

Towards MPGD-based (S)DHCAL

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Abstract. Digital and Semi-Digital Hadronic Calorimeters ((S)DHCAL) were suggested for future Colliders as part of the particle-flow concept. Though studied mostly with Resistive Plate Chambers (RPC), studies focusing on Micro-Pattern Gaseous Detector (MPGD)-based sampling elements have shown the potential advantages using such techniques.

In 2018, eight 48x48 cm² sampling elements based on resistive Micromegas and Resistive Plate WELL (RPWELL) technologies were assembled. They were tested within a small MPGD-based SDHCAL prototype incorporating in addition three 16x16 cm² Micromegas detectors and steel absorber plates recording hadronic showers of low-energy pions at the CERN/PS beam line. Preliminary results and analysis methodology are presented, using data samples recorded with pions with momenta in the range from 2 to 6 GeV/c.



1. Introduction

Particle-flow approach [1] is one of the leading concepts towards reaching the challenging jet energy resolution required by future lepton collider experiments ($\frac{\sigma}{E} \leq \frac{30\%}{\sqrt{E}}$, $[E] = GeV$). In this approach, the energy of each particle within a jet is measured in the best subsystem; charged particles in the tracking system, photons in the electromagnetic calorimeter and neutral hadrons in the hadronic calorimeter. The technique relies on assigning correctly the energy deposition clusters in the calorimeters to the original individual particles and minimizing its uncertainty, known as the confusion term [1]. This requires high granularity calorimeters - Particle-flow calorimeters.

Particle flow hadronic calorimeters consist of alternating layers of absorbers and sampling elements. Hadronic showers are mostly formed in the absorber, of which the material defines most of the total calorimeter's depth. The resulting signals, induced by the shower-particles entering the sampling elements, are measured by pads which define the calorimeter's transverse granularity.

Digital and Semi-Digital Hadronic Calorimeters ((S)DHCAL) can provide very high granularity (typically of 1 cm^2) using cost-effective (Semi-)Digital readout solutions (one- or two-bits ADC). In an (S)DHCAL, the energy measurement of a single particle relies on the approximated linear relation between the particle energy and the number of fired pads (hits)[2, 3]. Hence, in order to reach the targeted jet-energy resolution, the sampling element should have high detection efficiency at a low pad multiplicity (the number of pads fired per particle traversing the sampling element).

While (S)DHCAL employing glass Resistive Plate Chamber (RPC) sampling elements have been so far the most studied ones [4], past studies have shown that Micro-Pattern Gaseous Detector (MPGD)-based sampling elements could potentially outperform the glass-RPC sampling elements. As summarized in Table 1, the performance of sampling elements based on the Micromegas [5, 6] and Resistive-Plate WELL (RPWELL) [7] demonstrate lower pad multiplicity at similar detection efficiency. This could be translated into better hadron energy resolution as well as smaller confusion term, both leading to an improved jet energy resolution. Other advantages of MPGD-based sampling elements relative to the glass-RPC ones are reduced dependence on the particle rate, and usage of environment-friendly gas mixtures.

Table 1. A summary of sampling elements of different technologies [refs]

	Pad multiplicity	Efficiency
Glass RPC	1.5-2	98%
Micromegas	1.1	98%
Resistive Micromegas	~1.1	95%*
RPWELL	1.2	98%*

*Smaller active area

These results motivated the SCREAM project - Sampling Calorimetry with Resistive Anode MPGD. The project targets the construction of the first MPGD-based sampling calorimeter prototype combining two technologies: RPWELL and resistive Micromegas. Using Geant4 simulation of sampling calorimeter containing 2-cm-thick steel absorbers, we deduced the minimal calorimeter geometry required for a sufficient shower containment (Figure 1). At beam-energy up to 10 GeV and for showers which start in the first absorber, an optimal performance (minimal leakage yields best energy resolution) of such calorimeter requires an active area of $50 \times 50 \text{ cm}^2$. The needed calorimeter depth is ~ 16 radiation lengths - 15 layers - to contain electromagnetic showers, and 2.5 interaction lengths - 25 layers - to contain charged pion showers.

