Shashlik Calorimeters With Embedded SiPMs for Longitudinal Segmentation

A. Berra, C. Brizzolari, S. Cecchini, F. Chignoli, F. Cindolo, G. Collazuol, C. Delogu, A. Gola, C. Jollet,
A. Longhin, L. Ludovici, G. Mandrioli, A. Margotti, V. Mascagna, N. Mauri, R. Mazza, A. Meregaglia,
A. Paoloni, L. Pasqualini, G. Paternoster, L. Patrizii, C. Piemonte, M. Pozzato, F. Pupilli,
M. Prest, G. Sirri, F. Terranova, E. Vallazza, and L. Votano

***Abstract*— Effective longitudinal segmentation of shashlik calorimeters can be achieved taking advantage of the compactness and reliability of silicon photomultipliers. These photosensors can be embedded in the bulk of the calorimeter and are employed to design very compact shashlik modules that sample electromagnetic and hadronic showers every few radiation lengths. In this paper, we discuss the performance of a calorimeter made up of 12 such modules and able to sample showers every $\sim 4X_0$. In summer 2016, this prototype has been exposed to electrons, muons, and hadrons at CERN PS (East Area T9 beamline). The performances in terms of energy resolution, linearity, response to minimum ionizing particles, and reconstruction of the shower profile are discussed.**

***Index Terms*— Optoelectronics and photonic sensors, Scintillator counters.**

I. Introduction

SHASHLIK calorimeters [1], [2] have been widely used in collider and fixed target experiments since more than two decades. In the last few years, interest toward a new generation of these detectors has grown due to the possibility of combining the classical shashlik readout scheme with silicon-based photosensors [3]–[7] or extremely high radiation hard materials [8]–[10]. The INFN SCENTT Collaboration is developing longitudinally segmented shashlik modules embedding silicon photomultipliers (SiPMs) in the bulk of the calorimeter. In the SCENTT design, each fiber segment is directly connected to a SiPM. Instead of grouping fibers, all the SiPMs connected to fibers belonging to the same tile are hosted on a PCB in the back of an ultracompact module (UCM; see Fig. 1) and the output signal is summed and routed toward the front-end electronics. This readout scheme is extremely flexible: the length of the fibers crossing the scintillator/absorber tiles determines the longitudinal sampling of the calorimeter, while the tile size and the number of summed SiPMs fix the transverse granularity of the modules. The SCENTT calorimeters are modular and are assembled from arrays of UCMs, whose signal is brought to the front-end electronics (fast digitizers) by copper–Kapton lines. This construction scheme is motivated by neutrino physics applications [11]–[13], but it is suitable for collider and fixed target experiments as well.

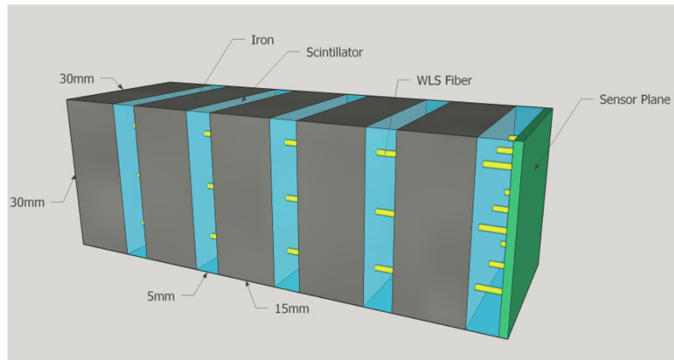


Fig. 1. Layout of the SCENTT UCM. The UCM samples $4.3X_0$ and has a transverse size of 3×3 cm^2. The scintillation light is collected by nine WLS fibers coupled to nine SiPMs located in the PCB ("sensor plane").

A proof of concept was performed in 2015 exposing standard shashlik devices with SiPMs located at the back of the calorimeter to test the fiber-to-PCB direct coupling scheme [14]. The first UCMs were built in spring 2016 and tested with electrons, muons, and pions in the 1–5 GeV energy range in July 2016 at the CERN East Area facility (T9 beamline). In this paper, the construction and cosmic ray tests of the UCM are described and the outcome of the July testbeam at CERN PS is discussed.

