A method for the separation and reconstructions of charged hadron and neutral hadron from their overlapped showers in an electromagnetic calorimeter *

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Abstract: The separation and reconstructions of charged hadron and neutral hadron from their overlapped showers in an electromagnetic calorimeter is very important for the reconstructions of some particles with hadronic decays, for example the tau reconstruction in the searches for the Standard Model and supersymmetric Higgs bosons at the LHC. In this paper, a method combining the shower cluster in an electromagnetic calorimeter and the parametric formula for hadron showers, was developed to separate the overlapped showers between charged hadron and neutral hadron. Taking the hadronic decay containing one charged pion and one neutral pion in the final status of tau for example, satisfied results of the separation of the overlapped showers, the reconstructions of the energy and positions of the hadrons were obtained. An improved result for the tau reconstruction with this decay model can be also achieved after the application of the proposed method.

Key words: separation and reconstructions, overlapped showers, parametric formula

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1 Introduction

At LHC, Higgs $\rightarrow\tau\tau$ is an important decay channel in the searches of Standard Model and supersymmetric Higgs bosons. About two-thirds of taus decay hadronically to charged hadron(s) and neutral pion(s), among which about one fourth of taus will decay to a median particle rho ($\rho^{\pm}$) and finally one neutrino, one charged pion and one neutral pion which will immediately decay into two photons and will be reconstructed as a photon candidate in the experiment for the very closure of the two photons. The overlapped shower of 2 photons from a neutral pion will also be thought of as a neutral pion and called a neutral pion in this paper for convenience. Both the charged pion and neutral pion will deposit energy in the electromagnetic calorimeter (ECAL), and their showers will overlap with each other. So it's very important to know the energy fraction belonging to the neutral pion for the reconstructions of both the energy and position for the neutral pion in ECAL, which is of course very important for the reconstructions of $\rho^{\pm}$ and $\tau^{\pm}$. The shower splitting is also important for the reconstruction of jets which play an important role in the physics analysis of many hadronic particles giving rise to jets and the measurement of the missing transverse energy based on jets.

In this paper, a technique was proposed to be used for the separation and reconstructions of charged hadron and neutral hadron from their overlapped showers in ECAL, combining the supercluster [1] in ECAL and the empirical formulae for the parameterization of the hadron showers [2]. The parameterization of the electromagnetic shower and the hadronic shower in an electromagnetic calorimeter has been studied in Refs. [3] and [2] respectively. The empirical formulae of both the showers can fit the shower shape well with the data of Alpha

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Magnetic Spectrometer II ECAL test beam. The empirical formula for the electromagnetic shower was also studied for the discrimination of unconverted γ/π^0 at the LHC [4]. Taking the channel $\tau^\pm \to \rho^\pm + \nu_{\tau^\pm} \to \pi^\pm + \pi^0 + \nu_{\tau^\pm}$ for example in this paper, the empirical formula for the hadronic shower was used in the process of the separation and reconstructions of charged hadron and neutral hadron from their overlapped showers. The results shown that the overlapped can be well split and the energy can be well assigned to the charged pion and neutral pion. The median particle can be well reconstructed with an improved result on the present reconstruction algorithm used in CMS experiment at LHC [5].

The setup of the detector with the GEANT4 package and the Supercluster algorithm in an electromagnetic calorimeter are simply introduced in Section 2. The simple description and validation of the parametric shower shape formula for the hadron shower are described in Section 3. The proposed technique and its performance are presented in Section 4. Finally the summary and outlook are in Section 5.

2 ECAL and Supercluster algorithm description

2.1 Electromagnetic calorimeter

In particle experiments, the electromagnetic calorimeter is one specifically designed to measure the energy of photons and electrons, which will deposit their energy in ECAL after the electromagnetic interaction and showering in ECAL. As Ref. [4], we constructed an ECAL geometry with GEANT4 package, as the ECAL barrel region of the CMS detector, to study the shower of electromagnetic style particles and develop the separation and reconstruction algorithm of hadrons from the overlapped shower in ECAL with the empirical formula for the charged hadron shower.

