

# T3B

## Add-on to the CALICE HCALs for a first Study of the Time Structure of Showers

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Calorimeter for ILC



# Outline

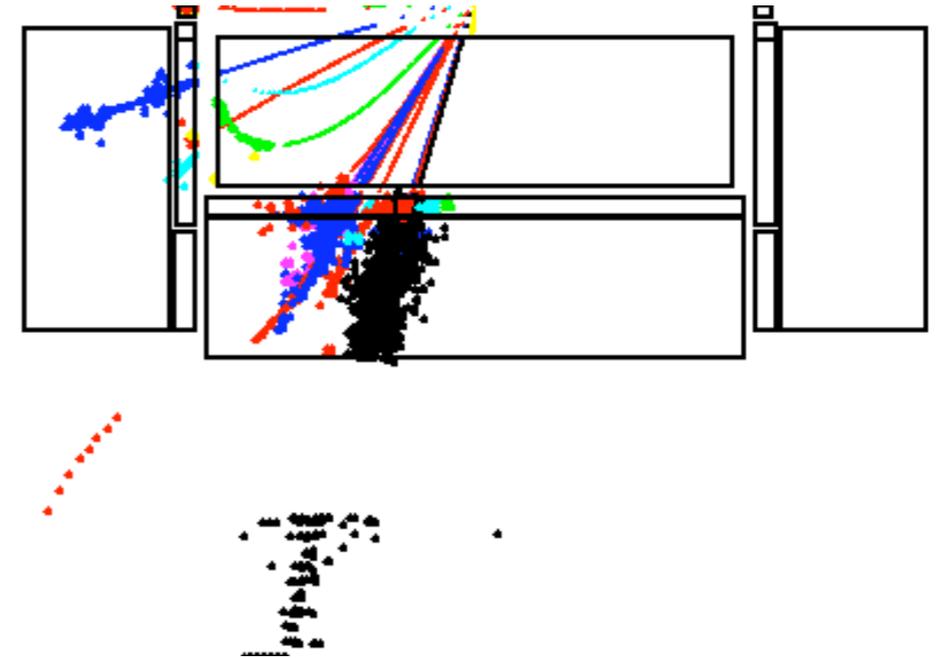
- Hadron Calorimetry at CLIC: Competing Requirements
- The Time Structure of Hadronic Showers
- First measurements in a Tungsten HCAL
  - The T3B Setup
  - First Results
- Extending the Program
  - Adding Shower Depth
  - High Energies, Comparison to Steel
- Summary & Outlook

# 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

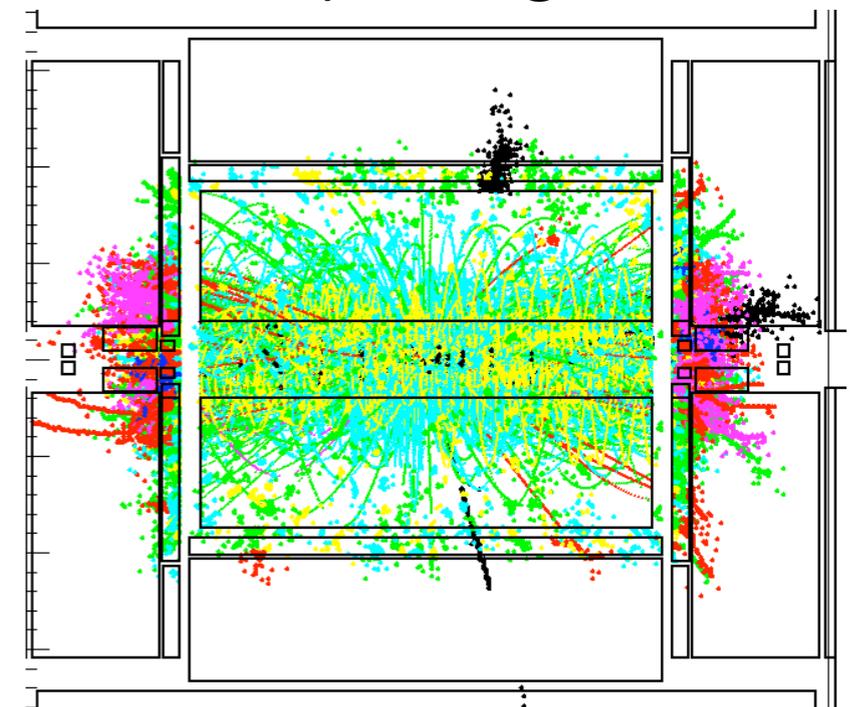
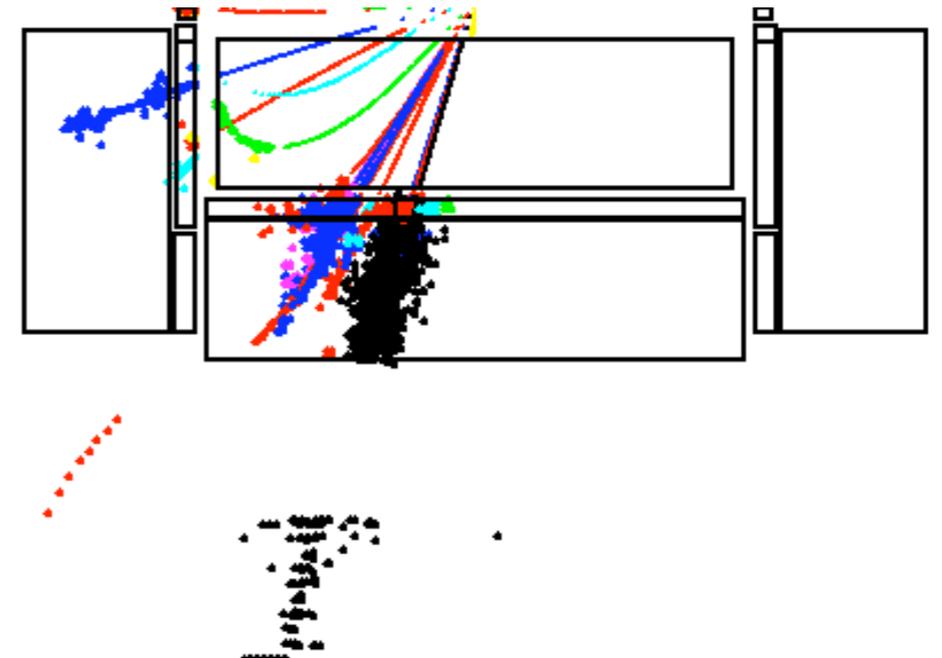


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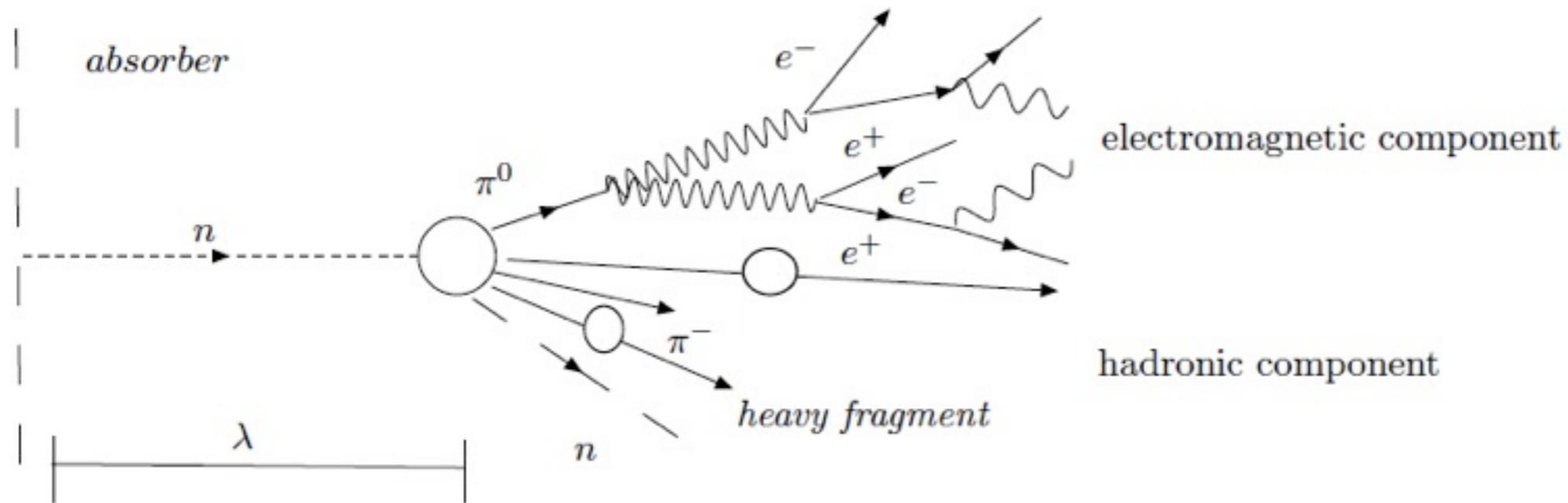
Shower containment and leakage is a crucial issue

- ⇒ A (very) deep hadron calorimeter is needed
- ⇒ Use compact absorbers to limit the detector radius: Tungsten a natural choice
- 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

