Testbeam performance of a shashlik calorimeter with fine-grained longitudinal segmentation

G. Ballerini, A. Berra, R. Boanta, C. Brizzolari, G. Brunetti, M.G. Catanesi, S. Cecchini, F. Cindolo, A. Coffani, G. Collazuol, E. Conti, F. Dal Corso, G. De Rosa, A. Gola, C. Jollet, A. Longhin, L. Ludovici, L. Magaletti, G. Mandrioli, A. Margotti, V. Mascagna, A. Meregaglia, M. Pari, L. Pasqualini, G. Paternoster, L. Patrizii, C. Piemonte, M. Pozzato, F. Pupilli, M. Prest, E. Radicioni, A.C. Ruggeri, G. Sirri, M. Soldani, M. Tenti, F. Terranova and E. Vallazza

a) Università degli Studi dell’Insubria, Via Valleggio 11, Como, Italy
b) INFN — Sezione di Milano Bicocca, Piazza della Scienza 3, Milano, Italy
c) Università degli Studi di Milano Bicocca, Piazza della Scienza 3, Milano, Italy
d) INFN — Sezione di Bari, Via E. Orabona 4, Bari, Italy
e) INFN — Sezione di Bologna, Via Berti Pichat 6, Bologna, Italy
f) Università degli Studi di Padova, Via Marzolo 8, Padova, Italy
g) INFN — Sezione di Padova, Via Marzolo 8, Padova, Italy
h) INFN — Sezione di Napoli, Via Cintia, Napoli, Italy
i) Fondazione Bruno Kessler, Via Sommarive 18, Povo, Trento, Italy
l) Institute Pluridisciplinaire Hubert Curien, 23 rue du Loess, Strasbourg, France
m) Centre de Etudes Nucleaires de Bordeaux Gradignan, 19 Chemin du Solarium, Bordeaux, France
n) INFN — Sezione di Roma, Piazzale Aldo Moro 2, Roma, Italy
o) Università degli Studi di Bologna, Via Irnerio 46, Bologna, Italy
p) INFN — Sezione di Trieste, Padriciano 99, 34012 Trieste, Italy

E-mail: francesco.terranova@cern.ch

Abstract: An iron-plastic-scintillator shashlik calorimeter with a 4.3 X_0 longitudinal segmentation was tested in November 2016 at the CERN East Area facility with charged particles up to 5 GeV. The performance of this detector in terms of electron energy resolution, linearity, response to muons and hadron showers are presented in this paper and compared with simulation. Such a fine-grained longitudinal segmentation is achieved using a very compact light readout system developed by the SCENTT and ENUBET Collaborations, which is based on fiber-SiPM coupling boards embedded in the bulk of the detector. We demonstrate that this system fulfills the requirements for neutrino physics applications and discuss performance and additional improvements.

Keywords: Calorimeters; Neutrino detectors; Photon detectors for UV, visible and IR photons (solid-state)

Corresponding author.
1 Introduction

Shashlik calorimeters [1, 2] are sampling calorimeters in which the scintillation light is read-out by wavelength shifting (WLS) fibers running perpendicularly to the absorber and converter plates. Shashlik devices are used since more than 20 years in particle physics [4–8] but the recent developments in the technology of silicon-based photosensors provide new solutions for light collection and readout [9–14] and open a broader range of applications for shashlik detectors [15, 16]. The most critical limitation of these calorimeters is due to longitudinal segmentation. Since the light is transmitted to the photosensors in a matrix of parallel WLS fibers, bundling and routing of the fibers must be performed at the back of the calorimeter, preventing longitudinal segmentation. Large area photosensors directly coupled to the scintillator provide longitudinal segmentation at the price of introducing dead areas [17]. In calorimetric applications [12–14] Silicon PhotoMultipliers (SiPM) offer performance comparable with conventional PMT but can be miniaturized down to the scale of a SMD component, whose size can be matched to the diameter of the WLS fibers [18].