The ECAL barrel is made of 61200 same-sized lead tungstate(PbWO4) crystals, covering pseudorapidity $|\eta| < 1.479$. The centers of the front faces of the crystals are at a radius 1.29 m from the global coordinate z-axis. The cross-section of the front face and rear face for each crystal corresponds to 0.0174×0.0174 (in units of radian$\times$radian) in η-ϕ plane, and each crystal is 230 mm long which corresponds to 25.8X0 with 1 radiation length (X0) equal to 0.89 cm. They are mounted in a quasi-projective geometry so that their axes make a small angle (3°) with respect to the vector from the nominal interaction point (i.e, the center of the detector setup), in both the η and ϕ directions. So in η-ϕ plane, the barrel crystals project approximatively to be a series of 360×170 squares, with which the lateral shower of a single charged hadron can be described well by the empirical formula as described in Section 2. Additionally, the same tracker detector located in the front of ECAL and magnetic field with 3.8 Tesla along the η direction are also constructed to measure the momentum of the track from charged hadron. More detailed descriptions can be found in Ref. [6].

2.2 Supercluster algorithm

Photons and electrons will shower in ECAL and deposit about 94% of their energy in 3×3 crystals, and 97% in 5×5 crystals. Especially for unconverted photons and electrons with less bremsstrahlung in the test beam, the fixed arrays can give a much better performance. But the presence of tracker material in front of ECAL, results in bremsstrahlung of electron and photon conversions. So the energy deposited from electrons and photons showering in the calorimeter will spread in ϕ direction due to the strong magnetic field. The hybrid supercluster algorithm [1] is developed to collect the separated and the bremsstrahlung energy in the ϕ direction. The algorithm starts from the discovery of a seed crystal with deposit energy greater than 0.35 GeV. The 1×3 ($\eta\times\phi$) or if 1×3 energy greater than 1 GeV then 1×5 crystal arrays in η direction will be included to the same supercluster, until the energy in 1×3 less than 0.1 GeV or at most including 11 such arrays. This kind of supercluster, in a very narrow η window and much wider ϕ window, gives very nice performance for electrons and photons in the ECAL as we described in the above section. Two photons from a neutral pion decay can deposit their energy very close to each other resulting in the overlapped shower being reconstructed as one hybrid supercluster. The position of the center of gravity (COG) of the supercluster in ECAL can be calculated with a good position resolution using the energy and position of each crystal contained in this supercluster, as decribed in Ref. [1] and Ref. [4]. More details about the algorithm can be found in Ref. [1].

3 Validation of the parametric formula of the hadronic shower

3.1 Description of the parametric shower shape formula

The longitudinal shower formula and lateral formula of the hadronic shower were studied in Ref. [2]. In the homogenous crystal we constructed in GEANT4, the shower shape of a single charged hadron particle is symmetrical around the shower direction. So the lateral shower in the transverse plane vertical to the particle direction is isotropic. In this paper, only the lateral shower formula was used to describe the shower shape due to the difficulty in finding out the shower start point of the hadronic shower in the constructed ECAL with only one crystal from the front to the rear. We can estimate the position of the COG of the supercluster in ECAL of the cascade shower using the energy and position of each crystal with a satisfied position resolution [1, 4]. Through the COG point we can make a transverse plane which is vertical to the shower direction. Then the whole shower shape will be projected to this plane. The deposited energy density can be described by the following parameterized function,

$$\frac{\mathrm{d}E}{\mathrm{d}r}=f(E,R,r)=2Er\frac{R}{(r+R)^3}, r=\sqrt{(x-x_c)^2+(y-y_c)^2}, \tag{1}$$

which is the transformed formula in the system of polar coordinates as the following formula developed in Ref. [2] with parameter $B=3$,

$$\frac{\mathrm{d}^2E}{\mathrm{d}x\mathrm{d}y}=\frac{E}{2\pi}\frac{\Gamma(B)}{\Gamma(B-2)}\frac{R^{B-2}}{(r+R)^B}. \tag{2}$$

In these formulae, r is the distance of the shower developing point to the COG in the transverse plane. E is the total deposited energy of the shower. R is a free parameter to describe the shower shape. We will validate the parametric formula with charged pion showers in the constructed ECAL in the next subsection.

