Journal of Physics: Conference Series **587** (2015) 012023 doi:10.1088/1742-6596/587/1/012023

Correction for PMT temperature dependence of the LHCf calorimeters

Eri Matsubayashi for the LHCf collaboration

Solar-Terrestrial Environment Laboratory,Nagoya University, Nagoya, Japan

E-mail: matsubayashi@stelab.nagoya-u.ac.jp

Abstract. LHCf is an experiment to measure the very forward production of particles at LHC in order to calibrate the hadronic interaction models used to simulate cosmic-ray air showers. The results obtained from $\sqrt{s}$=7 TeV proton-proton collisions have large systematic errors resulting from the energy scale shift of the reconstructed π^0 mass. It was found that one of the major sources of this shift is the temperature dependence of the PMT response used in the LHCf detectors. In order to correct the variation of the PMT gain by temperature, two types of temperature variation were considered. As a result, systematic errors resulting from the energy scale of Arm2 was improved by 30 %.

1. Introduction

LHCf experiment was motivated to calibrate the hadronic interaction models used to simulate cosmic-ray air showers with the experimental data obtained at LHC. LHCf was specifically designed for measurements of the very forward (pseudo-rapidity; η >8.4) production spectra of neutral particles which are most relevant to air showers development.

The LHCf data taking at $\sqrt{s}$=7 TeV proton-proton collisions has finished in the middle of July 2010 and from these data gamma-ray spectra and neutral pion spectra have been analyzed [1][2]. However these results have large systematic errors resulting from the energy scale shift. The energy scales of the LHCf calorimeters were determined by measuring the beams with known energy at CERN SPS in 2007 [3]. This energy scales were tested by the reconstructed invariant π^0 masses from the data obtained at LHC. However the reconstructed invariant mass peak deviated from the rest mass of π^0 135 MeV by 2 sigma. This disagreement was taken into account as a part of the systematic errors of the energy scale.

This large systematic error caused by energy scale is a big problem for LHCf detectors because this error becomes larger as the energy becomes higher, and the systematic error contributes a half of total error above 3 TeV. Therefore in order to proceed further analysis, we need to reduce this error.

It was found that one of the major sources of this error is temperature dependence of PMT response used in the LHCf detectors, while it was not corrected in the previous analyses. There was correlation between the reconstructed mass and the temperature of the PMT holders in the 2010 data. In order to correct the variation of the PMT gain by temperature, two types of temperature variation were considered.

In this paper, the detail of the data correction for PMT temperature dependence is presented together with a brief introduction of the LHCf and its future prospect.

2. LHCf calorimeters

LHCf has two independent detectors, called Arm1 and Arm2 installed in the instrumentation slots of the neutral particle absorbers (TANs) located ±140 m from the interaction point 1 (IP1) in LHC. Because of the dipole magnet installed in front of the detectors, charged particles are swept and only neutral particles come to the detectors. Each detector has a pair of shower calorimeters composed of 44 radiation lengths of tungsten and 16 sampling layers of plastic scintillator and 4 imaging layers as shown in Figure.1 and Figure.2.

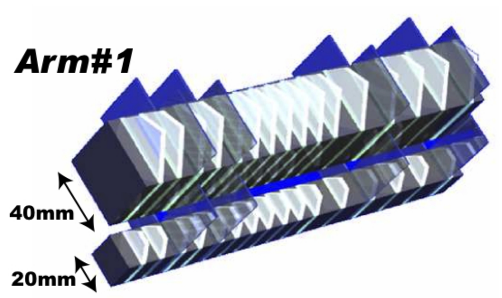

Figure 1. The schematic view of the Arm1 calorimeter.

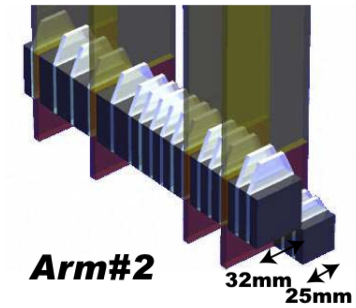

Figure 2. The schematic view of the Arm2 calorimeter.

3. Energy scale

The energy scale of each calorimeter was determined by the SPS calibration in 2007 by measuring 150 GeV electron beams. Charge Q_i measured in each PMT was converted to deposited energy dE_i by a conversion factor A_i obtained from calibration for all the PMTs (i=1∼32),

$$dE_i = Q_i \times A_i. \tag{1}$$

This energy scale can be tested from the data obtained at LHC. Since the LHCf detector is composed of two calorimeters, the detectors are able to measure the energy of two photons individually generated by the decay of a π^0 meson. The invariant mass $m_{\gamma\gamma}$ of the photon pair is reconstructed using the opening angle θ calculated from the incident positions and energies (E_{g1} and E_{g2}) of the photon pair.

$$m_{\gamma\gamma} = \sqrt{E_{g1} \cdot E_{g2} \cdot \theta^2}. \tag{2}$$

By comparing $m_{\gamma\gamma}$ with π^0 rest mass the energy scale is verified.