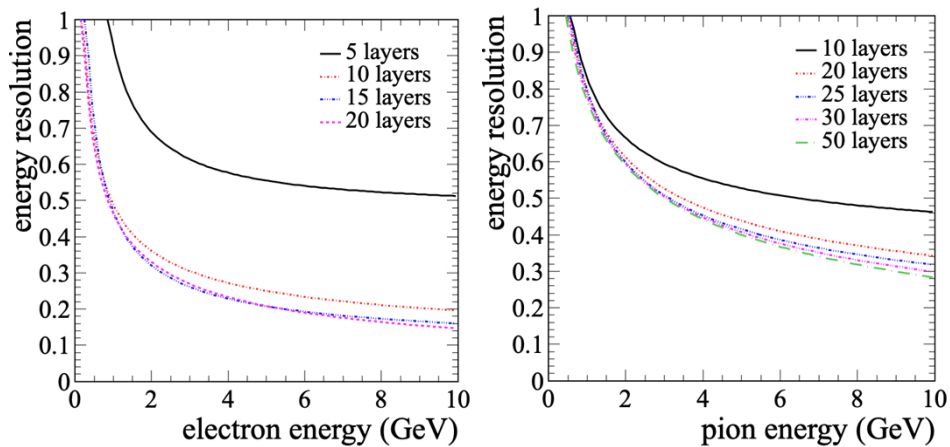


Figure 1. Monte Carlo simulation of the effect of the number of layers on the energy resolution for electrons (left) and pions (right) over the energy range covered by the PS accelerator at CERN. Pion resolution is calculated for showers initiated in the first absorber layer. While 15 layers are sufficient for full containment of electrons, 25 layers are necessary to lower the influence of hadron shower leakage.

For this application, we developed techniques for producing large-area ($48 \times 48 \text{ cm}^2$), 4.5 mm thick (excluding readout electronics) RPWELL detectors, incorporating $10^{10} \text{ } \Omega\text{cm}$ silicate glass resistive plates [8]. In order to maximize the acceptance of the sampling elements, the chambers were constructed without any support structure by gluing the WELL electrode onto the glass. The timetable was dictated by the LHC long shutdown (2019-2021), thus the design of the RPWELL sampling elements used in the presented experiment has significant room for improvement. In particular, thinner WELL electrode, 0.4 mm instead of 0.8 mm, with thickness uniformity $< 5\%$.

The large Micromegas prototypes consist of a Bulk mesh held at $128 \text{ } \mu\text{m}$ above the pad board by means of pillars. The board is a matrix of $1 \times 1 \text{ cm}^2$ pads. Resistive structures are built on the pad board prior to lamination of the Bulk mesh. They consist of a $75 \text{ } \mu\text{m}$ thick sandwich of patterned insulating foils (Kapton) and resistive foils ($100 \text{ k}\Omega/\square$). Resistive pads are connected to readout pads through an embedded resistor [9].

2. First operation of multiple MPGD-based sampling elements

In November 2018, the first small-SDHCAL prototype was investigated in CERN/PS with low energy (2-6 GeV/c) pion beam. It consisted of three $16 \times 16 \text{ cm}^2$ bulk Micromegas (two non-resistive and one resistive) and three $48 \times 48 \text{ cm}^2$ resistive Micromegas sampling elements followed by two $48 \times 48 \text{ cm}^2$ RPWELL ones (Figure 2). All eight sampling elements were equipped with semi-digital readout electronics based on the MICROROC chip [10], with pad-matrix of circular geometry (following the shower symmetry). The MICROROC features 64 channels with a low noise preamplifier, 2 shapers of different gain, 3 thresholds (set to 0.8, 1.4, and 3.8 fC), 127 event depth memory, and timestamping provided by a 5 MHz clock. All the chambers were read out with a single DAQ system using a data concentrator card (DCC) which distributed the clock and readout trigger to all the chamber front-end electronic boards. The calorimeter depth of $\sim 16 \text{ cm}$, corresponding to 0.8 interaction length (X_0) and ~ 8.9 radiation length, was determined mainly by 2-cm-thick steel absorber plates placed in-between the sampling elements. This depth is thinner than the optimal one and yields 45% (99.9%) chance of a pion (electron) -shower to start within the calorimeter.

