

Simulation of π^0 - γ Separation Study for Proposed CMS Forward Electromagnetic Calorimeter

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Abstract. The Forward Electromagnetic Calorimeter of the CMS detector is going to be upgraded in the high luminosity running as the energy of the present Electromagnetic Calorimeter (PbWO₄) will degrade in the high luminosity (luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) running due to extensive radiation (hadron flux $10^{13} \text{ neutrons cm}^{-2}$). Shashlik Electromagnetic Calorimeter which consists of alternate layers of 1.5 mm LYSO(Ce) crystal plates and 2.5 mm Tungsten absorbers, was a proposal for high luminosity running. One of the performance points for any electromagnetic calorimeter is the ability to separate π^0 s from true photons, since final states with photons are a clean and one of the most important final states in proton-proton collisions at the LHC. The objective of this project is to study the possibility of π^0 and γ separation in the Shashlik detector using Multivariate Analysis (MVA) technique.

1. Introduction

The performance of the Electromagnetic Calorimeter (ECAL), particularly the endcap component, will suffer due to the increased hadron flux ($10^{13} \text{ neutrons cm}^{-2}$) in a high luminosity environment (luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$). The transparency of the ECAL endcap will be degraded and as a result, its energy resolution will worsen. For integrated luminosity of 500 fb^{-1} , the transmission loss of light in the PbWO₄ crystals will be reduced by a factor larger than 25[1] in the forward region. It will be hard to recover the performance of the calorimeter through calibration. Thus it becomes important to replace the ECAL endcap with a new one which can survive in a high luminosity scenario and can give stable resolution as a function of integrated luminosity.

There were several proposals for upgrading the calorimeter system (ECAL + HCAL) for high luminosity run. For ECAL endcap, Shashlik ECAL, with alternate layers of scintillators and absorbers was one of the proposals for high luminosity running. Many materials were considered for the scintillator. Out of these inorganic scintillators, LYSO (cerium doped lutetium yttrium silicate) seems to be the best candidate based on the following considerations:

- (i) radiation hardness,
- (ii) fast response and also high light output,
- (iii) short radiation length (1.14 cm) leading to a smaller detector size.



Figure 1 shows the layout for the Shashlik detector.

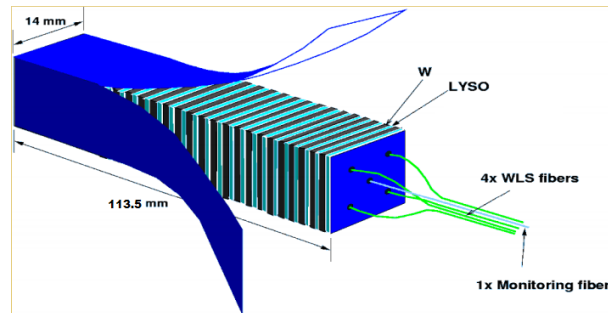


Figure 1. The layout of a Shashlik cell showing alternate layers of scintillator and absorber with 4 light collection fibers and one monitoring fiber.

2. Simulation

A stand-alone detector setup consisting of alternative layers of absorbers (2.5 mm thick tungsten) and scintillators (2 mm thick LYSO) was defined in the framework of GEANT4 [2]. GEANT4