II. Twelve-Module Prototype

The UCM modules tested in 2016 are made of 1.5-cm-thick iron slabs interleaved with 0.5-cm plastic scintillators. The 3×3 cm^2 scintillator tiles were machined and polished

Manuscript received November 30, 2016; revised February 1, 2017; accepted February 14, 2017. Date of publication February 20, 2017; date of current version April 14, 2017. This work was supported by the European Union's Horizon 2020 research and innovation program under Grant 654168 and Grant 681647.

A. Berra, C. Brizzolari, and M. Prest are with the University of Insubria, 21100 Varese, Italy, and also with INFN Milano-Bicocca, 20126 Milan, Italy.
S. Cecchini, F. Cindolo, G. Mandrioli, A. Margotti, N. Mauri, L. Patrizii, M. Pozzato, and G. Sirri are with INFN Bologna, 40127 Bologna, Italy.
F. Chignoli, C. Delogu, R. Mazza, and F. Terranova are with the University of Milano-Bicocca, 20126 Milan, Italy, and also with INFN Milano-Bicocca, 20126 Milan, Italy (e-mail: francesco.terranova@lnf.infn.it).
C. Jollet and A. Meregaglia are with IPHC, Université de Strasbourg CNRS/IN2P3, 67081 Strasbourg, France.
G. Collazuol, A. Longhin, and F. Pupilli are with INFN Padova, 35131 Padua, Italy.
A. Gola, G. Paternoster, and C. Piemonte are with Fondazione Bruno Kessler, 38122 Trento, Italy, and also with INFN TIFPA, 38123 Trento, Italy.
L. Ludovici is with INFN Roma, 00185 Rome, Italy.
V. Mascagna is with the University of Brescia, and also with INFN Pavia, 27100 Brescia, Italy.
A. Paoloni and L. Votano are with INFN LNF, 00044 Rome, Italy.
L. Pasqualini is with the University of Bologna, 40126 Bologna, Italy, and also with INFN Bologna, 40127 Bologna, Italy.
E. Vallazza is with INFN Trieste, 34149 Trieste, Italy.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

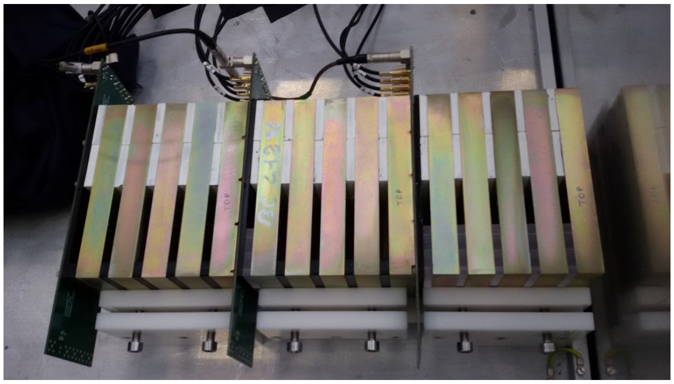


Fig. 2. Top view: 12-module prototype.

Fig. 3. Prototype during installation: the three longitudinal blocks are visible together with the PCB hosting the SiPMs.

from EJ-200 [15] (eight modules) and BC-412 [16] (four modules) sheets and painted with a diffusive TiO_2-based coating (EJ-510). Diffusive coating is used to increase the light collection efficiency. This method eases substantially 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; see Section IV). After painting, nine holes with a diameter of 1.2 ± 0.1 mm were drilled in each tile with a CNC machine. The surface of the iron slabs is 12×6 cm^2, i.e., each slab would fit eight UCM modules. In fact, during the CERN PS test, only half of it was filled with scintillator tiles.

