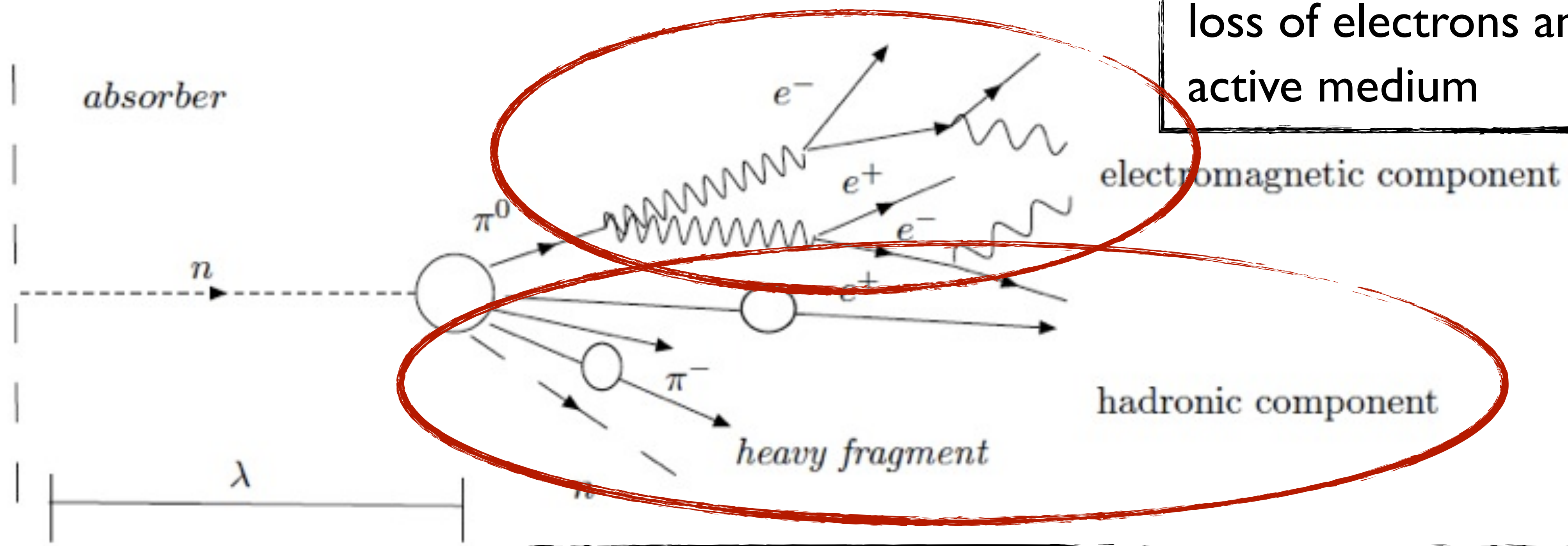


- instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium
- delayed component: photons, neutrons, protons from nuclear de-excitation, detected via $e^+e^-$, momentum transfer to protons in hydrogenous active medium, energy loss, contributions from time of flight of low energy particles

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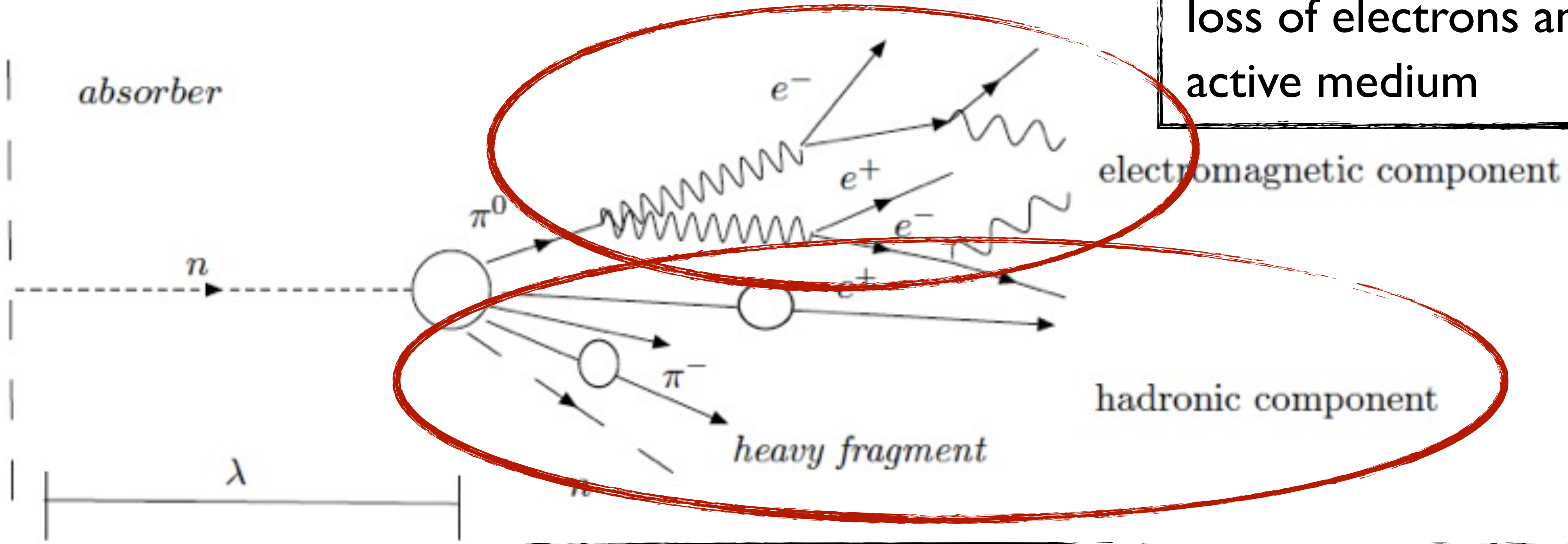


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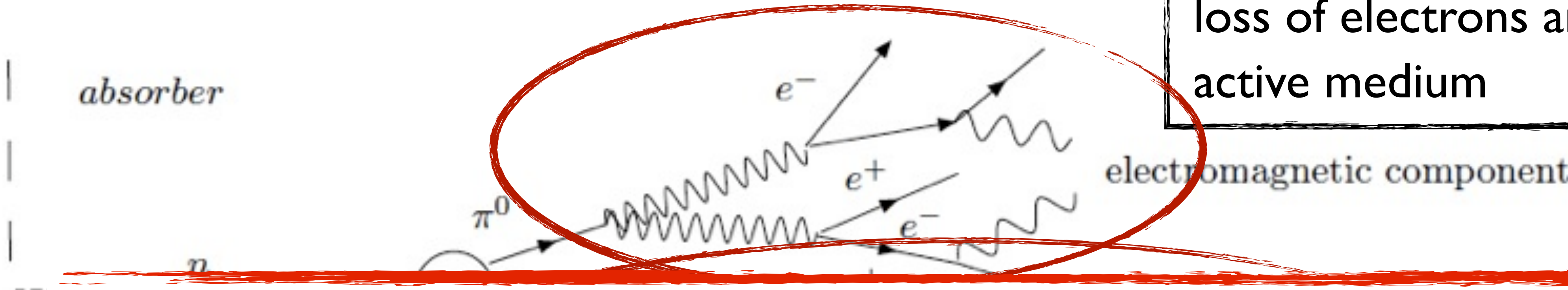


Detector optimization and performance studies rely on Geant4:
How well do the simulations reproduce the time structure
of the response in the CLIC HCAL?

...nergy

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# 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 g/cm$^3$) 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
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➯ First information on time structure, possibility for comparisons to Geant4, but: no complete "4D" shower reconstruction!

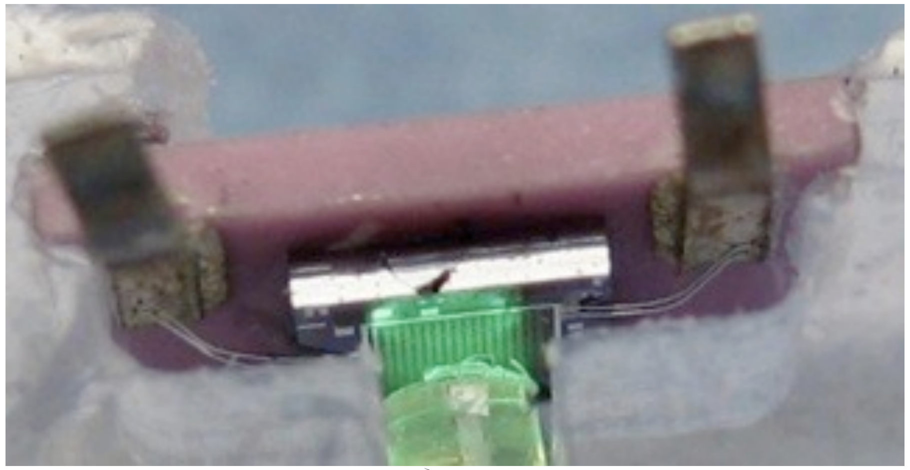
# T3B Technology: Scintillators and Photon Sensors

