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

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Abstract: The separation and reconstructions of charged hadron and neutral hadron from their overlapped showers in 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 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 forth of taus will decay to a median particle rho(rho) and final one neutrino, one charged pion and one neutral pion which will immediately decay into two photons and will reconstructed as a photon candidate in experiment for the very closure of the two photons. The overlapped shower of 2 photons from a neutral pion will also be thought as a neutral pion and called as 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 belong 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 and tau. 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\textsuperscript{1} in ECAL and the empirical formulae for the parametrization of the hadron showers \textsuperscript{2}. The parametrization of electromagnetic shower and hadronic shower in electromagnetic calorimeter has been studied in Ref \textsuperscript{3} and \textsuperscript{2} respectively. The empirical formulae of both the showers can fit the shower shape well with the data of Alpha Magnetic Spectrometer II ECAL test beam. And the empirical formula for the electromagnetic shower was also studied for the discrimination of unconverted gamma/neutral pion at the LHC\textsuperscript{2}. Taking the channel \( \tau^\pm \rightarrow \rho^\pm + \nu_\tau \) as 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. And the median particle can be well reconstructed with an improved result than the present reconstruction algorithm used in CMS experiment at LHC.

The setup of the detector with the GEANT4 package and the Supercluster algorithm in electromagnetic calorimeter are simply introduced in section 2. The simple description and validation of the parametric shower shape formula for 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 experiment, 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 [3], we constructed an ECAL geometry with GEANT4 package, as the ECAL barrel region of 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 charged hadron.

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 1.29m from the global coordinate $z-axis$. The cross-section of the front face and rear face for each crystal is corresponds to 0.0174×0.0174 (in unit of radian×radian) in $\eta-\phi$ plane, and each crystal 230mm long which is corresponding 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 $\eta$ and $\phi$ directions. So in $\eta-\phi$ 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. Additional the same tracker detector located in the front of ECAL and magnetic field with 3.8 Tesla along the $\eta$ direction are also constructed to measure the momentum of the track from charged hadron. More detail descriptions can be found in Ref [3].

2.2 Supercluster algorithm

Photons and electrons will shower in ECAL and deposit about 94% of their energy in $3 \times 3$ crystals, and 97% in $5 \times 5$ crystals. Especially for unconverted photons and electrons with less bremsstrahlung in test beam, the fixed arrays can give a much better performance. But the presence of tacker 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 $\phi$ direction due to the strong magnetic field. The hybrid supercluster algorithm [2] is developed to collect the separated and the bremsstrahlung energy in the $\phi$ direction. The algorithm start from the find of a seed crystal with deposit energy greater than 0.35GeV. The $1 \times 3 (\eta \times \phi)$ or if $1 \times 3$ energy greater than 1GeV then $1 \times 5$ crystal arrays in $\eta$ direction will be included to the same supercluster, until the energy in $1 \times 3$ less than 0.1GeV or at most including 11 such arrays. This kind of supercluster, in a very narrow $\eta$ window and much wider $\phi$ 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 to result in the overlapped shower can be 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 [2].

3 Validation of the parametric formula of hadronic shower

3.1 Description of the parametric shower shape formula

The longitudinal shower formula and lateral formula of hadronic shower were studied in Ref [2]. In the homogeneous crystal as we constructed in GEANT4, the shower shape of 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 to find 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 center of gravity (COG) of supercluster in ECAL of the cascade shower using the energy and position of each crystal with a satisfied position resolution[14]. 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,

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

(1)

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

$$\frac{d^2E}{dxdy} = \frac{E \Gamma(B)}{2\pi \Gamma(B-2)} \frac{R^{B-2}}{(r+R)^B}. \quad (2)$$