The 12-module prototype (Figs. 2 and 3) is made of 15 iron slabs interleaved by scintillators, corresponding to 4 (transverse) $\times 3$ (longitudinal) UCM modules. It has an overall length of $12.8 X_0$ and allows for $\sim$90% ($\sim$80%) containment of electromagnetic showers at 1 (5) GeV. The transverse containment of showers at 5 GeV amounts to 92%. The scintillation light is collected by Kuraray [17] Y11 weighted least squares (WLS) fibers (1-mm diameter) running through the UCM, i.e., through five iron+scintillator tiles. The fibers are inserted into a 3-D printed plastic mask located downstream of each UCM (Fig. 4). The grooves in the mask (Fig. 4) allow coupling the SiPMs that are soldered to the PCB (Fig. 5) with the WLS fibers. The SiPM sensors have 1 mm^2 active area with a 20-μm pixel size; the sensors are produced by FBK [18] and their most relevant parameters

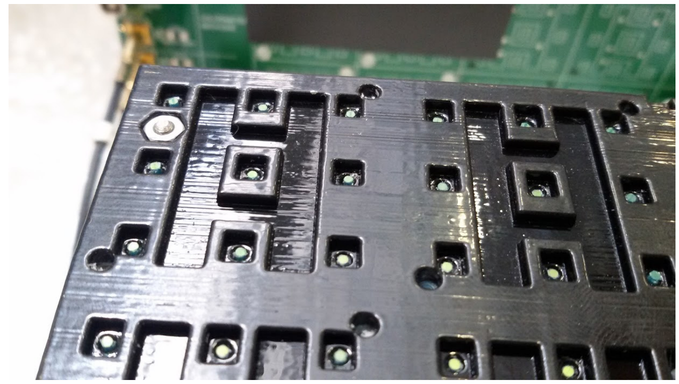


Fig. 4. Plastic mask connecting the WLS fibers with the SiPM PCB board.

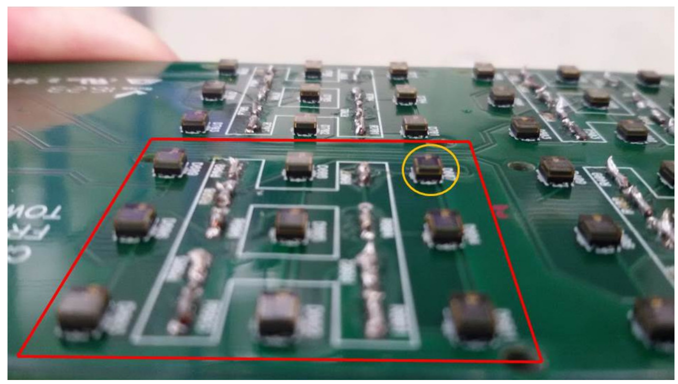


Fig. 5. SiPMs soldered to the PCB. One of the SiPM is shown by the orange circle. The red box indicates the SiPMs belonging to the same UCM.

TABLE I
PARAMETERS OF THE SiPM

Size	1 mm^2
Pixel size	20 μm $\times$ 20 μm
Fill factor	60%
Peak PDE	550 nm
Breakdown voltage	28 V
Overvoltage during operation	5 V

are listed in Table I. The photosensors are encapsulated in a resin package and soldered to the PCB, which provides the bias voltage and the leads for the signal. The output signal is the sum of the individual signals of the SiPMs in the UCM (nine SiPMs for each UCM), i.e., the SiPMs are connected in parallel and the front-end electronics record the sum of the SiPM currents. In this prototype, instead of using Kapton–copper lines, the PCB was equipped with a flap hosting the connector for the bias voltage (one line for four UCMs) and four MCX connectors for the signal, as shown in Fig. 3.

The 12-module prototype was exposed to electrons, muons, and pions in the range of interest for neutrino physics applications (1–5 GeV) at the CERN PS East Area facility from June 29 to July 11. The detector was positioned inside the T9 experimental area on a movable platform located at the back of two silicon strip detectors. The silicon detectors,

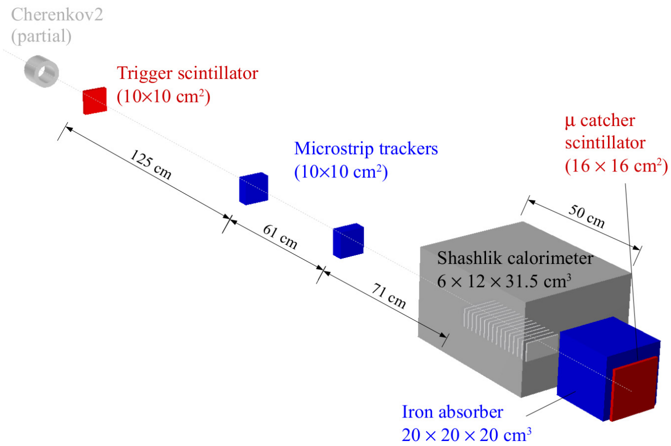


Fig. 6. Layout of the experimental area.

