Particle identification with LHCf Arm#1 detector

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***Abstract*. LHCf (LHC forward) is an experiment to measure neutral particles emitted in the very forward region of LHC collisions. The collision energy corresponds to 10^{17}eV pp collision in the laboratory system. Although the highest cosmic ray energy lies still far beyond, we expect collisions at LHC will give us an important clue to understand high energy cosmic ray phenomena. Through our test experiments and calculations, we showed the LHCf experiment can verify various interaction models employed in Monte Carlo simulation which is an indispensable tool to study cosmic-rays.**

In this paper, we focus our attention on the particle ID capability of LHCf. LHCf will measure the energy and transverse momentum spectra of incoming high energy photons and neutrons. Therefore it is crucial for LHCf to have high capability of distinguishing those two neutral particles. This is shown by analyzing a CERN SPS beam test data along with Monte Carlo simulations. Since electrons and photons, or protons and neutrons behave in an almost similar way in the detector, we investigated a rejection power of protons from electrons by a beam test at CERN SPS. It is found that LHCf Arm#1 detector has a good performance (more than 99% rejection power of hadron). The same rejection method was applied to Monte Carlo simulation events to find consistent results with the experimental data. MC simulations at LHC energies were also performed; a good rejection power which is enough for accomplishing the objective of the LHCf experiment is confirmed.

***Keywords*: LHC, Hadron interaction, Particle ID**

I. Introduction

The highest energy cosmic-rays (energy above 10^{19}eV) may have much undiscovered information about their origin, propagation, and interactions. Therefore reserch on them has great scientific interest, but it is not easy to observe them accurately. For example, existence of the GZK cut-off is one of the most important theme in the cosmic ray physics[1]. Although several observations have been made on it, there seems to be no established conclusion because of differences between the experimental data. Many of the uncertainties come from hadron interaction models employed in Monte Carlo (MC) simulations.

LHCf is an experiment to verify various interaction models by the measurement of neutral particles emitted in the very forward region at LHC collisions. The collision energy, 7TeV$\times$7TeV in the center of mass system, corresponds to 10^{17}eV proton-proton collision in the laboratory system. It is a truly unexplored region where examination of interaction models is effective. LHCf would bring in a sufficient accuracy of the cosmic-ray observation and an important clue to understand high energy cosmic ray phenomena. In this paper, we focus on to the particle identification capability of LHCf Arm#1 detector.

II. Experiment

A. The detectors

The LHCf apparatus is composed of two independent detectors, Arm#1 and Arm#2, for background rejection and redundancy. Each detector is installed in a mass of iron for neutral particle absorption, which is called TAN (Target Neutral Absorber). They are located at $\pm$140m from IP1 (interaction point 1, ATLAS region). Charged particles from the IP are swept away by dipole magnets before reaching the TAN and only neutral particles reach the detectors. In this paper, we present a result of the Arm#1 detector. The Arm#2 has a similar structure, and we can expect our present result is basically applied to

it.
The Arm#1 detector is composed of two calorimeter towers with transverse cross section of 20mm × 20mm and 40mm × 40mm as shown in Fig. 1. Figure 2 presents the longitudinal structure of the calorimeter. Each calorimeter contains tungsten plates, each of them has 7mm (2 radiation lengths; r.l.) thickness in the first 11 layers and 14mm (4 r.l.) thickness in latter 5 layers. The total thickness is 44 r.l. and 1.7λ in hadron interaction lengths. The calorimeters also contain sixteen plastic scintillator plates for energy measurement. Each of plastic scintillators has 3mm thickness and is interleaved between tungsten plates. In addition, the calorimeters have four layers of scintillating fiber (SciFi) belts in x and y directions to measure the shower position and to identify multi-hit events. They are inserted at 6, 10, 30 and 42 r.l. and read by Multi-anode PMTs (MAPMTs).

