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THE SEGMENTATION OF THE HADRON CALORIMETERS

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Abstract

The optimization of the segmentation of large hadron calorimeters is important in order to obtain good resolutions for jet physics at low costs of constructions for the next generation of the high energy experiments. The principles of the segmentation were discussed. As the example, the Monte Carlo calculation to optimize the segmentation of L3 Hadron Calorimeter Barrel was described. The comparison results on the reconstructed jet shape show that the optimized number of ADC channels is about 20K for the readout of 450K wires of the proportional chambers. The matching between the sandwiched Φ towers and Z towers is the dominant factor for angular resolution. Based on these Monte Carlo simulations, the optimized tower structure has been obtained.

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1. Introduction

Calorimeters are being used widely in the detectors of e^+e^- and $p\bar{p}$ collisions at the high energies. The hadron physics at the energy range of $10^2 - 10^3$ GeV requires the precise measurement of the energies and the shape of the jets, and to identify the inclusive muons. At very high energies, e.g. in the experiments at LEP and SSC, it is very difficult to measure the hadron events by drift chambers. Because the multiplicity in the events is too high ($\sim 10^2$). And it is difficult to obtain enough magnetic field in the detector to bend hadrons for the momentum measurement and the particle identification. In the other hand, the identification of hadrons is not longer important for most of interested hadron physics problems. In contrast, the energy resolution of the calorimeter varies approximately as $E^{-1/2}$. The calorimeters give also good performance despite the high multiplicity of the hadron events and the large machine backgrounds. Thus the hadron calorimeter is the way to provide the precise measurements of the energies and the positions of hadrons, and to be the muon analyzer for the identification of muons. Because the large volume and the enormous number of readout channels of the hadron calorimeter, the segmentation of the hadron calorimeters becomes very important for the design of the new generation of the detectors. One has to optimize the segmentation of the hadron calorimeter to satisfy the requirements from the hadron physics and to minimize the costs of the construction. The main requirements from the hadron physics at the energy range between $10^2 - 10^3$ GeV are following:

i) To measure the energies and the positions of the hadrons precisely in order to reconstruct the jets and to measure the energy flow. For some reactions one has to calculate the invariant masses of jets or superclusters. These are the basic requirement from all of the hadron physics problems. Among them, the most important and difficult reactions are :

$$e^+e^- \longrightarrow H^+H^- \longrightarrow 4jets, \quad (1)$$

$$e^+e^- \longrightarrow W^+W^- \longrightarrow 4jets. \quad (2)$$

ii) To absorb hadrons as the muon analyzer to identify muons.

iii) To trace inclusive muons.

iv) To distinguish electrons and charged pions.

To fulfill these requirements, optimizing the segmentation of the hadron calorimeter is one of the important stages in the design of the large hadron calorimeters. One has

to find the minimal number of readout channels and to choose the wire grouping. The segmentation must fulfill these physics requirements, and be easy for the construction and the maintenance to minimize the costs. The goals can be achieved by the Monte Carlo study on the segmentation of hadron calorimeters. Since the hadron events contain multiple jets with high multiplicity, and the hadron showers are very complicated with large fluctuations, one has to use the Monte Carlo calculation to simulate the responses of the hadron calorimeter for the most interested physics events in detail. Then the various segmentation schemes can be studied, and their resolutions are compared to find the optimized design. Based on the procedure, we have optimized the segmentation of L3 hadron calorimeter barrel. The hadron calorimeter of the L3 detector^[1,2] consists of three major parts: the central barrel, two end caps, and the muon filter which is the outer part of the barrel. Fig. 1 is the schematic drawing of the side view of the hadron calorimeter. The barrel part is divided into nine rings with sixteen identical Φ modules in each ring shown in fig. 2. It has the mirror symmetry about a plane through the interaction point perpendicular to the beams. The three outer rings on each end are slightly thinner to leave some space for cabling.

Fig. 3 shows a perspective view of a module with cover removed. The modules are sealed containers filled with depleted uranium plates alternating with wire chambers operating in the proportional mode with analog pulse height readout. The chambers are constructed from closed rectangular brass tubes, 5.6 mm x 10.6 mm outer dimensions with 0.3 mm walls. The lengths of tubes vary from 35.0 cm up to 61.5 cm. There are 60 chambers in each module of the central rings, and 53 chambers in each module of the outer rings. Alternate planes will have the wires at 90°, so that one set of wires (Φ wires) will be parallel to the beam, and the other set (Z wires) perpendicular to the beam.