The INFN SCENTT Collaboration has developed an ultra-compact module (UCM - figure 1) where every single fiber segment is directly connected to a SiPM. The array of SiPMs reading the UCM is hosted on a PCB (Printed Circuit Board) holder that integrates both the passive components and the signal routing toward the front-end electronics. The calorimeters are assembled grouping arrays of UCMs, whose size and thickness (in radiation lengths, $X_0$) are optimized for specific physics applications.

This scheme combines the compactness of SiPM-based calorimeters [19] with the flexibility offered by the shashlik technology in choosing the longitudinal sampling (length of the fiber crossing the scintillator/absorber tiles) and transverse granularity (tile size, number of fibers per unit surface and number of summed SiPM channels).
Figure 1. (a) Layout of the SCENTT ultra-compact module (UCM). The UCM samples $4.3X_0$ and has a transverse size of $3\times 3$ cm$^2$. The light is collected by 9 WLS fibers coupled to 9 SiPMs on the PCB connected to the plastic mask (“sensor plane”). (b) Photo of a UCM used for cosmic ray tests: the PCB is not mounted and the plastic mask holding the fibers is visible in the back of the detector.

The first UCM based calorimeter (“12-module prototype”) was tested in summer 2016 and results are reported in ref. [20]. The calorimeter tested in November 2016 allows for complete (i.e. transverse and longitudinal) containment of electromagnetic showers and longitudinal containment of hadronic showers in the energy range of interest for ENUBET [16] (1–5 GeV). In ENUBET, UCM-based calorimeters are employed to monitor positron production in the decay tunnel of conventional neutrino beams to perform a precise measurement of the $\nu_e$ flux originating from
kaon decays ($K^+ \rightarrow e^+\pi^0\nu_e$). For this application, a longitudinal segmentation of about $4X_0$ is needed to separate positrons from charged pions with a misidentification probability $<3\%$ [21]. The most cost-effective solution is based on an iron-plastic scintillator UCM with $3 \times 3$ cm$^2$ tiles (see section 2).

The calorimeter tested in November 2016 is made of 56 UCMs and a coarse grained energy catcher located on top of the UCM. The layout and construction technique employed for this detector are described in section 2. The calorimeter was characterized at the CERN East Area (T9 beamline): the experimental area and the ancillary detectors (silicon trackers, muon catcher, Cerenkov counters) are described in section 3. Simulation and equalization of the response are detailed in section 4 and the detector response to electromagnetic showers is discussed in section 5. The response to charged pions and comparisons with simulation are presented in section 6.

2 Layout and construction of the calorimeter

The calorimeter is made up of 56 UCM modules: $4 \times 2$ in the plane perpendicular to the beam and 7 in the longitudinal direction. On top of this system, an energy tail catcher (“hadronic module”) is positioned. The thickness of the iron absorber is 1.5 cm and the thickness of the scintillator tile is 0.5 cm. The light produced in the scintillator is readout by 9 WLS fibers (diameter: 1 mm, length:10 cm) and each UCM is composed by five tiles: it thus samples $4.3X_0$ along the development of the shower and 1.7 Moliere radius in the transverse plane.

The UCMs are assembled from $12 \times 6$ cm$^2$ iron slabs (standard EN-10025: S235–Fe 360) with 1.5 cm thickness (figure 2). The slabs are drilled with a CNC machine: the distance between holes is 1 cm and the diameter of the holes is $1.2 \pm 0.2$ mm. After drilling, electrolytic zinc-plating is employed to prevent oxidation.