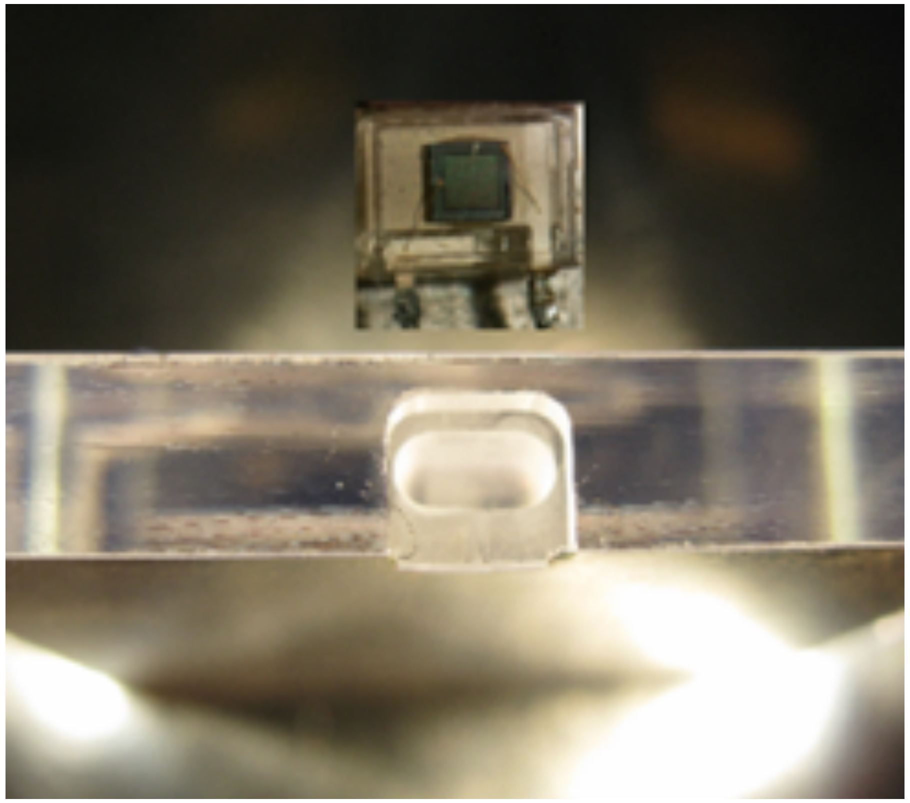
- Important features for timing measurement:
  - Fast response (good time resolution!)
  - Large signal (allows detection of small individual energy deposits)

Fiberless coupling of photon sensor to scintillator: Eliminate time constant of WLS

- Requires blue sensitive photon sensors
- Requires special shaping of coupling position to obtain uniform response over tile

NIM A620, 196 (2010)





~ x2 faster response without WLS

# T3B Technology: DAQ

- Key requirements:
  - Fast sampling to allow for single photon resolution: ~ 1 GHz or more
  - Long acquisition window per event: 2 μs or more
  - Fast trigger rate: faster than the CALICE HCAL, > a few kHz

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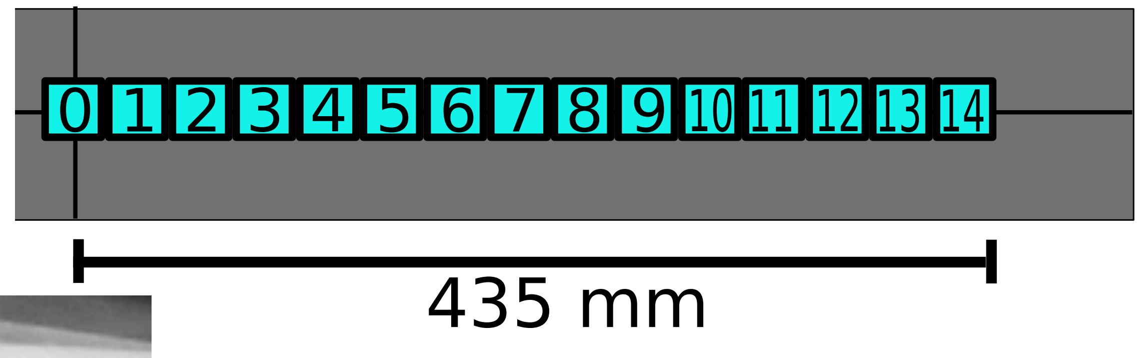
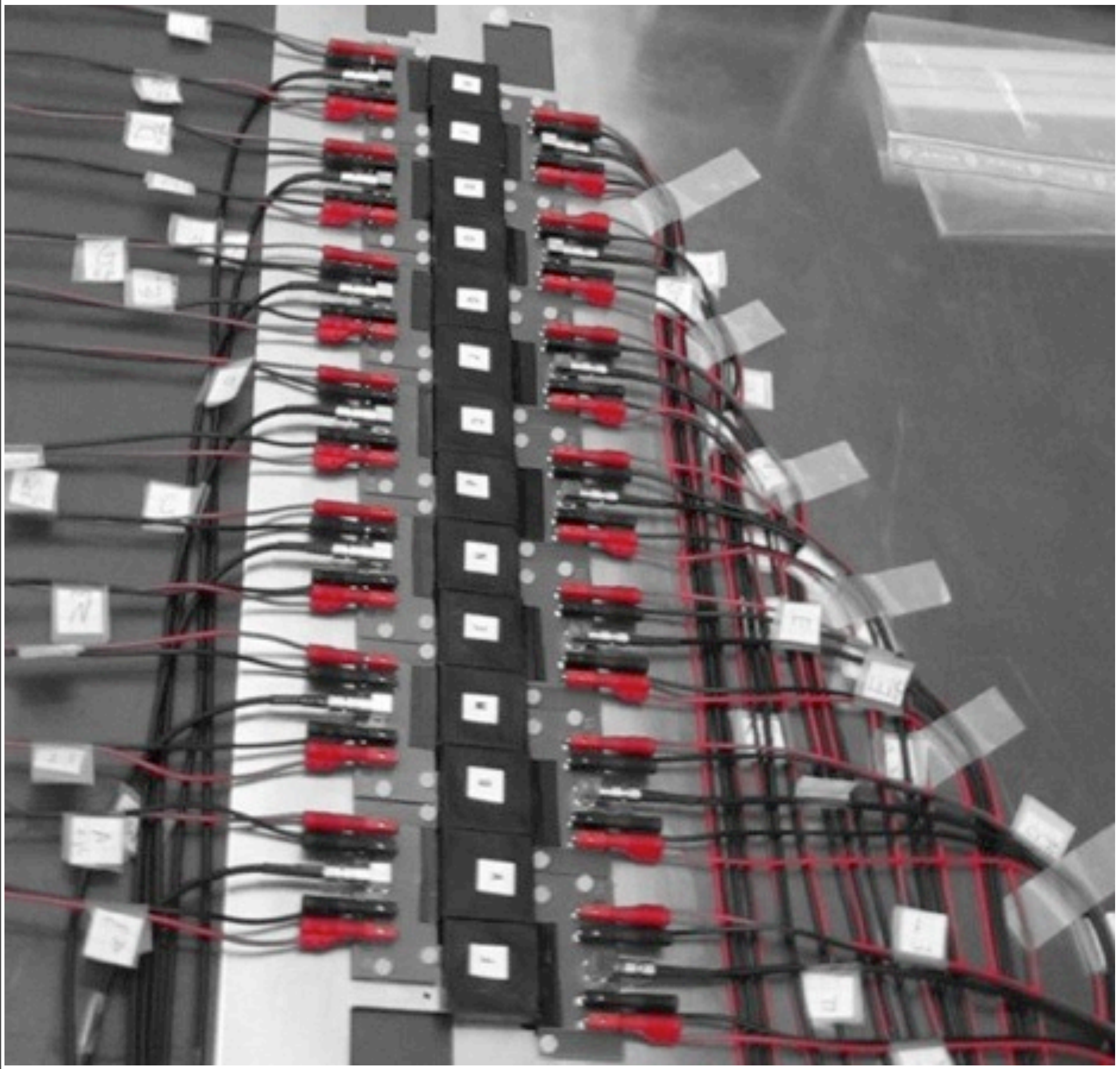
- Adopted solution for T3B: PicoScope 6403
  - 1.25 GHz sampling for 4 channels per unit
  - 1 GB buffer memory (shared between channels)
  - Burst trigger mode: Maximum rate determined by window length:
    ~ 500 kHz for 2μs acquisition window
  - 8 bit vertical resolution
  - Control & Readout via USB

# The T3B Setup

- 15 3 x 3 $cm^2$ scintillator cells, sampling the radial extent of the shower

beam axis through cell 0



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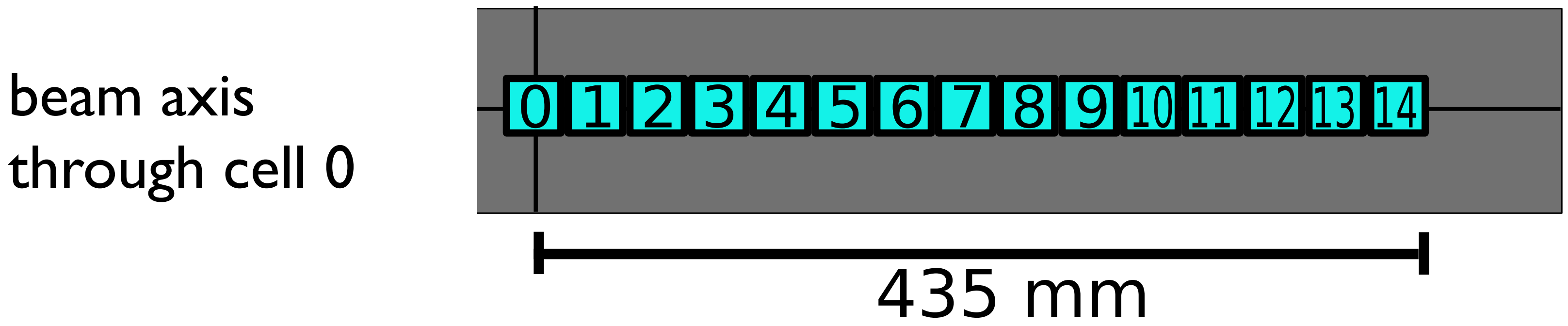



Stand-alone system:

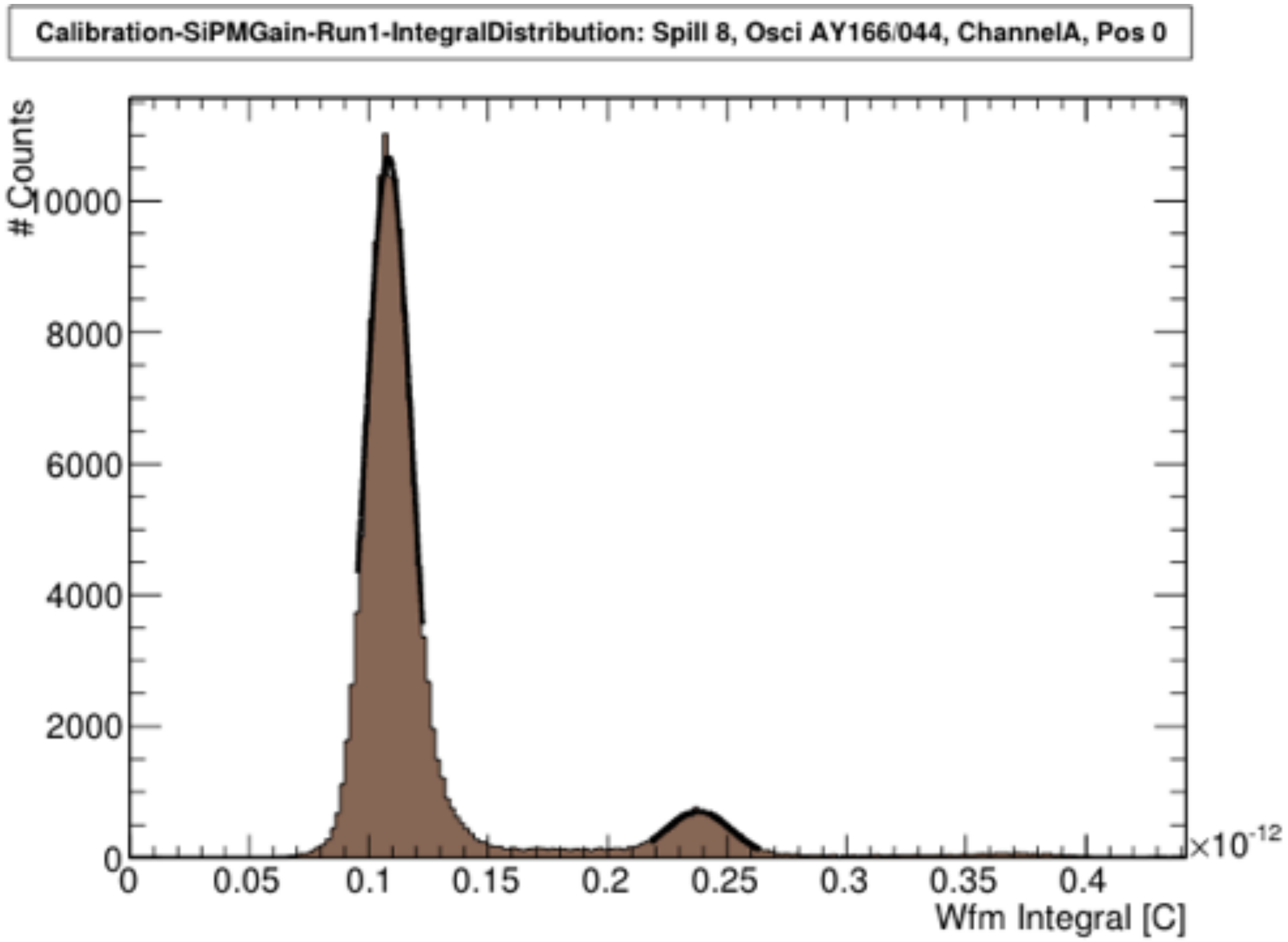
- Installed downstream of CALICE WHCAL, depth ~ 4 λ
- Each cell read out with 1.25 GS oscilloscope, 2.4 μs sampling time per event
- Calibration triggers on dark noise between spills

Synchronization with CALICE

- Triggered by CALICE trigger - common analysis possible in the future

# T3B Scintillator Tiles - Performance Studies

- Gain calibration of photon sensors: dark noise



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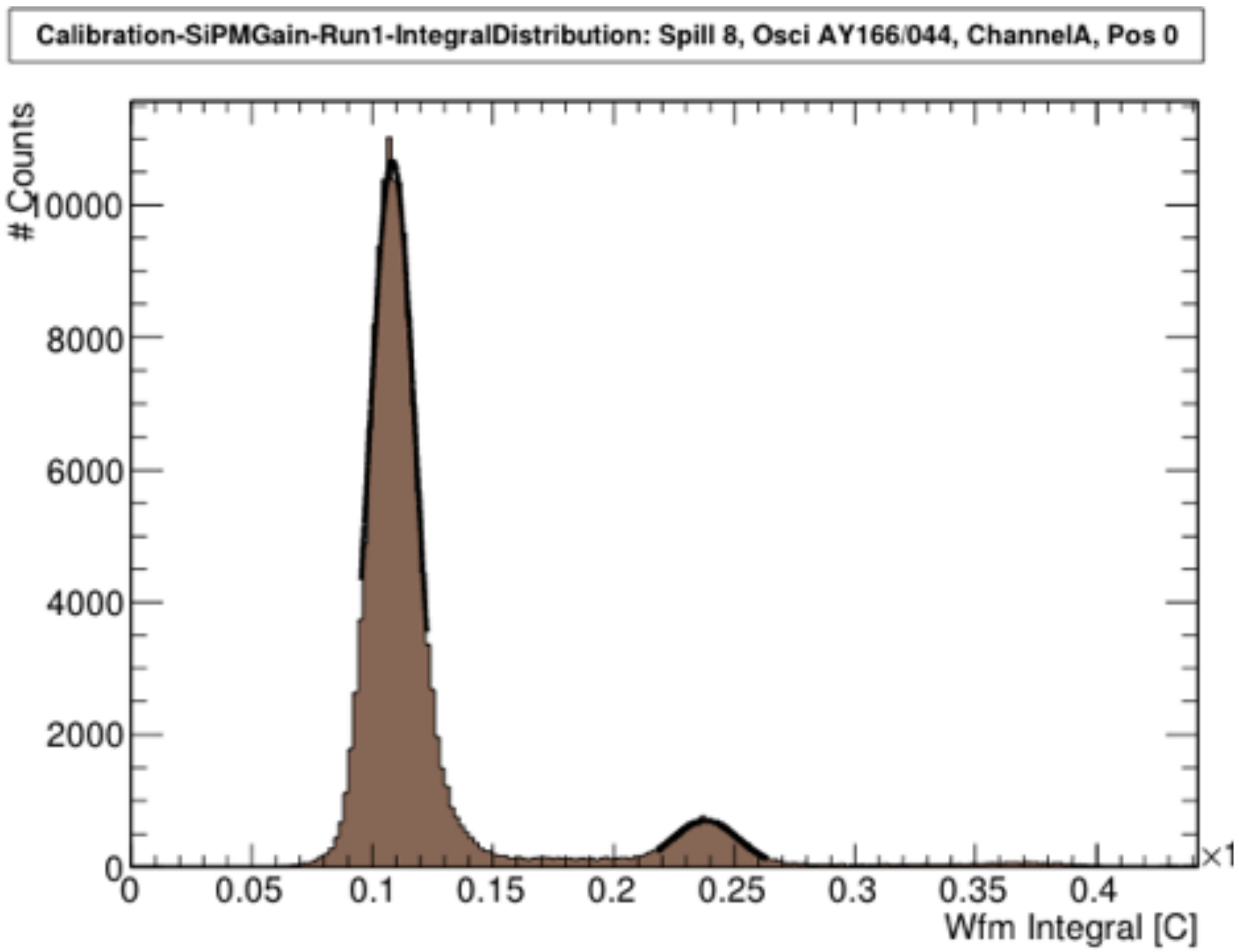