3.2 Verification and parameter determination

Single charged pion runs with incident energy ranging from 20 to 100 GeV were used to verify the formula. When the total deposited energy in ECAL is larger than 1 GeV, the energy of 5×5 crystals around the maximum energy crystal as Fig. 1(a), were fitted with formula 1 using χ^2 minimization method in MINUIT package. The fit minimized χ^2 is given by

$$\chi^2=\sum_{i=1}^{25}(E^i_{\text{fitted}}-E^i_{\text{deposited}})^2, \tag{3}$$

where $E^i_{\text{deposited}}$ is the energy deposited in ith cell; E^i_{fitted} is the energy in ith cell predicted by the formula 1. The integration algorithm for the formula along r direction is the same as described in Ref. [4].

From the study, more than 98% of the charged pion showers in ECAL were fitted successfully with formula 1. The fitting results including the shower shape in 5×5 cell array, χ^2/E^2 and R distributions are shown in Fig. 1. From the plot Fig. 1(b), the agreement between the

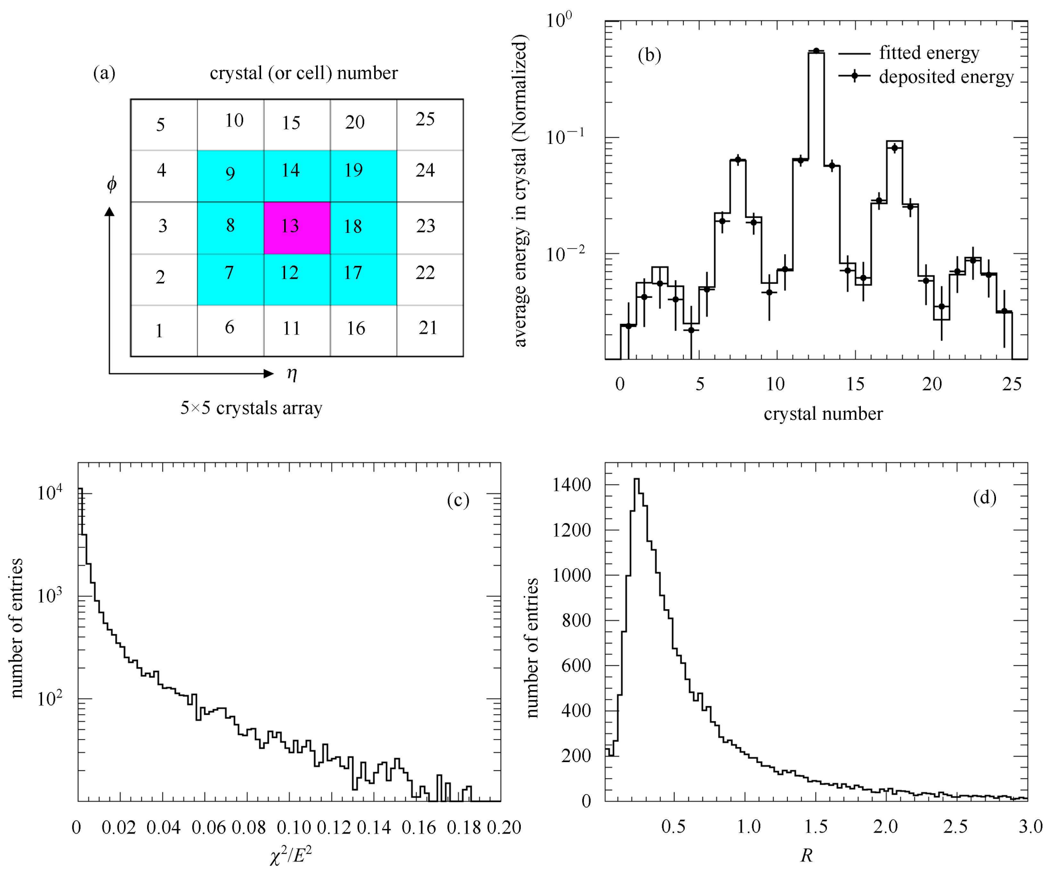

Fig. 1. (a) The numbering of 5×5 crystals array; (b) Comparisons of the average predicted energy with the average original deposit energy in each crystal of the 5×5 crystals array for 20–100 GeV charged pion samples. The dots represent the average original deposit energy in each crystal and the histogram represents the predicted one by formula 1; (c) The χ^2/E^2 distribution represent the goodness of the fitting; (d) The distribution of the only parameter R in formula 1.

shape calculated by formula 1 and the original deposited energy for the hadronic shower is satisfied. The maximum energy cell contains about 52% of the total energy. From Fig. 1(d), the value of the parameter R is about 0.25 with a maximum probability.