The operation of such a prototype with multiple MPGD-based sampling elements is a major step towards the assembly of an MPGD-based DHCAL. However, it does not permit precise evaluation of a calorimeter response due to its shallow depth compared to the geometric requirements mentioned above,

the difference in acceptance, and the sub-optimal design of the RPWELL sampling elements. Thus, the presented work is focused on single-layer performance, selection of shower events, and assessing the next steps.

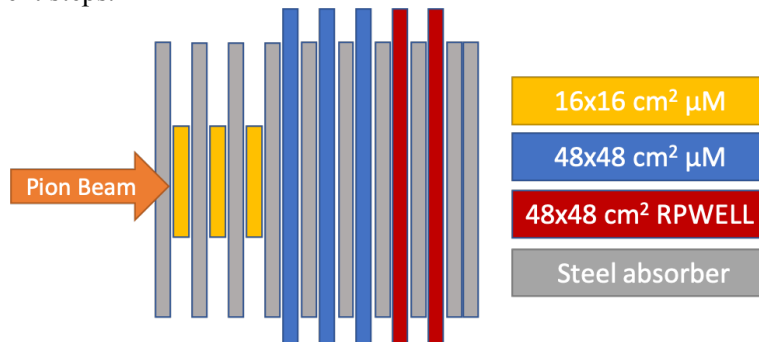


Figure 2. Small-SDHCAL prototype schematic description, consisting of three 16×16 cm² and three 48×48 cm² resistive Micromegas followed by two 48×48 cm² RPWELL sampling elements. 2-cm-thick steel absorber planes were inter-layered between the sampling elements.

2.1. Data sample

The prototype was exposed to a beam mixed beam of pions, electrons and kaons (Figure 3) at the CERN/PS test-beam facility with momenta in the range of 2-6 GeV/c. The number of acquired events at each beam-momentum value is presented in Table 2. The hits associated with the impinging particles are grouped based on a time selection (correlated with the trigger). The quality of the data is validated by comparing the data's number of hits distribution to that of a preliminary MC simulation. Such comparison is shown in Figure 4. Defining a particle that traversing all the layers of the setup, without showering, as a minimum-ionizing particle (MIP). An agreement can be seen in the MIP region, around 8 hits per event. However, the expected shower peak is not visible in the data. This could be improved by tuning the detectors response in the simulation and by better selection of events in the data, which includes showers that started before our setup.

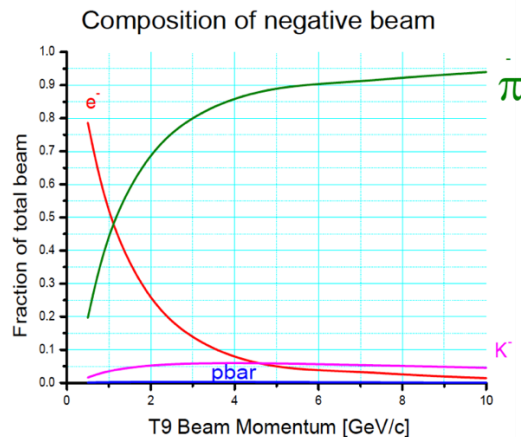


Figure 3. Composition of negative beam at CERN/PS T9 beam line.

The beam profiles in the different chambers of the prototype (Figure 5) are very clean, i.e. with very little noise. They also demonstrate the limited acceptance of the first three layers (16×16 cm² chambers) – ~14% of the large chambers active area. Figure 6 depicts an example of a pion shower recorded by all the sampling elements. The shadowed area in the two bottom plots indicates the region outside of the acceptance of the first 3 smaller sampling elements. Hits adjacent to this region suggest the loss of hits due to the limited acceptance - likely affecting the prototype's response.