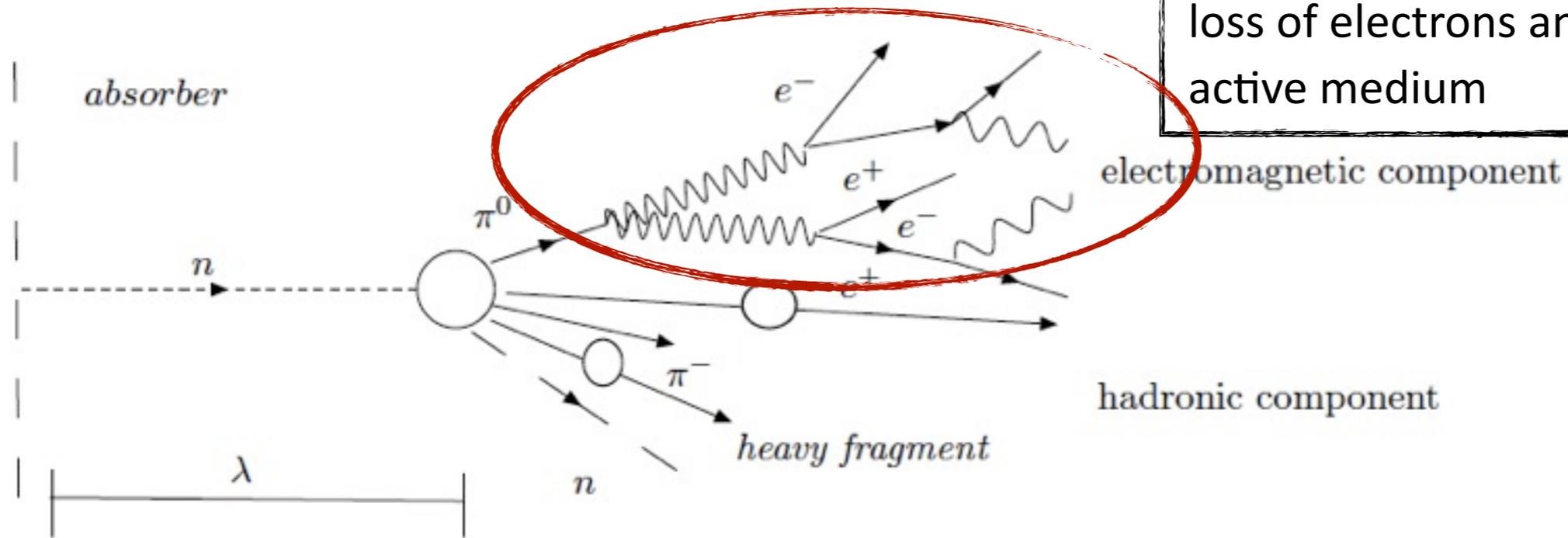
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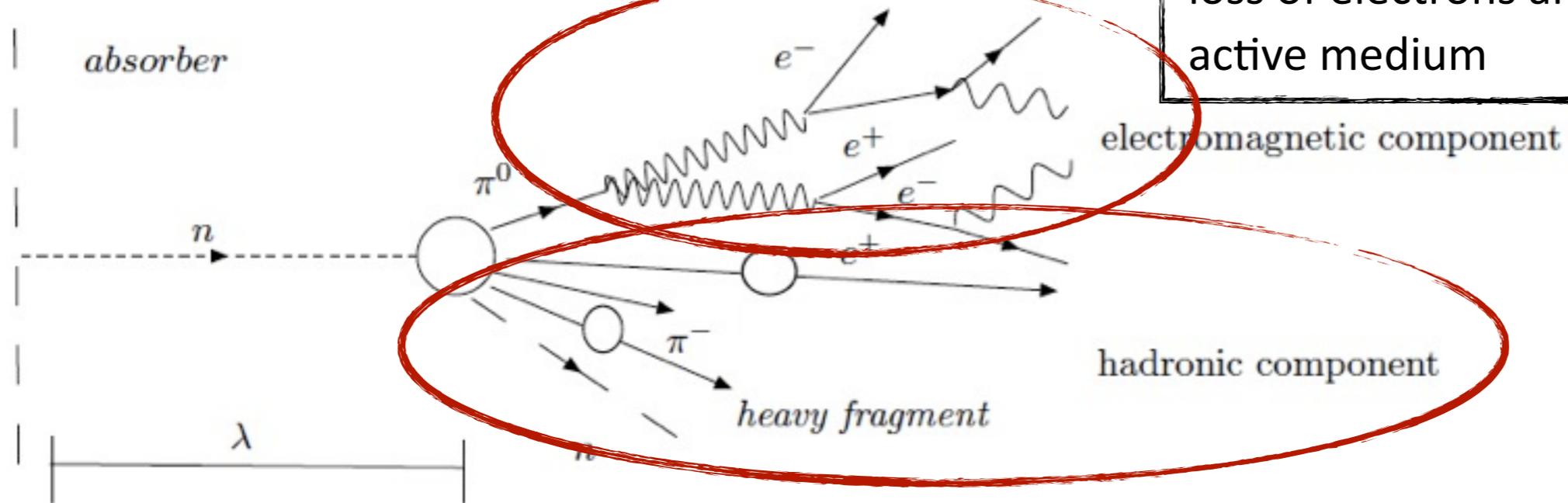
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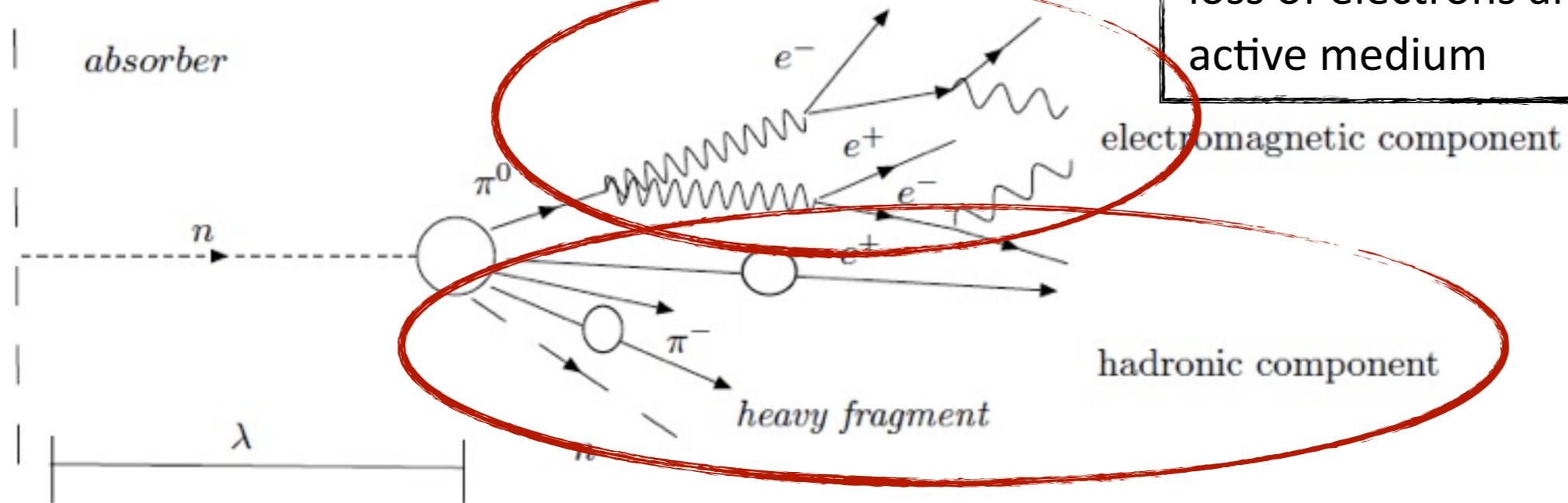


- instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium
- delayed component: photons, neutrons, protons from nuclear de-excitation, detected via  $e^+e^-$ , momentum transfer to protons in hydrogenous active medium, energy loss, contributions from time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

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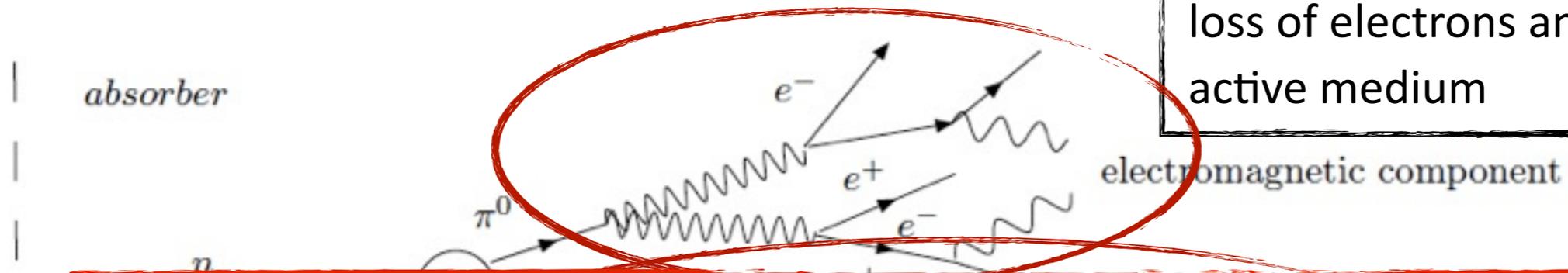
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Detector optimization and performance studies rely on Geant4:  
How well do the simulations reproduce the time structure  
of the response in the CLIC HCAL?

energy

lear

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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<sup>3</sup>) absorber
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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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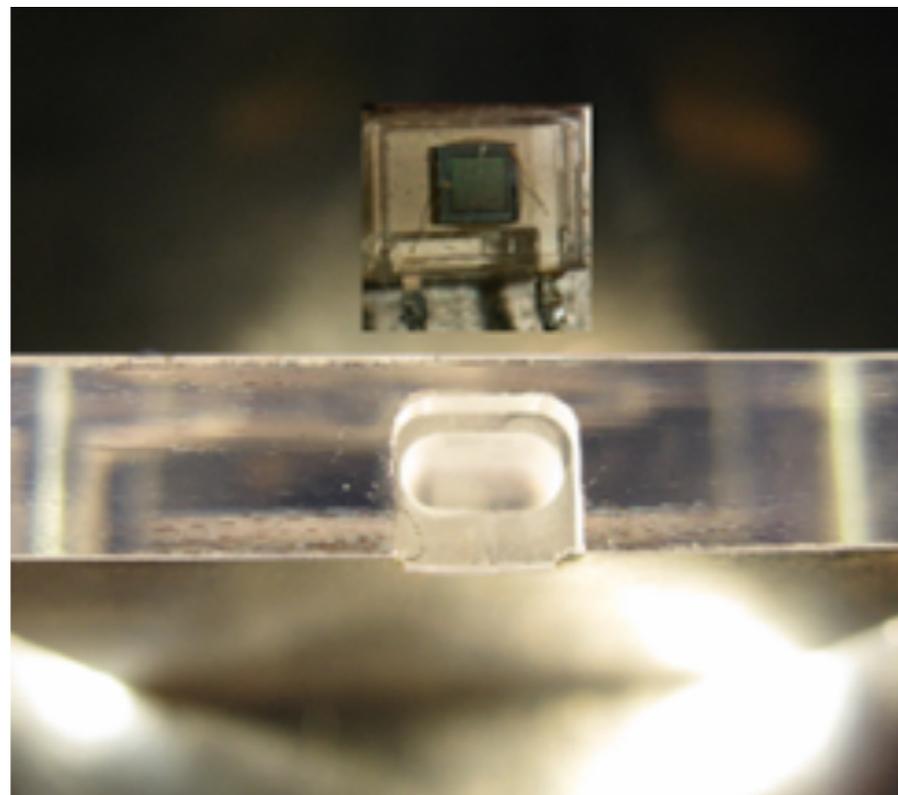
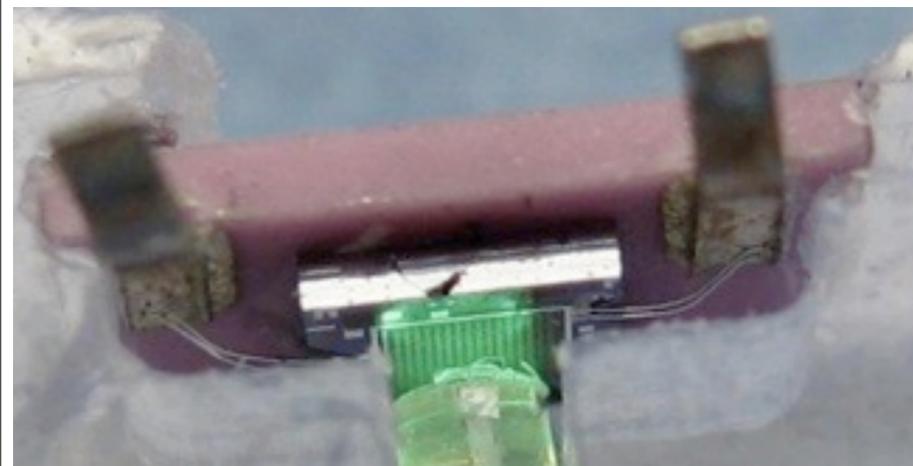
⇒ First information on time structure, possibility for comparisons to Geant4, but:  
no complete “4D” shower reconstruction!

# 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:  $\sim 1$  GHz or more
  - Long acquisition window per event:  $2 \mu\text{s}$  or more
  - Fast trigger rate: faster than the CALICE HCAL,  $>$  a few kHz

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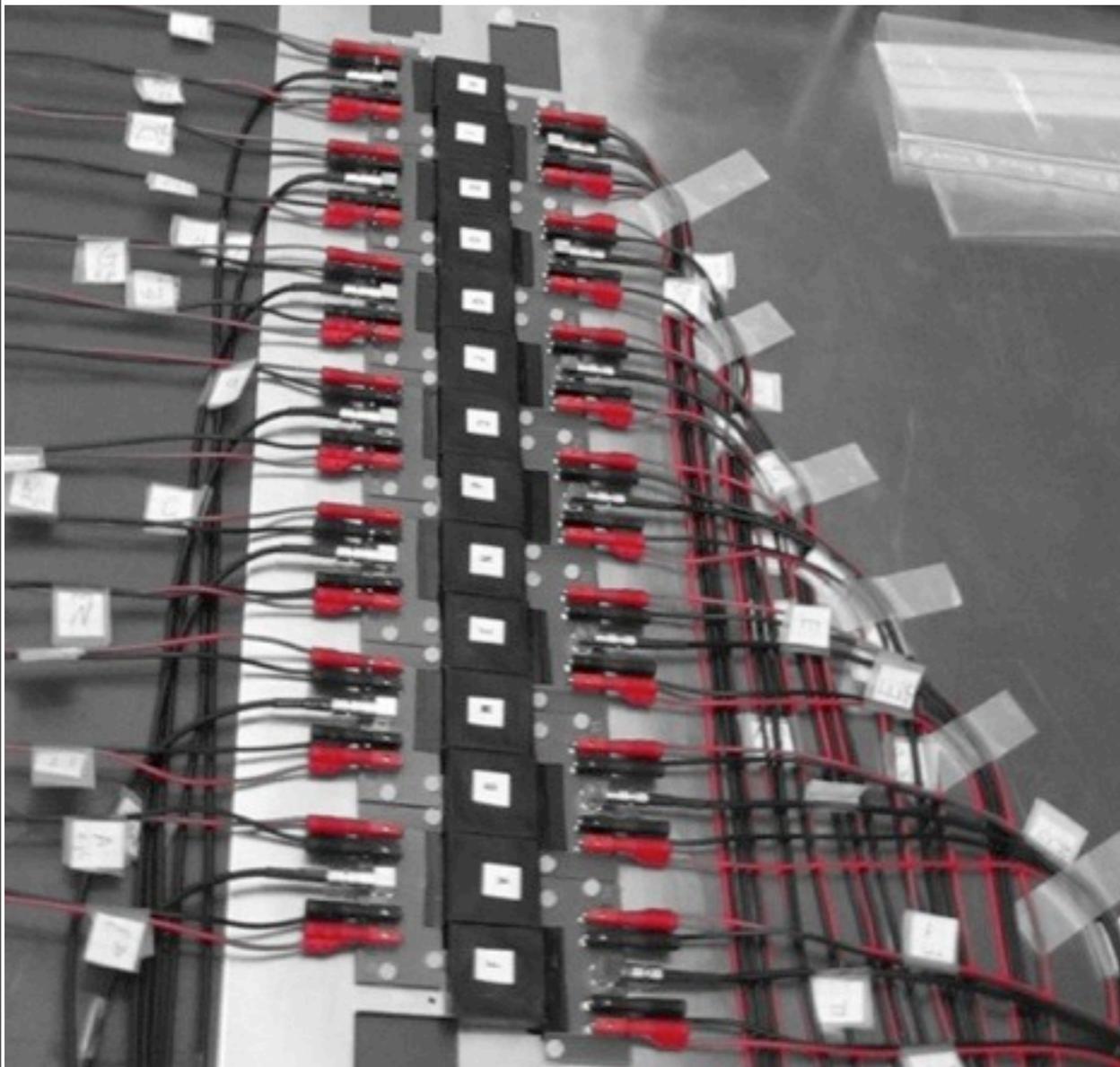
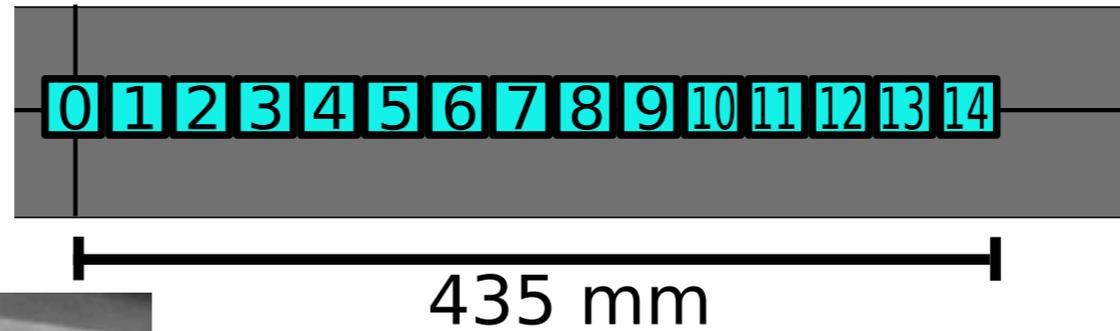
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- Adopted solution for T3B: PicoScope 6403
  - 1.25 GHz sampling for 4 channels per unit
  - 1 GB buffer memory (shared between channels)
  - Burst trigger mode: Maximum rate determined by window length:  
 $\sim 500$  kHz for  $2 \mu\text{s}$  acquisition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



