Preprint typeset in JINST style - HYPER VERSION

CALICE Analysis Note CAN-033
March 20, 2011

First T3B Results - Initial Study of the Time of First Hit in a Scintillator-Tungsten HCAL

The CALICE Collaboration*

This note contains preliminary CALICE results, and is for the use of members of the CALICE Collaboration and others to whom permission has been given.

ABSTRACT: We present the first study of the time structure of hadronic showers in the CALICE scintillator-tungsten sampling calorimeter by measuring the time of the first hit in a special timing layer, the T3B setup, about 4 λ_I deep in the calorimeter. This preliminary study, performed on incompletely calibrated data, is compared to Geant4 simulations and shows very good agreement between data and simulations for a model that includes high precision neutron tracking, while large discrepancies are observed for simulations without this component.

*Corresponding authors: Frank Simon (fsimon@mpp.mpg.de), Christian Soldner (soldner@mpp.mpg.de), Lars Weuste (weuste@mpp.mpg.de)

Contents

1. Introduction

For detector systems at CLIC [1], a hadronic calorimeter using tungsten absorbers is being considered to achieve a compact detector construction allowing the full containment of highly energetic jets while satisfying the space constraints imposed by the solenoidal magnet of the experiments. The high level of hadronic background from $\gamma\gamma \rightarrow$ hadrons, combined with the bunch to bunch spacing of 0.5 ns, requires aggressive time stamping to limit the impact of this background on physics measurements.

In the hadron calorimeter, the precision of timing is not only given by the detector technology, but also by the time structure of the hadronic cascade itself. This structure is influenced by fast components of essentially instantaneous energy deposits from high-energy charged hadrons and from electromagnetic sub-showers, and by slow components from neutrons and photons from nuclear processes. Apart from the shower physics, the time structure of the calorimeter response is also influenced by the sensitive medium and by the detector electronics. The choice of the sensitive medium strongly affects the sensitivity of the detector to different components of the hadronic cascade, such as highly energetic charged particles, photons and neutrons, which each have a different time evolution. In addition, time constants of the medium itself, such as decay times in scintillators, affect the measurement.

Since the evaluation of the performance of calorimetry at a CLIC detector relies on simulations based on GEANT4, it is crucial to study how well the time structure of the detector response for hadronic showers in a tungsten calorimeter is reproduced by the simulations. To provide first measurements for a calorimeter using plastic scintillators, the Tungsten Timing Test Beam (T3B) setup has been installed in the CALICE scintillator tungsten calorimeter (WHCAL) prototype, which was taking data in a first test beam campaign at the CERN PS in Fall 2010.

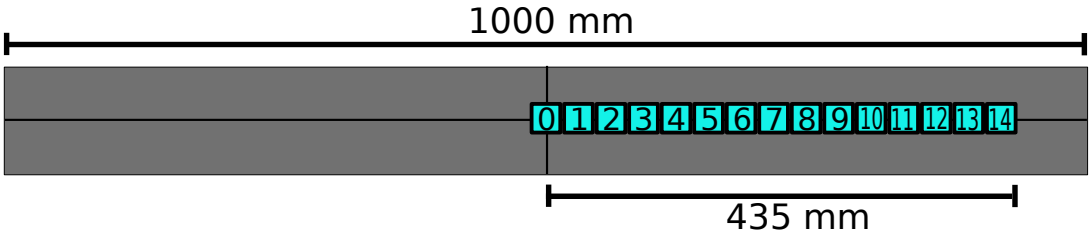

Figure 1. Layout of the T3B scintillator tiles. From the nominal beam axis, the setup extends by 15 mm to one and 435 mm to the other side.