Table 2. Number of acquired events at each beam-momentum value.

p_{beam} [GeV/c]	Number of Events
2	29,857
3	35,927
4	25,560
5	29,416
6	29,910

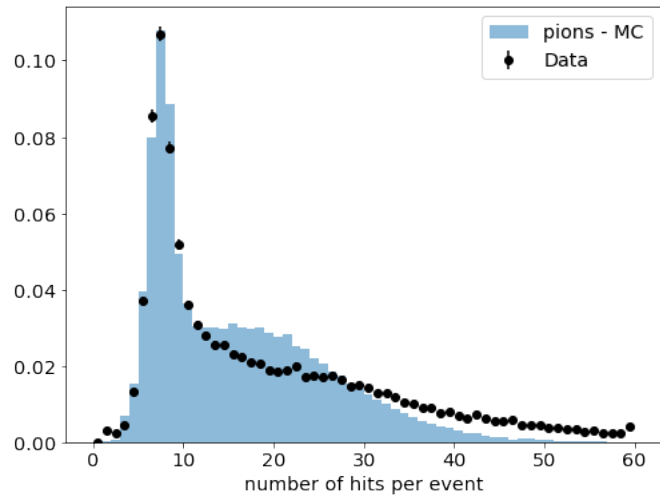


Figure 4. Distribution of number of hits per event for 5 GeV pion-beam, trigger-time correlated data and MC simulation, digital threshold set to 0.75 MIPs for layer 4, and 0.5 MIPs for the rest.

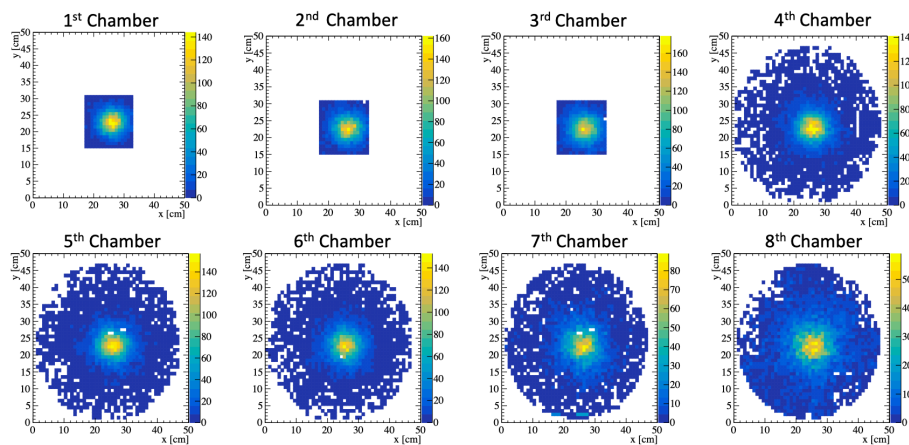


Figure 5. The beam profile recorded by each sampling element of the small-SDHCAL prototype (Figure 2).

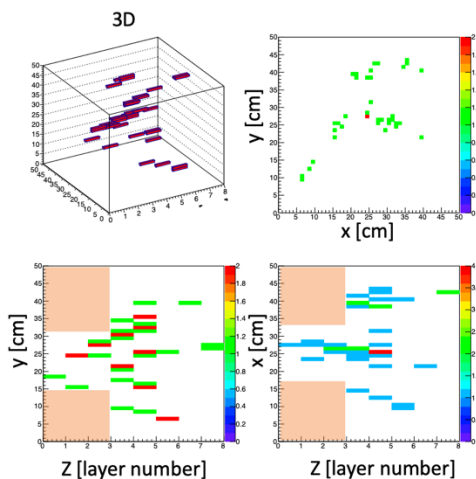


Figure 6. 4 GeV pion shower recorded with the small-SDHCAL prototype (Figure 2). From top left clockwise: 3D display, X-Y projection, Z-X projection, Z-Y projection. The peach-colored surfaces mark the regions that are outside of the chambers active area.

