PROCEEDINGS OF SCIENCE

Energy calibration for the SND@LHC hadronic calorimeter

Filippo Mei[a,b,*] **for the SND@LHC collaboration**

[a] *Università di Bologna,*
Via Zamboni 33, Bologna, Italy
[b] *INFN Bologna,*
Viale C. Berti Pichat 6/2, Bologna, Italy

E-mail: fmei@cern.ch

SND@LHC is a compact, standalone experiment located in the TI18 tunnel, 480 meters downstream of the ATLAS interaction point, designed to observe neutrinos produced in LHC proton-proton (pp) collisions. The SND@LHC detector allows for the identification of all three flavors of neutrino interactions in the pseudorapidity region $7.2 < \eta < 8.4$ within an unexplored energy range of 100 GeV < E < 1 TeV. The detector consists of two sections: an instrumented target and a hadron calorimeter. Energetic νN collisions in the target produce hadronic showers. To calibrate the hadronic calorimeter, a replica of the detector was exposed to hadron beams with energies ranging from 100 to 300 GeV at the CERN SPS H8 test beam line during the summer of 2023. The experimental setup allowed for the study of showers as a function of both energy and their starting position within the target depth. This calibration achieved an energy resolution of 12-20% for the reconstruction of hadronic showers.

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*Speaker

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1. The SND@LHC experiment

The SND@LHC detector was installed in TI18 in 2021 and it has been collecting data since the beginning of the LHC Run 3 in April 2022 [1]. The SND@LHC detector consists of a hybrid system with a $\sim$ 830 kg target made of tungsten plates interleaved with nuclear emulsion and electronic trackers, followed by a hadronic calorimeter and a muon identification system. Three planes of scintillating bars constitute the veto system, placed upstream of the detector, needed for tagging incoming charged particles. The SND@LHC experiment detects high energy neutrinos emerging from LHC collisions at very small angles, within an unexplored energy range of 100 GeV < E < 1 TeV. For all neutrino flavors, energetic νN collisions produce hadronic showers. The hadronic shower energy is one of the observables, together with shower direction and charged lepton track parameters, needed for estimating the incoming neutrino energy in charged current νN interactions. Moreover, the SND@LHC experiment will be able to test lepton flavor universality, study charmed hadron production and search for Feebly Interacting Particles.

2. Test Beam Setup

The test beam setup used a replica of the SND@LHC hadronic calorimeter (HCAL) system alongside an iron mock target instrumented with Scintillating Fiber modules (SciFi). The setup was exposed to pion beams with energies ranging from 100 to 300 GeV in the SPS H8 test beam line [2]. The goal was to calibrate the hadronic calorimeter response of the SND@LHC experiment. Therefore, detectors, front-end and data acquisition electronics were built to duplicate the hardware installed in 2022 in the LHC TI18 tunnel [1].

Three independently removable 10 cm thick (0.5 nuclear interaction lengths λ_{INT}) iron walls constituted the target, equipped with four SciFi station consisting of one horizontal and one vertical 13×13 mm^2 plane. Each plane comprised six staggered layers of 250 μm diameter polystyrene-based scintillating fibers read out by SiPM arrays.

Five Upstream (US) stations of large scintillating bars constituted the sensitive part in the HCAL, and were interleaved with 20 cm thick (1 λ_{INT}) iron walls. The US stations consisted each of ten bars of plastic ELJEN EJ 200, 60 mm wide, 830 mm long, 10 mm thick, wrapped in aluminized mylar foils and stacked horizontally. Each bar was read-out, at both left and right edge, with 6 "large" SiPMs (Hamamatsu Photonics MPPC S14160-6050HS, 6×6 mm^2) and 2 "small" SiPMs (Hamamatsu Photonics MPPC S14160-3050H, 3×3 mm^2).

A Downstream (DS) station, with two planes of 60 thin bars of 10 mm width, was also built and installed downstream the HCAL. In the first DS plane bars were arranged horizontally, in the second one vertically.

3. Analysis

Event by event, some preselection is applied on hits to reduce noise. Within an event, SciFi hits are considered “in time" if lying within ±0.5 LHC clock cycle ($\simeq$ 3 ns) from the most probable value t_{ref} of the SciFi hit distribution in time. US hits are considered “in time" if recorded within +3 LHC clock cycles ($\simeq$ 19 ns) from t_{ref}. In the US stations, only hits registered by large SiPMs