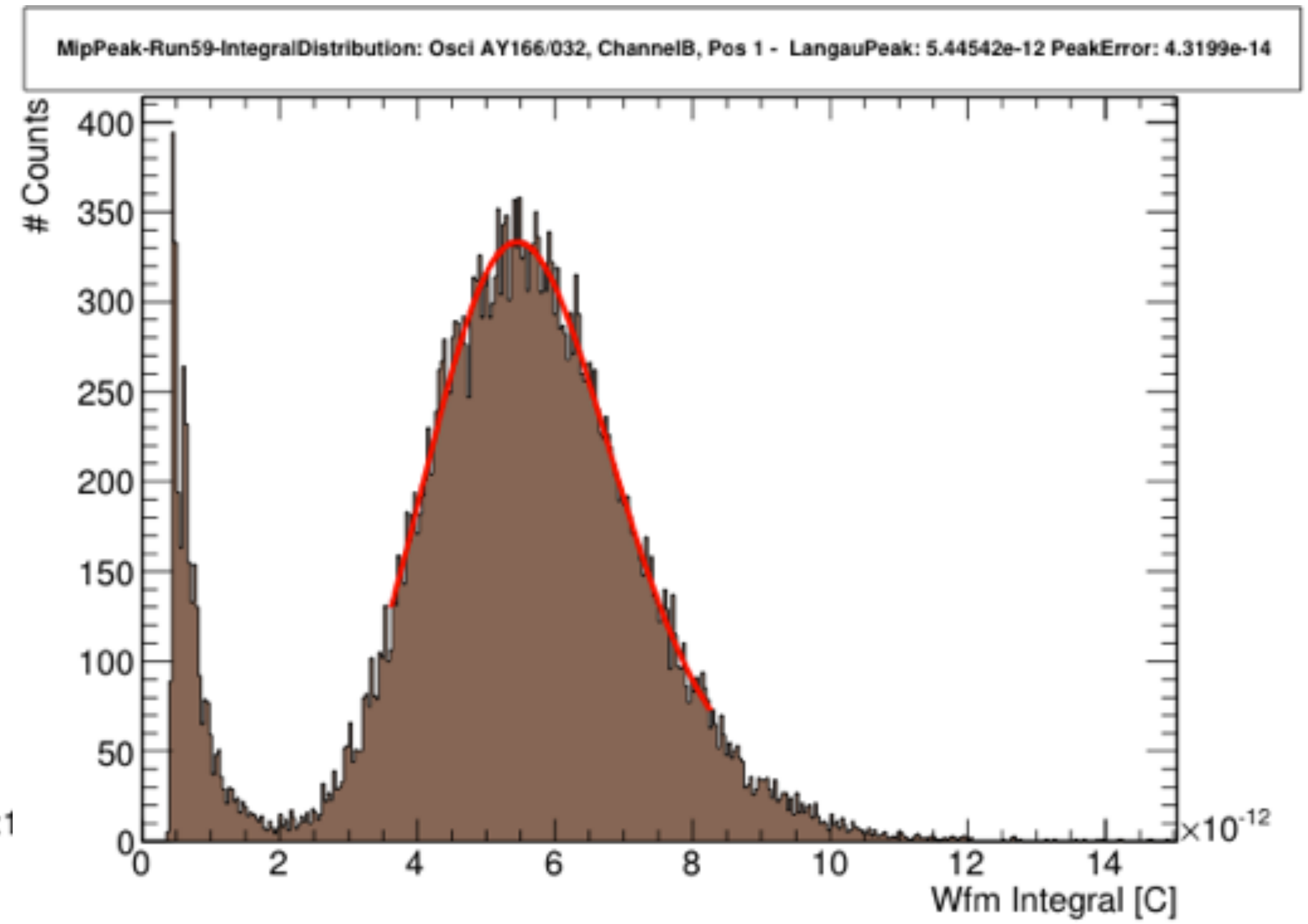


- Calibration of tile response to charged particles: Penetrating electrons from $^{90}Sr$ Calibration factor (most probable value) extracted from Landau conv. with Gaussian fit

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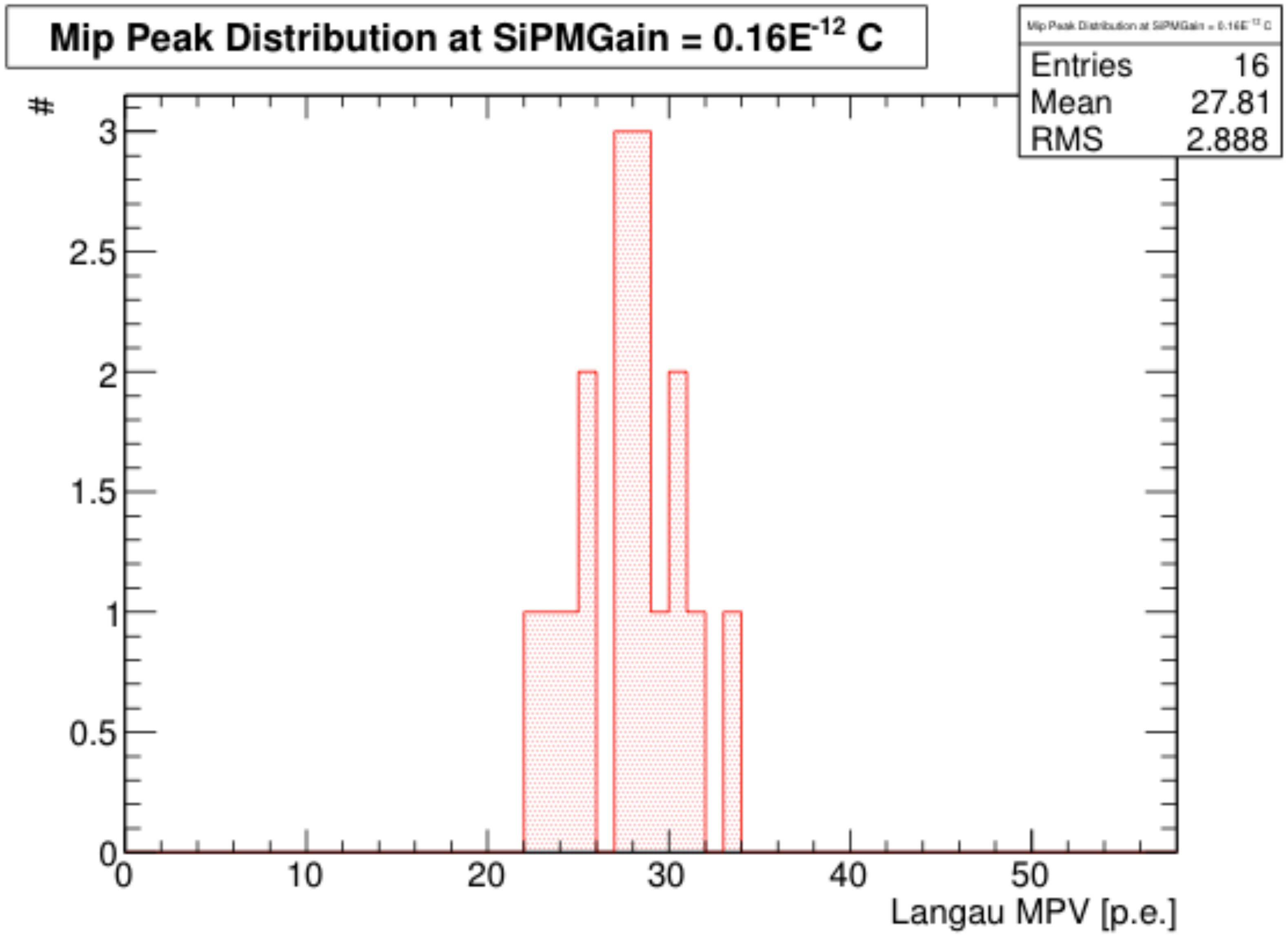
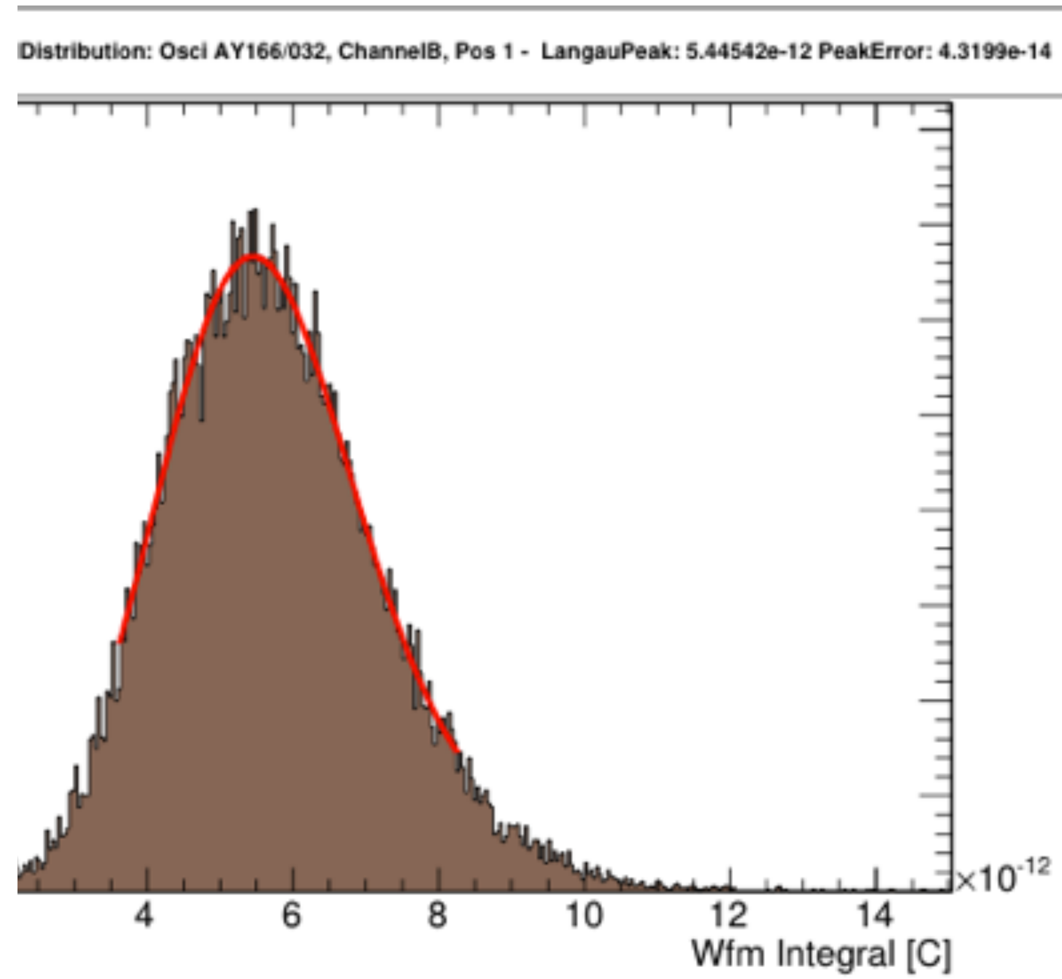


