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Studies for the electro-magnetic calorimeter *SplitCal* for the SHiP experiment at CERN with shower direction reconstruction capability

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Abstract: This paper describes the basic ideas and the first simulation results of a new electro-magnetic calorimeter concept, named *SplitCal*, aimed at optimising the measurement of photon direction in fixed-target experiment configuration, with high photon detection efficiency. This calorimeter was designed for the invariant mass reconstruction of axion-like particles decaying into two photons in the mass range 200 MeV to 1 GeV for the proposed proton beam dump experiment SHiP at CERN. Preliminary results indicate that angular resolutions better than obtained by past experiments can be achieved with this design. An implementation of this concept with real technologies is under study.

Keywords: Calorimeters,Large detector systems for particle and astro-particle physics

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1 Introduction

Very few experiments in the past optimised their calorimeter for angular resolution. One noticeable example is the ATLAS electro-magnetic calorimeter [1], aimed at measuring the Higgs boson mass in the two photon decay, where the photon direction in the pseudo-rapidity η is obtained from a straight line fit through the shower barycentre in two positions in depth. The angular resolution $\sigma_\theta \cdot \sqrt{E}$, where θ is the polar angle, is of the order of 50 mrad$\cdot\sqrt{\text{GeV}}$ at transverse energies between 25 GeV and 80 GeV. This paper describes the concept and the first simulations results of the new electro-magnetic calorimeter concept, named *SplitCal*, aimed at optimising the measurement of photon shower direction for fixed-target experiments, while keeping high detection efficiency.
The calorimeter is designed for the invariant mass reconstruction of events coming from the axion-like particle (ALP) decay into two photons, in the proposed proton beam dump experiment at CERN, SHiP. This experiment has a unique sensitivity to the ALP in the mass range 200 MeV to 1 GeV.
This detector is meant to replace the large size 5×10 m^2 electro-magnetic calorimeter described in the Technical Proposal (TP) [2], based on the Shashlik technology, that has no shower direction reconstruction capability, since it has only one longitudinal sampling, and would anyway have a prohibitive cost for readout with high space granularity.
The solution proposed here, the *SplitCal*, is fully compatible with the requirements of the experiment, that are a moderate energy resolution of the order of 10-15%/$\sqrt{E}$, with E in GeV, a measurement of the shower timing to few ns to suppress combinatorial background, and, compared to the Shashlik solution, provides other improvements such as the photon direction measurement and a better performance in terms of electron/hadron separation.

The basic idea behind a precise angular measurement of a shower is to sample the shower at two (or more) depths. The goal is to precisely measure the barycentre at these two depths while maximising the lever arm between them, while keeping the transverse shower size compact enough to avoid too much overlap with other showers or tracks of the event and the total cost of the calorimeter low enough to be affordable.

The proposed detector, aiming at covering the very large surface of 5×10 m^2, is a lead sampling calorimeter, with absorber plates orthogonal to the incoming beam direction, with two kinds of active layers. Most samplings will be equipped with scintillators for the energy and time measurement, with coarse spatial segmentation. Three high resolution layers, one located after 3 X_0 and the other two close to the shower maximum, will determine the transverse position of the shower at the three depths and allow for reconstruction of the photon angle.

To increase the lever arm for the angular measurement, the calorimeter is mechanically split in two parts in the longitudinal direction, with a gap between the first 3 X_0 and the rest of it of 1 m. With few mm transverse shower position resolution in the high precision layers, the target angular resolution is of the order of few mrad.

2 The SHiP experiment

The SHiP experiment [2] is a general purpose fixed target facility proposed at the CERN SPS accelerator to search for new physics in the largely unexplored domain of very weakly interacting particles with masses below O(10) GeV/c^2 and $c\tau$ of kilometres[3]. The 400 GeV/c proton beam extracted from the SPS will be dumped into a molybdenum-tungsten target, with the aim of accumulating 2×10^{20} protons on target (POT) during five years of operation. To suppress backgrounds a 5 m thick iron shield is placed behind the target to absorb hadrons and is followed by a series of magnets to deflect muons out of the acceptance of the spectrometer [4].

The detector is based on a 50 m long decay volume, housing a 5×10 m^2 spectrometer magnet which is sandwiched between tracker stations followed by a timing detector, calorimeter and muon detector. To suppress the background from neutrinos interacting in the fiducial volume, the decay volume is maintained under a vacuum of 1 mbar. The decay volume is surrounded by background taggers to detect the products of neutrino and muon inelastic scattering in the surrounding structures, which may produce long lived Standard Model V^0 particles, such as K_L, that have a similar decay topology to the expected signals.