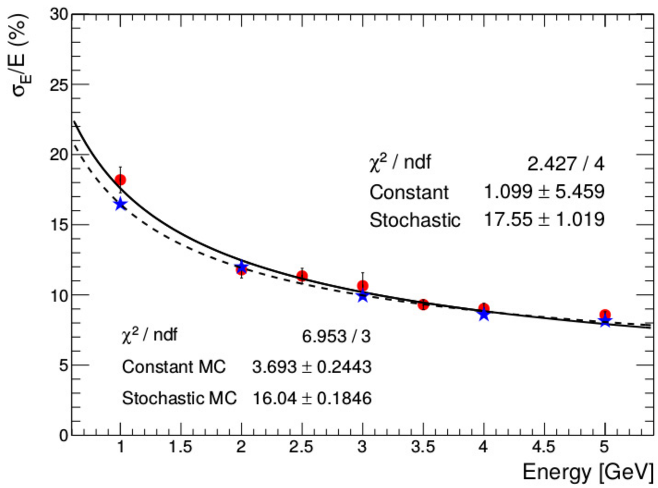


Fig. 7. Energy resolution of the 12-module prototype versus beam energy for data (see the red circles) and simulation (see the blue stars). The fit parameters for data and MC simulation are reported in the top and bottom legends, respectively.

described in [19], provide track reconstruction with a spatial resolution of 30 μm. Electrons are tagged by a pair of threshold Cherenkov counters filled with CO_2 located upstream of the silicon detectors and a 10×10 cm^2 plastic scintillator employed for the trigger. Finally, a scintillator pad ("muon catcher") is positioned after the calorimeter and a 20-cm-thick iron shield in order to identify muons or noninteracting pions. A layout of the experimental area is shown in Fig. 6.

During most of the runs, events in coincidence with the 400-ms beam spill are triggered by the front plastic scintillator. The summed SiPM signal (nine SiPMs per module, one channel per UCM) is recorded by a charge to digital (QDC) converter (CAEN [20] V792) and acquired together with the Cherenkov analog signals and the muon catcher. Special runs were performed replacing the QDC with a CAEN V1730 digitizer to test the waveform reconstruction algorithms [14]. The results reported in the following are based on the digitizer runs and are compatible with the measurements performed with the QDC.

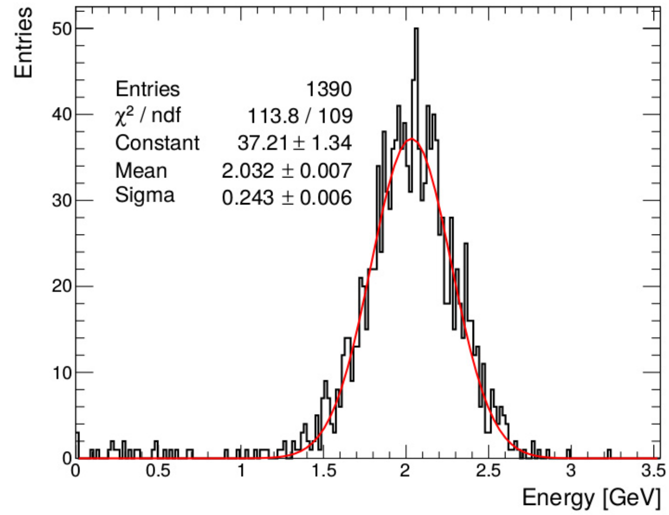


Fig. 8. Energy distribution in the 12-module prototype for 2-GeV electrons impinging on the central region (2×2 cm^2) of the detector. The red curve is the gaussian fit to the data. The fit parameters are listed in the legend.