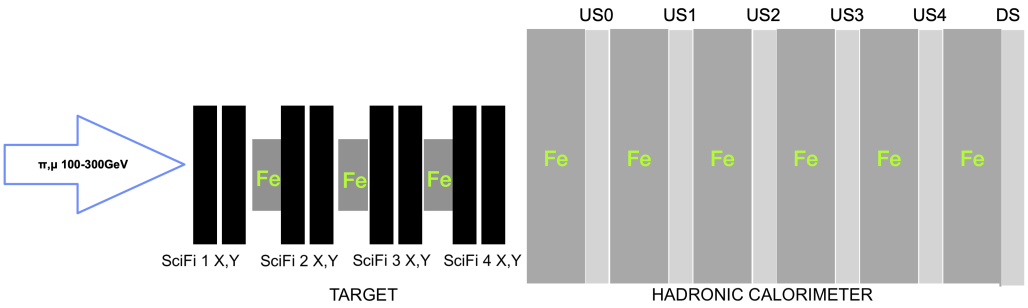

Figure 1: Sketch of the detector on the beam line. From left to right: the Target (three 10 cm thick iron walls interleaved with four SciFi X and Y planes) and the hadronic calorimeter (HCAL) (five US planes of scintillating bars interspaced with 20 cm thick iron walls, and a DS plane of thin scintillating bars).

were considered, since signals from small SiPMs were found to be dominated by cross talk from the large SiPMs.

3.1 Shower tagging

The first step in the analysis was to develop a shower tagging algorithm that, besides detecting the presence of a shower, estimated the shower origin point. The most upstream SciFi station satisfying the shower tagging requirement marks the start of the shower. The shower tagging algorithm looks for at least 36 hits within a sliding window 128 channels wide (3.2 cm), in both X and Y SciFi planes independently. This tagging algorithm gave consistent results across different test beam runs, hadron energies and number of blocks in the target. Only events tagged as showers are considered for energy calibration.

3.2 Energy calibration

The data samples collected in the target configuration with three walls were split into “calibration" and “test" samples. For every event, the main quantities considered were: origin of shower as measured with the shower tagging algorithm, the digitized integral charge (QDC) of the SiPM signals summed over “in time" SciFi hits (QDC_{SciFi}) and QDC sum of “in time" US hits (QDC_{US}).

Both the mean QDC_{SciFi} and QDC_{US} increase with beam energy. However, while the mean QDC_{SciFi} decreases the more downstream the shower originated along the target, the mean QDC_{US} increases the more downstream the shower started within the target. This behavior is expected and can be modeled as:

$$E_{tot} = k * QDC_{SciFi} + \alpha * QDC_{US} \tag{1}$$

where E_{tot} is the hadron energy, k and α two calibration constants to be determined.

A clear linear anti-correlation in the QDC_{SciFi}–QDC_{US} phase space is found across all beam energies and shower origins. Principal Component Analysis (PCA) can be used to calculate k and α of eq.(1) (Fig. 2). In fact, from the line describing the major axis of the phase space ellipse one extracts k and α.

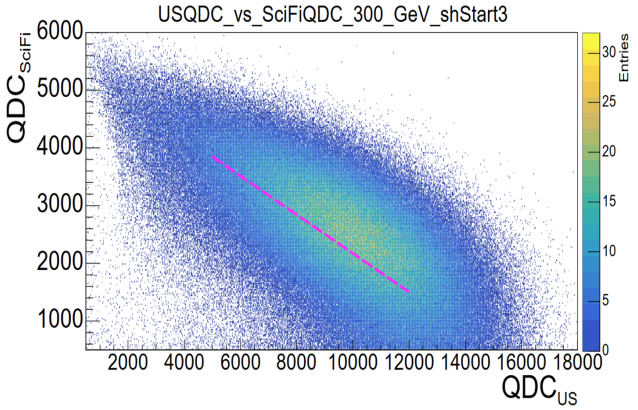

Figure 2: Given the anti-correlation between (QDC_{SciFi}) and QDC_{US}, PCA finds the major axis of the ellipse, used to evaluate the calibration constants k and α. The plot show data from 180 GeV beam energy for showers originated in target wall 2 (tagged by SciFi3).

The correlation is much less pronounced when the shower begins late in the final λ_{INT} of the target, the third iron wall in the test beam setup: in this configuration the shower is sampled by one SciFi station only (SciFi4) in the target, and the energy deposit is maximal in the first US layer, which can induce saturation of the SiPMs. Thus, these kind of showers cannot share the same calibration constants as the “ordinary" ones (with origin in the first two target iron walls) and the energy reconstruction is less precise.

3.3 Energy resolution

The hadron energy from data of the test samples are reconstructed using the obtained calibration constants. The standard deviation of the Gaussian fit to the core of each reconstructed energy distribution gives an estimate of the energy resolution. The reconstructed energy for showers starting in SciFi2 and SciFi3 is consistent with the true hadron energy across the whole energy range. The achieved energy resolution is shown in Fig. 3, ranging from 22% at 100 GeV to 12% at 300 GeV.