4 Method for separation and reconstruction of neutral pion and charged pion from their overlapped shower in ECAL

4.1 Description of the method

As described at the very beginning in the first section, for many physics objects in experiment such as the reconstructions of tau and jet, the final neutral pions and charged pions will be produced very close to each other in the higher energy hadron collider. Their showers in ECAL will overlap with each other and will be reconstructed as one supercluster in experiment. We tried to use the shower shape method with the parametric formula as described above to separate the overlapped shower and then obtain the energy and position of charged pion and neutral pion. This method is also taken as one of the applications of the hadronic shower shape formula in Ref. [2].

We take the most simple decay module of tau, $\tau^{\pm} \rightarrow \rho^{\pm}+\nu_{\tau^{\pm}} \rightarrow \pi^{\pm}+\pi^{0}+\nu_{\tau^{\pm}}$ which is almost one fourth of the tau decays, to describe the method. Fig. 2 is the schematic view of the shower overlapping of the neutral hadron and charged hadron. The two photons from a neutral pion are close to each other and will form the EM shower. The hadronic shower in ECAL from $\pi^{\pm}$ shower will also be very close to the EM shower. They will be reconstructed as one supercluster in ECAL. With

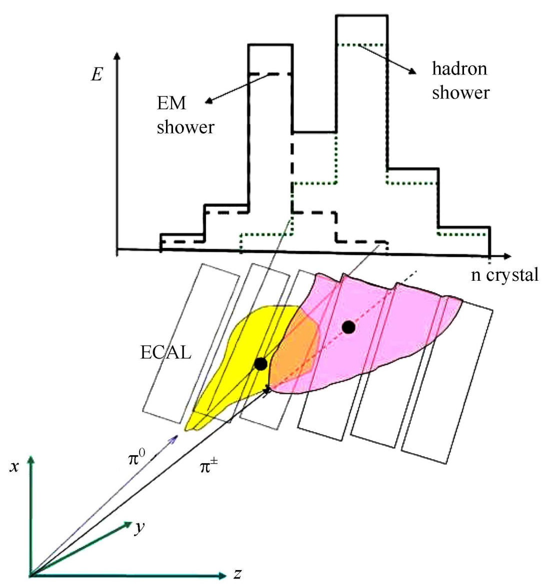

Fig. 2. Schematic view of the shower method.

the formula 1, we can calculate the hadron energy in each crystal, if we have the values of the following three variables, COG (center of gravity), total energy E, and parameter R. So for the method, first the fix or the estimation of their values will be considered in the following.

From Fig. 1(d), R=0.25 is applied in the formula for it has a peak value at about 0.25. The COG of $\pi^{\pm}$ shower should be close to the track reconstructed in the tracker material and extrapolated to the front face of ECAL. The radius of the COG is around 137.0 cm to the center of the constructed detector in section 2, as shown in Fig. 3(a). So the point on the track at radius=137.0 cm is chosen to be taken as the COG of the hadronic shower. For the shower from a single particle, the COG can also be calculated from the algorithm described in section 2.2 or in Ref. [4]. The difference of η and ϕ between these two points are shown in Fig. 3(b), (c). The σ of the difference between the reconstructed one and the truth is much lower than one crystal size as described in section 2. The maximum hit energy of $\pi^{\pm}$ shower is used to estimate the total deposit energy E, for it contains about 52% of $\pi^{\pm}$ energy as shown in Fig. 1(b). Now the key is to find the crystal which has maximum energy of the hadron shower. The crystal with the largest deposited energy in the all crystals with which the track will course through in ECAL, not always the most energic crystal in the shower, was chosen as the maximum energy of the hadron shower. The differences of crystal number between selected crystal for the seed of hadron and the most energic crystal in the shower is given in Fig. 3(d) and (e) in the η and ϕ direction respectively. From the plots, the probability of the selected crystal for the seed of hadron being also the most energic crystal in the shower is about 91% of all $\pi^{\pm}$ events both in the η and ϕ directions.

Now the process of the method is introduced here. There are several steps for the separation and reconstruction of neutral pion and charged pion from their overlapped shower, the hybrid supercluster in ECAL:

1) Firstly we extrapolated the $\pi^{\pm}$ track to the front face of ECAL. The energy ($E_{\rm maxHit}$) of the crystal which has the largest deposited energy the track passed through in ECAL, was selected as the center of the hadronic shower from the charged hadron. Then the total deposited energy from the charged pion in ECAL was estimated as $E=E_{\rm maxHit}/0.52$.