A part of the experimental data obtained on May 15th and 16th 2010 (LHC Fill 1104) during proton-proton collisions at $\sqrt{s}$=7 TeV were used for analysis, and we found the peak position of $m_{\gamma\gamma}$ distribution was slightly higher than the π^0 rest mass and the disagreement were 8.1% in Arm1 and 3.8 % in Arm2. This disagreement is larger than errors of calibration (±3.5%).

4. PMT temperature dependence

In order to find the cause of the energy scale problem, $m_{\gamma\gamma}$ were reconstructed in long term from 1 April to 25 May in 2010. Figure.3 presents the time variation of $m_{\gamma\gamma}$ as a function of the LHCf RUN number. The black points and red points represent $m_{\gamma\gamma}$ and temperature of the PMT holder, respectively. From Figure.3, it is clear that $m_{\gamma\gamma}$ correlates with the PMT holder temperature. It was found that the PMT (HAMAMATSU R7400U) has -0.25 %/°C temperature dependence for its gain [4]. We suspected that the one of the major reasons of the energy scale shift could be influence of the PMT temperature.

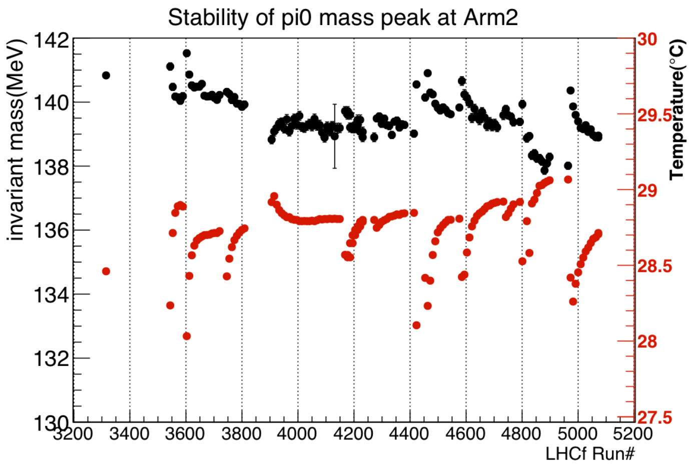

Figure 3. The time variation of $m_{\gamma\gamma}$ and the temperature of the PMT holder as a function of the LHCf RUN number. Black points and red points represent $m_{\gamma\gamma}$ and temperature of the PMT holder, respectively.

5. Correction for the temperature dependence

In order to correct the PMT gain variation, correction terms G_i were introduced in equation(1),

$$dE_i = G_i \times Q_i \times A_i. \tag{3}$$

However, as the PMT temperature T_{PMT} was not directly measured during the time of measurement at LHC and calibration at SPS, it was estimated by the elapsed time t since high voltage was applied and the high voltage value V,

$$T_{PMT}(t, V) = T_{ref} + \Delta T(V)(1 - exp(-t/\tau)). \tag{4}$$

It was assumed that T_{PMT} rose by the exponential function (time constant is τ) and T_{PMT} reached $T_{ref} + \Delta T$ where T_{ref} is an ambient temperature and $Delta$T is an asymptotic temperature increase.

Estimated PMT temperature was divided into two parts. One is the time-depending component named correction A, and the other is the time-independent component named correction B. The correction A corrects for the temperature variation during the LHC operation because of Joule heat from the PMT breeders. On the other hand, the correction B corrects for the temperature difference between the measurement at LHC and the calibration at SPS because of difference of applied high voltage and ambient temperature.

By taking these corrections into account, G_i is expressed as

$$G_i = \frac{1}{1 - a \cdot \{T_{ref}^{SPS} + \Delta T_i^{SPS} - (T_{ref}^{LHC} + \Delta T_i^{LHC}) + \Delta T_i^{LHC}(-t/\tau)\}}. \tag{5}$$

In order to calculate G_i, ΔT_i and τ of all PMTs in Arm2 were measured using platinum thermometers attached on the PMTs in the acrylic PMT holders. We applied two values of high voltage called high gain (around 600 V) and normal gain (around 500 V) applied in the SPS calibration and the LHC operation, respectively. The time constants τ were almost same for 32 PMTs and the average of τ was 3428± sec. On the other hand, ΔT_i were different for each PMT correlated with the location in the PMT holders. ΔT_i^{SPS} ranged from 5.2 °C to 12.0 °C and ΔT_i^{LHC} ranged from 3.4 °C to 8.1 °C.