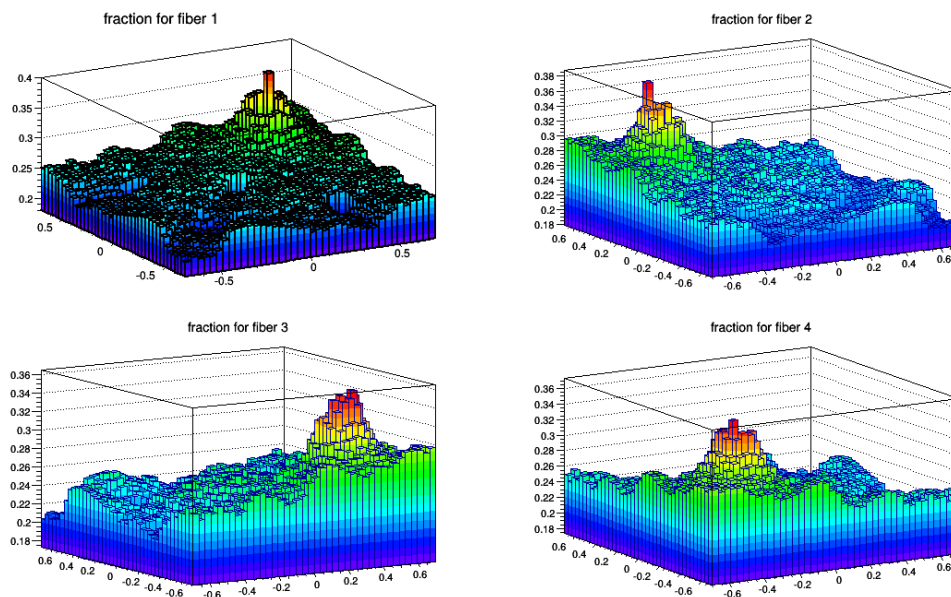


Figure 2. Figure on top-left shows the distribution of probability as a function of X,Y position for fiber 1, on the top-right for fiber 2, on the bottom-left for fiber 3 and on the bottom right for fiber 4. These four distributions are symmetric since the four fibers are symmetrically placed.

version 9.6.p02 was used with the physics list QGSP_FTFP_BERT. Light saturation effect was introduced through the use of Birk's law:

$$w = 1.0 - k_1 \cdot \ln \left(k_0 \cdot \frac{dE}{dx} \right)$$

with $k_0 = 0.0333 \text{ MeV}^{-1} \cdot \text{g} \cdot \text{mm}^{-2}$ and $k_1 = 0.254[3]$. The weight factor w was restricted in the range 0.1:1.0. For π^0 - γ separation studies, 28 layers of absorber and 29 layers of scintillators in

a 11×11 matrix was defined. Transverse size of each cell in each layer was chosen to be 14 mm. Five fiber paths are defined of which the central fiber was for calibration and the other four fibers were at positions $(\pm 3.5 \text{ mm}, \pm 3.5 \text{ mm})$ with respect to the center. They can be read out individually or to a combined output. The fibers were of diameter 1.6 mm and were inserted in holes of diameter 1.6 mm.

Energy deposit at a given point in the scintillator plate will be sampled differently by the four fibers. The probability of distribution of this light among the fibers depends on the transmission coefficient of the scintillator and hence on integrated luminosity. This has been estimated from a separate study using SLitrani[4].

3. π^0/γ Separation

Any search which has a final state of photons, has a background contribution from jets which fake real photons. This is because π^0 's in jets decay to 2γ 's almost 99.9% of the times. For high energy π^0 's the angle between the two photons becomes so small that it becomes very difficult to separate photons coming from the decay of π^0 , and the real photons which are coming either from the interaction vertex or from radiation off the leptons. With a transverse size of 14 mm for the detector layer, it becomes a tough task to separate out photons coming from the decay of π^0 and the real photons of energy more than 50 GeV.

In this study, an attempt has been made to explore the idea of exploiting the information from the four fibers for π^0 and γ separation. The idea behind using information from all the four fibers individually is that a larger fraction of the deposited energy from a single photon will be collected by the fiber which is closest to the impact point, while π^0 , decaying to a pair of photons will have two impact points on the Shashlik detector and the sharing of light among the fibers will significantly increase.

3.1. Shower Shapes

In general, the lateral shower profile tends to be broader for photons coming from π^0 compared to that of prompt photons. This holds true for lower energy π^0 's (less than 100 GeV). These shower shape variables are useful for discriminating between π^0 's and photons. For all shower shape variables, the tower with maximum energy deposit is first looked for and then the shape parameters are formed around it. The following shape variables are considered:

$S1/S9$: This ratio makes use of $S1$, the energy deposited in the maximum hit tower, and $S9$, the energy deposited in 3×3 array around the maximum hit tower. The left plots of figure 3 shows the distribution of $S1/S9$ for 50 GeV, 70 GeV and 150 GeV photons and π^0 's.