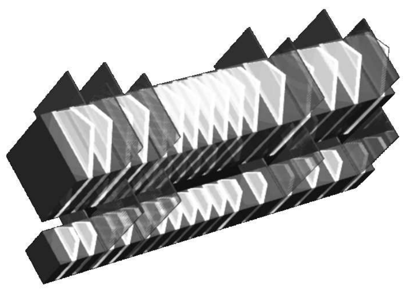

Fig. 1. The two calorimeter towers in Arm#1 detector

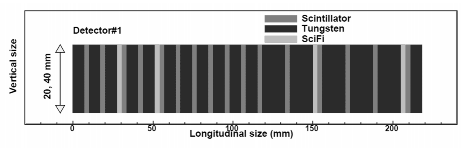

Fig. 2. Longitudinal structure of Arm#1 detector

B. Beam test at CERN SPS

In the summer of 2007, we had a beam test at the CERN SPS beam line. This test has been conducted for calibration and testing the performance of the detectors. In this beam test, we used electron beams with energies of 50,100,150,180 and 200GeV, proton beams with energies of 150 and 350GeV and muon beams with an energy of 150GeV. The setup of beam test is illustrated in Fig. 3. The detector was placed on a movable table. To calibrate the SciFi detectors, a silicon strip detector, ADAMO, was put between the detector and the trigger scintillators.

III. Particle ID in SPS beam test

A. Data analysis

The performance of the particle identification is analyzed by applying the following procedures with SPS beam test data. In the present analysis, we investigated the rejection power of proton events from electron events since electrons and photons,or protons and neutrons behave almost the same in the detector. We used 100GeV electron and 350GeV proton events because both are similar in terms of shower energy in the detector. As a proton rejection power better than 99% is needed to verify various interaction models by our calculation, we set 99% rejection power as a required condition.

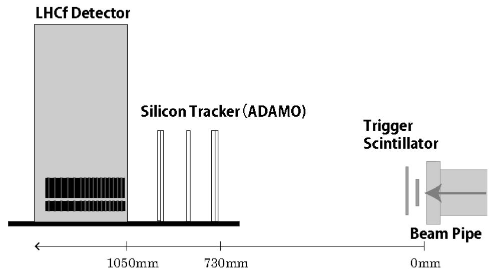

Fig. 3. Setup of the SPS experiment. Beam enters from right along the arrow. Two plastic scintillators were used to trigger beam particles. The ADAMO silicon tracker is placed in front of the LHCf detector. The detector and ADAMO were placed on a movable stage.

B. Shower development profile

First, we used the difference of the shower development between electrons and protons. This cut is named Cut A in this paper. We defined the following two parameters;
L20 (L90): Interpolated position from the first layer(in unit of a plastic scintillator layer) where the sum of the number of particles becomes 20% (90%) of the total number of particles.
Figure 4 shows the correlation of L20 to L90 with SPS beam test events.

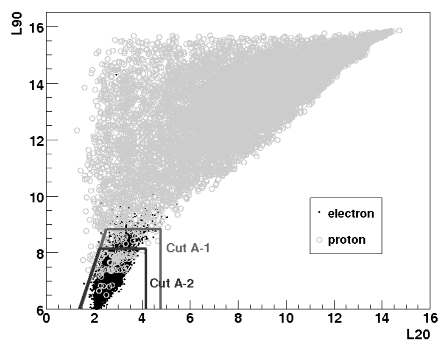

Fig. 4. Correlation of L20 to L90 with SPS beam test data

We defined two cuts, Cut A-1 and Cut A-2. Cut A-1 is to keep more than 98% of electrons, while Cut A-2 is to reject protons more than 99%. These cuts are applied by certain areas in Fig. 4. The areas are surrounded by three lines (vertical, horizontal and linear function line like “L90 = a L20 + b”). The lines are also shown in Fig. 4. Results of separation by Cut A are shown in TABLE I. We shall use Cut A-1 for further analysis.

TABLE I
E/P SEPARATION RESULTS BY THE SHOWER DEVELOPMENT PROFILE

particle	total	remained (Cut A-1)	remained (Cut A-2)
electron	6813	6692 (98.2%)	6184 (90.8%)
proton	12423	144 (1.16%)	75 (0.60%)

C. χ^2 test of EM-shower curve fitting

Second, we tried to reject proton events by using the shape of the shower transition curve. This cut is named Cut B. It is known that the ideal transition curve of the electro-magnetic shower is represented by the next equation[2].

$$\frac{dN}{dx} = \frac{N_0 b}{\Gamma(a)}(bx)^{a-1}e^{-bx} \tag{1}$$

The value of χ^2 is expected to be small for electron events and large for proton events. Figure 5 is the distribution of the χ^2 with SPS beam test data.