# The T3B Setup

- 15  $3 \times 3 \text{ cm}^2$  scintillator cells, sampling the radial extent of the shower

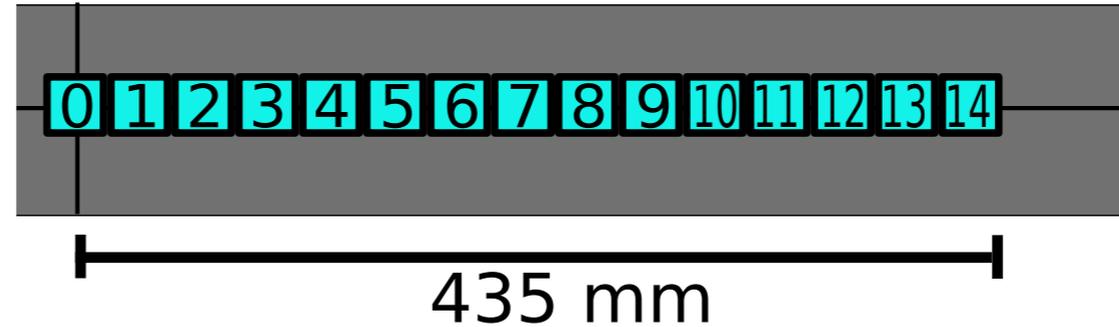
beam axis  
through cell 0



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Stand-alone system:

- Installed downstream of CALICE WHCAL, depth  $\sim 4 \lambda$
- Each cell read out with 1.25 GS oscilloscope,  $2.4 \mu\text{s}$  sampling time per event
- Calibration triggers on dark noise between spills

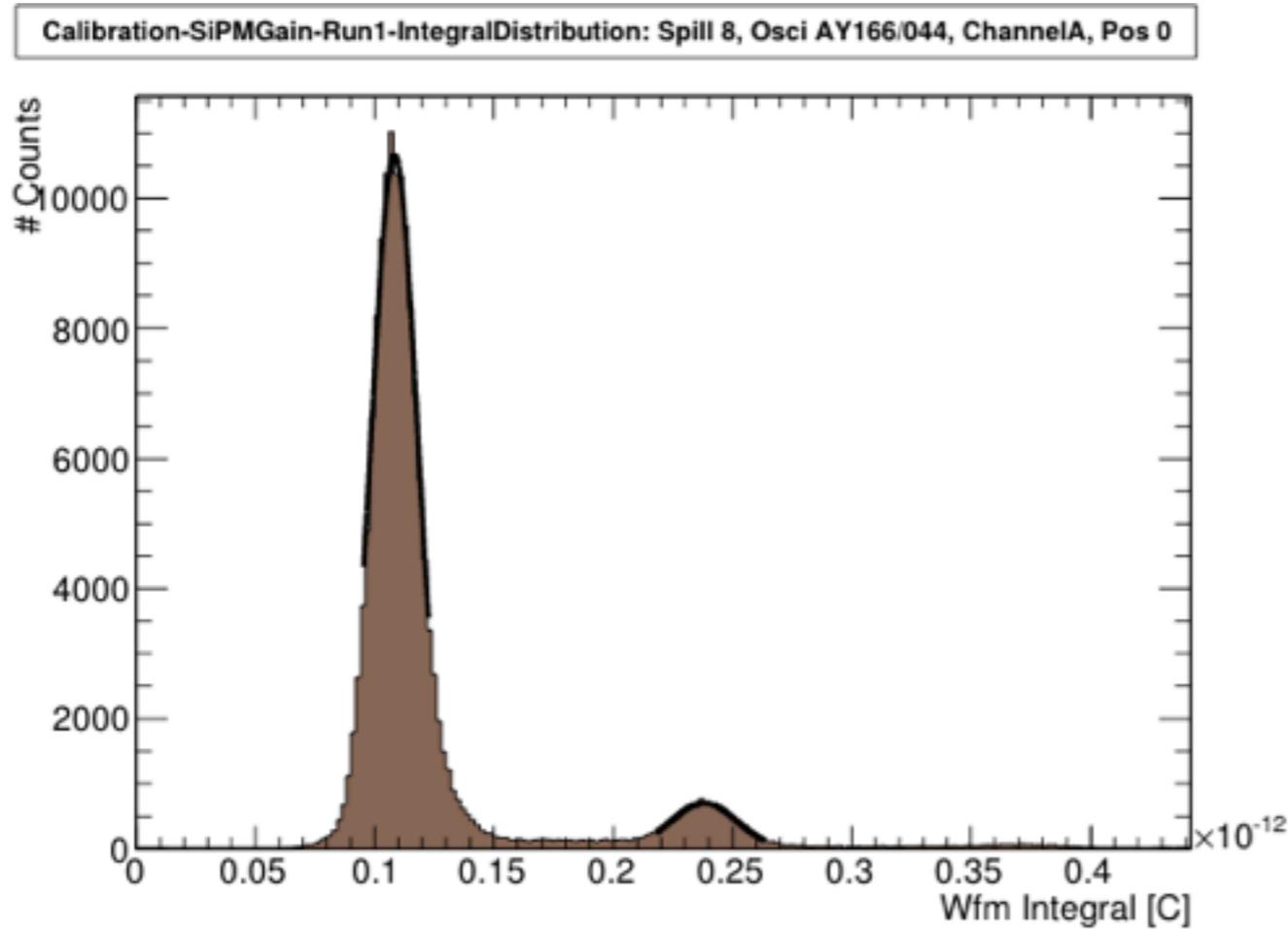
Synchronization with CALICE

- Triggered by CALICE trigger - common analysis possible



# T3B Scintillator Tiles - Performance Studies

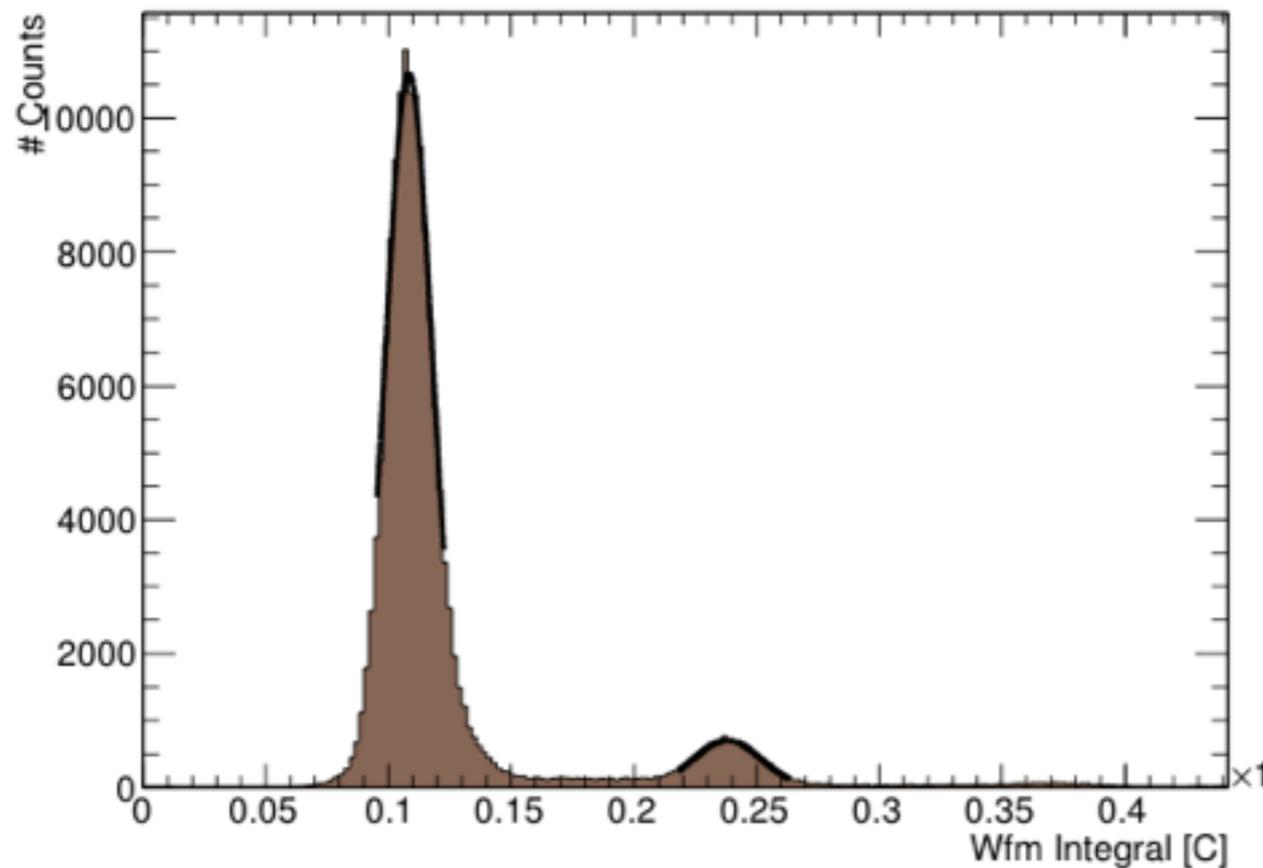
- Gain calibration of photon sensors: dark noise