$S1/S4$: This ratio uses $S4$, the energy deposited in 2×2 array including the maximum energy tower. Four possible 2×2 arrays are possible which include the maximum energy tower. The combination which corresponds to the largest sum total energy is used in determining the ratio. The middle plots of figure 3 shows the distributions of $S1/S4$ for 50, 70 and 150 GeV photons and π^0 's.

2-D distribution of F_{16} VS F_9 : The variables, F_9 and F_{16} , are defined through equation 1.

$$F_9 = \frac{S9 - S1}{S9}, F_{16} = \frac{S16 - S4}{S16} \quad (1)$$

where $S16$ is the energy deposited in the 4×4 array of towers which includes that 2×2 array of towers which has maximum energy in the four possible combinations as explained above. The right plots of figure 3 shows the 2-D distribution of F_{16} and F_9 for 50, 70 and 150 GeV photons and π^0 's.

The performance of the variables $S1/S9$, $S1/S4$ and F_{16} vs F_9 are summarized below:

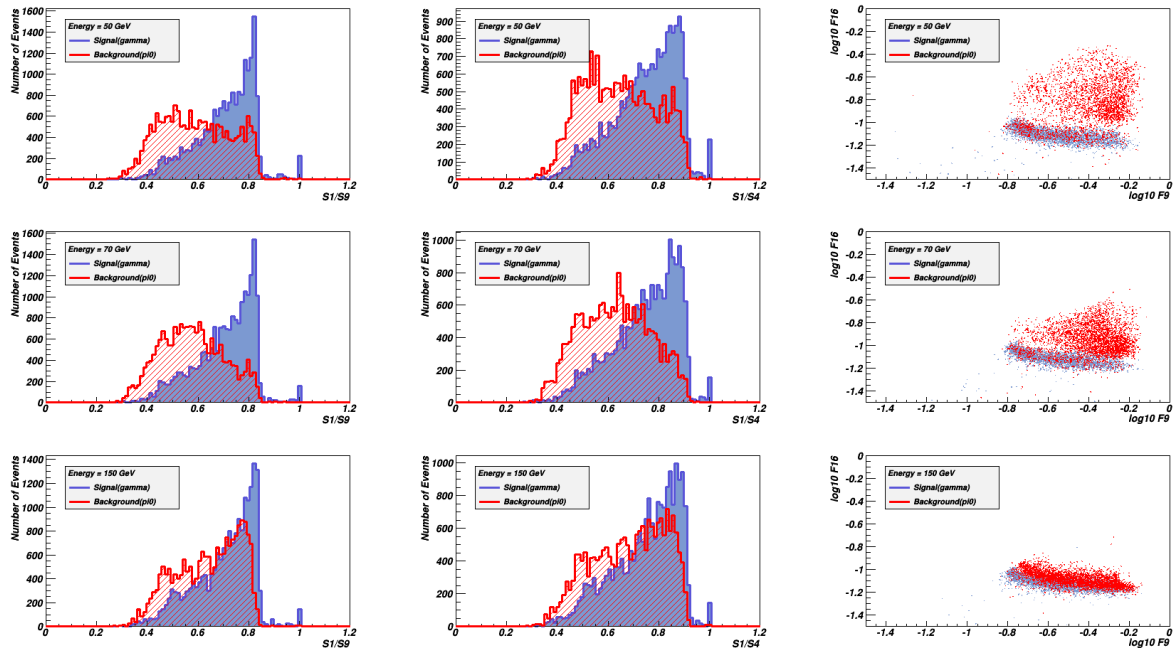


Figure 3. The distribution of $S1/S9$, $S1/S4$, $F9F16$ for 50 GeV, 70 GeV and 150 GeV photons and π^0 's. The blue hatched histogram is for photons and the red hatched histogram is for π^0 's.