In these formulae, $r$ is the distance of the shower developing point to COG in 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 $5 \times 5$ crystals around the maximum energy crystal as Fig.1(a), were fitted with formula(1) using $\chi^2$ minimization method in MINUIT package. The fit minimized $\chi^2$ is given by

$$\chi^2 = \sum_{i=1}^{25} (E_{fitted}^i - E_{deposited}^i)^2$$  

(3)

where $E_{deposited}^i$ is the energy deposited in $ith$ cell; $E_{fitted}^i$ 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 $5 \times 5$ cell array, $\chi^2/E^2$ and $R$ distributions are shown in Fig.1. From the plot Fig.1(b), the agreement between the shape calculated by formula(1) and the original deposited energy for the hadronic shower is satisfied. And the maximum energy cell contain about 52% of the total energy. From Fig.1(d), the value of the parameter $R$ is about 0.25 with a maximum probability.
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 closely with each other in higher energy hadron collider. Their showers in ECAL will be overlapped 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, $\tau^\pm \rightarrow \rho^\pm + \nu_\tau$, as almost one forth of the tau decays, to describe the method. The COG of the neutral hadron shower should be close to the track reconstructed in the tracker material and extrapolated to the front face of ECAL. The radius of 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 hadron shower. The radius of the COG is around 137.0 cm to the center of the constructed detector in section 2. 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 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 hadron shower. The crystal with the largest deposited energy in all crystals with which the track will path through in ECAL, not always the most energetic crystal in the shower was chosen as the maximum energy of hadron shower.

The differences of crystal number between selected crystal for the seed of hadron and the most energetic crystal in the shower is given in Fig. 3(d) and (e) in the $\eta$ and $\phi$ direction respectively. From the plots, the probability of the selected crystal for the seed of hadron being also the most energetic crystal in the shower is about 91% of all $\pi^\pm$ events both in the $\eta$ and $\phi$ 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 ($E_{\text{maxHit}}$) 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 $E = E_{\text{maxHit}}/0.52$.

2) The position on the track at $\text{radius} = 137.0\,\text{cm}$ was taken as the center of gravity of the shower from charged pion.

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

4) The remain energy in each crystal after the subtraction of the energy deposited by charged pion and calculated in 3), was taken as the deposited energy of the EM shower from the neutral pion.

5) The energy of $\pi^0$ can be obtained from the remain energy in each crystal of the overlapped supercluster. And the position of $\pi^0$ can be also calculated from the remain 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 $\pi^0$ from the overlapped shower in ECAL can be well reconstructed. With the method described above, the energy and position of charged pion and neutral pion were compared with the truth energy and position of $\pi^\pm$ and $\pi^0$ 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 charged pion as a minimum ionizing particle (MIP), the resolutions of the position and energy of $\pi^0$ were some little bit of 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 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 be 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 charged hadron from the estimated energy in ECAL after the shower splitting are also satisfied.
Fig. 4. The performance of $\pi^0$ and $\pi^\pm$ reconstruction from the split showers after the application of the proposed method in this paper. (a) The differences of position in $\eta$ and (b) $\phi$, and (c) energy $\Delta E$ between the reconstructed $\pi^0$ with the separation method and the truth one. (d) The differences of position in $\eta$ and (e) $\phi$, and (f) energy $\Delta E$ between the reconstructed $\pi^\pm$ with the separation method and the truth one.

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 [6], which is being used in the present reconstruction software in CMS experiment at the LHC, were also dawn in the same plot, as seen from Fig. 5. The HPS algorithm include 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 electromagnet plus the hadronic calorimeters to separate the energy of $\pi^\pm$ and $\pi^0$. 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 a little 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.
5 Summary and outlook

In this paper, the parametric formula of 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 to use the shower shape method as one of the applications of the parametric formulae of hadron shower. Taking the hadronic decay of tau, \( \tau^\pm \rightarrow \rho^\pm + \nu_{\tau} \rightarrow \pi^\pm + \pi^0 + \nu_{\tau} \) 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 \( \rho \) 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. And this technique can be also used in the jet reconstruction which also include 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 (MET) in experiment can be improved in the future, which is very important in many physics analysis at the LHC. We also noticed that the reconstructed positions in \( \phi \) direction have asymmetry distributions, due to the effect from the constructed magnetic field with 3.8 Tesla along the \( \eta \) direction. The effect from the magnetic field and the approximate process can also induce the asymmetry distribution of the reconstructed energy of the particle \( \rho \) 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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