2.2. Event selection

Each recorded event can contain a single hadronic shower (induced by an incoming pion or kaon), a single MIP, a single electromagnetic shower (induced by incoming electron), or any combination of these objects. Thus, the selection of events containing single hadronic showers is a key for assessing the response of the prototype. Figure 7 shows an example of event containing single hadronic shower – selected for analysis. Two MIPs event and event containing a shower starting before the calorimeter are shown in Figure 8a and Figure 8b, respectively. Such events should be rejected.

The event selection is based on the object's topology. In particular, we used the number of hits per layer and the number of hits-clusters as the main discriminating variables. The following topologies were defined:

- MIP topology – up to two adjacent hits per layer. To account for possible noise hits, more hits were allowed in up to two layers.
- Shower topology – a single MIP trajectory before the shower start. The shower start is defined as the first layer in a single shower event with more than three hits.
- Two MIPs or a shower that starts before our setup are identified by more than one separate hit-clusters; where a hit-cluster is a pad in the X-Y projection with more than 1 hit, and the separation is defined as distance between clusters that is larger than 5 cm (Figure 8b).

Events containing more than a single object or objects identified as MIPs were rejected. No selection criterion was defined to reject electron showers.

The selection is then validated based on the spread, RMS, of hits on the X-Y plan (Figure 9a), and the number of hits per event distribution (Figure 9b). For the former, it is expected that showers will have a larger RMS than MIPs, and a number of hits larger than the number of elements of our small prototype. Figure 9 depicts these parameters for 5 GeV/c data. The peak at low values of both parameters before the selection is related to the low number of hits and the highly aligned single MIP events. This vanishes naturally by cutting the MIP events. Showers that start before the setup could be associated with high number of hits and larger spread – which can explain the loss events in the higher values of the parameters.

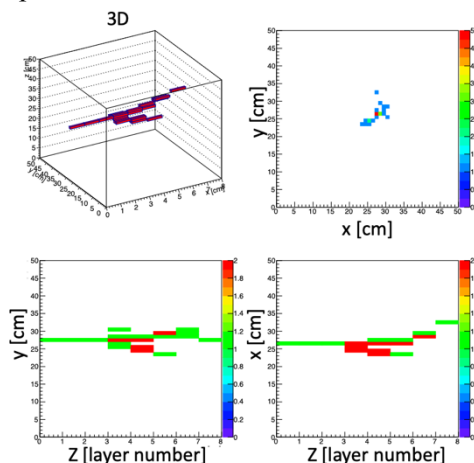


Figure 7. Example of a selected event. 4 GeV pion shower recorded with the small-SDHCAL prototype (Figure 2).

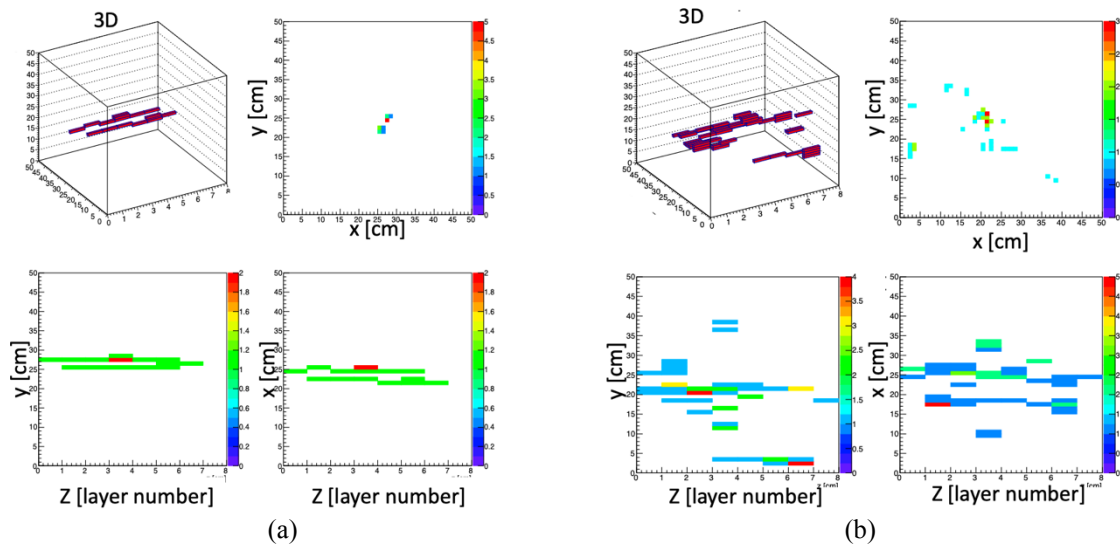


Figure 8. Example of rejected events: two MIPs (a) and a shower that start before the prototype (b). 4 GeV pion shower recorded with the small-SDHCAL prototype (Figure 2).