- Shower shape variables $S1/S9$ and $S1/S4$ lose the sensitivity for γ/π^0 separation at energies above 70 GeV;
- The 2-D distribution of F_{16} vs F_9 performs better for 70 GeV γ/π^0 discrimination compared to $S1/S9$ and $S1/S4$. But again it loses power for discrimination at energies above 70 GeV.

3.2. Study using Multivariate Analysis (MVA)

As has been seen from the previous Sections, 3.1, that the discriminating power is reduced significantly for π^0 's of energy above 100 GeV. An analysis has been carried out exploring the discriminating power gained by employing multivariate techniques to the problem. The following MVA classifiers were examined in this analysis:

- Boosted Decision Tree (BDT)
- Gradient Boosted Decision Trees (BDTG)
- Artificial Neural Network (ANN)

In this analysis, the TMVA[6] package within ROOT[5] was used. All the MVA techniques, mentioned above, are implemented in it. TMVA was trained with a sample of photons and π^0 's. Energy from each individual tower in 3×3 array, or energy from each fiber in the 3×3 array was fed into TMVA. This analysis was done using photons and π^0 's at 200 GeV. Two types of samples were produced:

Fixed gun sample: These were produced with the gun position fixed at (0 mm, 4 cm) in (x, y) , whereas, z being 3.195 m.

Random gun sample: In this case the gun position was uniformly distributed in X and Y directions between -7 mm and +7 mm i.e. within the central crystal.

Following two sets of training variables were used separately to train TMVA:

Coarse grain information: Input to TMVA is the ratio of energy from each tower in 3×3 array to total energy in 3×3 array.

Fine grain information: Input to TMVA is the ratio of energy from each individual fiber in 3×3 array to total energy in 3×3 array.

These energies are scaled to the total energy collected in the 3×3 array.

3.2.1. MVA using fixed gun samples In this case the TMVA was trained and tested independently using 10000 events from fixed gun samples of 200 GeV photons and π^0 's. Two sets of training variables, coarse grain and fine grain information were used separately to train the TMVA. Figure 4 shows the background rejection versus signal efficiency curve for the case of both coarse grain and fine grain information.

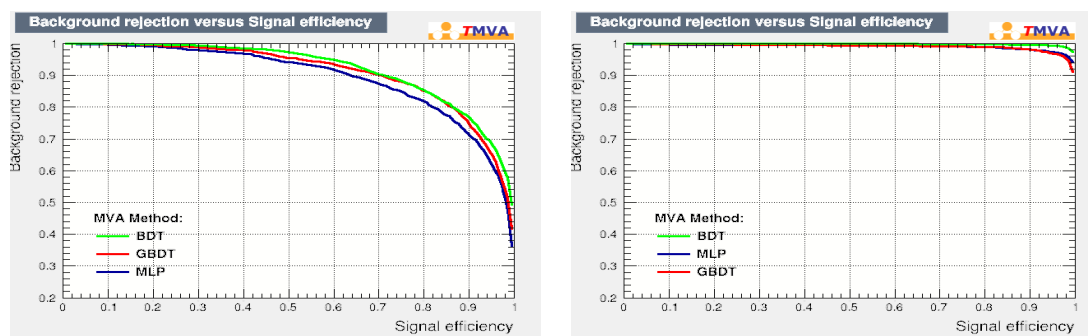


Figure 4. he background rejection versus signal efficiency curve of different MVA methods for fixed gun sample. The figure on the left are for coarse grain information and that on the right refers to fine grain information.