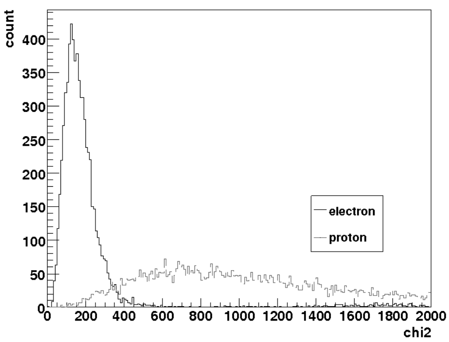

Fig. 5. Distribution of χ^2 value for electrons and protons

As expected, it can be seen that χ^2 of electron events are smaller than proton events on average. Results of e-p separation by this χ^2 test is shown in TABLE II. When this cut is applied to the events in addition to previous cut (Cut A-1), we get the numbers as shown in TABLE III (Cut C in the TABLE is discussed below).

TABLE II
E/P SEPARATION RESULTS BY THE χ^2 TEST

particle	total	remained ($\chi^2 < 300$)	remained ($\chi^2 < 250$)
electron	6813	6191 (90.9%)	5731 (84.1%)
proton	12423	255 (2.05%)	145 (1.17%)

D. Rejection of successive events

By the combination of the two cuts, more than 99% of the proton events were rejected. To explore possibilities for further rejection power, we checked all of the remaining proton events by event-viewer; we found events with successive interaction features of hadrons (multi peak events). We defined the next parameter to reject these proton events.

$$R_{2peak} = \frac{(N_{max} \text{ of the latter 5 layers})}{N_{max}} \tag{2}$$

N_{max} represents the maximum number of particles. The distribution of R_{2peak} is shown in Fig. 6 for the events remained after applying previous two cuts (Cut A and Cut B). We regarded events as proton when R_{2peak} is above 0.06. This cut is named Cut C. The result of each cut is summarized in TABLE III.

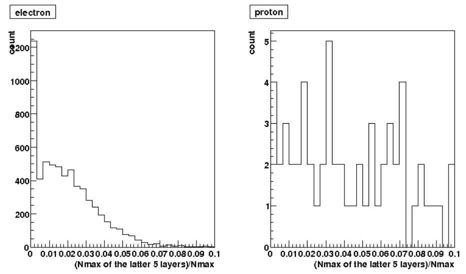

Fig. 6. Distribution of (N_{max} of the latter 5 layers)/N_{max} with remaining events

TABLE III
E/P SEPARATION RESULTS BY COMBINATION OF THREE CUTS

particle	total	Cut A-1	+ Cut B ($\chi^2 < 300$)	+ Cut C
electron	6813	6692 (98.2%)	6145 (90.2%)	6023 (88.4%)
proton	12423	144 (1.16%)	62 (0.50%)	40 (0.32%)

We see from TABLE III that, with this Cut C, proton events are further reduced by 35% while losing electron events only by 2%. However, there are still some remaining proton events. Since remaining electron and proton events are very alike in transition curves, it is difficult to reject more protons by an analysis of the plastic scintillator data. However, there is a possibility to get an additional rejection power by using the SciFi data. Moreover, we should consider that there is a possibility that the proton beam itself is contaminated by electrons or vice versa.

IV. PARTICLE ID IN MC SIMULATION

A. At the SPS energy

We applied the same method to MC simulation events. All simulation events are generated by Epics[3] with dpmjet3.03 as the hadronic interaction model[4]. The detector configuration with the SPS beam test setup are considered in this simulation. We generated 100GeV electron and 350GeV proton events for validity checking of above analysis. For the same analysis as the SPS beam test with simulation events, the correlation of L20 to L90 in the Cut A-1 is shown in Fig. 7. Figure 8 presents the distribution of χ^2 value by fitting EM-shower curve function to simulation events. Very similar tendency in the both graph as in the SPS data is seen. Therefore we separated electron and proton events by the same parameters in SPS beam test data analysis. We also calculated R_{2peak} for the proton events remained after applying the first two cuts. Figure 9 shows the distribution of R_{2peak}. Results of e-p separation by these three cuts in simulation events are summarized