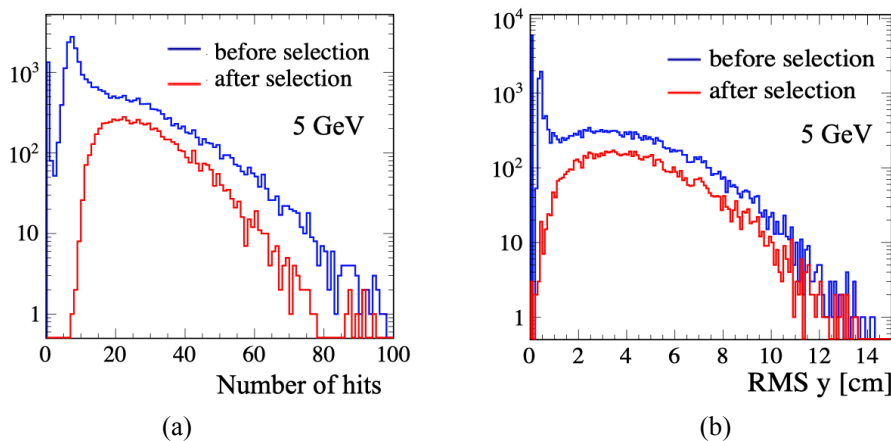


Figure 9. Number of hits per event (a) and spread of hits per events (b) for acquisition run with 5 GeV/c beam recorded with the small-SDHCAL prototype (Figure 2).

Due to small calorimeter depth and poor shower containment, we do not expect a linear relation between the incoming pion energy and the total number of hits. Instead, for showers starting in the same layer of the prototype, a single peak is expected in the total number of hits distribution. However, as shown in Figure 10, in some cases a two-peaks structure was observed. The effect was more pronounced in events recorded at the lower beam energy, and for shower starting in one of the first three layers. Two possible effects could contribute to this behavior. The first is electron contamination. As mention earlier, no selection was applied for rejecting events containing electron showers. The electron fraction in the beam composition at the PS is increasing as the beam momentum is decreased (Figure 3). The electromagnetic showers, initiated by the electrons, are highly collimated (Molière radius of 1.8 cm), and more prone to interact in the first layers ($5 \text{ layers} \cong 8 X_0$) thus, introducing higher number of hits per event. This can induce the peak in the higher number of hits. The second effect could be due to the limited acceptance in the first layers; hits in wider showers could reside outside of the acceptance – contributing to a peak in the lower number of hits.