2. The T3B Setup

The T3B setup consists of fifteen 3×3 cm^2 scintillator tiles with a thickness of 5 mm, directly read out with 1 mm^2 Hamamatsu MPPC50P SiPMs with four hundred 50×50 μm^2 pixels. The scintillator tiles have a "dimple" drilled into the side face at the SiPM coupling position to achieve a uniform response over the full active area. Variations of the response over the surface area are smaller than 5% over most of the tile surface [2]. The SiPMs with 50×50 μm^2 pixels (instead of 25×25 μm^2 pixels used for the studies discussed in [2]) have been chosen due to their increased photon detection efficiency in order to provide better sensitivity to small energies, which is of particular importance for late energy deposits in the hadronic cascade. The T3B scintillator tiles provide a signal of approximately 27 photo electrons (p.e.) for minimum ionizing particles, including afterpulses of the photon sensor. The response to muons is discussed in more detail in Section 3.

The photon sensors are read out with 4-channel USB oscilloscopes[1] with 1.25 GS per second, using long acquisition windows of 2.4 μs per event to record the time structure of the energy deposits in the scintillator in detail. Each SiPM was connected to a preamplifier board (as described in [2]), which then feeds the signal to the oscilloscope via coaxial cable. The bias voltage for each channel was adjusted by a resistor divider network, which was powered from one common high voltage source. The scintillator cells were individually packaged in light-tight tape. The preamplifier boards with packaged scintillator cells were mounted on a 2 mm thick aluminum plate and protected by a 1 mm thick aluminum top cover, forming a robust cassette.

The T3B scintillator tiles are arranged in one row extending from the center of the calorimeter layer out to one side of the detector. The first tile is centered on the nominal beam position, thus the setup extends 15 mm beyond the nominal beam center on one and 435 mm on the other side, as shown in Figure 1. This permits the measurement of a full radial timing profile of the hadronic shower at the position of T3B, given sufficient statistics. The limited coverage however only allows averages over many events to be measured, and is not suitable for the study of the time evolution on an event by event basis.

In the 2010 test beam period, the T3B setup was installed behind the last layer of the CALICE WHCAL, which consisted of 30 tungsten absorber plates, 1 cm thick, supported by a 1 mm thick steel plate in addition. Behind each of the 30 absorber layers, one active layer of the CALICE analog HCAL [3] was installed. After those 30 layers, additional slots without absorber plates

[1] PicoTech PicoScope 6403 (http://www.picotech.com/)

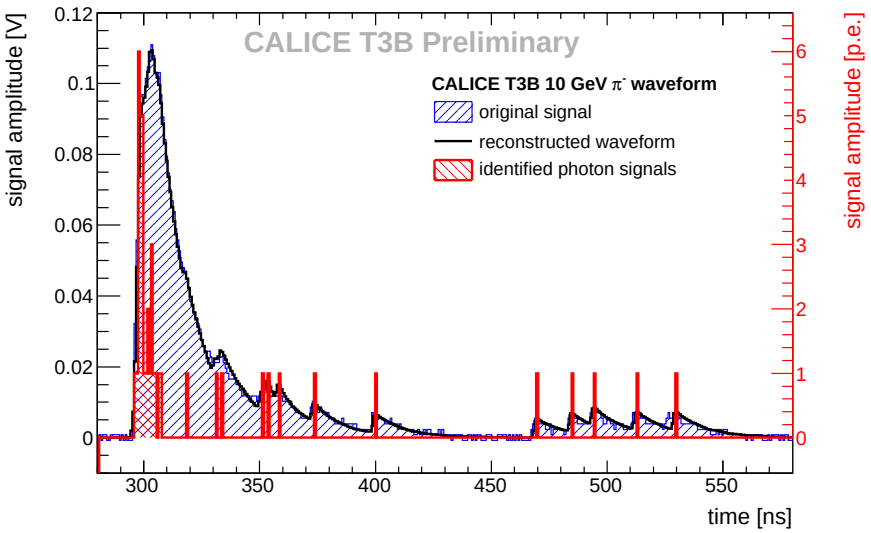

Figure 2. Typical waveform with a high initial signal, decomposed into individual photon signals during the data analysis. Very good agreement of the original waveform and the reconstructed signal from standard single photo-electron distributions is observed.

were included in the mechanical structure. The first layer downstream of the calorimeter was used by a CALICE Micromegas test module [4], while the second downstream layer was occupied by T3B. The T3B setup was located at a depth of approximately 4 λ_I.