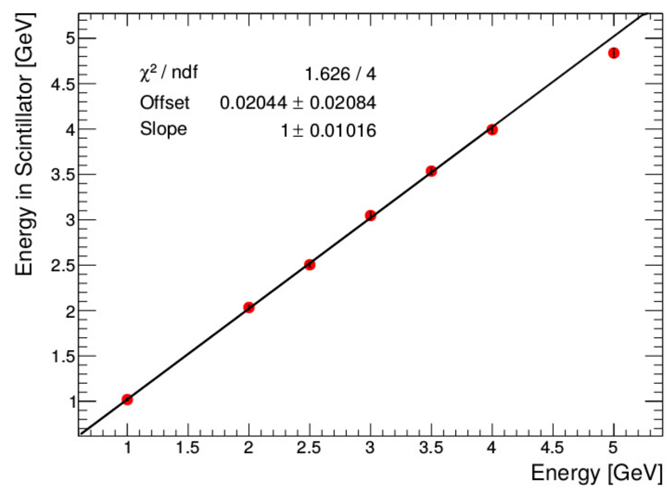


Fig. 9. Reconstructed energy versus beam momentum for electrons in the 12-module prototype. The linear fit is performed including data from 1 to 4 GeV.

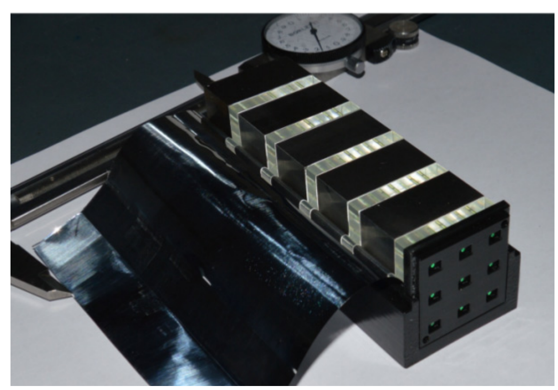
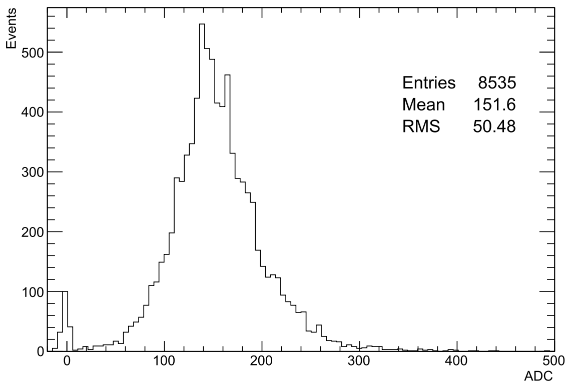


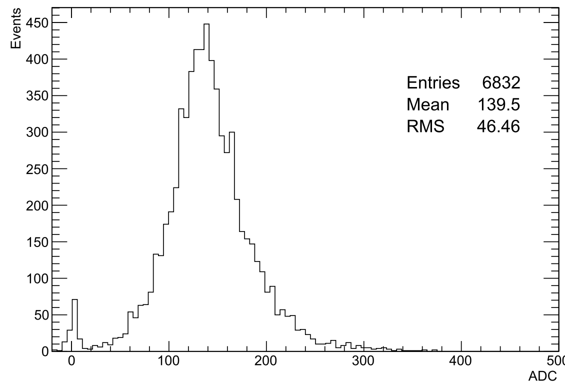
Fig. 10. Calorimeter module employed for the cosmic ray test to evaluate the performance of different light reflector solutions.