2) The position on the track at radius=137.0 cm was taken as the center of gravity of the shower from the charged pion.

3) The energy deposited in each crystal from the charged pion can be calculated by the formula 1 for the hadronic shower as described in the above section.

4) The remaining energy in each crystal after the substraction of the energy deposited by charged pion and

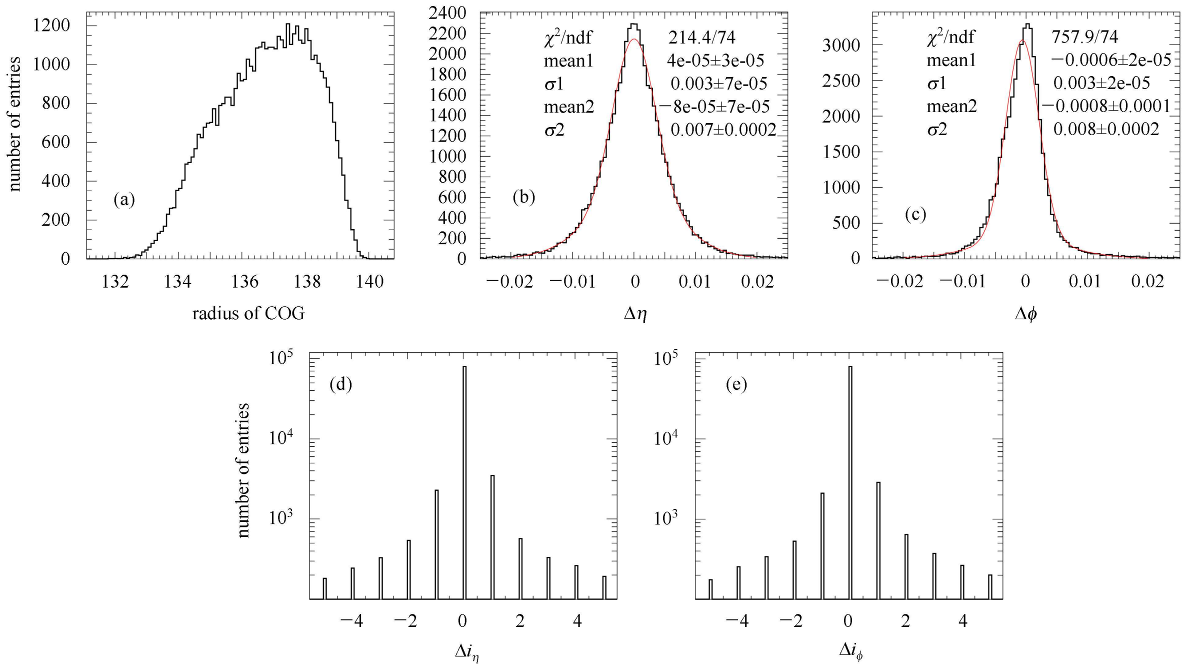

Fig. 3. (a) Radius distribution of the COG of the charged hadron showers from $\pi^{\pm}$. (b) Differences of η and (c) ϕ between COG and its estimated point on the track of the incident $\pi^{\pm}$. (d) Differences of crystal number between maximum hit crystal and its estimate in η direction and (e) in ϕ direction for the single charged hadron shower from $\pi^{\pm}$.

calculated in 3), was taken as the deposited energy of the EM shower from the neutral pion.

5) The energy of π^0 can be obtained from the remaining energy in each crystal of the overlapped supercluster. The position of π^0 can also be calculated from the remaining energy of the position of each crystal using the energy weighted algorithm as described in the Ref. [4].

4.2 Results of the method

Combining the supercluster and the lateral hadron shower formula with several approximate calculations, the deposited energy and position of $\pi^{\pm}$ and π^0 from the overlapped shower in ECAL can be well reconstructed. With the method described above, the energy and position of the charged pion and neutral pion were compared with the true energy and position of $\pi^{\pm}$ and π^0 respectively, as shown in Fig. 4(a), (b) and (c). Since all the overlapped showers were contained during the analysis, including the energy loss in ECAL by the charged pion as a minimum ionizing particle (MIP), the resolutions of the position and energy of π^0 were a little bit large from our method. But the result is satisfied for us to solve the shower overlapping problem in ECAL for the first time to use such a technique. This will result in a much better reconstruction of the higher object such as $\rho^{\pm}$ and jets. The reconstructed position and energy of the charged pions from the split shower method were also compared with the true ones in Fig. 4(d), (e) and (f), although the momentum and position from the tracks were used for the further analysis in the next paragraph. The results of the position and energy of the charged hadron from the estimated energy in ECAL after the shower splitting are also satisfied.