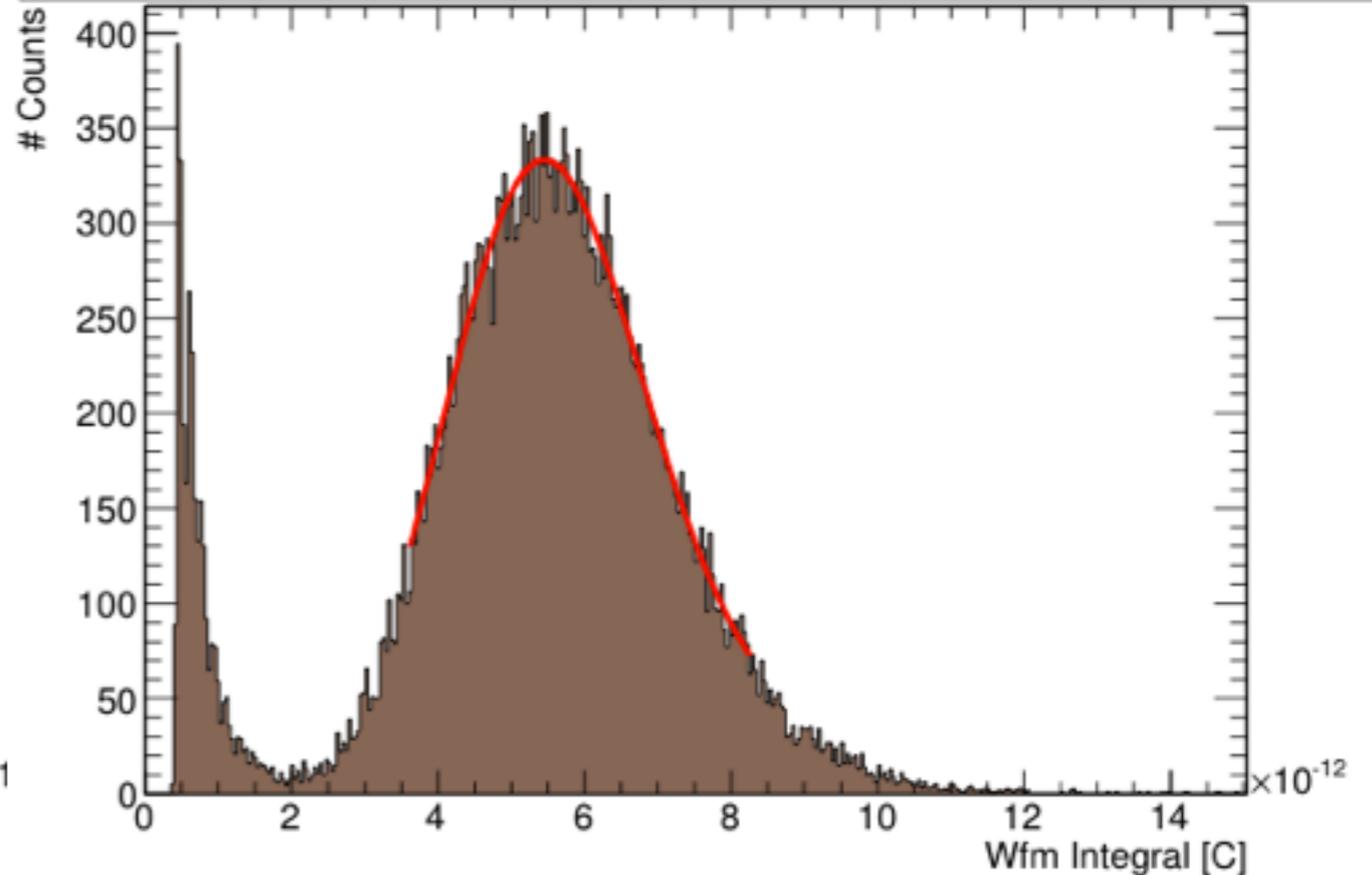
# T3B Scintillator Tiles - Performance Studies

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Calibration-SiPMGain-Run1-IntegralDistribution: Spill 8, Osci AY166/044, ChannelA, Pos 0



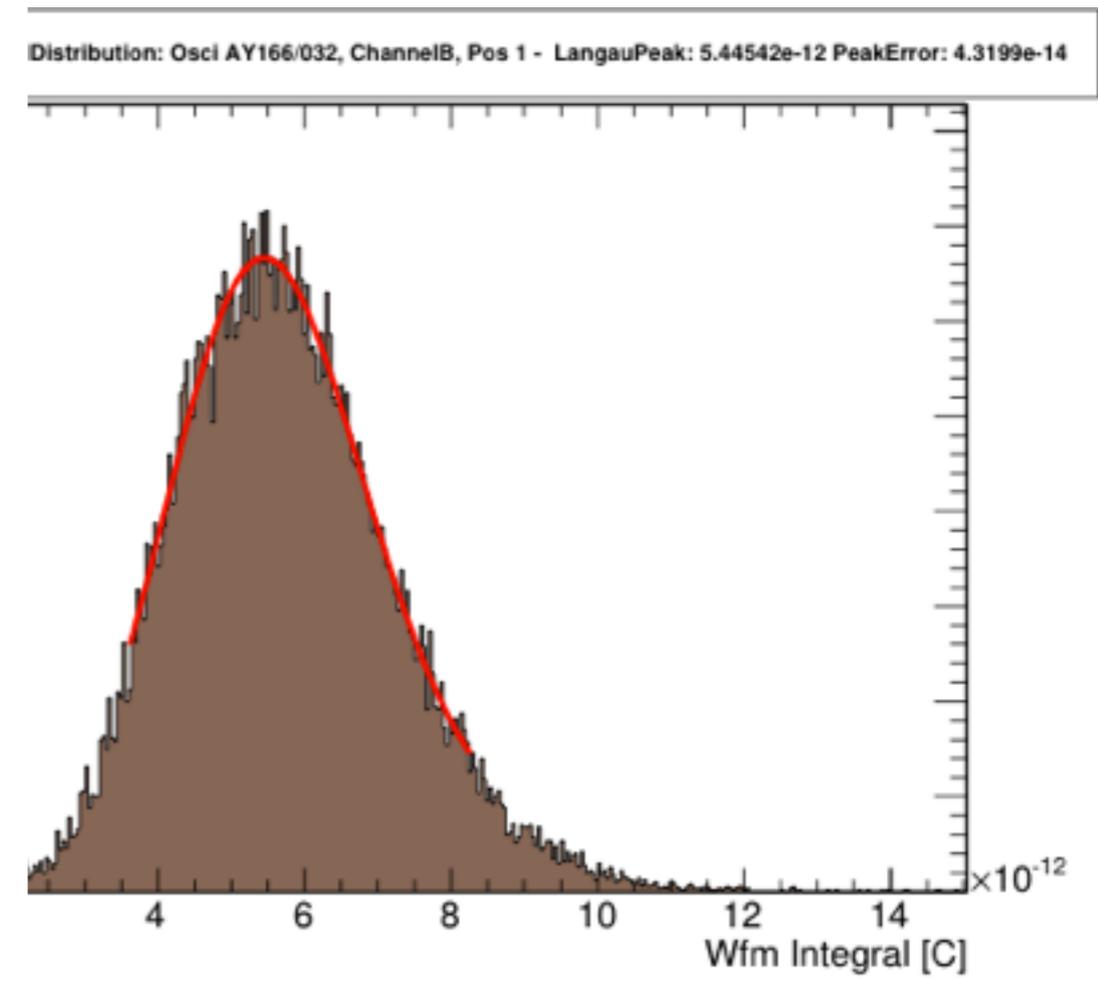
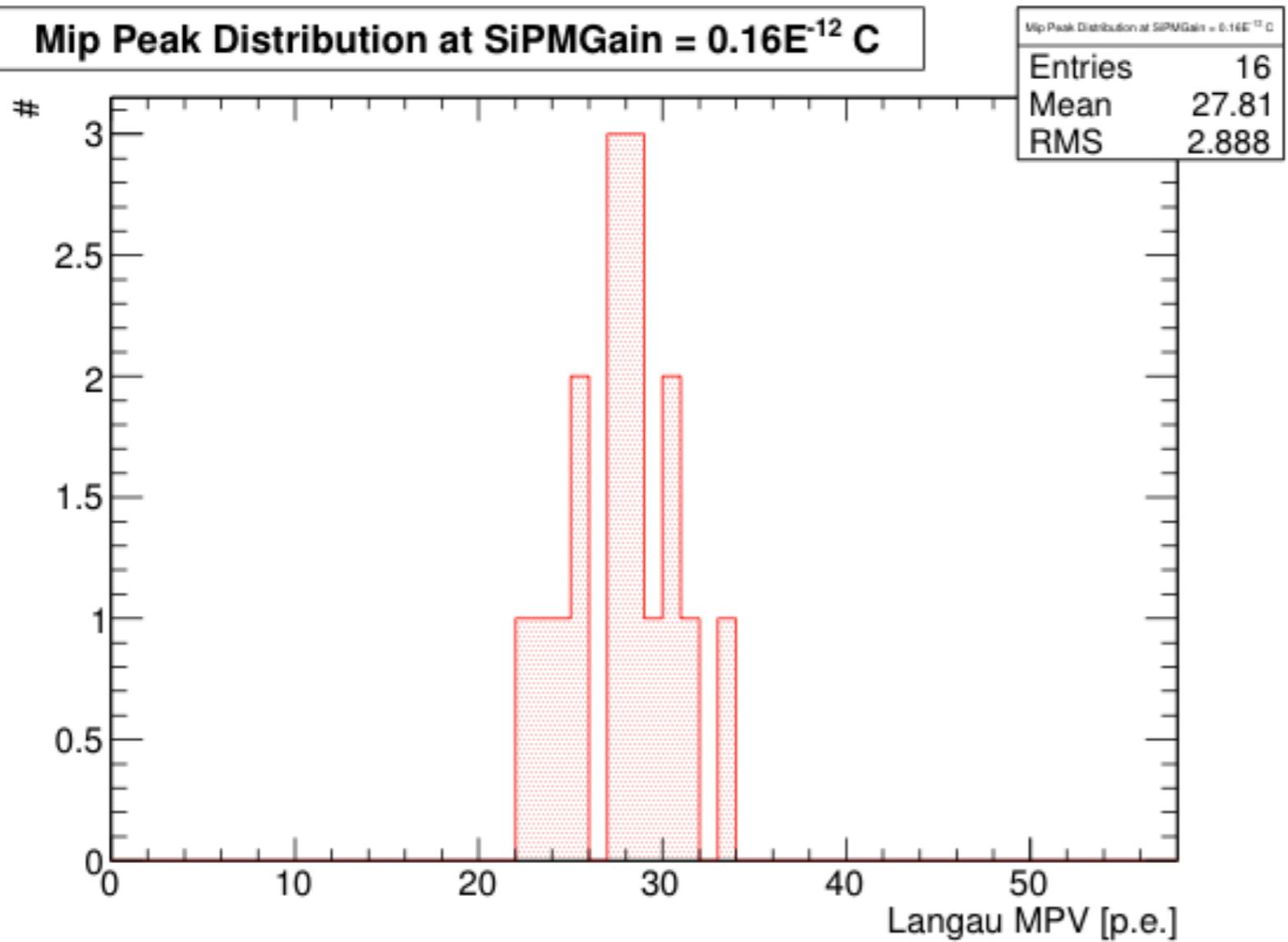
MipPeak-Run59-IntegralDistribution: Osci AY166/032, ChannelB, Pos 1 - LangauPeak: 5.44542e-12 PeakError: 4.3199e-14



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

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- Gain calibration of photon sensors: dark noise



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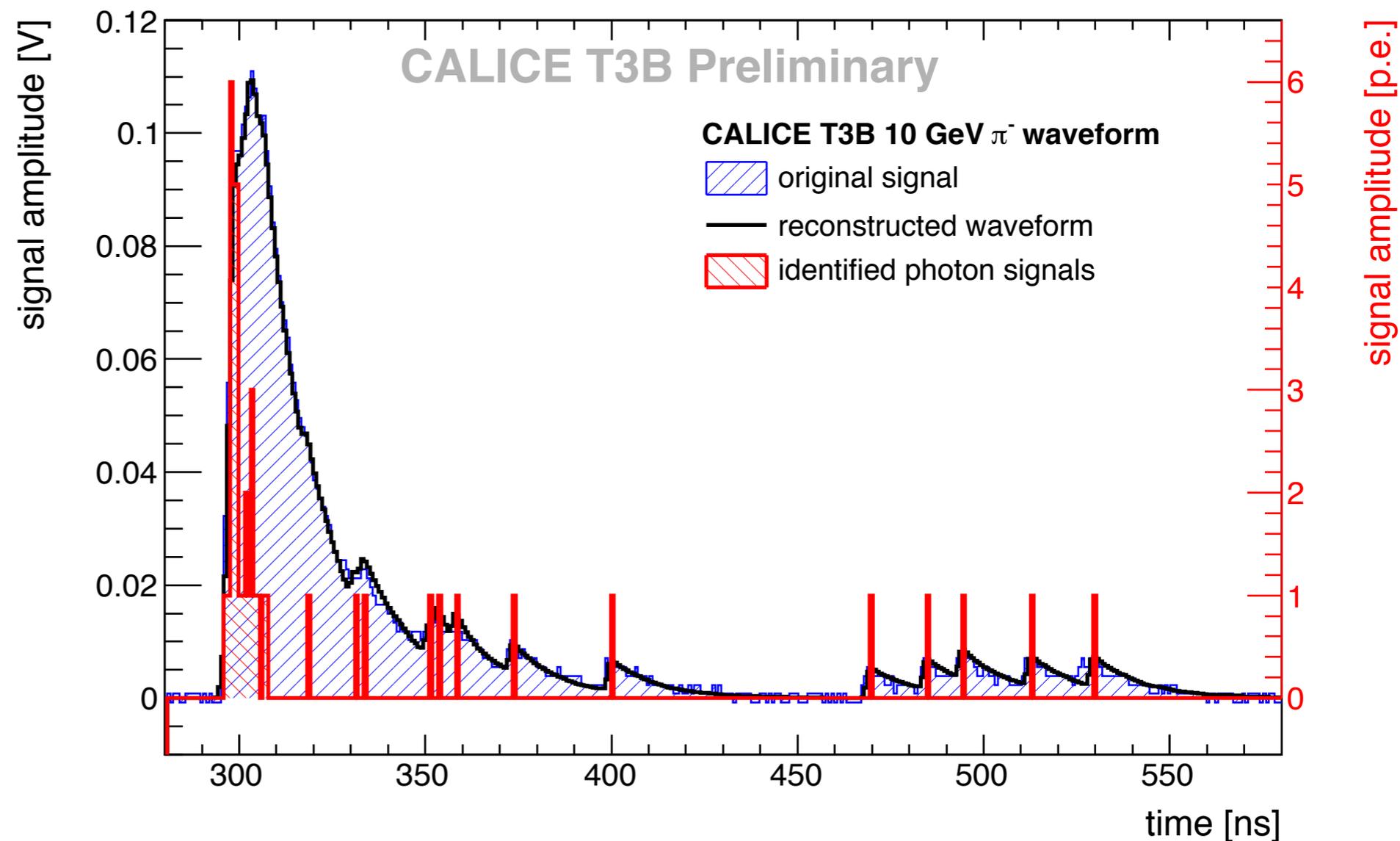
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- Distribution of response over sample of T3B tiles: 10% RMS variation