![Image](image.png)

**Figure 2.** An iron slab after drilling and before zinc coating. The four 2 mm holes for the threaded bolt are located in the proximity of the corners.
The scintillator tiles (3×3 cm², thickness 0.5 cm) are machined using the same procedure employed for the 12-module prototype [20]: the tiles were machined and polished from EJ-200 [22] plastic scintillator sheets and painted with a diffusive TiO₂-based coating (EJ-510). Diffusive coating is used to increase the light collection efficiency and eases the assembly of the modules compared with more conventional techniques employed in shashlik devices (e.g. insertion of Tyvek® foils between the scintillator and absorber tiles). The painted scintillators are positioned into the CNC machine in stacks (up to 4 tiles per stack) and drilled. Each tile has 9 holes with a diameter of 1.2±0.1 mm. A module of 8 UCMs is assembled from five iron slabs interleaved with planes of scintillator tiles (8 tiles per slab). The 1 mm diameter WLS fibers cross the modules through the holes up to the last scintillator plane and are connected to a plastic mask located downstream of the module, as shown in figure 3.

Figure 3. A module of 8 UCMs before the installation of the PCB. The WLS fibers are hold by the black plastic mask on top.

The plastic mask (see figure 4) is built using a 3D printer: it is grooved in order to fix the fibers in the back of the module and couple them with the PCB hosting the SiPMs. Four threaded bolts (2 mm diameter) cross the module and are fixed to the plastic mask by nuts positioned into the mask itself. The fibers used for the first six modules are Kuraray [23] Y11 multi-clad (1 mm diameter). The last module is equipped with Saint Gobain [24] BCF92 multi-clad fibers. These fibers offer a fast response (2.7 ns) compared with Y11 (10 ns) but exhibit a poorer optical matching to EJ-200, resulting in a 30% reduction of the light yield.

The energy tail catcher (hadronic module) is built using the same technology as for the UCM modules with a coarser granularity. The size of the iron slabs is 18×9 cm² (1.5 cm thickness). The hole density (1 hole/cm², 1.2 mm diameter) is the same as for the fine-grained modules. The scintillator tiles of the hadronic module are, however, much larger: each tile is 18×9 cm² (thickness 0.5 cm) and the hadronic module is made of 31 iron slabs interleaved with scintillator tiles. The tiles are painted and drilled using the same procedure employed for the fine-grained modules and the light is read out by BCF92 fibers (1 mm diameter).
Figure 4. The plastic mask holding the fibers and the PCB (not shown). The grooves in the proximity of the fibers host the SiPMs.

The layout of the calorimeter with the hadronic module on top of the fine-grained modules is shown in figure 5 (a). During the testbeam the calorimeter was rotated by 90° (see section 3) and positioned on the movable platform shown in figure 5 (b).

The light transmitted by the fibers is read by 1 mm² SiPMs with 20 µm cell size. The sensors are developed by FBK [25] and are based on the n-on-p RGB-HD technology. Each SiPM hosts 2500 cells in a 1 mm² square with a fill factor of 66% [26]. Each module, corresponding to 8 UCMs, requires the installation of 9×8=72 SiPMs. The fine grained calorimeter (7 modules) hence hosts 504 SiPMs and the hadron module is read by 162 SiPMs. These SiPMs were produced by FBK from a single wafer and encapsulated in a chip-scale epoxy package (SMD package) by Advansid srl [27]. The V-I response was characterized at the production site. Since all SiPMs of the calorimeter were produced starting from the same silicon wafer and in a single lot, the breakdown voltage is very uniform among the sensors: 28.2±0.1 V.

The SiPMs are mounted as standard SMD components on a custom 6-layer PCB hosting all the sensors belonging to the same module (figure 6). The SiPMs belonging to the same UCM are connected in parallel and read out without amplification through a 47 pF decoupling capacitor.

The PCB is equipped with a flap hosting 8 MCX connectors to read the signal of the UCMs (figure 7). In the PCBs used for the calorimeter the bias is the same for all SiPMs and it is distributed by a coaxial cable. During the testbeam all the SiPMs were biased at 36 V and the equalization among UCMs performed using the response to minimum ionizing particles (see section 4).