3.2.2. MVA using random gun samples Here TMVA was trained and tested separately using 10000 events from random gun samples of 200 GeV photons and π^0 's. Two sets of training variables, coarse grain and fine grain information were used separately to train the TMVA. Figure 5 shows the background rejection versus signal efficiency curve for the case of both

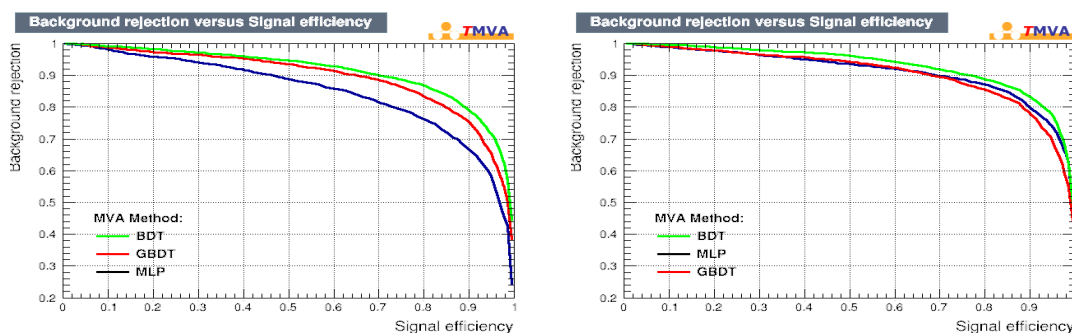


Figure 5. The background rejection versus signal efficiency curve of different MVA methods for random gun sample. The figure on the left are for coarse grain information and that on the right refer to fine grain information.

coarse grain and fine grain information. It can be seen from the figure 4 and 5, that the fine grain information is better for discriminating signal from from background.

3.3. Application of random gun samples in real application

In this case the TMVA was trained using 20000 events from random gun samples of 200 GeV photons and π^0 's. The ratio of energy from each individual fiber in the 3×3 array to total energy were used as training variables for the TMVA. Two different samples were used to train the TMVA:

Unbinned random sample: The random gun sample was produced over all regions of the central crystal.

Binned random sample: The central crystal was divided into 7×7 bins. Random samples were produced in each bin separately.

For both the cases, the TMVA was tested using 20000 events from random gun samples of 200 GeV photons and π^0 's produced over all regions of the central crystal. Figure 6 shows background rejection versus signal efficiency plots for binned as well as unbinned random gun sample.

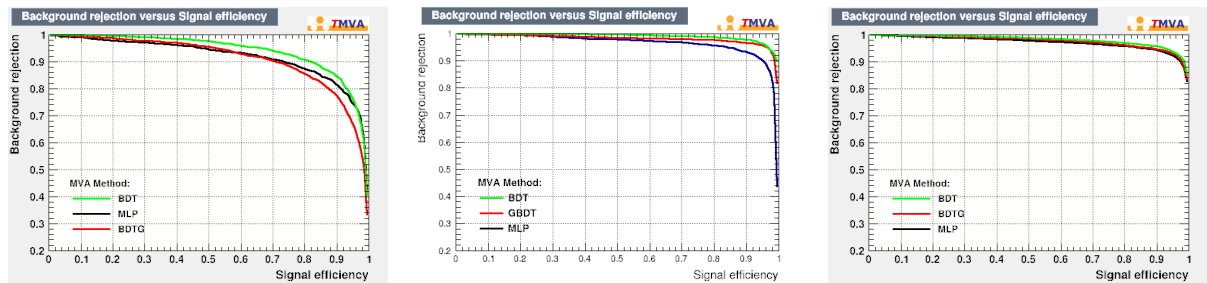


Figure 6. Background rejection versus signal efficiency for binned and unbinned random samples. The left figure is for unbinned random sample, the middle figure is for a bin where the sample is randomized over a region from -1 mm to $+1$ mm around centre of the central crystal in both X and Y direction and the bottom right figure is for a region from -1 mm to $+1$ mm in the X direction and $+3$ mm to $+5$ mm in the Y direction.