3.4 Comparison with Monte Carlo simulation

The energy calibration procedure for Monte Carlo simulated data follows a similar approach as that used for the experimental data. However, rather than using the total signal per event recorded in the SciFi and US detectors, the calibration is performed using the total energy losses per event in these detectors. This yields the energy response and resolution corresponding to an ideal scenario. The energy calibration performed with the test beam data yielded, for ‘ordinary’ showers, an energy resolution in reasonable agreement with the Monte Carlo ideal case (Fig. 4).

4. Conclusions

To calibrate the energy measurement, a replica of the SND@LHC detector was exposed to hadron beams of 100–300 GeV at the CERN SPS H8 beamline. The setup included a full-scale hadron calorimeter and a partial target section, replicating three of the five SND@LHC target walls.

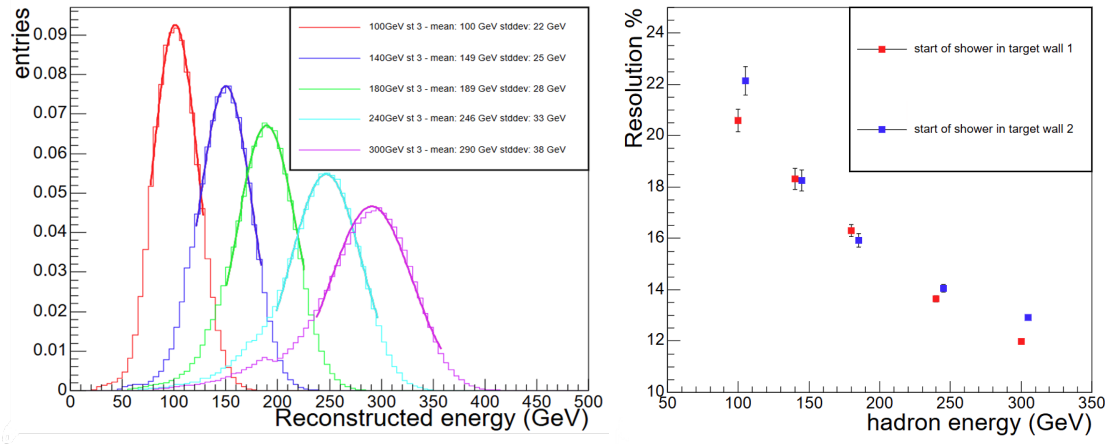

Figure 3: On the left, reconstructed energy E_{tot} for showers originated in target wall 2 (tagged by SciFi3), with several beam energies. On the right, energy resolution (standard deviation of the reconstructed energy divided by the beam energy) as a function of the pion beam energy.

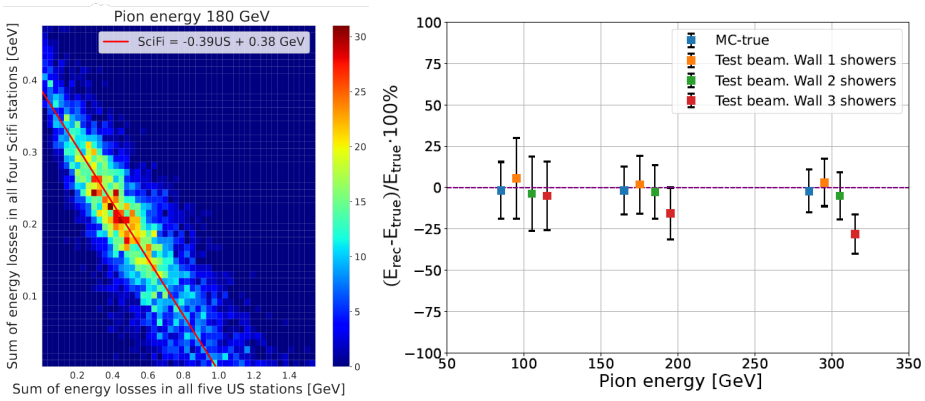

Figure 4: Results from Monte Carlo simulation. On the left, deposited energy in SciFi vs US, and, on the right, relative offset between reconstructed energy E_{reco} and initial pion energy E_{true}, including comparison with results form test beam data.

The study focused on the dependence of energy sharing between the target and calorimeter on the shower origin depth, identified using the in-time hit density in SciFi tracking planes. Energy calibration was performed using Principal Component Analysis to derive QDC-to-GeV conversion factors. For “ordinary" showers, with origin in the first two target iron walls, an energy resolution ranging from 22% at 100 GeV to 12% at 300 GeV was achieved, consistent with Monte Carlo expectations.

References

[1] SND@LHC collaboration, SND@LHC: The Scattering and Neutrino Detector at the LHC. JINST 19 P05067 (2024)

[2] SND@LHC collaboration, Studies of Hadronic Showers in SND@LHC. arXiv:2504.01716 (2025), submitted for publication to JINST