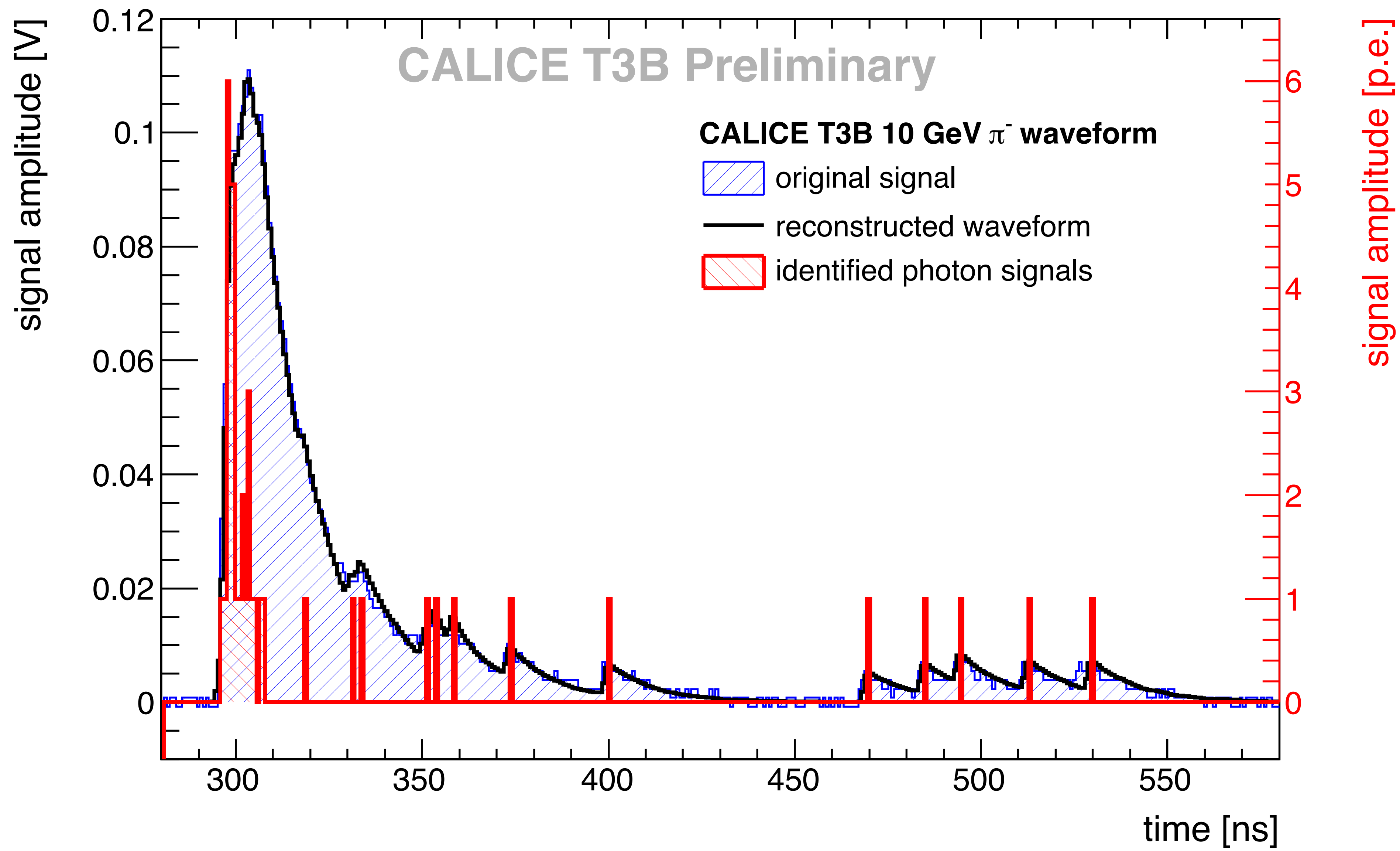

: Penetrating electrons from $^{90}$Sr
ed from Landau conv. with Gaussian fit

- Distribution of response over sample of T3B tiles: 10% RMS variation

# Data Analysis - Technique

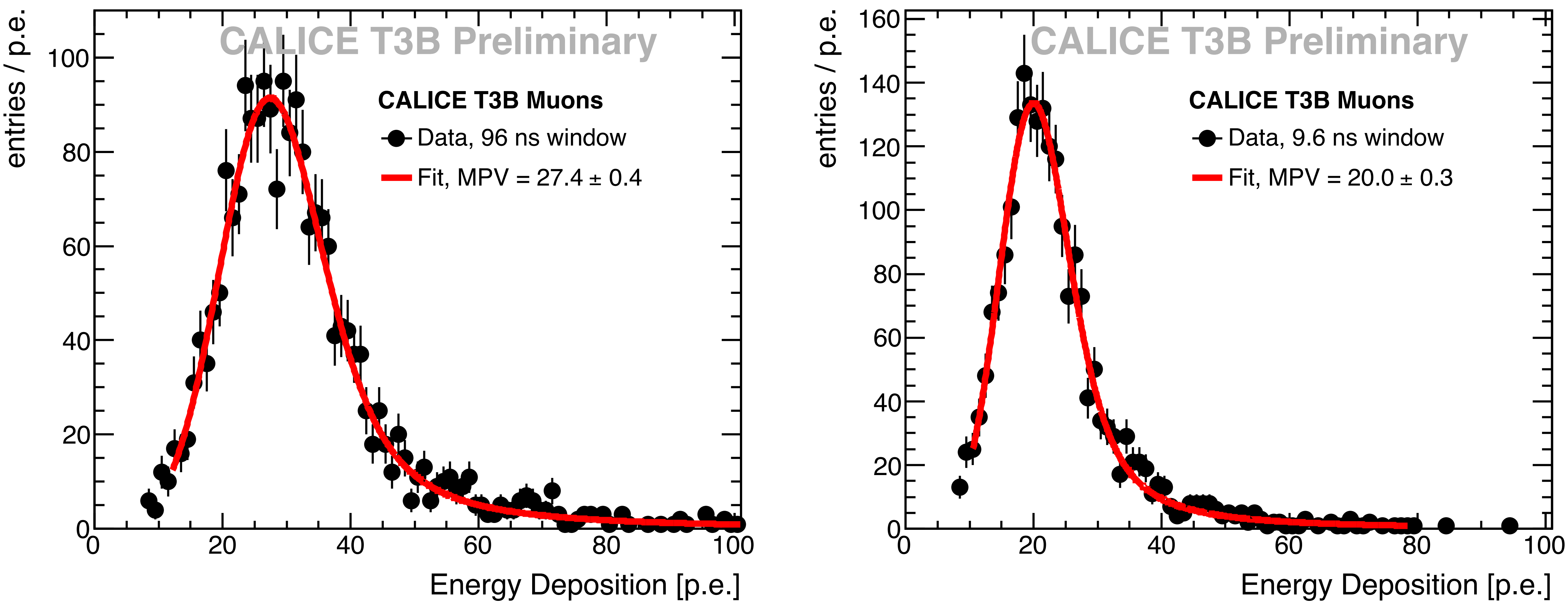
- For each channel, a complete waveform with 3000 samples (800 ps /sample) is saved
- Waveform decomposed into individual photon signals, using averaged 1 p.e. signals
  - Average 1 p.e. signal taken from calibration runs between spills, refreshed every 5 minutes: Continuous automatic gain calibration

- Reconstruction of the time of each photo-electron



# First Results - Muons

- Energy of muons reconstructed in the central T3B tile
    - Full reconstruction with waveform decomposition
    - Used to calibrate the response for tile 0, consistent result for tile 1 - only small cell-to-cell variation expected



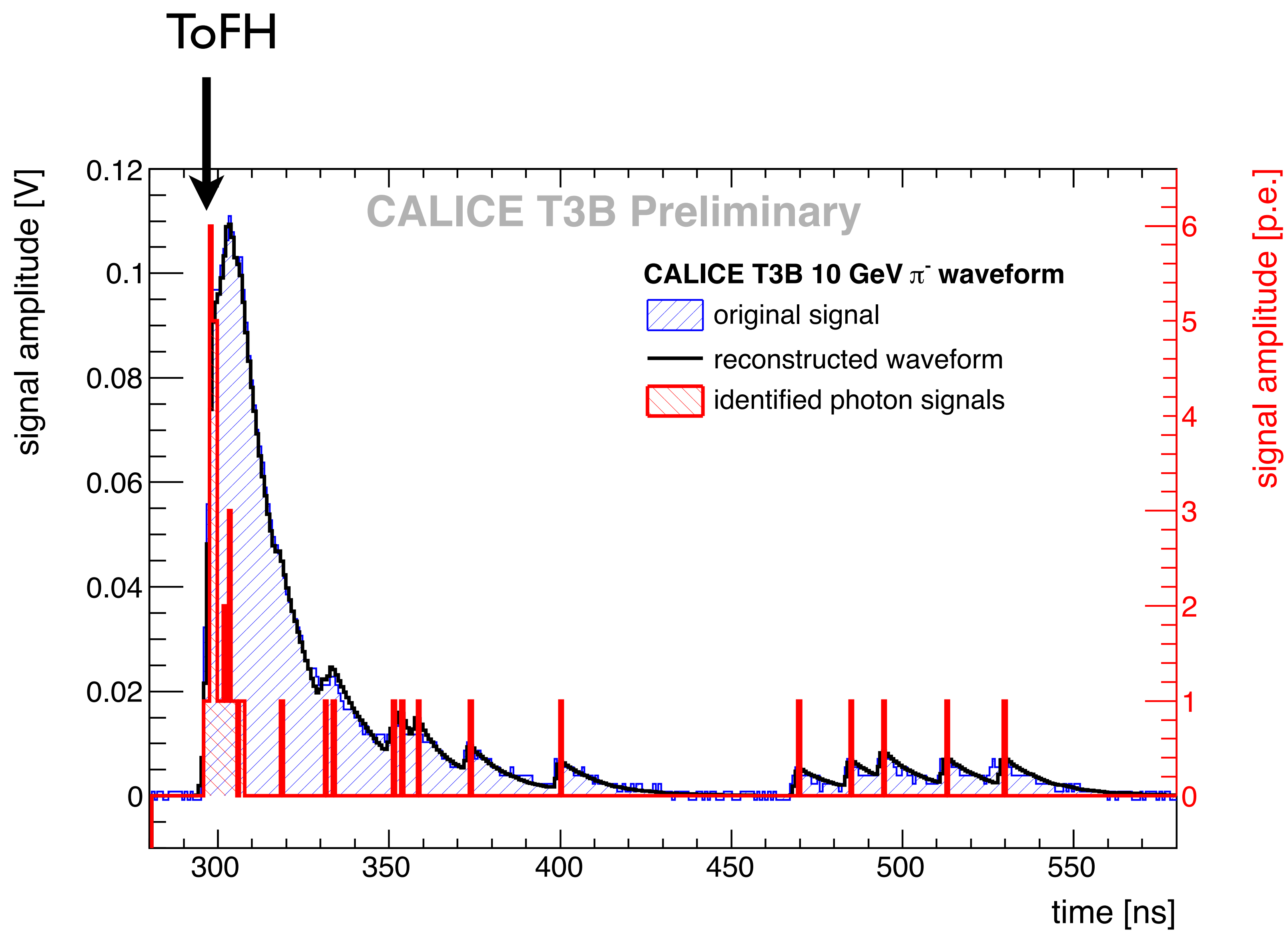

- Two integration times: Short time window rejects a significant fraction of SiPM afterpulses