# Data Analysis - Technique

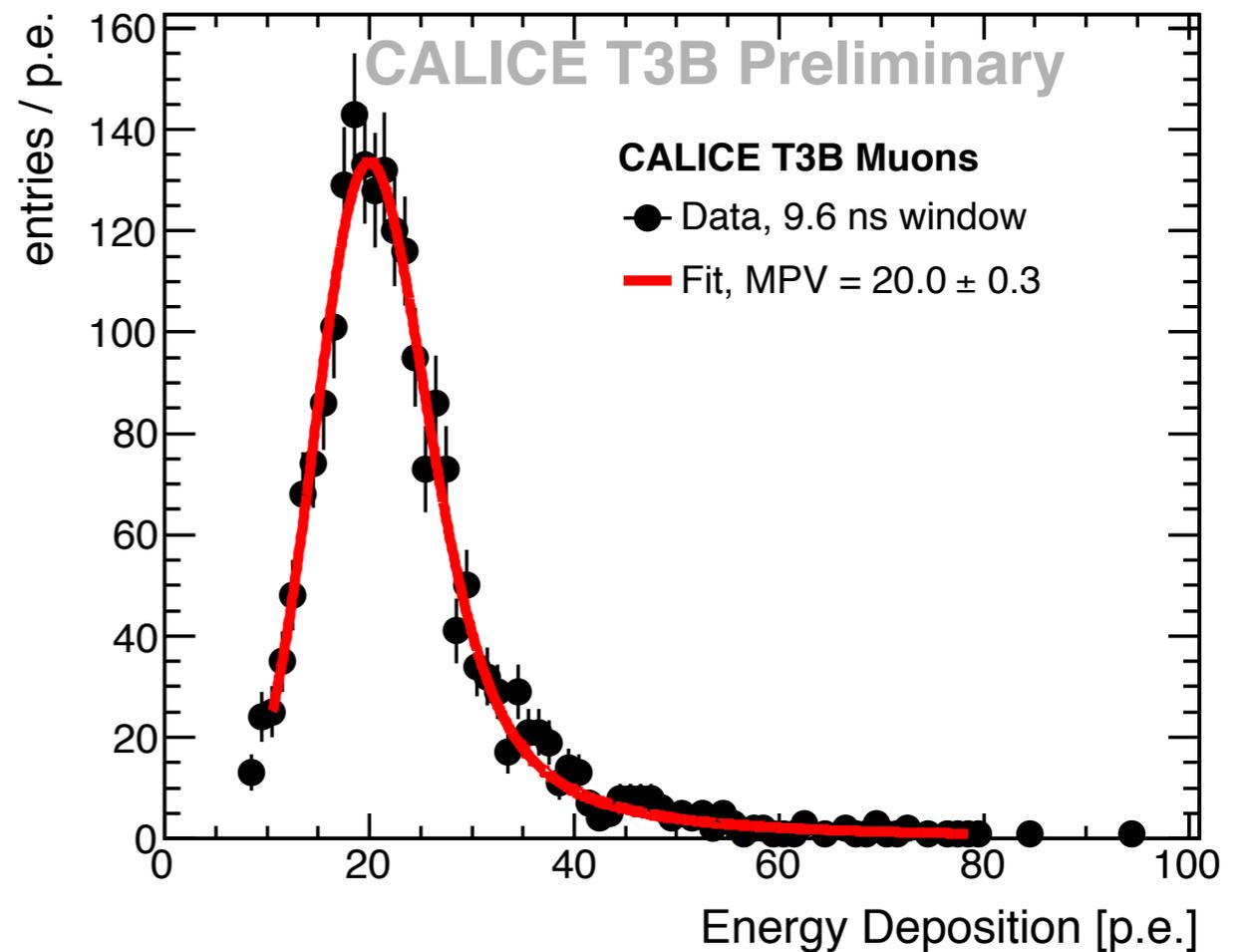
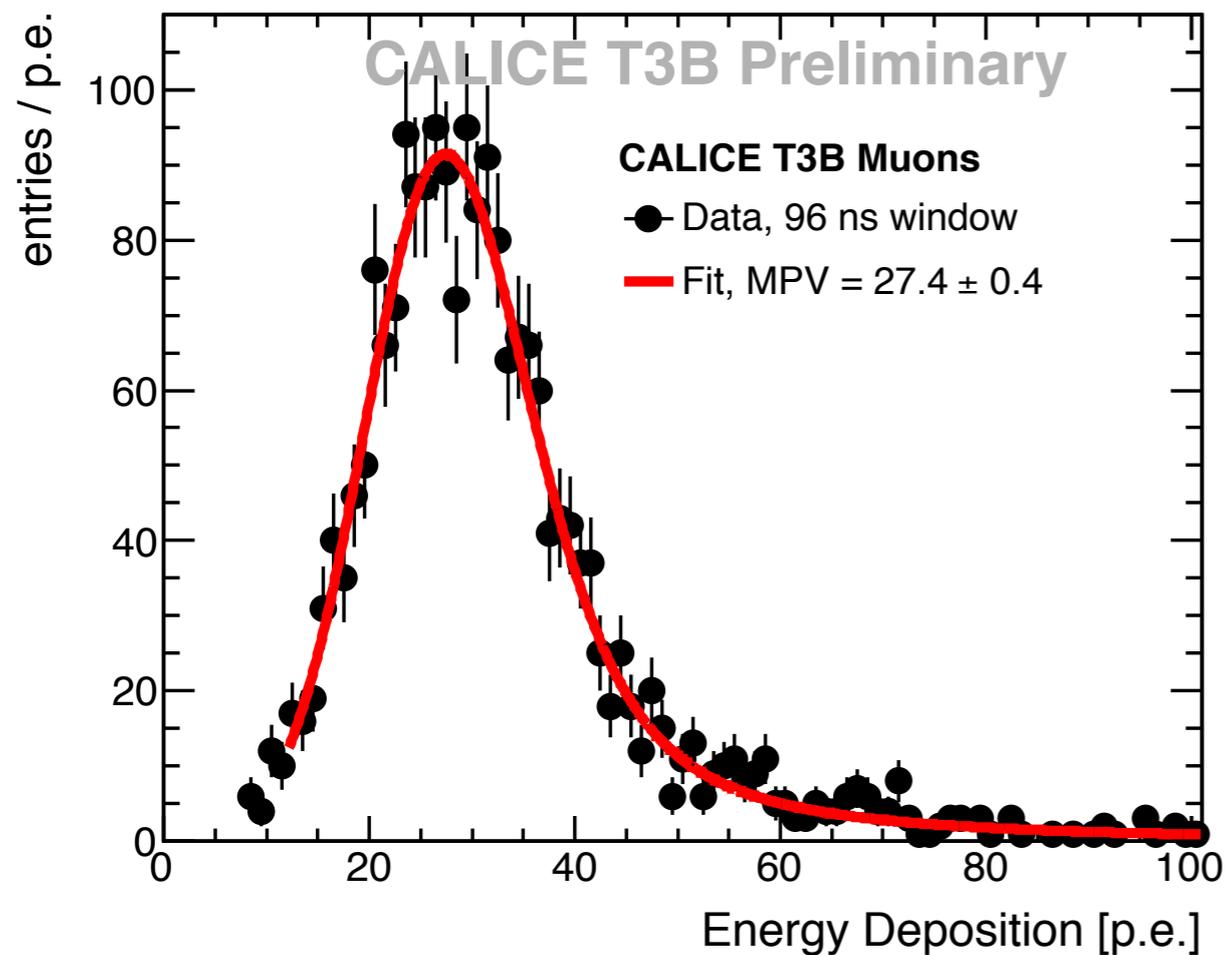
- For each channel, a complete waveform with 3000 samples (800 ps /sample) is saved
- Waveform decomposed into individual photon signals, using averaged 1 p.e. signals
  - Average 1 p.e. signal taken from calibration runs between spills, refreshed every 5 minutes: Continuous automatic gain calibration

- 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



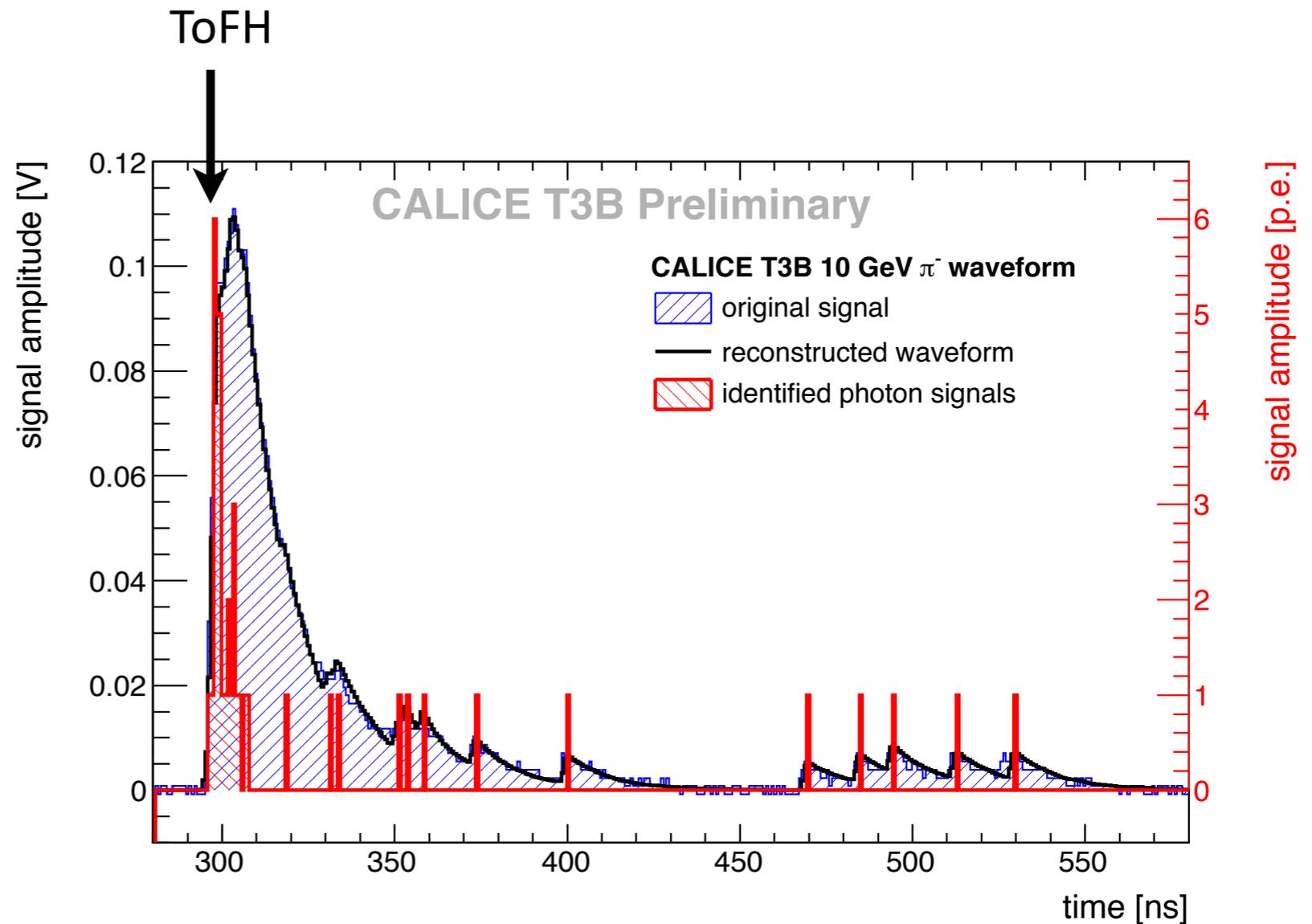
- Two integration times: Short time window rejects a significant fraction of SiPM afterpulses

# First Results - Muon Timing

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

Time of First Hit for Muons:

- Response to instantaneous energy deposit

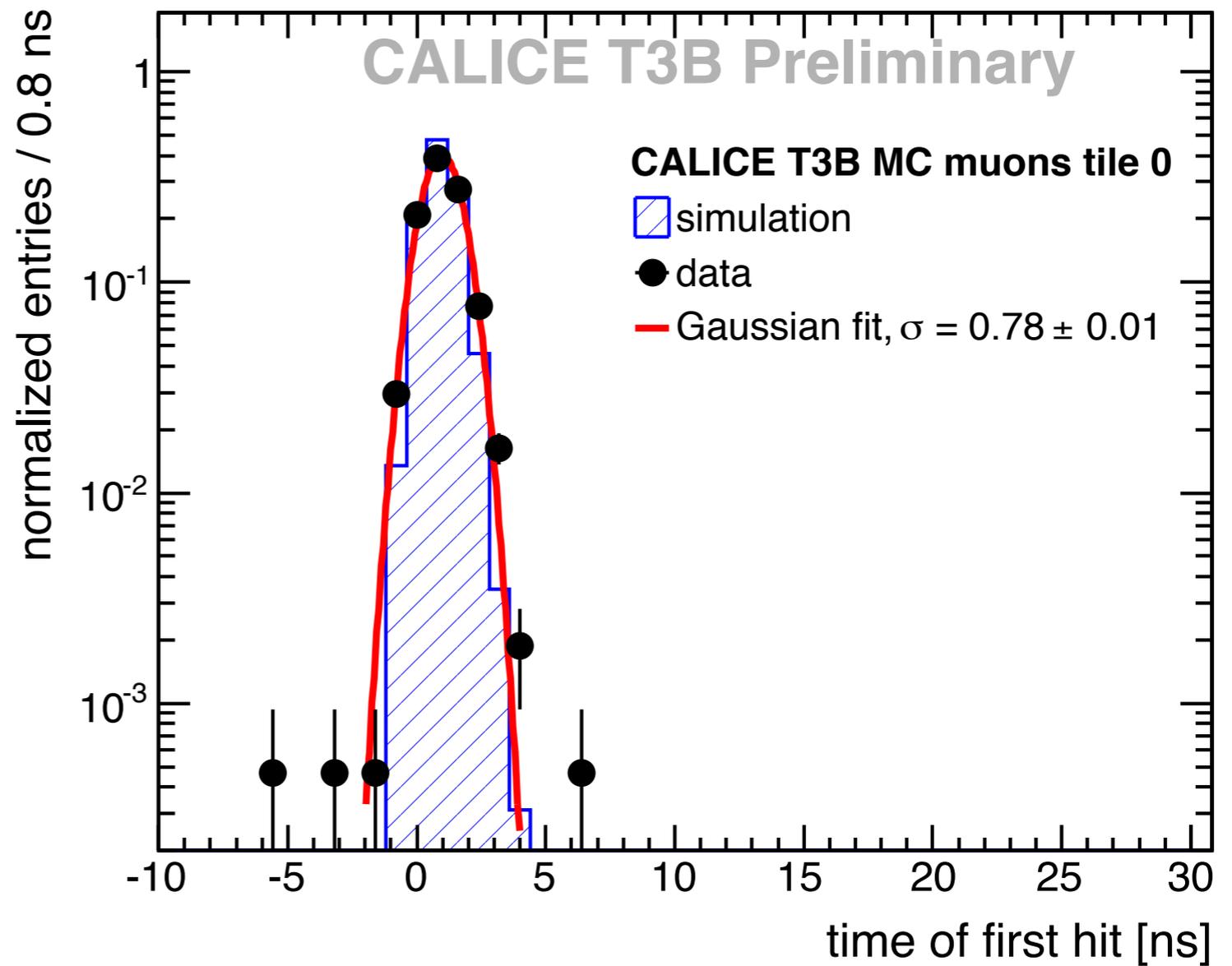


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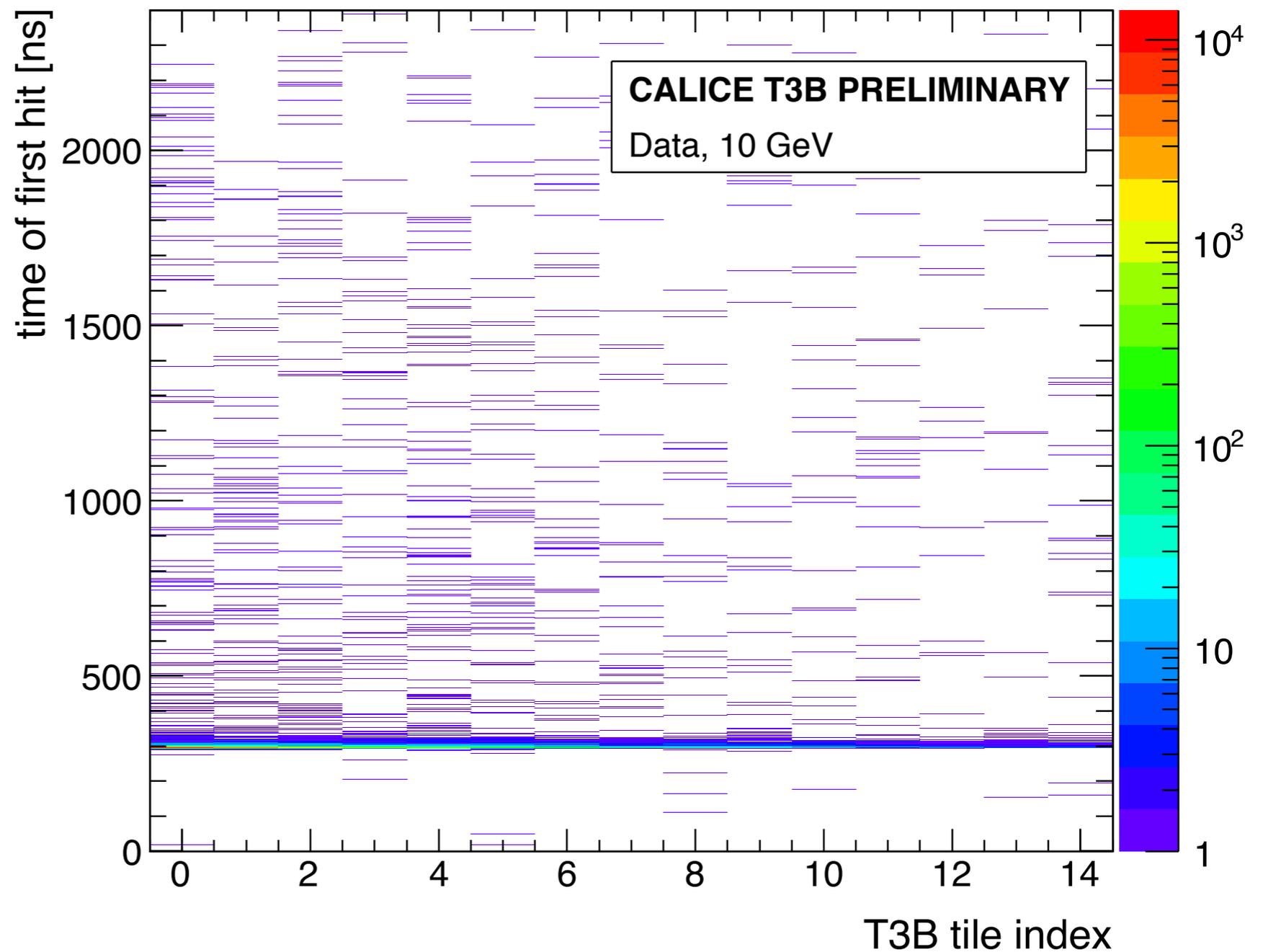
Time of First Hit for Muons:

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



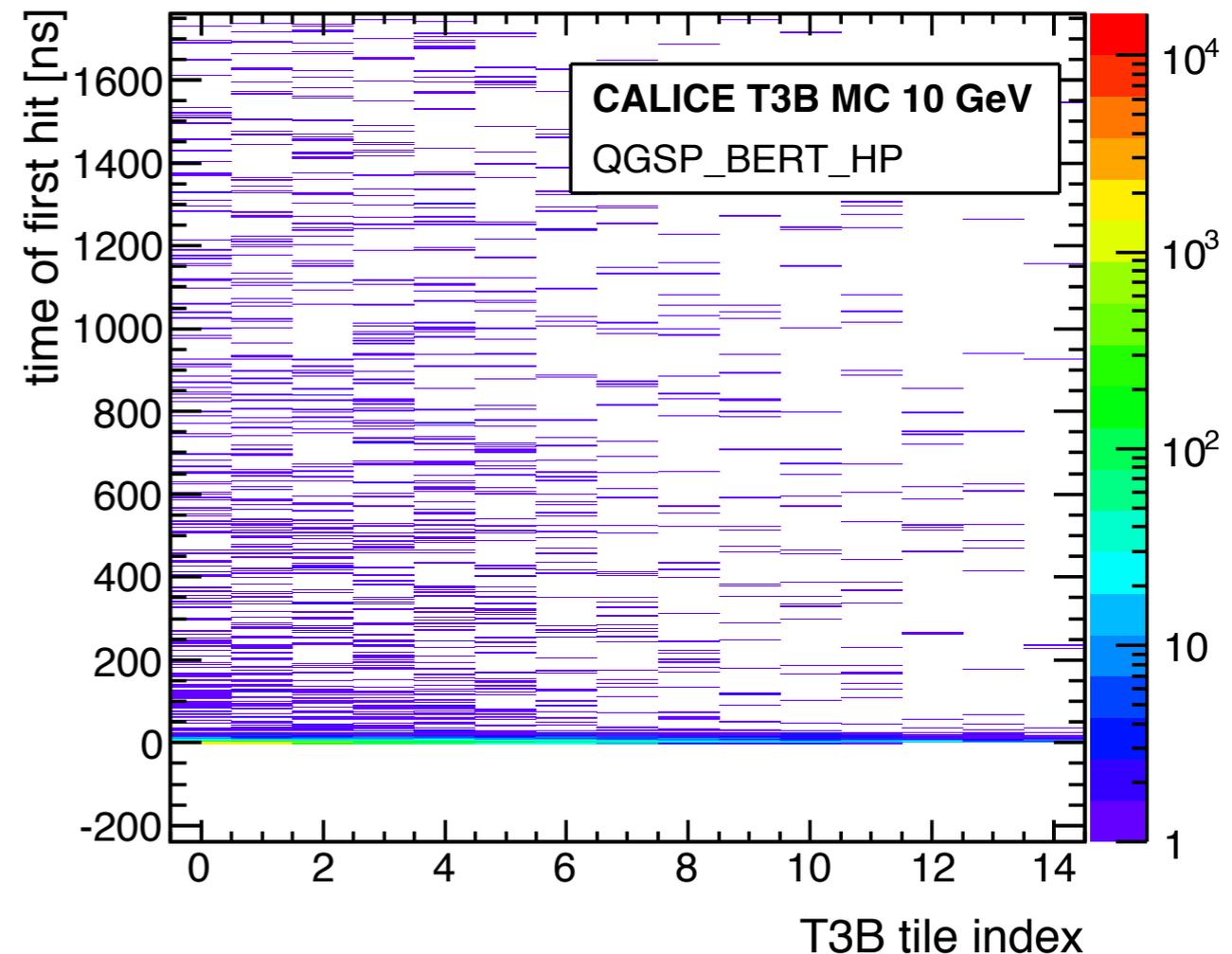
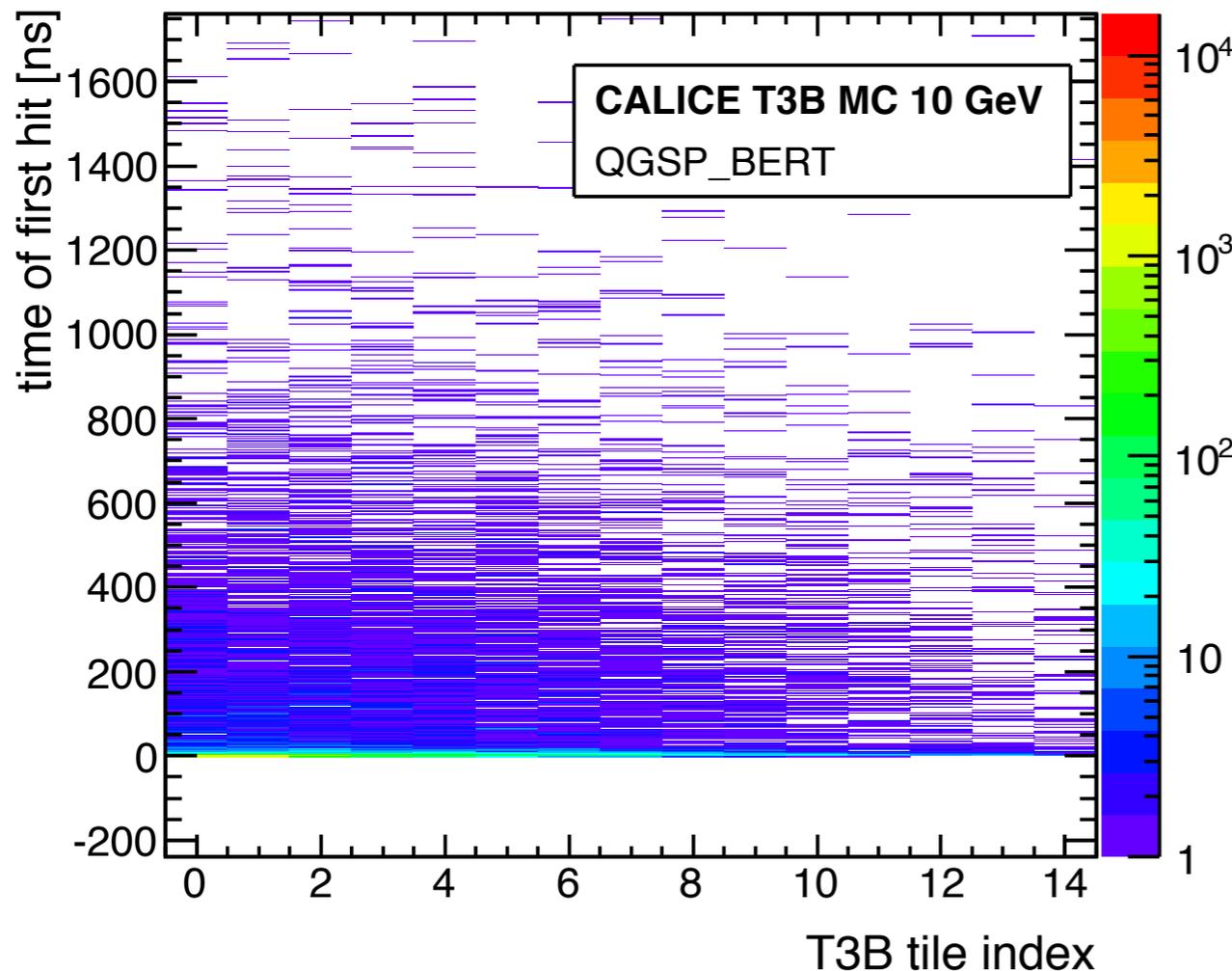
# First Results - Pion Data