The SHiP detector response is simulated in the GEANT4 [5] framework. All the simulation, *FairSHiP*, is performed within the FairRoot [6] framework.

3 Physics channels with photons

Almost all the new long lived particles that are going to be searched for with SHiP have decays that also contain neutral pions, both with and without charged particles.

The benchmark channel that we considered for the *SplitCal* design is the ALP with coupling to photon-only, i.e. that has only the decay to two photons, whose theoretical framework is discussed in [7], for which SHiP has unique sensitivity in the mass range between 200 MeV and 1 GeV. In the phenomenological study [7], the authors only considered a final state with two reconstructed

photons in the detector, with energy E>3 GeV and minimum distance on the calorimeter surface of 10 cm.
Background suppression, at least as far as we understand it now, does not depend on the capability of reconstructing the photon direction while mass reconstruction is crucially dependent on it.

4 Backgrounds for two photon final states

The proposed beam dump experiment is in itself a low background experiment, since the dump is meant to absorb all particles coming from the beam interaction in the target but the neutrinos and the high energy muons. This background was simulated in the context of *FairSHiP*. The neutrinos and the muons can interact in the material upstream, aside or inside the decay vessel and yield photons that mimic the signal. To suppress this kind of background both charged and neutral particle veto detectors of different kinds are used, exploiting the high multiplicity topology of both deep inelastic neutrino and muon scattering events. Coherent neutral current neutrino scattering, with the production of the single neutral pion, is in principle an irreducible background but, since most interactions occur at the entrance window of the decay vessel, it can be suppressed by a kinematical cut by only measuring the energy and the position in the calorimeter and making the hypothesis of the neutral pion mass, with a small signal inefficiency of the order of 5% for a 600 MeV ALP mass. With these cuts, the MonteCarlo simulation shows that for the whole SHiP data-taking, one expects for the ALP search with the two-photon decay less than 0.1 background events.

5 Simulation of axion-like particles with photon couplings and calorimeter requirements

A Toy MonteCarlo (ToyMC) simulation was developed, based on the theoretical formulae of [7]. ALPs were assumed to be produced in the target and let decay in the decay vessel, a 2.5 m radius cylinder, 50 m long and 70 m downstream the target (the exact shape of the decay vessel is not relevant for this study). Fig 1 left shows the angle of incidence θ on the *SplitCal* of photons vs energy E for 600 MeV ALP mass, showing that angles are up to 30 mrad and are correlated with energy. Fig 1 right shows the distance d between the two photons at the *SplitCal* surface for 600 MeV ALP mass. For lower ALP masses the distribution of d shrinks to lower values making shower separation and direction reconstruction more challenging.

The two photons of the ALP decay were smeared in angle and energy according to resolutions consistent with the values obtained from the *SplitCal* simulation, discussed in section 7, i.e. an angular resolution of $\sigma_\theta \cdot \sqrt{\mathrm{E}} = 16$ mrad $\cdot\sqrt{\mathrm{GeV}}$ and a relative energy resolution $\sigma_{\mathrm{E}}/\mathrm{E} = 15\%/\sqrt{\mathrm{E}}$ (a precise determination of the coefficients of these functions from the *SplitCal* simulation is left for future work). For small angles, the invariant mass is proportional to $\mathrm{E} \cdot \theta$; for ALP decays in the SHiP experiments, the angular resolution is by far the dominant contribution to the mass resolution. Mass resolution, obtained by fitting mass distributions with a Gaussian, turns out to be in the ToyMC 66 MeV, 110 MeV and 115 MeV for 0.2 GeV, 0.6 GeV and 1 GeV ALP mass , respectively.
Given the search for ALPs in SHiP is without background after the selection cuts described above, no further cut needs in principle to be applied. However, requiring a good vertex reconstruction inside the decay vessel, can slightly improve the mass resolution and reduce the tails at the cost of