The hadronic module is read out using a 18×9 cm² PCB, corresponding to 18 UCMs. Unlike the fine-grained modules, however, the tiles of the UCMs are not optically isolated. All PCBs are connected to the back of the modules using PTFE screws positioned between the PCB and the plastic mask. The SiPMs are aligned to the fibers in the transverse plane with a precision of 0.1 mm via the mechanical coupling of the PCB with the plastic mask.
Figure 5. (a) Layout of the calorimeter: 7 fine-grained modules and, on top, the hadronic module (b) Photo of the calorimeter during the installation on the movable platform. The calorimeter is rotated by 90° with respect to the layout.

The signals from the UCM are recorded by a set of 8 channel v1720 CAEN [28] digitizers (12 bit, 250 MS). All waveforms are recorded by the DAQ. A reduced dataset is produced for analysis employing a peak finding algorithm to the waveform data [18].

3 Test setup in the T9 beamline

The calorimeter was exposed to electrons, muons and pions at the CERN PS East Area facility for two weeks in November 2016. The momentum of the particles was varied between 1 and 5 GeV, i.e.
in the range of interest for ENUBET. The detector was positioned inside a metallic box to ensure light tightness and mounted on a platform in the T9 experimental area in front of two silicon strip detectors (see figure 8). During the data taking the calorimeter was tilted at different angles (0, 50, 100, 200 mrad) with respect to the beam direction (figure 9).

The silicon detectors [20, 29] provide track reconstruction with a spatial resolution of 30 µm. A pair of threshold Cherenkov counters filled with CO₂ are located upstream of the silicon detectors. The maximum operation pressure of the counters is 2.5 bar: they were thus used to separate electrons from heavier particles (µ or π) below 3 GeV. Between 3 GeV and 5 GeV the two counters were operated at different pressures to identify electrons, muons and pions.
Figure 8. Layout of the instrumentation in the experimental area. Detectors include the Calorimeter, two Cherenkov counters (Cher A and B), two silicon chambers (SiBC), the muon catcher (scint 1 and 2) and the trigger scintillator plane (Scinti).

Figure 9. The calorimeter positioned inside the metallic box and tilted by 100 mrad with respect to the beam axis using a threaded bolt (top left of the image).

A $10 \times 10$ cm$^2$ plastic scintillator located between the silicon and Cherenkov detectors is employed as trigger for the DAQ. Two pads of plastic scintillator (“muon catcher”) are positioned after the calorimeter between a 20 cm thick iron shield in order to identify muons or non-interacting pions.

Particles in the beamline are obtained from the interaction of the primary 24 GeV/c protons of the CERN-PS accelerator with a fixed target. During the test, we employed the T9 “electron enriched” target. It consists of an Aluminum tungsten target ($3 \times 5 \times 100$ cm$^2$) followed by a tungsten cylinder (diameter: 10 cm, length: 3 cm). We set the collimators in order to provide a momentum bite of 1%. At 3 GeV the beam composition as measured by the Cherenkov counters is 9% electrons, 14% muons and 77% hadrons. We only selected negative particles in the beamline and the contamination of protons and undecayed kaons is thus negligible.
The DAQ system is based on a standard VME system controlled by a SBS Bit3 model 620 bridge, optically linked to a Linux PC-system. The DAQ is located in the proximity of the calorimeter, inside the experimental area. Slow control parameters (HV settings for the Cherenkov counters and the scintillators) and configuration setting for DAQ (start-stop of the run, quality control) are performed by a dedicated PC in the Control Room connected to the DAQ PC using a Gigabit Ethernet link. The acquisition is triggered by the coincidence of the beam spill (400 ms) and the signal in the plastic scintillator. The signals from the Cherenkov counters and muon catcher are recorded for each trigger and used off-line for particle identification. Zero suppression in the silicon chambers is performed in the front-end electronics [29]. During the test, ∼500 particles per spill and 200-500 spills per run were recorded. The acquisition rate was limited by the waveform digitizers.