There are in total about 450K wires in the Hadron Calorimeter Barrel. Obviously, to readout all of wires individually is impractical. Since the hadron showers are very wider and have large fluctuation, wires should be grouped for ADC readout to reduce the electronics. We have to find the wire grouping scheme, which uses the minimal electronics while not significantly decreasing the resolutions of the Hadron Calorimeter.

2. Monte Carlo Simulation

To find the optimized solution, a Monte Carlo calculation has been carried out to simulate the response of the Hadron Calorimeter on the hadron events from the reaction (1) at the C.M.S. energy 90 GeV. We assume that each charged Higgs decays into a pair of c and s quarks, then the quarks fragment to form jets. In the final states, 4 jets are observed. This reaction is one of most difficult physics tasks for the Hadron Calorimeter at LEP. To find the mass of charged Higgs particle, one has to reconstruct 4 jets at first. We assume that the closest jet pair is a supercluster, and the remainder two jets is another supercluster. Each supercluster is from the decay of a charged Higgs. Then the invariant mass distribution for each supercluster is calculated. If Charged Higgs pairs could be produced at LEP, one would observe a peak in the invariant mass distribution of the superclusters of 4-jet events.

For the detector simulation, we use programs GEANT3^[3] and GEL3^[4], which contains the geometry of L3 detector and drives GEANT3 to do the simulation. The simulation outputs the energy deposits in each BGO crystal and each tube of Hadron Calorimeter. That gives the flexibility to put various schemes of wire grouping into the analysis program. Then the resolutions of each wire grouping scheme were compared.

A hadron event deposits its energy in both BGO and Hadron Calorimeter. The total energy of an event, E_{TOT} , can be expressed:

$$E_{TOT} = G_B \cdot E_B + G_H \cdot E_H \quad (3)$$

where E_B and E_H are the energy deposits in BGO and Hadron Calorimeter proportional chamber, respectively. G_B and G_H are the geometry factors for BGO and Hadron calorimeter. To find the geometry factors, we simulated a sample of 90 GeV hadron events. Then the resolution of their total energy distribution calculated from formula (3) was optimized to fit the best values of G_B and G_H . The minimum FWHM of the total energy distribution is 19 GeV, corresponding to $G_B = 1.37$ and $G_H = 37700$.

GEANT3 uses the codes from GHEISHA^[5] to simulate hadron showers. The GHEISHA codes were used to simulate the test beam setup of L3 Hadron Calorimeter at CERN. The data taken from the test beam are in good agreement with the predictions of Monte Carlo calculations^[6]. The results of Monte Carlo simulation by GEANT3 show that the energy resolution of pions is very similar both with BGO and without BGO in the front of L3 Hadron Calorimeter.

3. Wire Grouping

The wires are grouped in two dimensions: grouping the neighbouring wires within a plane, and grouping the wires in the neighbouring planes. We call a group of tubes a tower. The center position of a group of tubes is defined to be the position of the tower. Only the wires with the same direction can be grouped. There is no wire grouping between different modules. The towers with wires parallel to the beam line are called Φ -towers, since they measure Φ precisely. Similarly, the towers with wires perpendicular to the beam line are called Z-towers.

A tube measures the coordinate perpendicular to its wire precisely. But the coordinate parallel to its wire is poorly measured. Since the wire directions in the neighbouring planes are perpendicular, matching the measurements in the neighbouring planes will improve the position resolution significantly. After wire grouping, the matching has to be done between the sandwiched Φ -towers and Z-towers. The θ coordinate of a Φ -tower is defined to be the energy weighted average of the θ values of the Z-towers sandwiched with the Φ -tower. Similarly, The Φ coordinate of a Z-tower is defined to be the energy weighted average of the Φ values of the Φ -towers sandwiched with the Z-tower. Namely, the second coordinates of towers are calculated according to the formulas:

$$\phi(Z_{ij}) = \frac{\sum_k E(\phi_{ik})\phi(\Phi_{ik})}{\sum_k E(\phi_{ik})}, \quad (4)$$

$$\theta(\Phi_{ij}) = \frac{\sum_k E(Z_{ik})\theta(Z_{ik})}{\sum_k E(Z_{ik})}, \quad (5)$$

where the summation is over all of the sandwiched towers. If there is not any hit in the sandwiched towers, the summation is over the hits in the towers next to the sandwiched towers. Fig. 4 shows an example. The towers Z_{21} , Φ_{23} and Φ_{24} fired. According to (4),

$$\phi(Z_{21}) = \frac{(E(\Phi_{23})\phi(\Phi_{23}) + E(\Phi_{24})\phi(\Phi_{24}))}{(E(\Phi_{23}) + E(\Phi_{24}))}.$$