During data taking, T3B was triggered by the main CALICE trigger, which will allow a matching of CALICE and T3B events in future analyses. In total, T3B uses four USB oscilloscopes totaling 16 channels, with the one channel not used for SiPM readout employed to monitor the signal from the trigger scintillators to allow the rejection of CALICE calibration triggers and the identification of double particle events. Between spills, T3B was taking dark rate events to allow a continuous monitoring of the SiPM gain. In future analyses, a correction based on the observed variations of the gain will be performed, but for the present studies, no corrections were applied.

3. Data Analysis

For the present note, a data set consisting of approximately 718 000 10 GeV π^- events was analyzed, using T3B in standalone mode without attempting to correlate the events with CALICE WHCAL events to obtain additional information about the showers. The negative beam polarity was chosen to avoid a contamination with protons. At 10 GeV, the electron contamination of the beam is negligible, and this highest available energy at the T9 PS beam line provides the largest hadronic activity, and thus the highest signal statistics in T3B. The muon contamination of the beam, which was not rejected, was around 10%. The size of the trigger counters limits the influence of muons to the two central tiles. Data quality cuts reduced the event sample to 645 000 accepted events by rejecting spills with inconsistent trigger numbers for the four T3B oscilloscopes, most likely linked to CALICE calibration triggers during the T3B end of spill phase. 58 000 events have an identified first hit that satisfies the analysis requirements discussed below in one of the T3B cells.

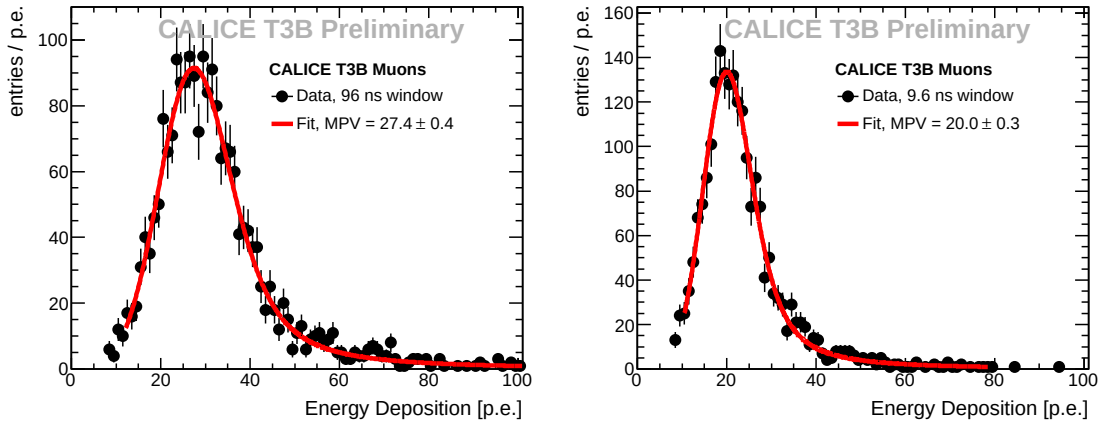

Figure 3. Measured spectrum for muons in the central T3B scintillator tile, reconstructed by identifying the time of individual photon signals in the SiPM, for two different integration time windows: 96 ns from the first identified photon (*left*) and a time window of 9.6 ns (*right*). The distributions were fitted with a Landau function convolved with a Gaussian to extract the most probable value. In both cases, the χ^2 per degree of freedom is around 0.8, indicating a good fit quality.