TABLE IV
E/P SEPARATION RESULTS WITH SPS AND SIMULATION EVENTS IN SAME ENERGY

particle	total	Cut A-1	+ Cut B ($\chi^2 < 300$)	+ Cut C
electron (SPS)	6813	6692 (98.2%)	6145 (90.2%)	6023 (88.4%)
electron (Simulation)	5000	4871 (97.4%)	4522 (90.4%)	4356 (87.1%)
proton (SPS)	12423	144 (1.16%)	62 (0.50%)	40 (0.32%)
proton (Simulation)	5000	36 (0.72%)	7 (0.14%)	3 (0.06%)

TABLE V
E/P SEPARATION RESULTS WITH SIMULATION EVENTS IN DIFFERENT ENERGIES

particle	total	Cut A-1	+ Cut B	+ Cut C
electron (100GeV)	5000	4871 (97.4%)	4522 (90.4%)	4356 (87.1%)
electron (1TeV)	5000	4942 (98.8%)	4897 (97.9%)	4580 (91.6%)
proton (350GeV)	5000	36 (0.72%)	7 (0.14%)	3 (0.06%)
proton (3.5TeV)	5000	20 (0.40%)	7 (0.14%)	0 (0.00%)

in TABLE IV with the results of SPS beam test data analysis. As presented in the TABLE IV, the rate of remaining electron events are remarkably consistent. A little difference in proton events could be caused by beam contamination in SPS and the interaction model characteristics.

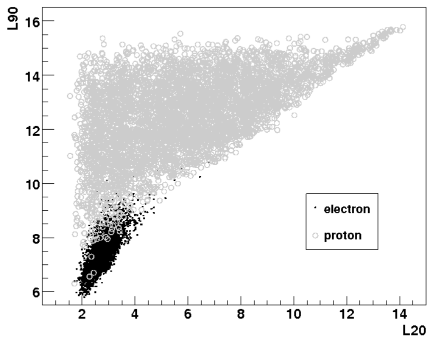

Fig. 7. Correlation of L20 to L90 with simulation events

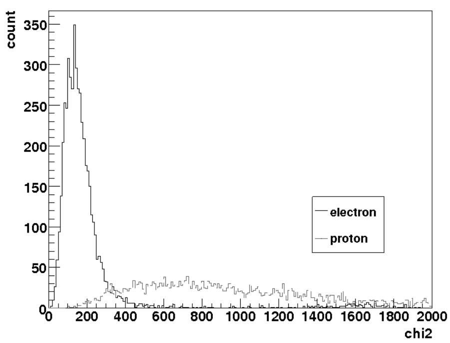

Fig. 8. Distribution of χ^2 value with simulation events

B. At the LHC energy region

Also we generated 1TeV electron and 3.5TeV proton events by MC simulation to confirm whether the same method is applicable in the LHC energy region. TABLE V shows the results by the same method in two different energies with MC simulation events. Some cut parameters were changed for this energy region. In the TABLE V, high energy events have more rejection power. It means that this method is valid in several energy regions in the LHCf experiment.

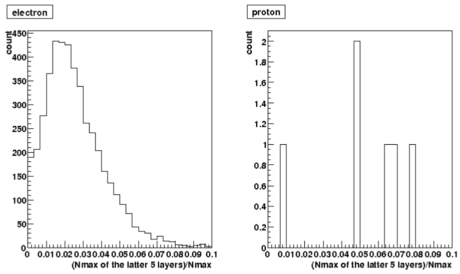

Fig. 9. Distribution of (N_{max} of the latter 5 layers)/N_{max} with remaining events in simulation

V. SUMMARY

With our LHCf detector, a method for discriminating protons and electrons with sufficient reliability at 100GeV region have been confirmed by SPS beam test. The MC simulation could well reproduce the result. The same MC at LHC energies also have proved that our method works fine. This would mean our LHCf detector is expected to have the required particle ID capability.

VI. ACKNOWLEDGMENT

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REFERENCES

[1] K. Greisen, *Physical Review Letters, 16, 748-750, 1966*
[2] E. Longo, I. Sestili, *Nucl. Instrum. Methods, 128,283, 1975*
[3] K. Kasahara, *Epics Home Page*, http://cosmos.n.kanagawa-u.ac.jp/EPICSHome/
[4] TS. Roesler, R. Engel and J. Ranft, *hep-ph/0012252, Proc. of Monte Carlo 2000, Lisboa, Oct.2000, Springer, p.1033*
[5] The LHCf Collaboration *JINST, 2008, JINST 3 S08006*
[6] T. Sako et al. *Nucl. Instrum. Methods, A578 (2007) 146*