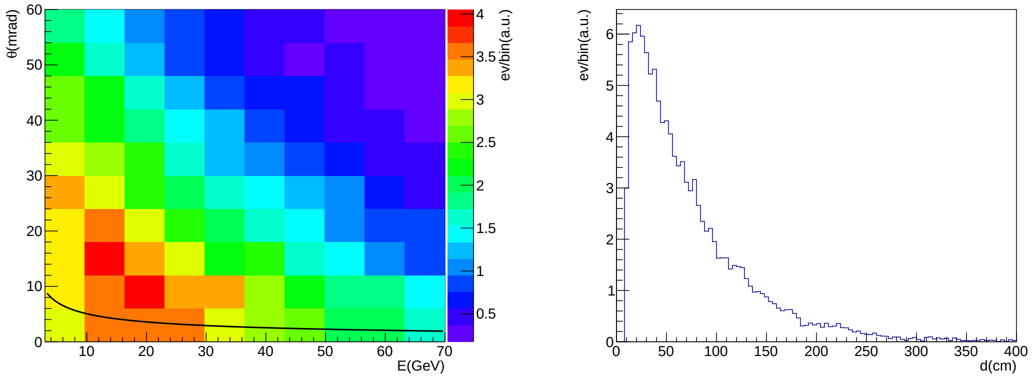


Figure 1: Left: angle of incidence θ of photons (in mrad) vs energy E (in GeV); right: distance between the two photons at the *SplitCal* surface for 600 MeV ALP mass decaying to two photons in the ToyMC. Superposed on the left figure is the line for $\sigma_\theta \cdot \sqrt{\mathrm{E}} = 16$ mrad $\cdot\sqrt{\mathrm{GeV}}$

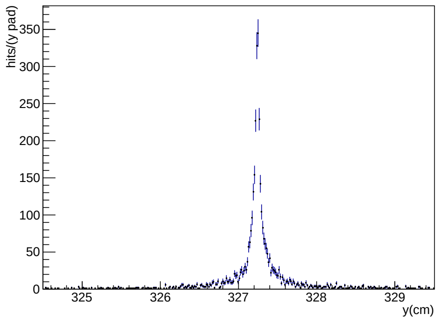
some efficiency loss. These further cuts could be applied in case of discovery. A kinematic fit of the event would probably lead to a further improvement but has not been studied yet.

6 Basic concept of the *SplitCal* calorimeter

The proposed detector, implemented in *FairShip*, aiming at covering the 5 $\times$10 m^2 surface, is a 25 X_0 lead sampling calorimeter, with lead absorber plates orthogonal to the proton beam direction, with two kinds of active layers. Most samplings are equipped with scintillator bars, that in a realistic implementation could be of extruded type read-out by WLS fibres as for the SHiP muon detector [2], with a relatively coarse spatial segmentation. The lead absorbers are 0.5 X_0 thick, i.e. 0.28 cm, while the scintillator is 0.56 cm thick. Three high resolution gas detector layers, 1.12 cm thick, one located after 3 X_0 and the other two around the shower maximum at 10 X_0 and 13 X_0, to cover the range for both low and high energy showers, will determine the transverse position of the shower at the three depths and allow for reconstruction of the photon angle. To obtain the desired performance, high spatial segmentation of the order of 200 μm is needed in the three high resolution layers, that could be achieved with e.g. micro-pattern detectors. The calorimeter is mechanically split in two parts in the longitudinal direction, with a gap between the first 3 X_0 and the rest of it of about 1 m.

7 Performance on MonteCarlo

To test the performance of this calorimeter with *FairShip*, single photons were generated starting from the center of the evacuated decay vessel, at about 20 m from the calorimeter surface with an angle of 5^o with respect to beam direction in the vertical plane. The material in front of the calorimeter is dominated by the decay vessel end-plate. However, since this paper is focussed at determining the intrinsic *SplitCal* response, this material was removed and assumed to be negligible.



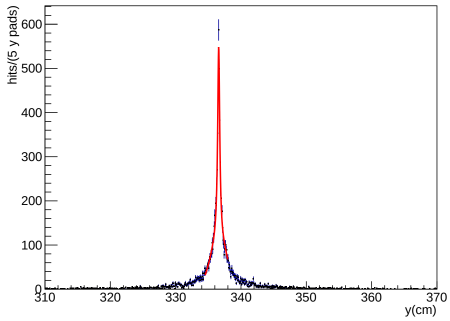


Figure 2: Transverse shower shape, i.e. number of hit pads vs position in the y direction in the first (left) and the third (right) precision layer of the *SplitCal* for 100 generated 20 GeV photons as described in the text. Note the different axes range by a factor of 10 between the two plots. Overlaid to the right plot is a fit to the sum of a Lorentzian and a Gaussian with a common mean. On the right plot pads are grouped by five.