The data were analyzed on a cell by cell level. As a first step, zero suppression based on pedestals determined on a spill-by-spill basis was applied. Then, a threshold on the total zero-suppressed integral of the complete waveform equivalent to 0.3 MIP (corresponding to about 8 p.e.) was applied to consider a cell for further analysis in order to reduce the processing time for the complete data set. Then, the waveform was decomposed into individual photon equivalents to provide precise information on the arrival time of photons at the light sensor. This was done by consecutively subtracting single photon signals from local maxima detected in the waveform, until no maxima above approximately 0.5 p.e. remained. The single photon signals were obtained from noise events taken between spills and are determined for each tile separately. This results in an implicit gain calibration, since possible cell-to-cell gain differences lead to corresponding differences in the average single photon signals used in the analysis. The resulting number of photons is thus independent of the SiPM gain. This reference signal was refreshed every 10 spills, typically corresponding to time intervals of less than 5 minutes. This provided continuous automatic corrections of gain variations due to temperature changes. The temperature was monitored by one temperature sensor included in the T3B cassette. The temperature range of the data considered here was on the order of 0.8 °C, resulting in gain variations of approximately 3%.

Figure 2 shows one example of a waveform decomposed using this reconstruction technique. To check the quality of this analysis, a waveform based on the identified photon signals was built up with the reference single photon signals and compared to the original waveform. The very good agreement between measurement and the reconstructed waveform demonstrates the quality of reconstruction.

Figure 3 shows the distribution of the energy reconstructed with this technique in the central tile of T3B for muons obtained in a special data run with an absorber in the beam line. The deposited energy was determined with two different integration windows, 96 ns from the first identified photons, shown in Figure 3 *left* and 9.6 ns, shown in Figure 3 *right*. The most probable value

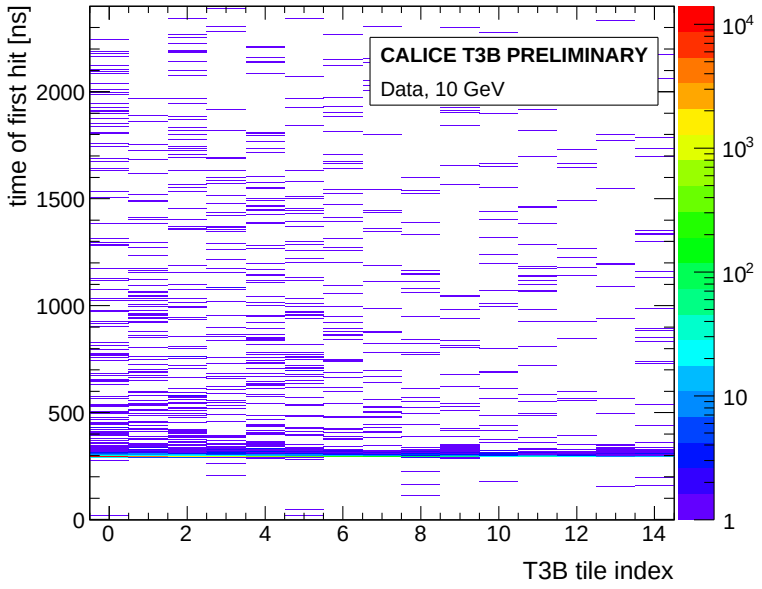

Figure 4. Distribution of the time of first hit for all 15 T3B channels for 10 GeV π^-.

of both distributions was extracted by fitting a Landau function convolved with a Gaussian. The integration time has a considerable effect on the most probable value, which is reduced by almost 30% from 27.4 ± 0.4 p.e. to 20.0 ± 0.3 p.e. for the reduced integration window. Also the width of the signal is reduced considerably. This is due to the partial exclusion of contributions from afterpulses of the photon sensor.