4 Simulation and signal equalization

The signal response to minimum ionizing particles (mip) of each UCM was measured using a high statistics sample of non-interacting pions (mip peak) at 9 GeV and checked with a low statistics muon sample at 4 GeV. The distribution of the signal response for each UCM is show in figure 10. Variation of the signal response among UCM hosted in the same plastic mask and SiPM board amounts to 20–30%. Changes of the response among boards are also visible both for the UCM equipped with Y11 and with BCF-92 fibers. The response is stable in time within the uncertainty of the position of the mip-like peak (figure 11) and it is not correlated with changes in temperature. The dominant contribution to response non-uniformity is due to misalignment of the fibers with respect to the SiPM and the use of SiPMs of the same size as the diameter of the fibers [31]. Ancillary measurements performed with single UCMs (figure 12) show that the current mechanical system based on the plastic mask provides a tolerance of 0.3 mm, which results in a light collection efficiency reduction of about 25% and an average number of photoelectrons per mip of ∼40.

The detector response was simulated with GEANT4 [32–34]. The simulation includes the iron-scintillator tiles, the WLS fibers and additional material due to the plastic mask and PCB. It does not include photon generation, transport and the misalignment between the fibers and the photosensors. The expected signal in each UCM is thus proportional to the energy deposit in the scintillator smeared with the contribution due to photoelectron statistics. The physics list employed is FTFP_BERT_HP [34, 35].

The relative response of each UCM is equalized using the mip peak. Figure 13 shows the response of the detector for 4 GeV muons impinging on the front face of the calorimeter.

5 Response to electrons

The response to electromagnetic showers was evaluated selecting electrons in the 1–5 GeV energy range. The impact point of the particles is estimated from the silicon chambers with a precision of 200 µm.

The calorimeter under test provides full containment of electromagnetic showers up to 5 GeV for particles impinging on the front face and from the lateral side (tilted runs). The tilted geometry
Figure 10. Signal response to minimum ionizing particles (mip) of each UCM. The UCMs belonging to the same module are indicated between vertical lines. The WLS fibers used for the module are also shown.

Figure 11. Response of one of the UCM to mips as a function of time (in seconds).
**Figure 12.** Pulse height reduction as a function of the distance between the SiPM and the WLS fibers. The closest point (0.3 mm) corresponds to the thickness of the epoxy package of the SiPM.

**Figure 13.** Distribution of the energy deposited in the scintillator by 4 GeV muons impinging on the front face of the calorimeter for data (blue dots) and simulation (red line).
reproduces the operating condition of the calorimeter in the decay tunnel of neutrino beams, where positrons from $K^+ \rightarrow e^+\pi^0\nu_e$ reach the detector with an average angle of $\sim 100$ mrad [16, 30].

The energy and tilt angles of relevance for neutrino physics applications were tested with dedicated runs at 1, 2, 3, 4, and 5 GeV and tilts of 0, 50, 100, and 200 mrad. Electrons are selected by the Cherenkov counters located upstream the silicon detectors. The silicon chambers are used to select single particles impinging in a fiducial area with negligible lateral leakage. For particles impinging on the from face (0 mrad runs), the fiducial area is $6 \times 4$ cm$^2$ (see figure 14). The fiducial areas for tilted runs corresponds to particles impinging in the two innermost UCM from below (see figure 14).

![Fiducial area for 0 mrad runs](Image)

![Fiducial area for 100 mrad runs](Image)

Figure 14. Fiducial areas (gold) selected on the front face of the calorimeter projecting the tracks reconstructed by the silicon chambers to the uppermost UCM. The left red area corresponds to particles impinging in the uppermost UCM from below with an angle of 100 mrad.

The energy resolution as a function of the beam energy for particles impinging on the front face (0 mrad runs) is shown in figure 15 for data (red squares) and simulation (blue stars). The points are fitted to $\sigma_E/E = S/\sqrt{E(\text{GeV})} + C$, $S$ and $C$ being the sampling (stochastic) and constant term, respectively. Figure 16 show the resolution for particles impinging at 100 and 200 mrad.

The 0 mrad runs support the finding of the 12-module prototype, i.e. that the dominant contribution to the resolution is due to the sampling term and that the energy response is not affected by the light readout scheme employed to achieve longitudinal segmentation. In addition, the analysis of the tilted runs indicates that the performance of the calorimeter is similar to the 0 mrad run in the angular range of interest for ENUBET. This behaviour, which is very relevant for neutrino physics applications, is properly simulated by GEANT4.