III. Energy Resolution and Linearity

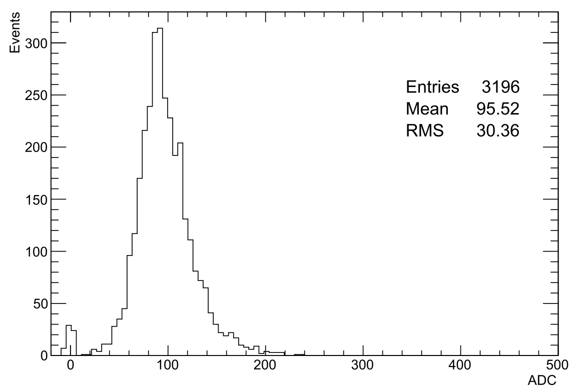
The electromagnetic response of the calorimeter was tested using electrons with energy ranging from 1 to 5 GeV. The electron energy resolution of the module is dominated by the



(a) Tyvek



(b) TiO_2 painting



(c) No diffusive

Fig. 11. Comparison of the signal response to vertical cosmic ray muons for three UCM modules with different light reflector solutions. (a) Tyvek foils interleaved between the scintillator tiles and the iron slabs. (b) Diffusive TiO_2 painting. (c) No diffusive material. See the text for details.

thickness (1.5 cm) of the iron slabs. That thickness was chosen to achieve an energy resolution better than $25\%/(E(\mathrm{GeV}))^{1/2}$ in monitoring the positron production along the decay tunnel of multi-GeV neutrino beams [11]. The expected resolution of the 12-module prototype was estimated with a GEANT4 simulation of the energy deposit in the scintillator, assuming full light transmission and collection.

The energy resolution was measured selecting electrons tagged by the Cherenkov counters and impinging on the central region (2×2 cm^2) of the calorimeter. The signal response of each UCM is equalized using the peak of the minimum ionizing particles. The energy resolution as a function of beam energy is shown in Fig. 7 for data (see the red circles) and simulation (see the blue stars) and is fitted to $\sigma_E/E = S/(E(\mathrm{GeV}))^{1/2} \oplus C$, S and C being the sampling (stochastic) and constant term, respectively. The fit parameters are shown in Fig. 7 for data and Monte Carlo (MC) simulation. The uncertainty on the T9 beam energy is negligibly small ($\sim$1%). Fig. 8 shows the energy distribution at 2 GeV fitted with a Gaussian function (see the red line).

The results of the electron energy scan confirm that the dominant contribution is due to the sampling term and that the energy response is not affected by the employed fiber–SiPM matching system. In particular, the energy resolution at 1 GeV (4 GeV) is 18% (11%) for data and 16.5% (10%) for MC simulation, well within the specifications for positron monitoring in neutrino beams.

The calorimeter energy response is linear up to 4 GeV (see Fig. 9); at 5 GeV, a deviation from linearity at the level of 3.2% is observed both in digitizer and QDC runs. Such a deviation is most likely a combined effect of longitudinal shower containment and partial saturation of the SiPM: a full simulation including photon production and optical transport is in progress to clarify the origin of this effect.

IV. Response to Minimum Ionizing Particles and Shower Profile

The SCENTT UCM module has been designed to provide a clear muon/electron separation in the few GeV energy range. The response of the module to minimum ionizing particles (mip) was studied with cosmic rays and with muon beams. Cosmic ray tests were of great practical value to estimate the performance of the TiO_2 diffusive painting compared with that of the standard light confining technique based on Tyvek sheets. These tests were performed with individual modules (Fig. 10) positioned vertically inside a muon telescope, i.e., between two silicon chambers triggered by plastic scintillators.

Vertical muons crossing the entire UCM module were selected tracking their trajectory using the silicon chambers.

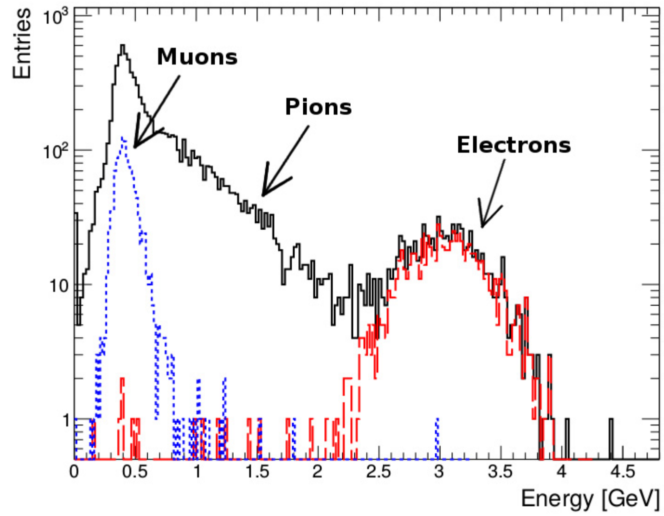


Fig. 12. Energy response of the 12-module prototype to tagged electrons (see the red dashed line), tagged muons (see the blue dotted line), and all particles (see the black line) at 3 GeV.