The final analysis for 10 GeV π^- events was performed on the decomposed waveform, using the timing of each identified photon. Here, signals were considered where at least 8 p.e. were detected within 12 time bins (9.6 ns). The narrow time window considered leads to a reduction of the typical MIP amplitude, since a considerable fraction of the SiPM afterpulses were excluded, as discussed above. The threshold corresponds to the equivalent of 0.4 MIPs. The time of hit was then taken from the timing of the second detected photon of that hit. It was observed that using the first instead of the second photon leads to additional jitter due to single p.e. dark counts before the starting time of the real hit. At typical dark count rates of a few 100 kHz, the probability for such events within the integration time window is on the 10^{-3} level. The time of first hit for a T3B cell is given by the starting time of the first such hit in the waveform.

At present, no cell-to-cell calibration is performed, leading to some uncertainty on the overall MIP scale for each cell. The MIP scale is only determined in the central T3B tiles using muon data. The result of a fit to muon data in the adjacent tile, which is statistically limited, yields a 5% lower most probable value, consistent within errors with the fit to the distribution in the central tile. In general, only small cell-to-cell variations of the light yield are expected for the directly coupled scintillator tiles used in T3B. For the determination of the time of the first hit in a given cell, this missing calibration only contributes to higher order corrections from the application of thresholds, and does not influence the timing measurement itself.

Figure 4 shows the distribution of the time of first hit as a function of radial position, given

by the T3B cell index, showing the expected cluster of events at early times in coincidence with the timing of the original beam particle, but also considerable late activity in the shower. Further analysis of this distribution, together with simulation studies, are discussed below.

4. First Simulation Studies

Simplified simulations, based on a direct implementation of the WHCAL geometry in Geant4 (version 4.9.3.p01), were performed to provide first comparisons to the T3B results. In the simulations, the setup was implemented as a 31 layer WHCAL detector, with absorber plates consisting of 10 mm tungsten alloy (93% W, 1.8% Cu, 5.2% Ni, density 17.6 g/cm^3) and 1 mm steel. The active modules were simulated according to the CALICE simulation model, with two 2 mm thick steel cover plates, 5 mm thick polystyrene scintillator and additional PCB, cable and fiber and air layers. The T3B setup itself was not explicitly included, but was approximated as the 31st layer of the simulation setup, with the Micromegas detector upstream of T3B taken as an extra absorber layer. While this is not an exact description of the real test beam setup, for the variables studied at present these deviations are assumed not to lead to significant effects on the results.

For the simulations, Geant4 was run with a range cut of 50 μm, and a reduction of the visible energy in the scintillator for slow, heavily ionizing particles was accounted for by using Birks' law [5]. 800 000 events, roughly corresponding to the available real data set, were simulated with the `QGSP_BERT` and `QGSP_BERT_HP` physics lists. The latter provides additional high precision neutron tracking, and is expected to give an improved description of the shower evolution in heavy absorbers, while the former is the list mostly used in the simulation of LHC detectors and for linear collider optimization studies. For the events generated for the present study, the high precision neutron tracking increased the required CPU time for event simulation by approximately a factor of five. The beam profile was taken into account by a Gaussian smearing of the primary particle position along the horizontal and vertical axis with a width of 8 mm, motivated by the beam profile measured with the tracking system in the WHCAL test beam.

The analysis of the simulation data followed the real data analysis closely. For each of the 15 T3B cells, a histogram with the energy deposits as a function of time, with 800 ps resolution, was built for each event. In the histogram filling process, energy deposits were transformed from the energy scale to a calibration scale in units of minimum ionizing particles (MIPs), by taking a conversion factor of 815 keV / MIP determined from simulated muons. This transformation allows direct comparison to the real data. A total energy deposit of 0.3 MIP in the full time window of 2.4 μs was required for a further analysis of each cell.