The calorimeter shows linear response in the whole range of interest within $< 3\%$ in both standard (0 mrad) and tilted runs (see figure 17). Again, such performance is within the needs for neutrino physics applications. Unlike the 12-module prototype, where non-linearities at high energy could be attributed to longitudinal leakage, the calorimeter under test provides full containment and the dynamic range of the SiPM is such that saturation effects are negligible. Residual non-linearities will be tested with an improved fiber-to-SiPM connection system and up to a higher energy range.

6 Response to charged pions

Longitudinal segmentation is commonly employed in calorimetry for electron/hadron separation. In fact, a longitudinally segmented calorimeter is needed in ENUBET for $e^+ /\pi^+$ separation in the
Figure 15. Energy resolution versus beam momentum for particles impinging on the front face (0 mrad run) for data (blue squares) and simulation (red triangles). The fit parameters for simulation (MC) and data are shown in the top and bottom insets.

few GeV range. In order to validate the ENUBET simulation, a comparison of the calorimeter response for (negative) pions and electrons has been carried out.

Figure 18 left (right) shows the average energy deposited in the scintillator (data/MC ratio) as a function of shower depth for 3 GeV pions and electrons. The depth is expressed in number of UCM, i.e. figure 18 shows the average energy per event that is deposited in the UCMs located at a depth \( n \) with respect to the impact point. \( n = 1 \) \((n = 7)\) corresponds to the most upstream (downstream) UCM with respect to the beam and each UCM samples 0.44 nuclear interaction lengths \((\lambda_0)\). The whole calorimeter depth corresponds to \( 7 \times 4.3X_0 = 30.1X_0 \) and 3.09 \( \lambda_0 \).

The fiducial area is selected as in section 5 using the silicon trackers. In this plot, the energy of the hadronic module is not employed since this module is not longitudinally segmented. The longitudinal profile is reproduced by MC within 10% for pions and 5% for electrons. These differences are due to limitations both in the detector description (photon production and transport, local variations in the SiPM-to-fiber matching, light saturation effects [36, 37]) and in the simulation of hadronic showers [38].

Finally, the energy response of the detector (sum of the signal in all UCMs) for electrons, muons and pions at 3 GeV is shown in figure 19. In this plot, the energy scale is determined by the electron response. The MC response for muons and interacting pions is re-scaled by 1.10 and 0.91, respectively to account for the MC limitations mentioned above. The correction coefficients provide a good agreement with data in the full energy range (1–5 GeV).
Figure 16. Energy resolution versus beam momentum for particles impinging at 100 mrad (upper plot) and 200 mrad (lower plot) for data (blue squares) and simulation (red triangles). The fit parameters for simulation (MC) and data are shown in the top and bottom insets.
Figure 17. Energy reconstructed in the calorimeter versus beam energy for a 0 mrad (upper plot) and 100 mrad (lower plot) run. The horizontal errors correspond to the momentum bite of the beam.
Figure 18. (Left) Average energy deposited in the scintillator as a function of shower depth for 3 GeV pions and electrons. The depth is expressed in n. of UCM (see text). Each UCM corresponds to 0.44 $\lambda_0$. (Right) Energy ratio between data and MC.

Figure 19. Distribution of the energy deposited in the scintillator (in MeV) for electrons, muons and pions in a 3 GeV, 0 mrad run. The beam composition as measured by the Cherenkov detectors is shown in parenthesis. The black dots (thick yellow line) is the sum of all particle signals in data (MC).
7 Conclusions

Fine grained longitudinal segmentation can be achieved in shashlik calorimeters embedding the SiPMs in the bulk of the calorimeter through a direct fiber to SiPM connection. We studied a calorimeter made of 56 modules with a granularity of 4.3 $X_0$ optimized for neutrino physics applications and we validated its performance at the CERN East Area facility. The electromagnetic energy resolution — $17\%/\sqrt{E(\text{GeV})}$ — and linearity — <3% in the 1–5 GeV range — is appropriate for the needs of ENUBET. No significant changes are observed in tilted runs up to 200 mrad compared with runs where particles impinge on the front face.