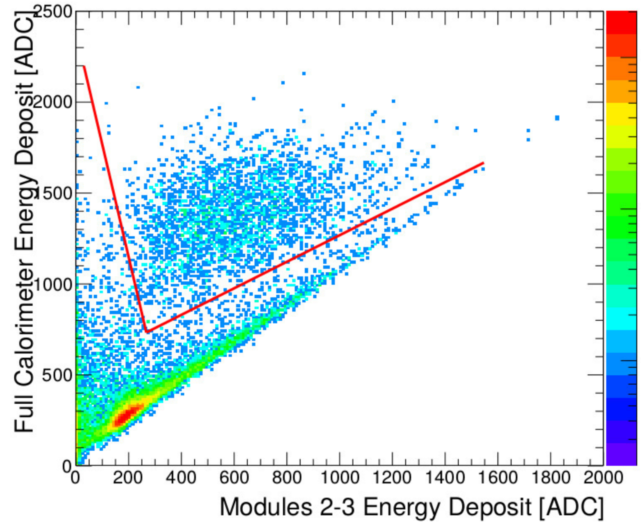


Fig. 13. Full signal (ADC counts) in the calorimeter versus the signal in the proximity of the shower maximum (sum of the second and third longitudinal modules) for 2-GeV particles.

A comparison of the response to mip was made for three types of modules.

1) The UCM with diffusive Tyvek foils inserted between the scintillator tile and the absorber.
2) The UCM with tiles painted with the diffusive TiO_2 coating.
3) The UCM with no diffusive material. In this case, the tiles were mounted in direct contact with the iron slabs and the iron was galvanized with a reflective zinc coating to increase its optical reflectivity.

As expected, the maximum signal amplitude for muons crossing the UCM was achieved by modules equipped with Tyvek foils. The signals from TiO_2-painted and zinc-coated modules are 8% and 37%, respectively, lower than from the Tyvek UCM (Fig. 11). These results support the choice of the TiO_2 coating, which represents a viable compromise between maximum light yield and ease of construction.

The 12-module prototype was tested at the CERN T9 beamline using a pure muon sample selected by the Cherenkov detectors and by the muon catcher at energies above 3 GeV. The energy response for tagged electrons (see the red dashed line) and muons (see the blue dotted line) is shown in Fig. 12. The black line shows the overall energy response, which is dominated by noninteracting or partially contained pions.

Beyond the 12-module prototype, a larger size calorimeter ensuring full containment of hadronic showers at energies below 5 GeV is foreseen. Still, the 12-module prototype can be used to trace the early (full) longitudinal profile of hadronic (electromagnetic) showers. The energy deposit sum of second and third longitudinal modules versus the total energy is shown in Fig. 13 for 2-GeV particles. The electron energy deposition pattern can be clearly distinguished from the hadron shower profile (see the red lines in Fig. 13). A systematic study of the e^-/π^- separation capability will be performed in the forthcoming months using the full-size ($\sim 12 \times 15 \times 70$ cm^3) detector.

V. Conclusion

In summer 2016, a 12-module shashlik calorimeter prototype was exposed to charged particles from 1 to 5 GeV at the CERN PS East Area facility. The prototype employs a novel scintillator light readout scheme: each WLS fiber segment is directly connected to a SiPM embedded in the bulk of the calorimeter. The calorimeter is made of standalone modules allowing longitudinal segmentation without introducing dead zones. The testbeam demonstrates that this scheme retains the same performance as that of standard shashlik calorimeters without longitudinal segmentation. In particular, an energy resolution of 18% (11%) at 1 GeV (4 GeV) was achieved, corresponding to a stochastic term of 17.5%, in agreement with MC expectations. The calorimeter response is linear in the region of interest for neutrino physics application, while a nonlinearity of $\sim$3% is observed at 5 GeV. The response to minimum ionizing particles has also been tested both at T9 and with cosmic rays. Cosmic ray tests demonstrate that light yield losses due to the TiO_2 diffusive coating amount to $\sim$ 8% compared with the more common technique based on Tyvek foils. Finally, a preliminary characterization of the longitudinal energy deposit of electrons and hadrons along the modules up to 12.8 X_0 has been performed.