The Geant4 simulations of the T3B setup do not take into account the time structure of the response of the system to an instantaneous signal. This structure originates from scintillator time constants, photon travel times and SiPM response. This smearing in time was included in the simulations by distributing the number of photons corresponding to the energy deposited in each 800 ps time bin according to the time distribution of identified photons in the data for muon signals, which represent instantaneous energy deposits. This distribution was obtained by using the data reconstruction technique described in Section 3 and is shown in Figure 5 *left*. A Landau function with a sigma of 1.3 ns was found to give a good description of the distribution, and was used to provide a parametrization for the simulations. With a more refined analysis, a function which

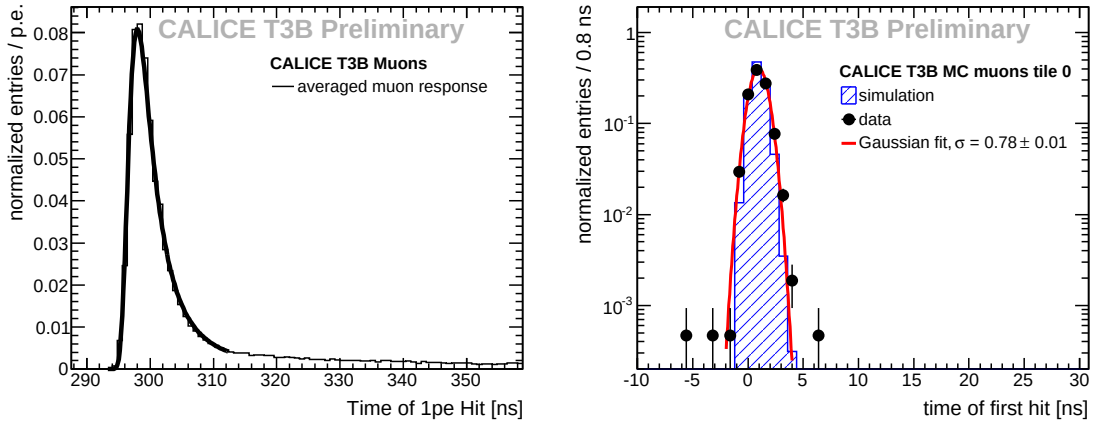

Figure 5. *Right:* Averaged time distribution of the identified photons in muon events.The distribution was fitted with a Landau function, which is used to model the time distribution of individual photons in the simulation. *Left:* Time of first hit for muons in the central T3B tile, compared to simulations. The data points were fitted with a Gaussian to extract the width of the distribution as a measure for the time resolution.

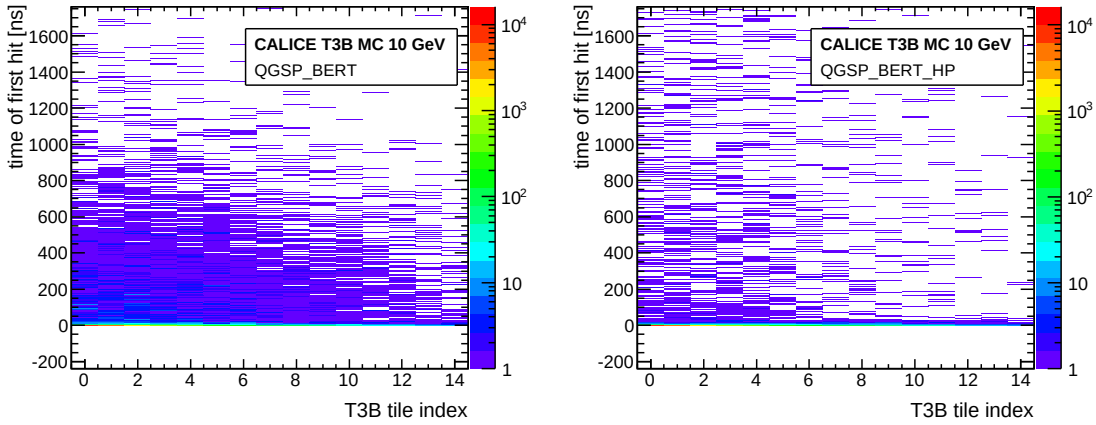

Figure 6. Simulation of the distribution of the time of first hit for all 15 T3B channels for 10 GeV π^- with `QGSP_BERT` (*left*) and `QGSP_BERT_HP` (*right*).

allows a physical interpretation in terms of scintillator rise and decay times, photon travel times and photon sensor afterpulsing may be found.