3.4. Comparison of various methods

A comparison in performance is made among all the methods described in the previous sections. This comparison is shown for 200 GeV photons and π^0 's. If a method shows good separation

Variable	Background rejection (%)		
	$\epsilon_{\text{signal}}=80\%$	$\epsilon_{\text{signal}}=85\%$	$\epsilon_{\text{signal}}=90\%$
S1/S9	33.2	27.7	21.2
S1/S4	32.7	26.8	20.1
MVA(BDTG): coarse grain (fixed gun sample)	86.3	82	76.5
MVA(BDTG): fine grain (fixed gun sample)	99.1	99	98.5
MVA(BDTG): fine grain (unbinned random gun sample)	86.3	83.3	78.9
MVA(BDTG): fine grain (binned random gun sample)	92.3	91	89.3

Table 1. Table showing the background rejection for signal efficiencies of 80%, 85% and 90% for various methods. This is shown for energy point of 200 GeV.

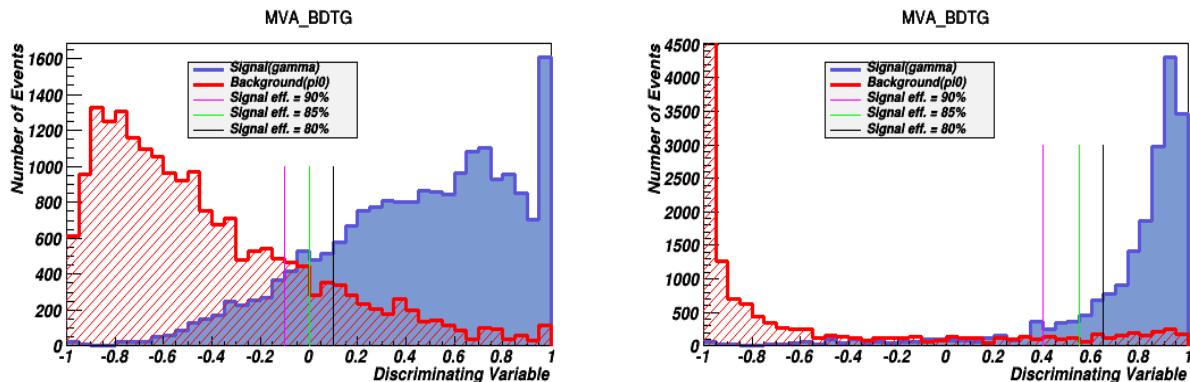


Figure 7. Comparison of BDTG MVA method for unbinned and binned random gun sample. The black, green and pink lines are the point where the cut is applied to achieve 80%, 85% and 90% signal efficiency respectively.

power for this high energy point, then it is good for lower energy points as well. BDT gives the best response for the case of both coarse grain and fine grain information as can be seen from figures 4 and 5. The response of BDTG is more or less same like BDT. Here the comparison is made using the BDTG. Table 1 shows the background rejection for all the various methods for a signal efficiencies of 80%, 85% and 90%.

4. Summary

A simulation study of $\pi^0 - \gamma$ separation of the Shashlik detector, proposed as a candidate of CMS endcap electromagnetic calorimeter in the Phase II upgrade, has been presented in this paper. This study shows that the fine grain information of the shower profile collected by individual fibers is useful for separation between π^0 and γ at high energies. With the MVA technique a background rejection efficiency of 90% with signal efficiency 90% is achieved, which is approximately three times better than the best background rejection that could be achieved by cut-based methods. We conclude that the $\pi^0 - \gamma$ separation power of the Shashlik calorimeter can be improved significantly by employing an MVA based method with fine grain information as input and this approach should work with other types of calorimeters.

5. References

- [1] Technical Proposal for the Phase-II Upgrade of the CMS Detector 2015 *CERN LHCC 010, LHCC-P 008*.
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- [3] Y. Koba et al., Scintillation Efficiency of Inorganic Scintillators for Intermediate Energy Charged Particles 2011 *Progress in Nuclear Science and Technology* **1** 218
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- [5] ROOT <http://root.cern.ch/drupal/>
- [6] A. Hoecker et al. TMVA Toolkit for Multivariate Data Analysis with ROOT 2013 <http://tmva.sourceforge.net/>