

# The time structure of hadronic showers in calorimeters with scintillator and with gas readout

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The time structure of hadronic showers plays a key role when evaluating the timing capabilities of calorimeter systems. Such structure is characterized by a prompt component from relativistic particles and by late components predominantly connected to neutrons in the cascade. Moreover the choice of the detector's active medium impacts its neutron sensitivity and, therefore, the ratio between the various time components. Studying these differences is of particular interest in the context of the development of detector concepts for the Compact Linear Collider (CLIC), where time stamping of signals is of key importance to reject pile-up from hadrons produced in two-photon processes, and where tungsten is used as absorber material for the hadronic calorimeters.

For this purpose, two experimental setups, namely T3B (Tungsten Timing Test Beam), based on scintillating tiles coupled to SiPMs, and FastRPC, which uses glass RPCs, have been installed on a calorimeter with Tungsten absorbers. Both setups consist of a radial strip of 15 cells with a size of  $3 \times 3$  cm<sup>2</sup>, each read out with high-sampling, deep-buffer oscilloscopes, capable of providing information on the time structure of hadronic showers in the calorimeter with nanosecond precision. The small number of channels is insufficient for event-by-event measurements, but is used to measure the average time structure of showers in large data samples. In addition, the information from the main calorimeters can be used to reconstruct the position of the first inelastic hadronic interaction event by event, allowing to measure the time structure of the shower at various depths with respect to the shower start, which can be used to measure the averaged timing profile over the full longitudinal and lateral extent of the shower. For the T3B setup, data with steel absorbers are available as well. For both experiments, a sophisticated calibration and reconstruction framework has been developed. To provide a robust base for comparison between the two systems and to eliminate effects from afterpulsing, the time of first hit is studied, which is defined by the time of the first energy deposit corresponding to at least the equivalent of 0.3 minimum-ionizing particles within 9.6 ns in a given cell in an event. Due to the high granularity of the readout, the probability for multiple hits in one cell in one event is on the percent level. The use of the time of first hit rather than using all observed hits thus does not result in an appreciable bias.

With both setups, hadronic showers lead to a considerable late signal component compared to the muon reference. T3B and FastRPC show a discrepancy of up to a factor of eight in the time region from 10 ns to 50 ns, a region where signals are expected to originate to a large extent from MeV-scale spallation neutrons. Due to the low density and the low hydrogen content in the RPCs, their sensitivity to this component is significantly reduced compared to plastic scintillator. These late components are substantially more pronounced in tungsten than in steel, stressing the importance of a realistic modeling of the time structure when developing tungsten-based calorimeter systems for future collider detectors. For the scintillator results, detailed comparisons to GEANT4 simulations with different hadronic shower models have already been performed. These show that while the distributions in steel are generally well modeled, the reproduction of the tungsten results requires physics lists with high precision neutron treatment, such as QGSP BERT HP.

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