The reconstructed position and mass of median particle $\rho^{\pm}$, i.e., the visible position and mass of $\tau^{\pm}$ in experiment can be obtained. During the calculation, the momentum and position from the track were used for the charged pion. As comparisons, the results from the HPS(hadron plus strip) algorithm [5]. which is being used in the present reconstruction software in CMS experiment at the LHC, were also drawn in the same plot, as seen from Fig. 5. The HPS algorithm includes firstly the recalibration of the energy of ECAL shower using MIP events and then the comparison between the momentum of tracks and the corresponding energy in the electromagnet plus the hadronic calorimeters to separate the energy of $\pi^{\pm}$ and π^0. From the comparisons, we can see that improved results can be obtained after the application of the method for separation and reconstruction of neutral pion and charged pion from their overlapped shower in ECAL. We can get slightly better results for the position and energy reconstructions and much better result of the mass reconstruction for the median particle $\rho^{\pm}$. The fitted mass value is about 2.0% lower than the PDG value.

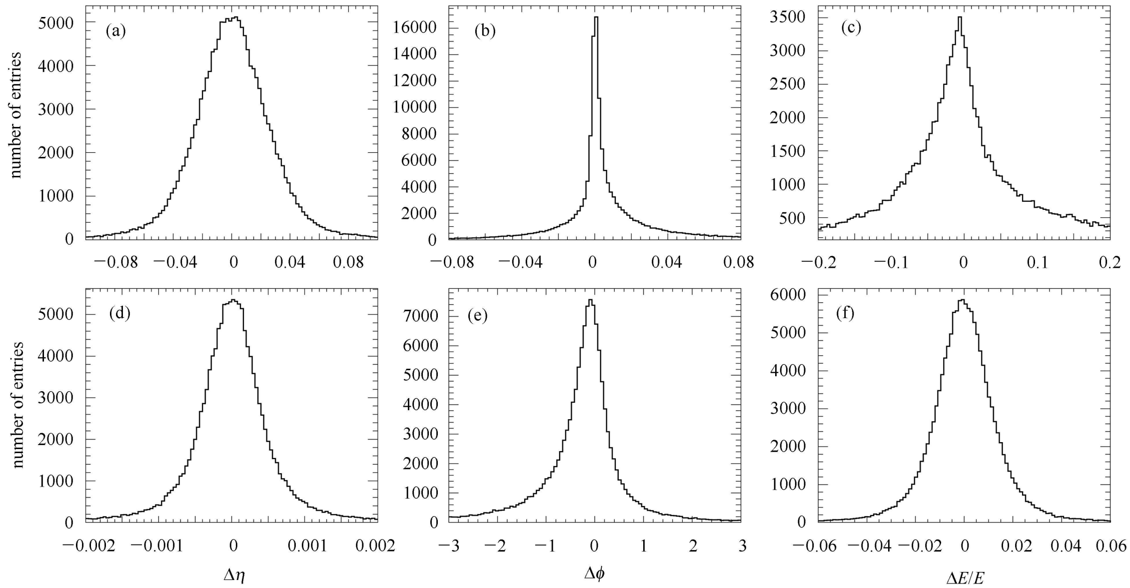

Fig. 4. The performance of π^0 and $\pi^{\pm}$ reconstruction from the split showers after the application of the proposed method in this pair. (a) The differences of position in η and (b) ϕ, and (c) energy $\dfrac{\Delta E}{E}$ between the reconstructed π^0 with the separation method and the true one. (d) The differences of position in η and (e) ϕ, and (f) energy $\dfrac{\Delta E}{E}$ between the reconstructed $\pi^{\pm}$ with the separation method and the true one.