The fiber-to-SiPM mechanical coupling system needs additional improvements since it presently dominates the non-uniformity of the response among UCMs. This effect can be corrected equalizing the UCM response to mip and does not compromise the detector performance. The MC properly simulates the response to electrons and muons. The longitudinal energy profiles of partially contained pions is reproduced by MC with a precision of 10%. Further improvements in the description of the UCM signals call for an amelioration of the SiPM-to-fiber connection system and a full optical simulation.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168 and no. 681647. The authors gratefully acknowledge CERN and the PS staff for successfully operating the East Experimental Area and for continuous supports to the users. We thank L. Gatignon, M. Jeckel and H. Wilkens for help and suggestions during the data taking on the PS-T9 beamline. We are grateful to the INFN workshops of Bologna, LNF, Milano Bicocca and Padova for the construction of detector and, in particular, to D. Agugliaro, S. Banfi, F. Chignoli, M Furini, R. Gaigher, L. Garizzo, R. Mazza, L. Ramina and F. Zuffa. Finally, we wish to thank V. Bonvicini, P. Branchini and A. Lanza for suggestions and support in the design and construction phase of the experiment.

References

[1] H. Fessler et al., A tower structured scintillator lead photon calorimeter using a novel fiber optics readout system, Nucl. Instrum. Meth. A 228 (1985) 303.
[2] G. S. Atoyan et al., Lead-scintillator electromagnetic calorimeter with wavelength shifting fiber readout, Nucl. Instrum. Meth. A 320 (1992) 144.
[3] J. Badier et al., Shashlik calorimeter: Beam test results, Nucl. Instrum. Meth. A 348 (1994) 74.
[4] DELPHI STIC collaboration, S.J. Alvsvaag et al., The small angle tile calorimeter in the DELPHI experiment, Nucl. Instrum. Meth. A 425 (1999) 106.
[5] PHENIX collaboration, L. Aphecetche et al., PHENIX calorimeter, Nucl. Instrum. Meth. A 499 (2003) 521.
[6] HERA-B collaboration, A. Zoccoli et al., The electromagnetic calorimeter of the HERA-B experiment, Nucl. Instrum. Meth. A 446 (2000) 246.
[7] ZEUS collaboration, F. Goebel, *Performance of the ZEUS forward plug calorimeter*, *Nucl. Instrum. Meth.* A 453 (2000) 230.

[8] LHCb collaboration, R. Dzhelyadin, *The LHCb calorimeter detectors*, *Nucl. Instrum. Meth.* A 581 (2007) 384.

[9] G.S. Atoyan et al., *An improved Shashlyk calorimeter*, *Nucl. Instrum. Meth.* A 584 (2008) 291 [arXiv:0709.4514].

[10] ALICE collaboration, A. Fantoni et al., *The ALICE electromagnetic calorimeter: EMCAL*, *J. Phys. Conf. Ser.* 293 (2011) 012043.

[11] N. Anfimov et al., *Shashlyk EM calorimeter prototype readout by MAPD with superhigh pixel density for COMPASS II*, *Nucl. Instrum. Meth.* A 718 (2013) 75.

[12] A. Berra et al., *Silicon photomultipliers as a readout system for a scintillator-lead Shashlik calorimeter*, *IEEE Trans. Nucl. Sci.* 58 (2011) 1297.

[13] A. Berra et al., *A shashlik calorimeter readout with silicon photomultipliers with no amplification of the output signal*, 2011 JINST 6 P10004.

[14] A. Berra et al., *Characterization of a DAQ system for the readout of a SiPM based shashlik calorimeter*, *Nucl. Instrum. Meth.* A 735 (2014) 422.