And according to (5),

$$\theta(\Phi_{23}) = \theta(\Phi_{24}) = \theta(Z_{21}).$$

Tab. 1 compares the resolutions of θ and Φ measurements for single particle before and after matching. It shows that matching improves the angular resolutions by about factor 5. Thus obtaining good matching is very important for the position measurements. Obviously, the matching calculation for a tower could be contaminated, if there are multiple hits in the sandwiched towers from other particles. For instance, jets in hadron

events of 90 GeV typically contain about 20 - 40 particles in the cone of half opening angle 20° . Such multiple hits will decrease the resolution of position measurements. The larger the volume of the sandwiched towers, the bigger the probability of multiple hits. This is one of the main considerations in choosing the size of towers.

A scheme of wire grouping can be defined by the following three numbers:

N_R : the number of the tower segments along the radial direction; The outer rings are thinner, its N_R will be reduce by about 20%;

N_ϕ : the number of the tower segments per module along the Φ -direction;

N_Z : the number of the tower segments per module along the Z-direction.

Fig. 5 gives an example of a wire grouping scheme for the module of central rings, which $N_R = 10$ for both Z-wire and Φ -wire grouping, namely, the segments of towers along radial direction contain 1, 2, 2, 2, 3, 4, 4, 4, 4 and 4 planes, respectively. $N_\phi = 9$ for grouping of Φ wires, and $N_Z = 9$ for grouping for Z wires .

Following the procedure described above, the analysis program groups the hits into towers according to various wire grouping schemes, and reconstructs 4 jets. We define the jet angle to be the angle between the direction of the original quark and the axis of the reconstructed jet. The program calculates the invariant mass distribution of superclusters, and the jet angle distribution. The results show that these two physics quantities are not very sensitive to the wire grouping scheme. The wire grouping can vary over a rather wide range, while the resolutions of the invariant mass distribution and the jet angle distribution stay almost the same. That can be understood from the following facts. These comprehensive quantities are not very sensitive to the resolution of the position measurements. In the other hand, about two thirds of the energies of the hadron events is deposited in the BGO crystals. Thus the change in the wire grouping makes only a minor effect on these comprehensive quantities. To investigate the effect of wire grouping, one has to look at a quantity which depends on the Hadron Calorimeter only and discribes the sharpness of a jet shape. The angle distribution between the direction of original quarks and each tower in reconstructed jets is such good quantity.

4. Optimizing the Number of ADC Readout Channels

To investigate the possibility to reduce the readout electronics, various wire grouping schemes with different total number of ADC channels have been simulated by the program and their resolutions have been computed. Fig. 6 shows the average angle between the direction of an original quark and the towers in the reconstructed jet as the function of the number of ADC channels. For a given number of the ADC channels, there is difference in the resolution between different schemes of tower arrangement. Generally, the average angle decreases sharply when the number of ADC channels increase from 5K to about 20K. Above 30K channels, the average angle decreases very slowly. This result shows that the optimized number of ADC channels should be between 20K and 25K. If the number of channels is less than 20K, the resolution deteriorates rapidly. But if the number of channels is more than 30K, the resolution does not improve much. We also made similar studies by using the jet width, which is the half opening angle of the cone along the jet axis containing 90% of the hadron energy of the jet. The jet width as the function of the number of ADC readout channels gave the same conclusion as the average angle.

5. Optimizing the Tower Structure

In the range of number of ADC channels between 20K and 30K, the Monte Carlo calculation shows that the structure with towers thinner in depth and wider in angular range has a better resolution than the one with thicker and narrower towers. This phenomenon can be understood by the following facts: each tower measures one coordinate very well, but the another coordinate poorly. Thus its angular resolution is dominated by the resolution of the coordinate which poorly measured. The matching between orthogonal towers is used to improve the resolution of the measurement of the second coordinate. The angular resolution of the measurement by a tower is determined by how well one can match. This in fact depends on the frequency of the multiple hits from other particles. The frequency depends on both the surface of the volume, which is fixed to be the surface of the module, and the thickness of the volume, which is proportional to the number of planes in the sandwiched towers. Since the hadron showers have large fluctuation, and contain many neutrons, the smaller volume gives less ambiguity in the matching. The volume is only proportion to the number of planes in the tower, but indenpent of the width of the tower. For instance, a Z-tower with 5 planes and 3 wires per plane has to match with the hits in the volume of 5 sandwiched chambers of Φ -plane. But a Z-tower with 3 planes and 5 wires per plane only has to match with the hits in the volume of 3 chambers of Φ -plane. The two towers have the same number of wires, but the second one, which is thinner in depth, and wider in angular range, gives a better matching. Thus one has to compromise the width and the thickness of the towers to obtain the optimized tower structure.