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

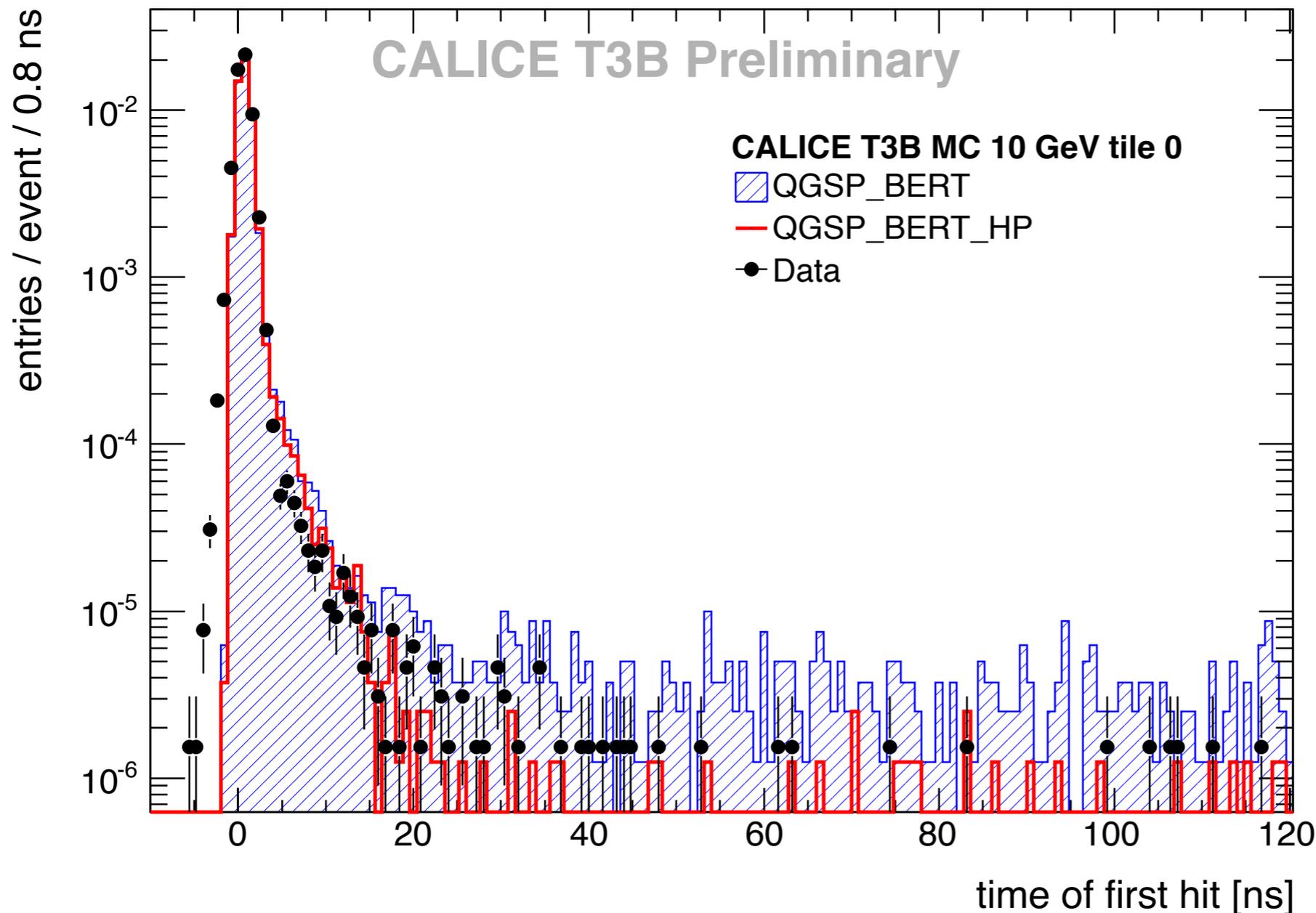


# Time of First Hit in Simulations

- 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



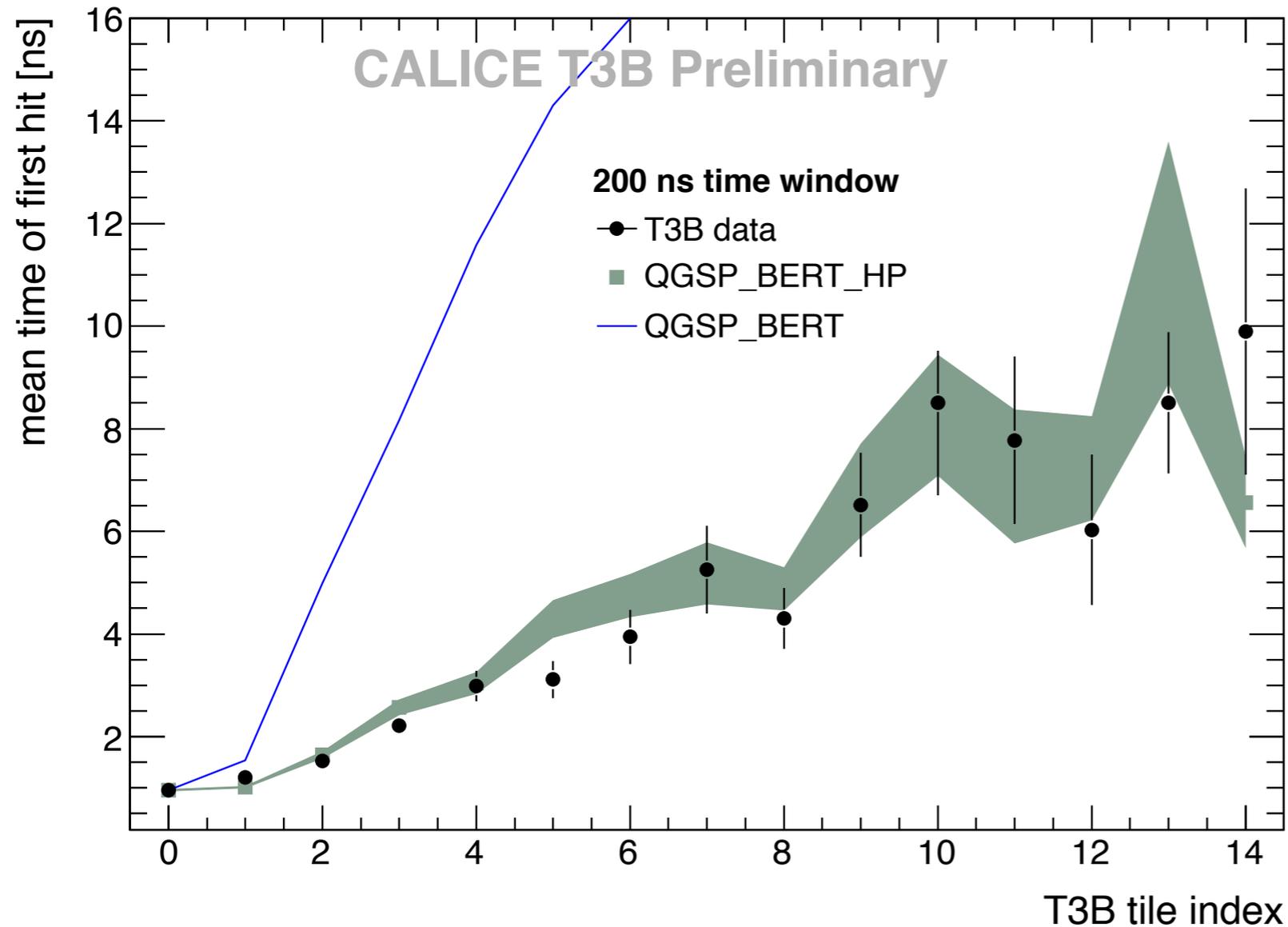
# Data & Simulations - First Results



**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

# Data & Simulations - First Results



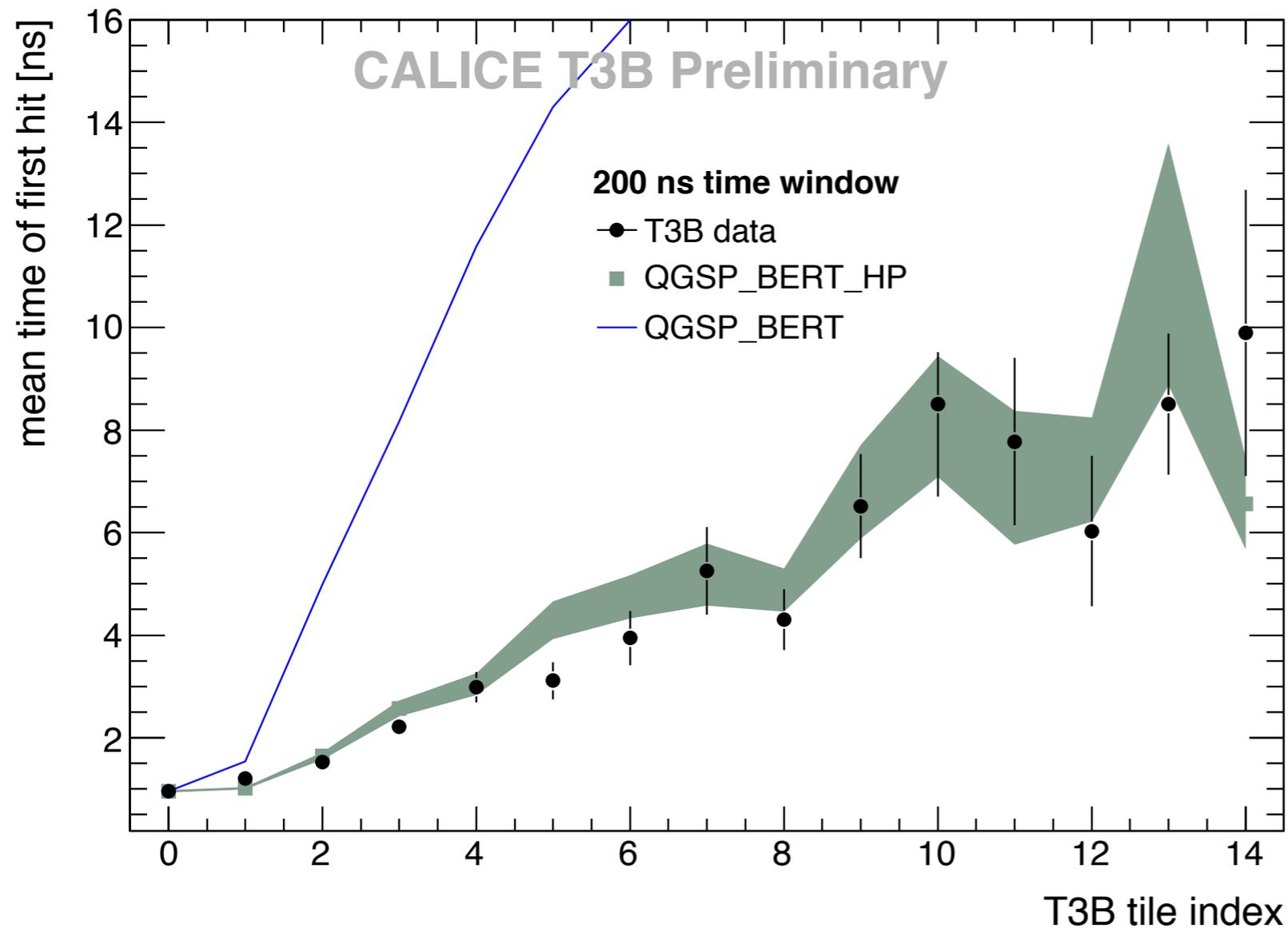
## Compact Comparison:

### 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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## Compact Comparison:

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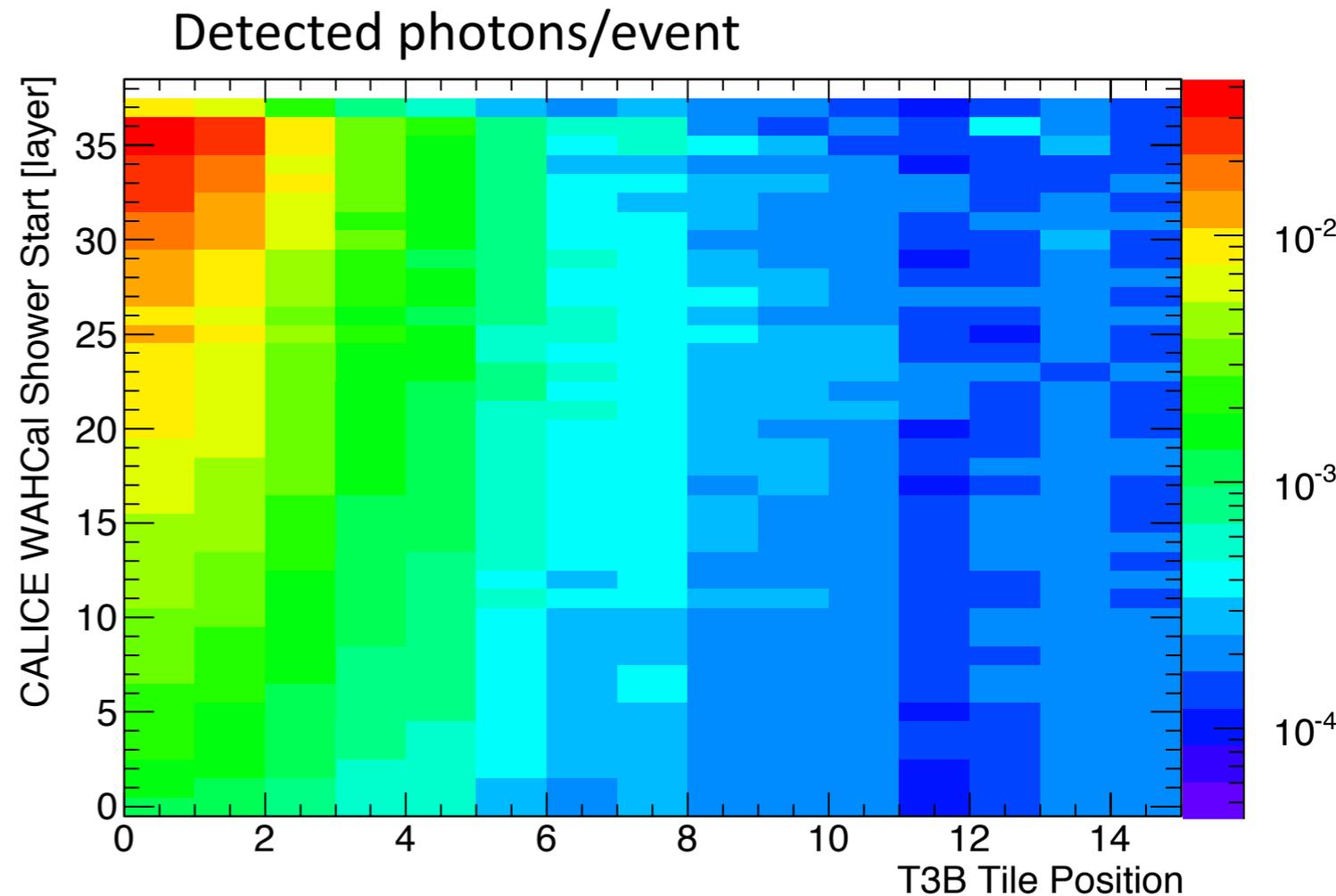
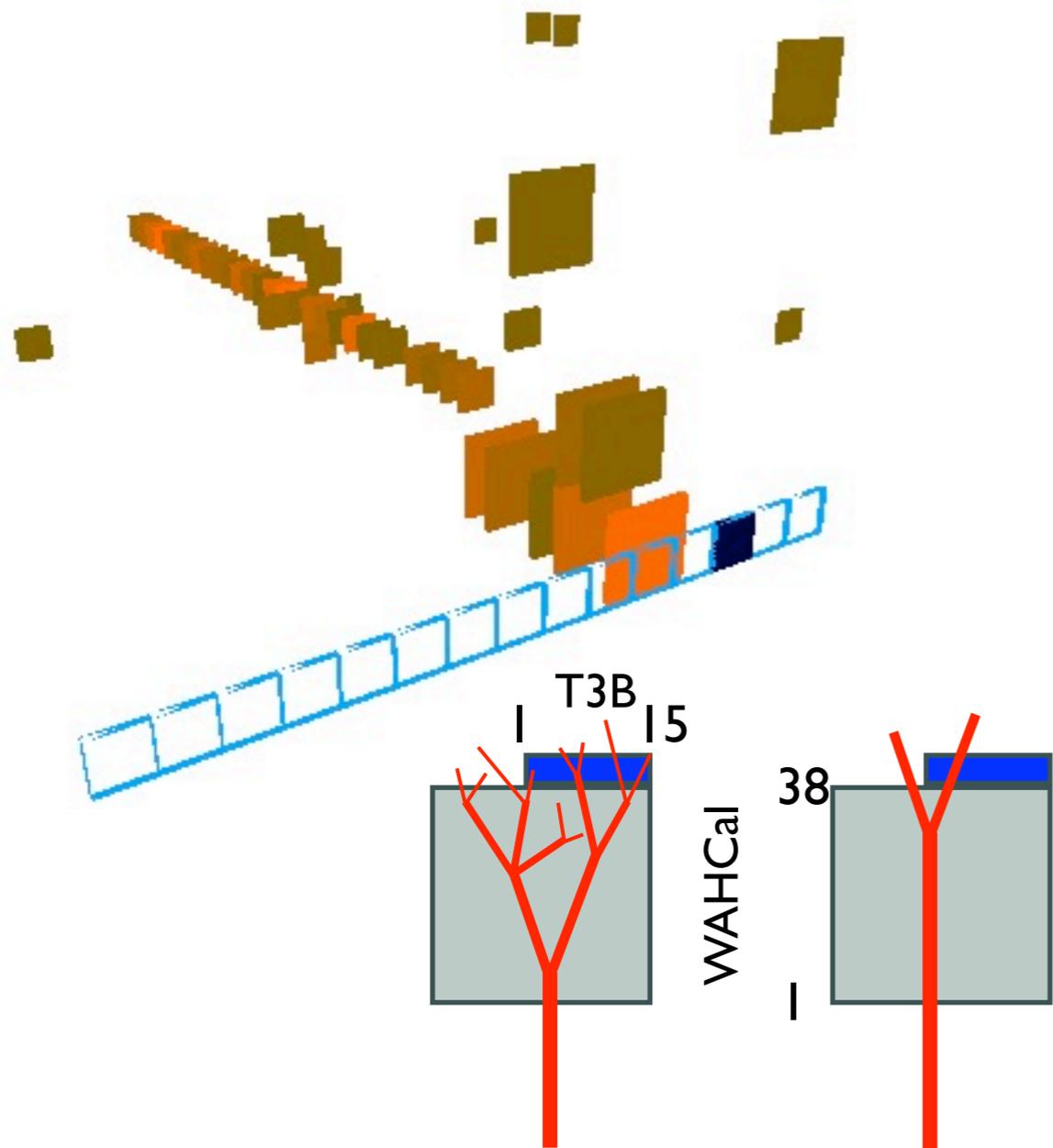
- calculated in a time window of 200 ns (-10 ns to 190 ns from maximum in tile 0)

- Data consistently described by QGSP\_BERT\_HP
  - QGSP\_BERT deviates strongly
- ⇒ High precision neutron tracking or other means to suppress excessive late energy depositions necessary to describe observed time structure in T3B

# Extending the Program: Shower Depth

- T3B events can be correlated with events recorded in the main AHCAL
  - Provide event-by-event information on the shower start: Allows time measurements as a function of depth in the shower

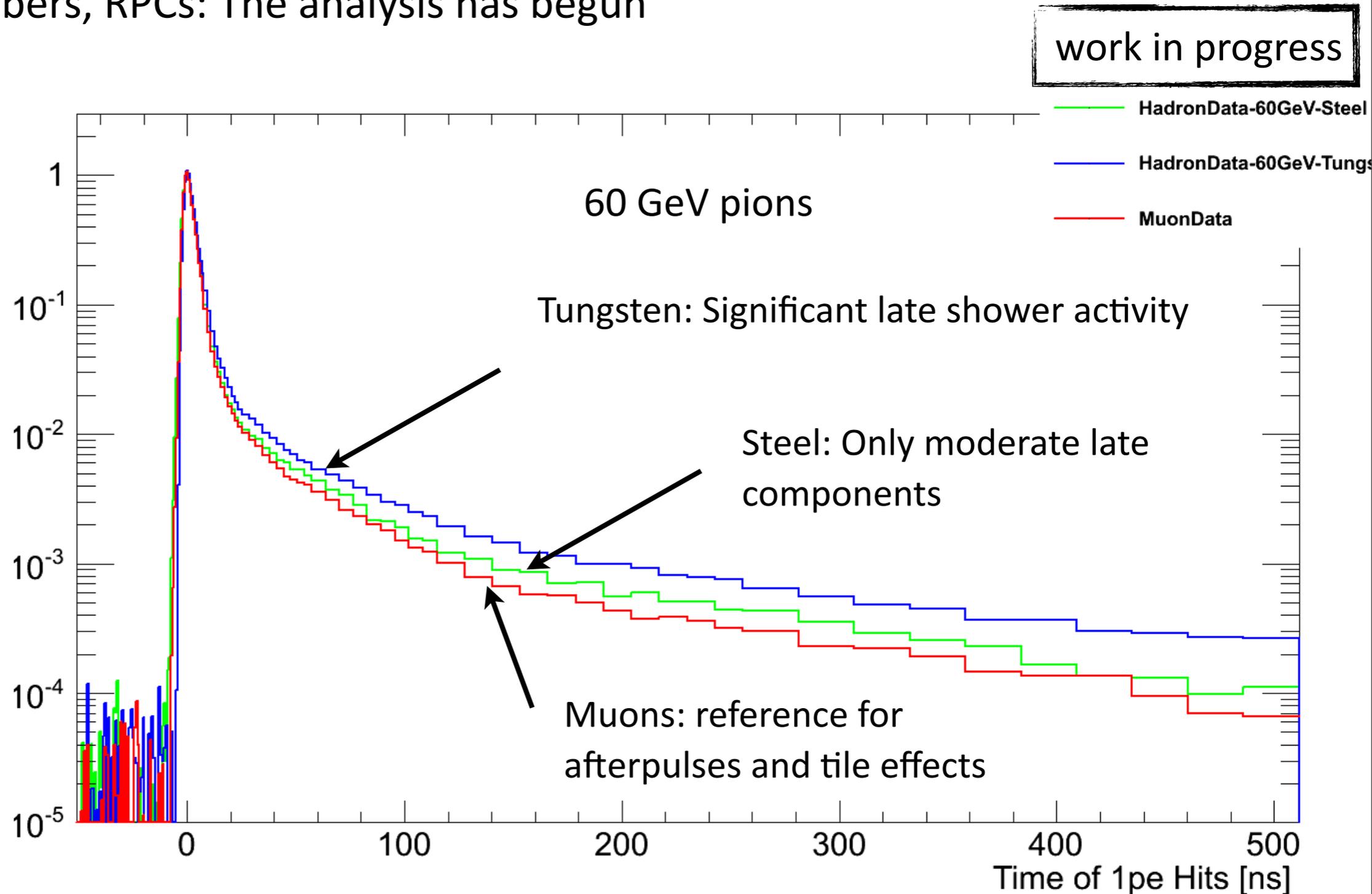
work in progress



SPS Data, 60 GeV

# Extending the Program - Tungsten vs Steel

- At the SPS, T3B has also taken data together with the CALICE SDHCAL:  
Steel absorbers, RPCs: The analysis has begun



# 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
- Analysis of SPS period is underway: Timing vs shower depth, Steel vs Tungsten, ...

# 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