Acknowledgment

The authors would like to thank the CERN and PS staff for successfully operating the East Experimental Area and for providing continuous support to the users; L. Gatignon, M. Jeckel, and H. Wilkens for the help and suggestions during the data taking on the PS-T9 beamline; the INFN Workshops of Bologna, LNF, Milano-Bicocca, and Padova for the construction of the 12-module prototype; and V. Bonvicini, P. Branchini, and A. Lanza for the 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. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 228, pp. 303–308, Jan. 1985.

[2] G. S. Atoyan *et al.*, "Lead-scintillator electromagnetic calorimeter with wavelength shifting fiber readout," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 320, pp. 144–154, Aug. 1992.

[3] G. S. Atoyan *et al.*, "An improved shashlyk calorimeter," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 584, nos. 2–3, pp. 291–303, 2008.

[4] A. Fantoni, "The ALICE electromagnetic calorimeter: EMCAL," *J. Phys. Conf. Ser.*, vol. 293, no. 1, p. 012043, 2011.

[5] N. Anfimov *et al.*, "Shashlyk EM calorimeter prototype readout by MAPD with superhigh pixel density for COMPASS II," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 718, pp. 75–77, Aug. 2013.

[6] A. Berra *et al.*, "Silicon photomultipliers as a readout system for a scintillator-lead shashlik calorimeter," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 3, pp. 1297–1307, Jun. 2011.

[7] A. Berra *et al.*, "Characterization of a DAQ system for the readout of a SiPM based shashlik calorimeter," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 735, pp. 422–430, Jan. 2014.

[8] H. Li, "Longevity of the CMS ECAL and scintillator-based options for electromagnetic calorimetry at HL-LHC," *IEEE Trans. Nucl. Sci.*, vol. 63, no. 2, pp. 580–585, Apr. 2016.

[9] A. Ledovskoy, "A finely-segmented radiation-tolerant shashlik electromagnetic calorimeter," in *Proc. IEEE NSS/MIC*, in press.

[10] R. Becker *et al.*, "Beam test results for a tungsten-cerium fluoride sampling calorimeter with wavelength-shifting fiber readout," *J. Instrum.*, vol. 10, p. P07002, Jul. 2015.

[11] A. Longhin, L. Ludovici, and F. Terranova, "A novel technique for the measurement of the electron neutrino cross section," *Eur. Phys. J. C*, vol. 75, p. 155, Apr. 2015.

[12] A. Berra *et al.*, "A non-conventional neutrino beamline for the measurement of the electron neutrino cross section," in *Proc. 17th Int. Workshop Neutrino Factories Future Neutrino Facilities (NuFact)*, Rio de Janeiro, Brazil, Aug. 2015, pp. 368–377.

[13] A. Berra *et al.*, "Enabling precise measurements of flux in accelerator neutrino beams: The ENUBET project," CERN, Geneve, Switzerland, Tech. Rep. CERN-SPSC-2016-036, SPSC-EOI-014.

[14] A. Berra *et al.*, "A compact light readout system for longitudinally segmented shashlik calorimeters," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 830, pp. 345–354, Sep. 2016.

[15] ELJEN Technol., Sweetwater, TX, USA.

[16] Saint-Gobain Group, Courbevoie, France.

[17] Kuraray Co., Ltd., Tokyo, Japan.

[18] Fondazione Bruno Kessler, Trento, Italy.

[19] M. Prest *et al.*, "The AGILE silicon tracker: An innovative gamma-ray instrument for space," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 501, no. 1, pp. 280–287, 2003.

[20] CAEN S.p.A., Viareggio, Italy.