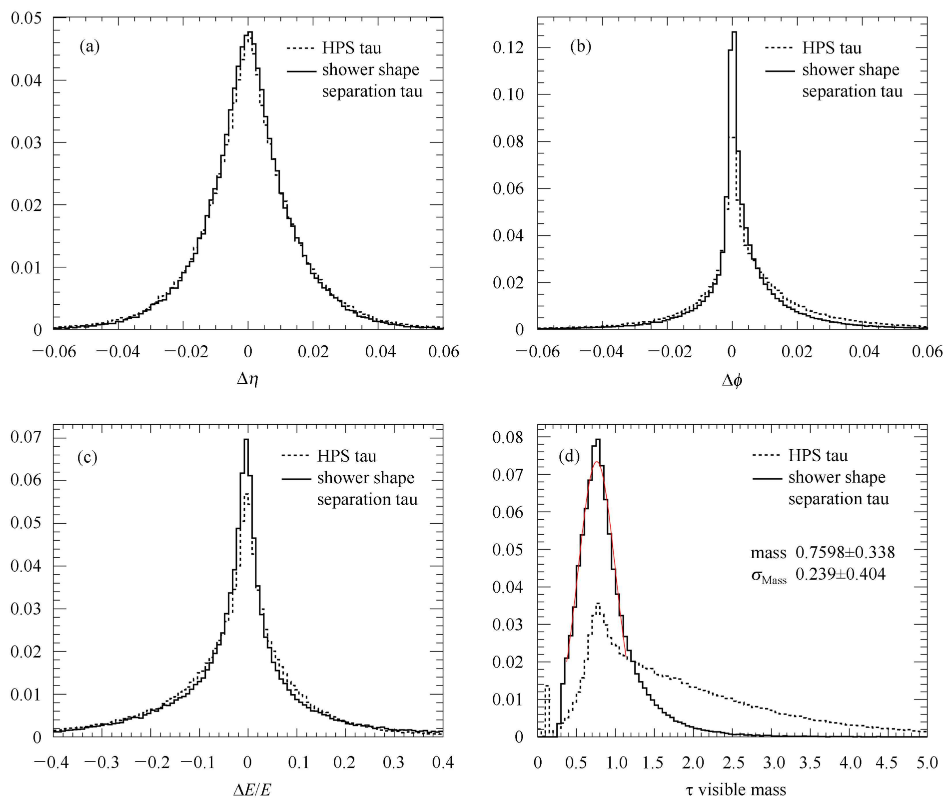

Fig. 5. The performance of $\rho^{\pm}$ reconstruction after the application of the proposed method in this paper. (a) The differences of position in η and (b) ϕ directions, and (c) the difference on the energy $\dfrac{\Delta E}{E}$ between the reconstructed ρ with the separation method and the true one. (d) The visible mass of reconstructed $\tau^{\pm}(\rho^{\pm})$.

5 Summary and outlook

In this paper, the parametric formula of the hadronic shower was used for the substraction of the energy deposited by the charged hadron from the overlapped shower from a charged hadron and a neutral hadron in ECAL. This is the first time the shower shape method has been used as one of the applications of the parametric formulae of the hadron shower. Taking the hadronic decay of tau, $\tau^{\pm}\rightarrow\rho^{\pm}+\nu_{\tau^{\pm}}\rightarrow\pi^{\pm}+\pi^{0}+\nu_{\tau^{\pm}}$ for example, the energy and position for the neutral pion can be reconstructed satisfactorily after the separation with the proposed technique in this paper. Finally improved results of the position, energy and mass reconstructions of the median particle ρ were obtained, comparing with the present algorithm used in CMS at the LHC.

In this paper, we take only the one prong hadronic decay of tau for example to describe the method we proposed. In the near future, this method will be studied to be used in the tau analysis with multiplicity decay including several charged pions and neutral pions. This technique can also be used in the jet reconstruction which also includes the shower overlapping problem between charged hadrons and neutral hadrons in ECAL. The reconstructed resolutions both of position and energy of the jet and even the missing transverse energy in the experiment can be improved in the future, which is very important in many physics analyses at the LHC. We also noticed that the reconstructed positions in ϕ direction have asymmetry distributions, due to the effect from the constructed magnetic field with 3.8 Tesla along the η direction. The effect from the magnetic field and the approximate process can also induce the asymmetry distribution of the reconstructed energy of the particle ρ in Fig. 5(c). In the future analysis, the correction from the magnetic field and the re-optimization of the approximations should be considered.

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