There are some other considerations for choosing the wire grouping scheme:

- i) The Φ -tower and the Z-tower should have an approximately equal width. And both widths should be not smaller than the width of a BGO crystal.
- ii) The inner towers which are close to the beam line should have fewer planes than the outer towers to obtain an approxamately equal dynamical range of ADC.
- iii) Monte Carlo simulation on the Uranium noise^[7] shows that the results of wire grouping are not sensitive to Uranium noise.

From the Monte Carlo studies, the tower structure with $N_R = 10$, $N_\phi = 9$ and $N_Z = 9$ has been chosen for the Hadron Calorimeter Barrel. To obtain a better tracing for inclusive muons, the first Φ -planes and the first Z-planes of every module are not grouped with neighbouring planes. The number of wires per tower varies between 7 and

Table 1 The Angular Resolution of Towers

		Before Match	After Match
Z-towers	$\Delta \cos \theta$	0.006 - 0.015	
	$\Delta \phi$	7.7°	$1.0^\circ - 1.5^\circ$
ϕ -towers	$\Delta \cos \theta$	0.1 - 0.17	0.02 - 0.03
	$\Delta \phi$	0.6°	

26 except in the first plane, where it varies between 3 to 5. In total, there are 22K ADC channels for the readout of the barrel.

Naturally, all of Φ -towers should be pointed back to the intersection point. For the grouping of Z-towers, the following three types of schemes have been studied to compare their resolutions:

i) vertical tower structure. The Z-towers are perpendicular to the beam line. The cross sections of Z-towers in R-Z plane are square. Fig. 7a is an example of vertical tower structure.

ii) semi-tilted tower structure. All of Z-towers in a module have the same slope determined by line between the center of the module and the interaction point, shown an example in Fig. 7b.

iii) tilted tower structure. The Z-towers are tilted to the intersection point, shown an example in Fig. 7c.

The Monte Carlo studies yield similar resolutions for these three types of Z-tower structure. The measured jet shapes are not sensitive to the differences of the Z-tower structures. This conclusion allows us to choose the vertical Z-tower structure, which is easiest and cheapest in construction, testing and maintenance. The Fig.5 are the final decision on the wire grouping for the modules of central rings. The grouping in the modules of outer rings is also similar.

Conclusion

The segmentation of hadron calorimeters is important to optimize the design of large high energy experiments. Using Monte Carlo simulations, one can find the segmentation scheme which is fulfill the requirements from hadron physics with the minium costs of constructions. The Monte Carlo studies on L3 hadron calorimeter show that the resolutions of the comprehensive physics quantities, such as the jet angle and the invariant mass of superclusters are not very sensitive to the tower structure over a quite large range. The comparision on the reconstructed jet energy flow shows that the optimized number of ADC channels is about 20K for the readout of the 450K wires of the proportional chambers for L3 Hadron Calorimeter Barrel. The matching between the sandwiched Φ -tower and Z-tower is the dominant factor for the angular resolution. The thinner and wider towers gives better resolutions than the thicker and narrower towers. The optimized tower structure has been obtained basing on these Monte Carlo simulations.

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Figure Captions

Fig. 1: The longitudinal section through the L3 hadron calorimeter (one half only).

Fig. 2: The assembly of 144 modules into 9 rings.

Fig. 3: The perspective view of one barrel module with cover removed.

Fig. 4: The example of matching coordinate measurements between Φ -tower and Z-tower. The tubes with hits are shaded.

Fig. 5: The example of a wire grouping scheme in the module of central rings: a) grouping for Φ wires; b) grouping for Z wires.

Fig. 6: The average angle between the direction of original quarks and the towers in reconstructed jets as the function of the numbers of ADC channels for the reaction (1).

Fig. 7: a) The vertical tower structure. b) The semi-tilted tower structure. c) The tilted tower structure.

Fig. 1

Fig. 3

Fig. 2

Fig. 4

Fig. 5

Fig. 6

a)

b)

c)

Fig. 7