# 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



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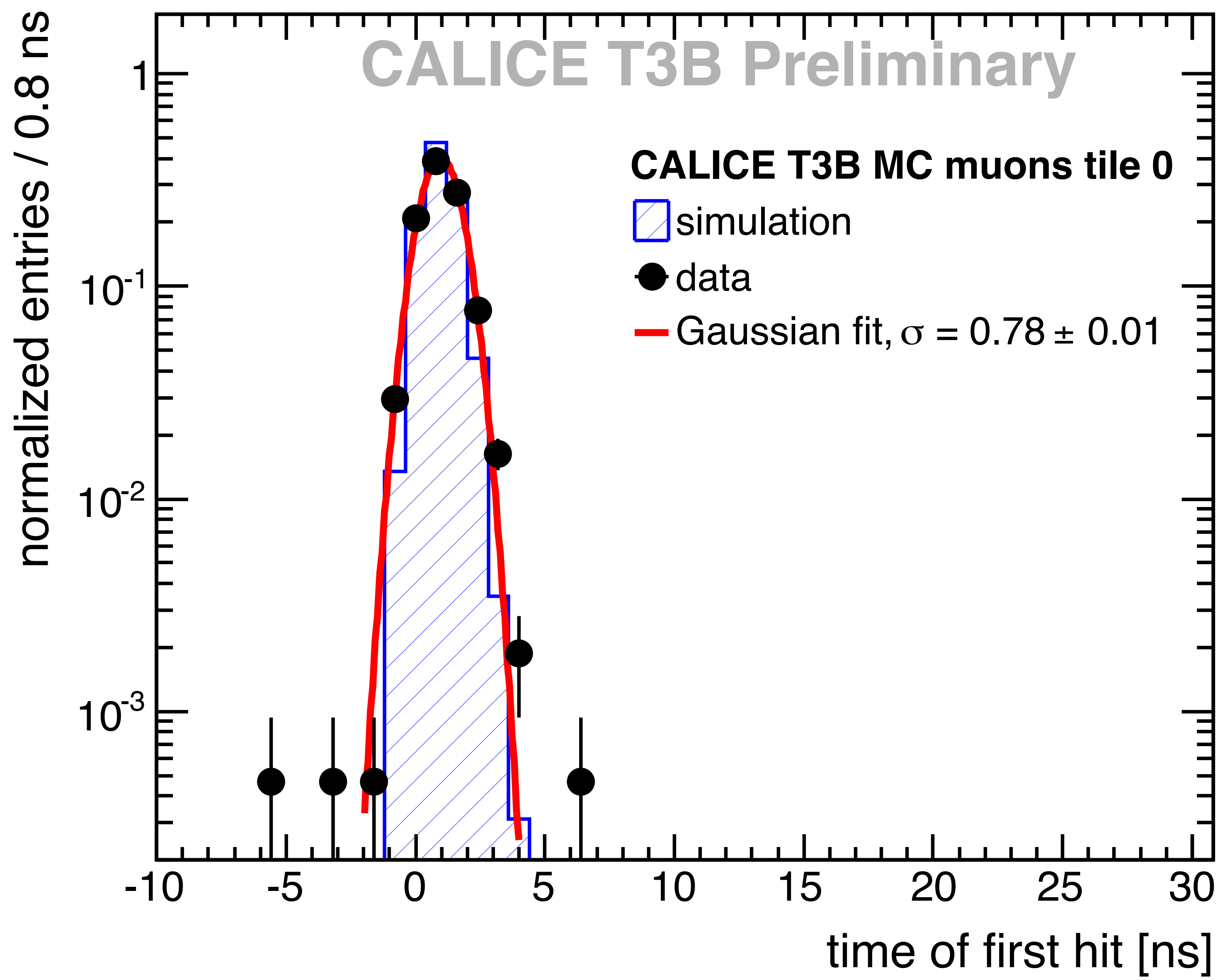
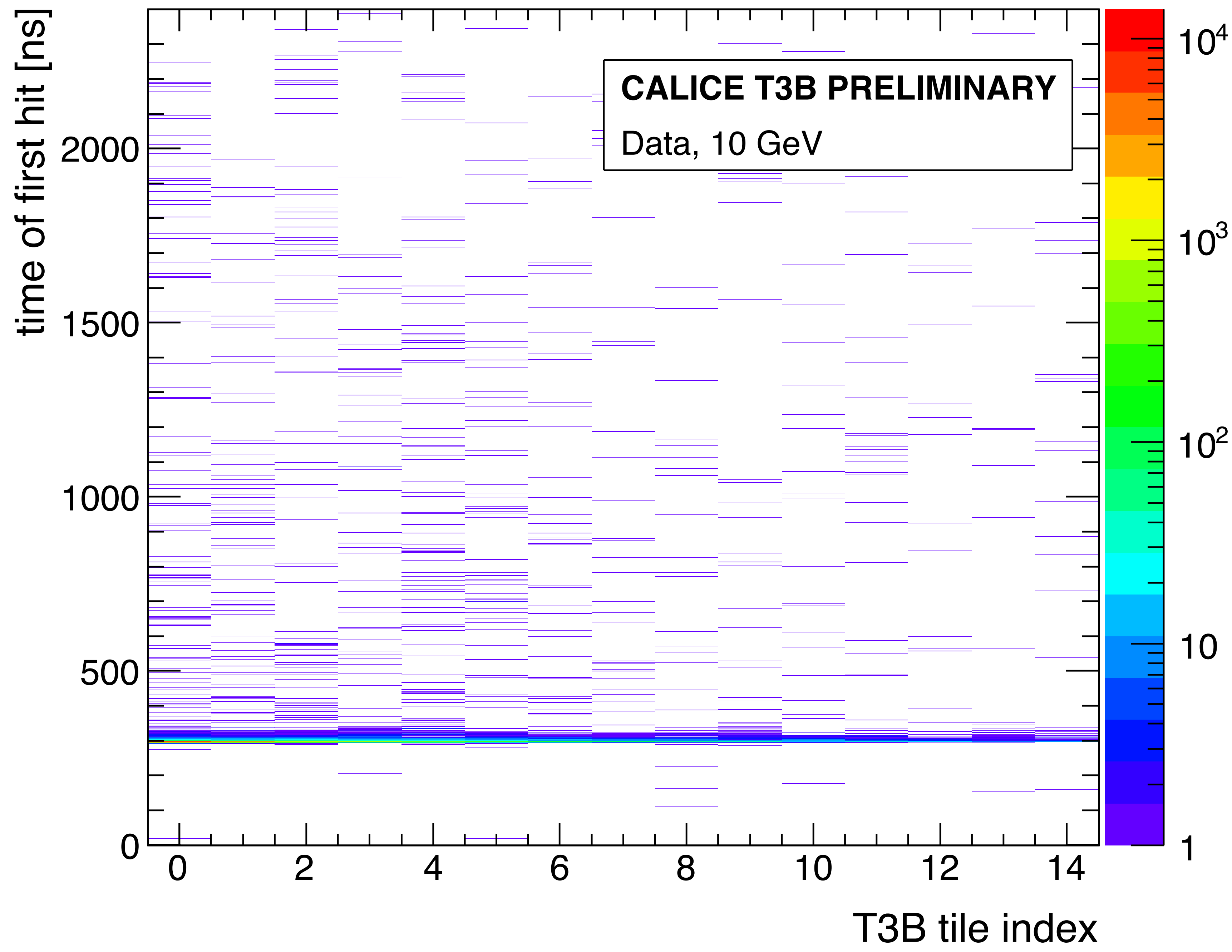
Time of First Hit for Muons:

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



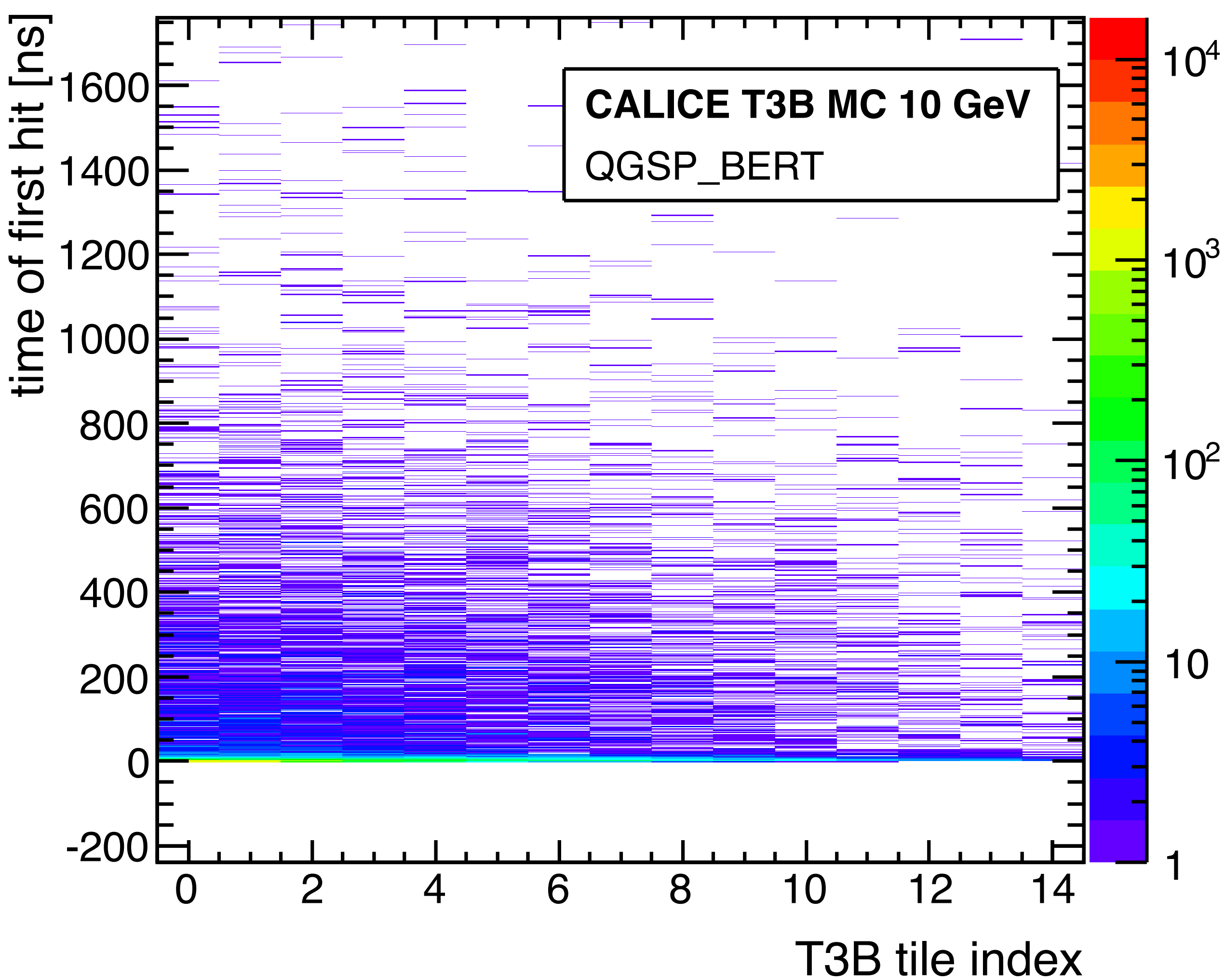
# First Results - Pion Data

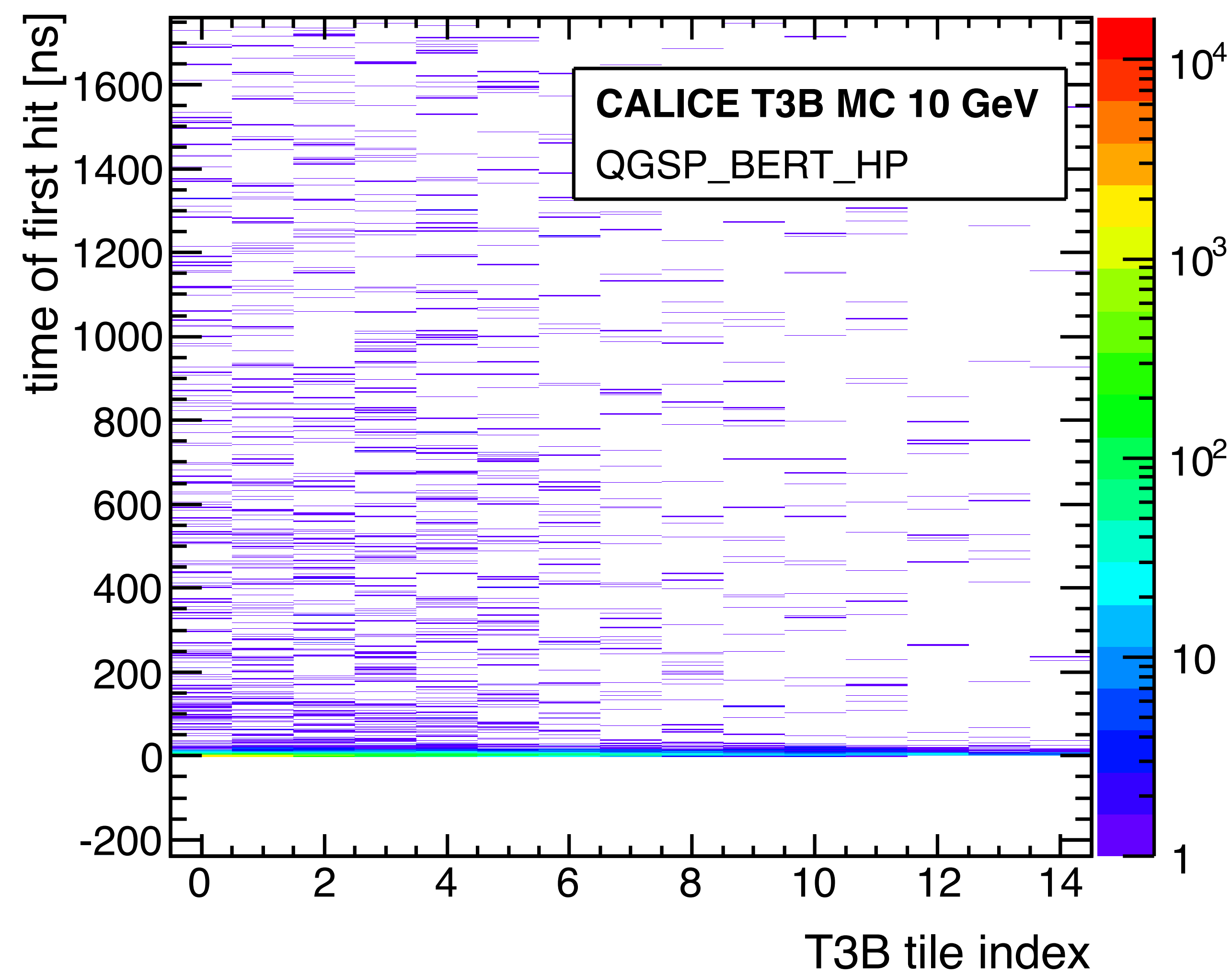
- Data taken in CALICE WHCAL Testbeam at CERN PS
  - Current analysis: Highest energy - 10 GeV $\pi^-$
  - Time of First Hit