Using the parametrization of the signal shape for an instantaneous energy distribution, a simulated photon distribution was built up which was used for further analysis. The time of first hit was determined from the start of an energy deposit, given by the first bin with an energy above zero, which contains a minimum of 0.4 MIP within 12 time bins (9.6 ns). Figure 5 *right* shows the time of first hit determined for muons, compared to simulations with muons using the described smearing technique. Here, the time of the data distribution is shifted so that the maxima of the two distributions fall into the same time bin. The good agreement of the simulated distribution and data validates this parametric inclusion of detector effects on the measured time distributions.

The data points were fitted with a Gaussian to extract the width of the distribution as a measure

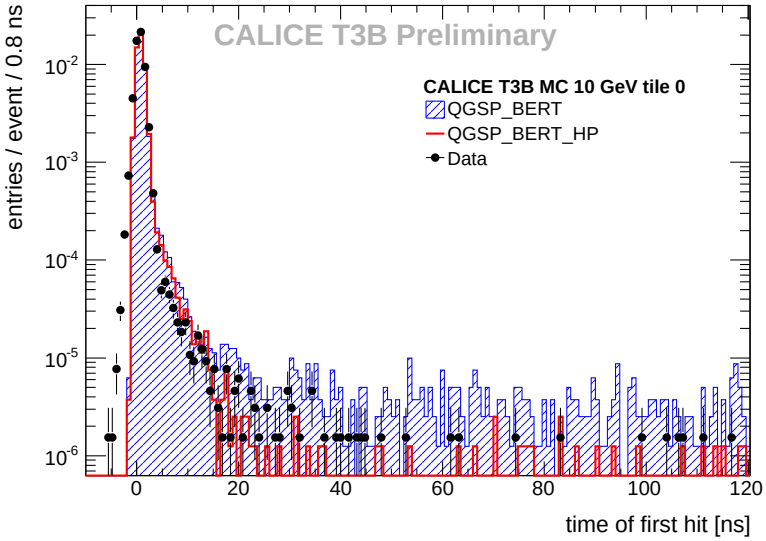

Figure 7. Comparison of the time of first hit distribution in tile 0 simulated for 10 GeV π^- with `QGSP_BERT` and `QGSP_BERT_HP` with data.

for the time resolution of the T3B system for instantaneous energy deposits. The width of 800 ps demonstrates that sub-ns resolution, including time jitters of the CALICE trigger system, can be achieved with the T3B setup for such hits.

Figure 6 shows the simulated distribution of the time of first hit over all T3B tiles for the two considered physics lists, `QGSP_BERT` and `QGSP_BERT_HP` for 10 GeV π^-. These figures illustrate a striking difference in the late shower evolution for the two models. The delayed energy deposits are considerably reduced in the model including high precision neutron tracking. This is further demonstrated in Figure 7, which shows the distribution of the time of first hit in the central tile of T3B which sits close to the beam axis. Here, both physics lists are compared to the distribution observed in data. The tail of the hit distribution beyond 20 ns is considerably reduced in `QGSP_BERT_HP` compared to `QGSP_BERT`, and is consistent with the observation in data. The main peak is reasonably well described by both models.

5. Results

A measure which provides a good indication of the intrinsic time stamping possibilities in the calorimeter is the time when a cell which contains energy in a given event is first hit. To provide first robust comparisons between data and simulations, the mean time of first hit for each of the T3B cells was determined from the distribution of the first hit as discussed in Section 3. The mean was formed within a time window of 200 ns, starting 10 ns before the maximum of the distribution in T3B tile 0, and extending to 190 ns after the maximum. This time window covers the time relevant for calorimetry at CLIC, where the duration for one bunch train is expected to be 156 ns, and is also comparable to the shaping time of 180 ns used in the front end electronics of the CALICE analog HCAL modules.