It is left to future work the optimisation of the material in front of the *SplitCal*.
In these first simulations we did not implement any realistic detector for the readout but we only considered the energy released in the active layers (scintillator and gas) at given position in space and assume an analog readout for the scintillator layers, assuming that on average 0.5% of the total energy will actually be converted to light and finally readout at the WLS fibre end, and a digital readout for the high precision gas layers with zero threshold. The granularity of the high resolution layers was defined as pads of 150 x 150 μm^2.
A relatively small price to pay with the *SplitCal* design is a small inefficiency due to probability that showers start after 3 X_0. This inefficiency is of a few %.
The relative energy resolution σ_E/E for 20 GeV photons turns out to be 4.9%. It should be noticed that in this layout there are no scintillator layers where the high precision layers are located and the energy was only reconstructed summing up that deposited in the scintillator layers.
An outstanding issue in this detector is the presence of shower satellites, i.e. energy deposits far away from the shower core, that make position reconstruction quite challenging since they give rise to long tails in the transverse shower shape. Fig. 2 shows, for 100 generated 20 GeV photons, the transverse shower shape, i.e. the number of hit pads vs position in the y direction in the first and third precision layers. On average, in the first (third) precision layer, about 60 (100) pads per showers are hit.

The mean positions in x and y were reconstructed from the median distribution along the two axes. No two-dimensional pattern recognition algorithm was tried yet, so this procedure is to be considered preliminary. The best results were obtained when cutting away tails beyond ± 1 cm and ± 5 cm, respectively for the first and second/third high precision layers, i.e. shower hits outside the distribution cores, as shown in Fig. 2. This could be achieved in the pattern recognition software with an iterative procedure and its optimisation is left for future work.
The position resolutions, obtained from a Gaussian fit, in the three high precision planes are 230 μm,

2.5 mm and 2.3 mm, respectively, for 20 GeV photons. The resolution is better in the first high precision layer due to the shower being much narrower while the number of hit pads is comparable. The shower angle was reconstructed independently in the two x-z and y-z planes by fitting a straight line between the three median points in the high resolution layers. The angular resolution, obtained from a Gaussian fit, in the y-z plane $\sigma_{\theta_{yz}}$ turns out to be 2.1 mrad for 20 GeV, 3.5 mrad for 10 GeV and 6.5 mrad for 6 GeV photons. It should be noticed that the 20 GeV value is much better than the corresponding one measured in the ATLAS e.m. calorimeter [1].

One potential improvement of the angular resolution that is under study comes from fitting an analytical shape to the transverse shower distribution, using the sum of a Lorentzian and a Gaussian with a common mean. The fit template is derived from the cumulative distribution of 100 generated events, as shown for 20 GeV photons in Fig 2 for the third precision layer. The widths of the Gaussian and of the Lorentzian functions and their amplitude ratio were fixed to the values of this fit and only the mean and the absolute normalisation were left free to float event-by-event. With this method the Gaussian-fit position resolution for the third high precision layer improved from 2.3 mm to 2.1 mm. The full implementation of this procedure in the angular fit is still underway. With real data the fit template could be extracted from electron showers from muon decays in flight, that were estimated to be in excess of one million per year of running.

A detailed account of the electron/hadron separation performance is beyond the scope of the present paper and will be discussed in another work.

8 Outlook

This paper described the concept and first simulation results of the *SplitCal* calorimeter for the proposed SHiP experiment at CERN. It should be pointed out that the ideas described in this paper are very preliminary and that no real optimisation of the setup has been done yet. A detailed optimised design and implementation of the *SplitCal* with real technologies is under study.

References

[1] A. Airapetian *et al.* [ATLAS Collaboration], *ATLAS calorimeter performance Technical Design Report*, CERN-LHCC-96-40.

[2] SHiP collaboration, M. Anelli et al., *A facility to Search for Hidden Particles (SHiP) at the CERN SPS*, arXiv:1504.04956.

[3] S. Alekhin et. al, *Rep. Prog. Phys.* **79** (2016) 124201.

[4] A. Akmete *et al.* 2017 *Journal of High Energy Physics* **12** (2017) 05011

[5] GEANT4 collaboration, S. Agostinelli et al., *N*ucl. Instrum. Meth. A **506** (2003) 250.

[6] MM. Al-Turany, D. Bertini, R. Karabowicz, D. Kresan, P. Malzacher, T. Stockmanns et al., The FairRoot framework, *J. Phys. Conf. Ser.* **396** (2012) 022001.

[7] B. Dobrich *et al. Journal of High Energy Physics* **1602** (2016) 018