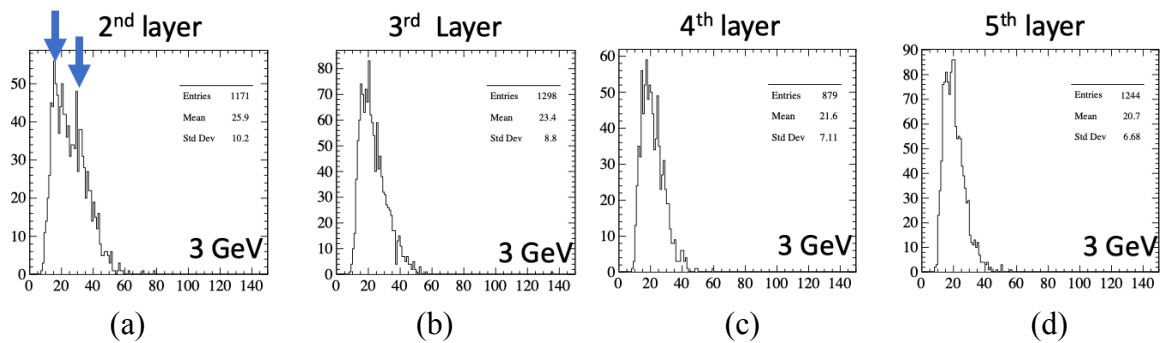


Figure 10. Number of hits per event distribution for 3 GeV pion-showers that start at the 2nd layer (a), 3rd layer (b), 4th layer (c), and 5th layer (d). The two arrows in the top left distribution indicate the two observed peaks.

2.3. The Response of a single technology SDHCAL

Denoting the layer of the shower origin as Layer 0, the depth of a single sampling element in a specific shower is defined by its distance from Layer 0. In this manner, one can assess the expected response of a virtual calorimeter prototype fully equipped by a single MPGD technology. Figure 11 depicts the longitudinal pion-shower profile in a virtual 50-layers 1 m² Micromegas SDHCAL, measured at high energy pion beam with 4 prototypes inside the CALICE steel RPC-SDHCAL; while the assessed response of a virtual 7-layers 48x48 cm² RPWELL prototype is presented in Figure 12. These results will serve as a baseline for future MC simulations.

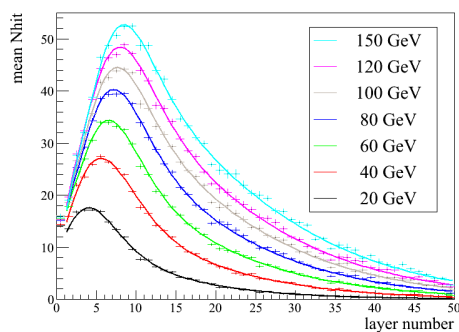


Figure 11. Longitudinal pion shower profile in a virtual 50-layers 1 m² Micromegas SDHCAL as measured with 4 prototypes inside the CALICE steel RPC-SDHCAL[11].

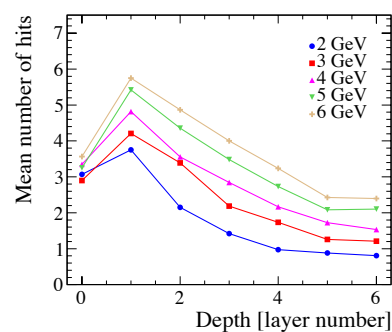


Figure 12. Longitudinal pion shower profile in a virtual 7-layers 48×48 cm² RPWELL SDHCAL as measured with a single prototype inside our 8-layers setup.

3. Summary and Outlook

The first prototype of multiple Micromegas- and RPWELL-based semi-digital sampling elements was operated for the first time in a low-energy charged particle beam. Data recorded with low-energy pions was analyzed and experience was gained in identifying different event topologies. It marks a major step towards the assembly of an MPGD-based DHCAL and the assessment of the performance of such DHCAL.

As part of this setup, large-area (48×48 cm²) RPWELL detectors were constructed for the first time. It was also the first operation of RPWELL detector with MICROROC readout; successful scaling up of the active area from 30×30 cm² to 48×48 cm²; and first experience with shower analysis of such setup.

Entering the new realm of such analysis requires MC simulations to understand the expected difference in pion and electron showers in calorimeters of different depths. This will help us to refine our shower selections, and as a result to extrapolate the performance to prototypes with more layers. In

addition, the MICROROC chip allows us to extract more statistics from the acquired data, as the chip writes more events than the ones that are correlated with the $1 \times 1 \text{ cm}^2$ trigger region that was used in our test beam.

Efforts to improve the RPWELL design are in progress, as construction of new sampling elements is planned with thinner and more uniform electrodes, and better grounding and shielding. We hope to test in 2021 a new SDHCAL prototype consisting four $48 \times 48 \text{ cm}^2$ resistive Micromegas and six $48 \times 48 \text{ cm}^2$ RPWELL sampling elements with three $16 \times 16 \text{ cm}^2$ bulk Micromegas as telescope.

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