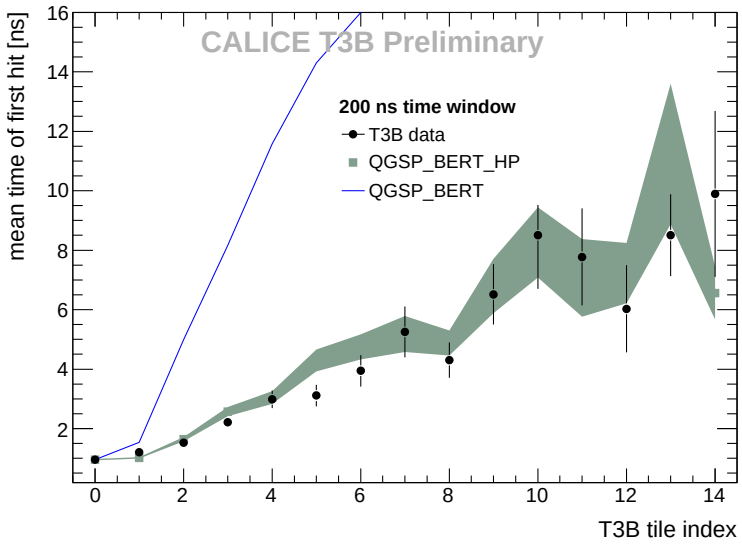

Figure 8. Mean time of first hit for 10 GeV π^- as a function of radial distance from the shower core (a tile index of 10 corresponds to approximately 30 cm). The data are compared with simulations using QGSP_BERT and QGSP_BERT_HP. The error bars and the width of the area in the case of QGSP_BERT_HP simulations show the statistical error, while for QGSP_BERT the errors are omitted for clarity.

Figure 8 shows the mean time of first hit as a function of the radial distance from the shower axis. The beam axis passes through T3B tile 0, so that a tile index of 10 corresponds to a distance of approximately 30 cm. The measurement is compared to the simulations with the two physics lists, QGSP_BERT and QGSP_BERT_HP. While QGSP_BERT_HP gives an excellent description of the data, QGSP_BERT shows very large discrepancies, with significantly overestimated late contributions at larger radii. This demonstrates the importance of the high precision neutron tracking in Geant4 for a realistic reproduction of the time evolution of hadronic showers in tungsten.

6. Summary

We have presented first preliminary results of the measurement of one aspect of the time structure of hadronic showers of 10 GeV π^- in the CALICE scintillator-tungsten hadronic calorimeter at a depth of approximately 4 λ_I using the T3B setup. The comparison of the data to simulations performed with a simplified detector model has shown very good agreement for the QGSP_BERT_HP physics list, while large discrepancies were observed for QGSP_BERT. The use of high precision neutron tracking reduces the number of late hits considerably, and brings the simulation in agreement with observation.

References

[1] R. W. Assmann, F. Becker, R. Bossart, H. Burkhardt, H.-H. Braun, G. Carron, W. Coosemans, R. Corsini *et al.*, *A 3-TeV e+ e- linear collider based on CLIC technology*, CERN-2000-008 (2000).

[2] F. Simon, C. Soldner, *Uniformity Studies of Scintillator Tiles directly coupled to SiPMs for Imaging Calorimetry*, Nucl. Instrum. Meth. **A620**, 196-201 (2010).

[3] C. Adloff, Y. Karyotakis, J. Repond *et al.*, *Construction and Commissioning of the CALICE Analog Hadron Calorimeter Prototype*, JINST **5**, P05004 (2010).

[4] C. Adloff, D. Attie, J. Blaha, S. Cap, M. Chefdeville, P. Colas, A. Dalmaz, C. Drancourt *et al.*, *MICROMEGAS chambers for hadronic calorimetry at a future linear collider*, JINST **4**, P11023 (2009).

[5] J.B. Birks, *Theory and Practice of Scintillation Counting*, Pergamon Press (1964).