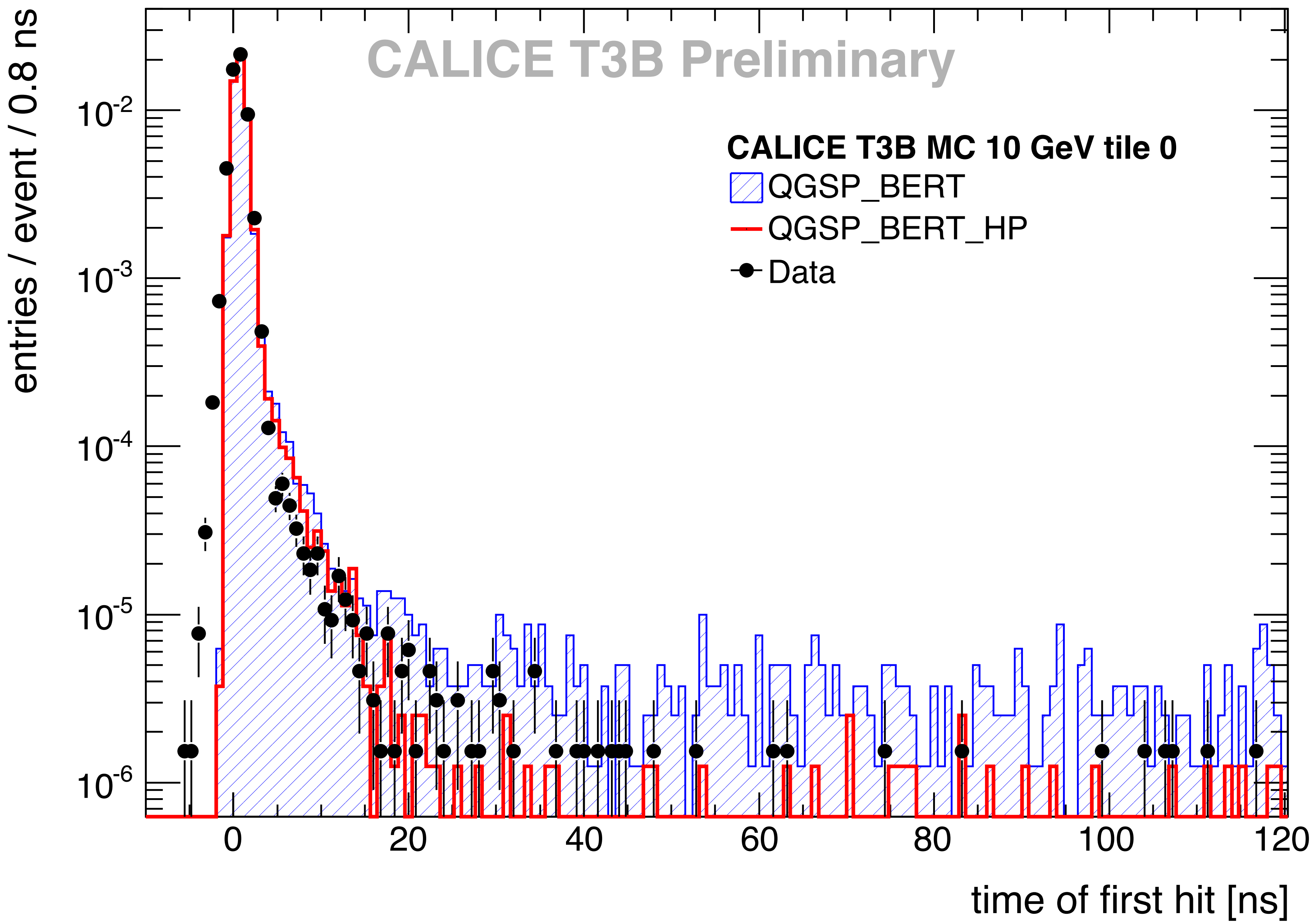
# Time of First Hit in Simulations

- 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




**Central T3B cell:**

Distribution of the Time of First Hit

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

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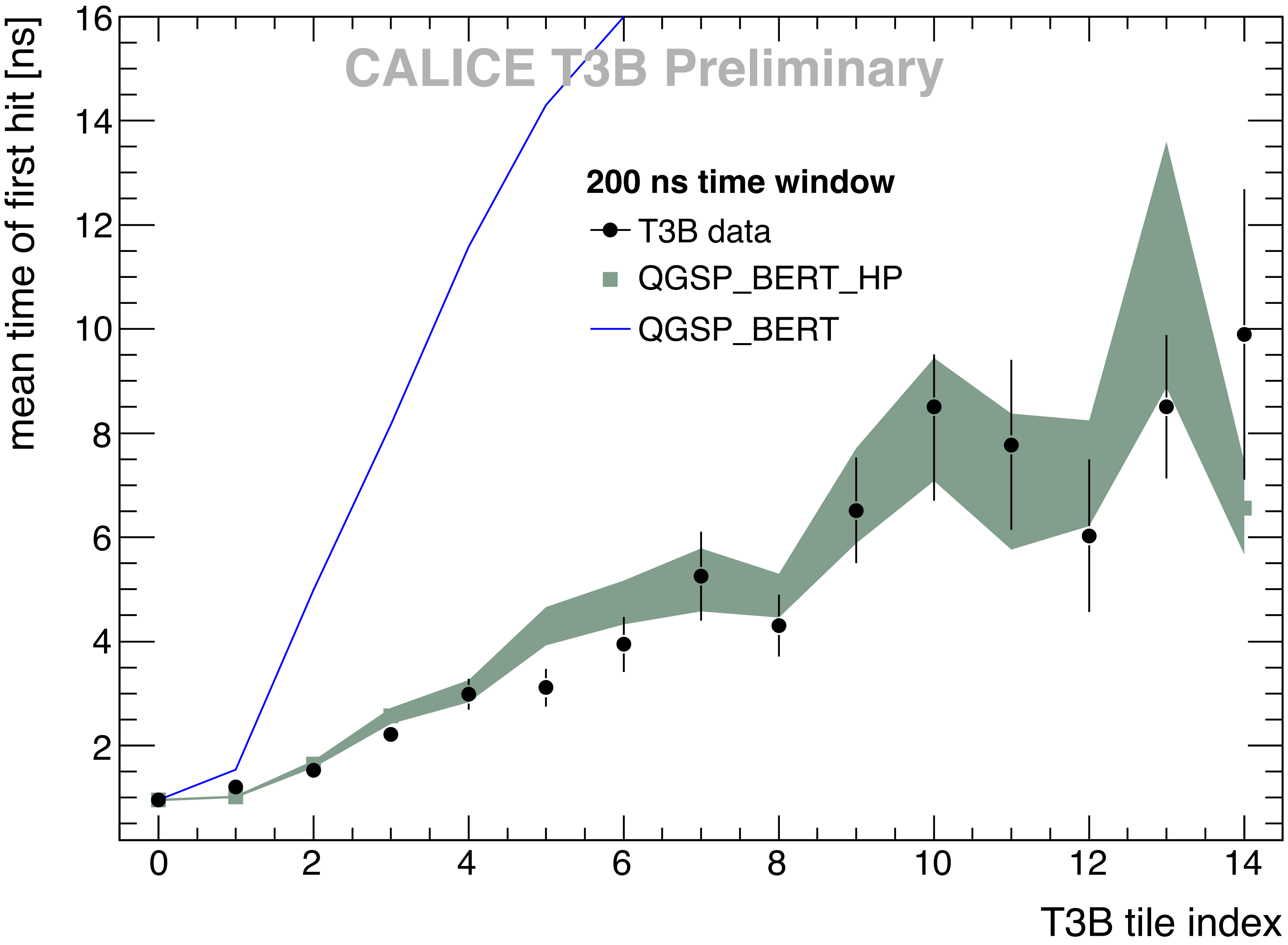


**Compact Comparison:**

Mean Time of First Hit

- calculated in a time window of 200 ns (-10 ns to 190 ns from maximum in tile 0)

- Data consistently described by QGSP_BERT_HP
  - QGSP_BERT deviates strongly

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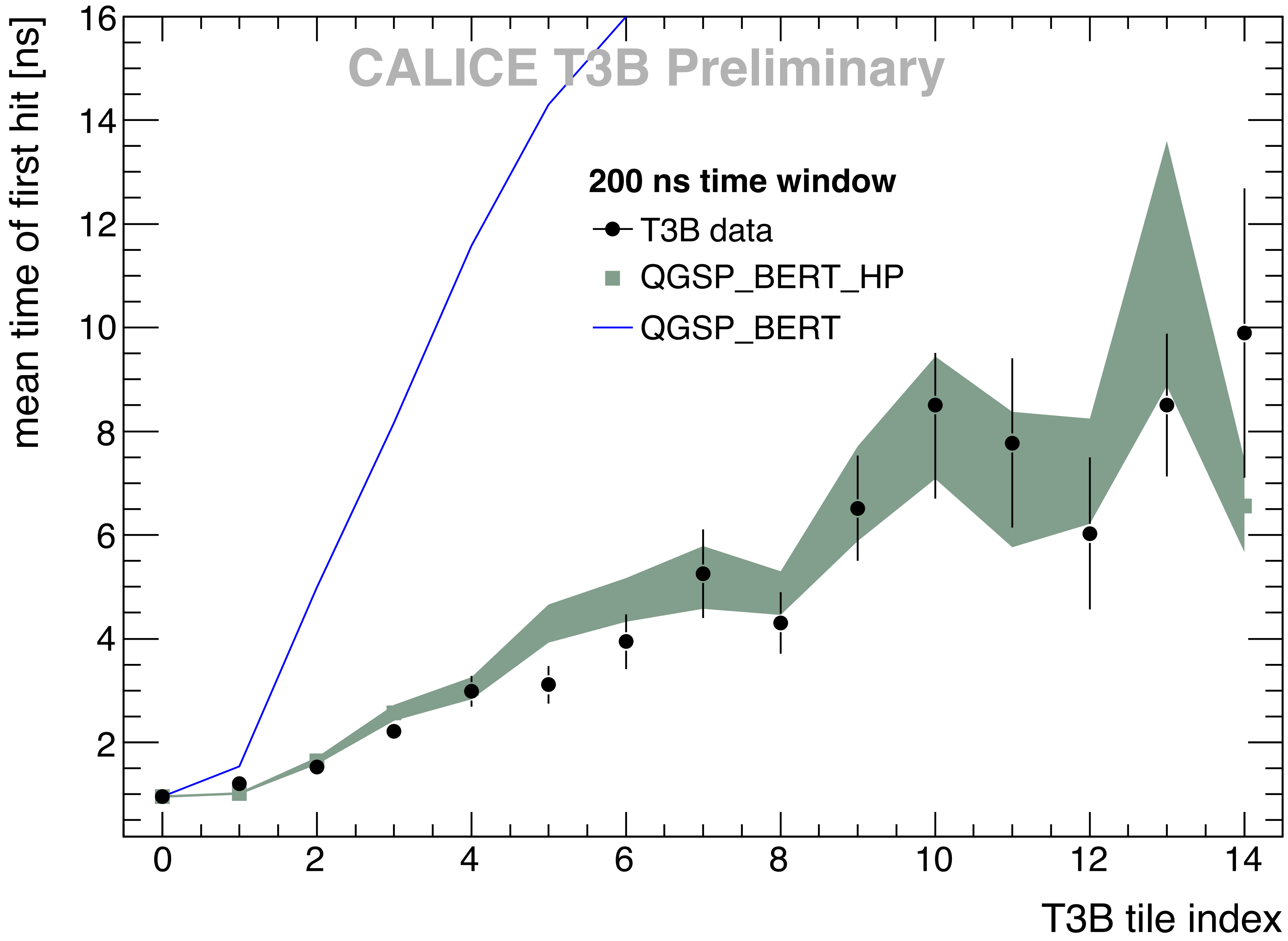


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➯ High precision neutron tracking or other means to suppress excessive late energy depositions necessary to describe observed time structure in T3B

# Summary & Outlook

- Time resolution is important at CLIC: High hadron background combined with 2 GHz bunch crossing frequency
- Hadronic showers are not instantaneous: Limits to the time resolution of the hadronic calorimeters

- CALICE T3B is a dedicated experiment to provide first measurements of the time structure in a scintillator-tungsten HCAL
  - Scintillator tiles with direct SiPM readout - Good cell-to-cell response uniformity
  - Readout with USB oscilloscopes: Long time windows, high trigger rates
  - Analysis technique based on waveform decomposition - Automatic gain calibration with dark noise

- First results from PS beam period: Moderate amount of late-starting hits observed: Consistent with Geant4 simulations using QGSP_BERT_HP

# Backup

# Simulations

- Geant 4.9.3.p01, Simplified simulation setup:
  - 31 layer HCAL, with 1 cm W + 1 mm Steel absorber
  - CALICE AHCAL cassette (2 x 2 mm Steel, 5 mm scintillator + PCB, cables, air)
    - Use T3B as the last layer of the setup
- Simulation of the time structure:
  - record the time and energy deposit of each Geant4 step in the T3B scintillator volume
  - bin in 800 ps time bins, convert to number of photons according to the energy in the bin
  - smear the time distribution of the photons according to observed time distribution of muon signals
    - ad-hoc fit with a Landau: σ ~ 1.3 ns