[15] SHIP collaboration, M. Anelli et al., *A facility to Search for Hidden Particles (SHiP) at the CERN SPS*, arXiv:1504.04956 [CERN-SPSC-2015-016].

[16] ENUBET collaboration, A. Berra et al., *Enabling precise measurements of flux in accelerator neutrino beams: the ENUBET project*, CERN-SPSC-2016-036 (2016).

[17] CALEIDO collaboration, A.C. Benvenuti et al., *An electromagnetic shashlik calorimeter with longitudinal segmentation*, *Nucl. Instrum. Meth.* A 432 (1999) 232.

[18] A. Berra et al., *A compact light readout system for longitudinally segmented shashlik calorimeters*, *Nucl. Instrum. Meth.* A 830 (2016) 345 [arXiv:1605.09630].

[19] CALICE collaboration, C. Adloff et al., *Construction and Commissioning of the CALICE Analog Hadron Calorimeter Prototype*, 2010 JINST 5 P05004.

[20] SCENTT collaboration, A. Berra et al., *Shashlik calorimeters with embedded SiPMs for longitudinal segmentation*, *IEEE Trans. Nucl. Sci.* 64 (2017) 1056.

[21] A. Meregaglia, *ENUBET: Enhanced NeUtrino BEams from kaon Tagging*, 2016 JINST 11 C12040.

[22] ELJEN Technology, 1300 W. Broadway, Sweetwater, TX 79556, U.S.A.

[23] KURARAY CO., LTD., Ote Center Building,1-1-3, Otemachi, Chiyoda-ku, Tokyo 100-8115, Japan.

[24] Saint-Gobain Group, Les Miroirs 18, avenue d’Alsace, 92400 Courbevoie, France.

[25] Fondazione Bruno Kessler, via Santa Croce 77, I-38100, Trento, Italy.

[26] F. Acerbi, *High-density cell and high-efficiency silicon photomultipliers*, talk given at the 2015 Single Photon Workshop (SPW2015), July 13–17, Geneva, Switzerland (2017).

[27] Advansid s.r.t., Via Sommarive 18, I-38123, Povo, Trento, Italy.

[28] CAEN S.p.A. Via Vetraia, 11, 55049, Viareggio, Lucca, Italy.

[29] M. Prest et al., *The AGILE silicon tracker: an innovative gamma-ray instrument for space*, *Nucl. Instrum. Meth.* A 501 (2003) 280.
[30] A. Longhin, L. Ludovici and F. Terranova, *A novel technique for the measurement of the electron neutrino cross section*, *Eur. Phys. J. C* 75 (2015) 155.

[31] G. Balbi et al., *Test and simulation of plastic scintillator strips readout by silicon photomultipliers*, 2014 *JINST* 9 T04004.

[32] GEANT4 collaboration, S. Agostinelli et al., *GEANT4 — a Simulation toolkit*, *Nucl. Instrum. Meth. A* 506 (2003) 250.

[33] GEANT4 collaboration, J. Allison et al., *GEANT4 developments and applications*, *IEEE Trans. Nucl Sci.* 53 (2006) 270.

[34] J. Allison et al., *Recent developments in GEANT4*, *Nucl. Instrum. Meth. A* 835 (2016) 186.

[35] GEANT4 Hadronic Working Group, A. Dotti, *Description of hadron-induced showers in calorimeters using the GEANT4 simulation toolkit*, *IEEE Nucl. Sci. Symp. Conf. Rec. NSS/MIC* (2012).

[36] J.B. Birks, *The theory and practice of scintillation counting*, Pergamon, Oxford U.K. (1964).

[37] N. Akchurin et al., *Lessons from Monte Carlo simulations of the performance of a dual-readout fiber calorimeter*, *Nucl. Instrum. Meth. A* 762 (2014) 100.

[38] GEANT4 physics validation and verification (ATLAS TileCal), http://geant4.cern.ch/results/validation_plots/full_setup/HEP_detectors/ATLAS/atlas_calo.shtml