As for T_{ref}^{SPS} and T_{ref}^{LHC}, the temperature data were measured in-situ by nearby sensors. T_{ref}^{SPS} values were about 3 °C higher than T_{ref}^{LHC}.

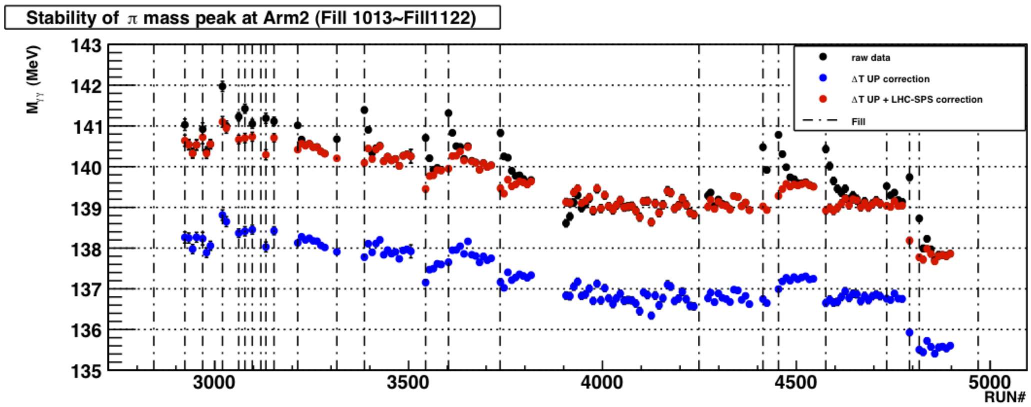

Figure 4. The improvements of the $m_{\gamma\gamma}s$ by corrections. The horizontal axis shows RUN number, the vertical axis shows the reconstructed invariant mass. The black points show the results before corrections, the red points show the results of the correction A, the blue points show the results of the correction A and correction B. The vertical dashed lines show the beginning of the fills.

6. Result of correction

After correction for the PMT gain of Arm2 during the measurement at the $\sqrt{s} = 7\,TeV$, $m_{\gamma\gamma}s$ were reconstructed. Figure.4 shows the variation of the $m_{\gamma\gamma}s$ after the correction A and the correction A+B. The horizontal and the vertical axis are the same as Figure.3. In Figure.4 the black, red and blue points show the results before correction, after the correction A and after the correction A and B, respectively. The vertical dashed lines show the beginning of the fills.

By correction A, the amplitude of the short-term variation of $m_{\gamma\gamma}s$ during a single fill were improved from 1.5 MeV to 0.5 MeV. By adding the correction B $m_{\gamma\gamma}s$ decreased by about 2 MeV as whole periods. In the case of Fill 1104, which was used for this analysis, $m_{\gamma\gamma}$ decreased from 139.9 MeV to 137.4 MeV, that means the disagreement decreased from 3.8 % to 1.8 %. Because of this improvement, systematic errors resulting from the energy scale of Arm2 was improved by about 30 %.

However $m_{\gamma\gamma}s$ were going down by about 3 MeV step by step after RUN 3600. The cause of these changes is probably a radiation damage of the scintillators because there is correlation between the corrected $m_{\gamma\gamma}$ and dose measured at the back of the Arm2 detector.

7. Conclusions

The LHCf results at $\sqrt{s}$=7 TeV proton-proton collisions had large systematic errors resulting from the energy scale shift. It was found that one of the major reasons of the energy shift is the temperature dependence of the PMT gains. In order to correct this effect, the temperature variation during the LHC operation because of the Joule heat from the PMT breeders and the temperature difference between the time of calibration at SPS and operation at LHC were considered. By these corrections, energy scale shift of Arm2 was improved from 3.8 % to 1.8 %, and systematic error caused by the energy scale were improved by about 30 %.

However this correction is still preliminary efforts because a temperature coefficient of PMT gain was taken from the catalog values. It is necessary to take into account actual temperature coefficient of each PMT by the measurement.

This correction method will be applied to the Arm1 data having a larger shift of $m_{\gamma\gamma}$ than the Arm2. In near future the spectra of photons and π^0 will be updated with smaller systematic uncertainty. This study is also fed back to the measurement at $\sqrt{s}$=13 TeV proton-proton collisions planed in 2015.

8. Acknowledgement
We thank the CERN staff and the ATLAS collaboration for their essential contributions to the successful operation of LHCf. This work is partly supported by Grant-in-Aids for Science Research by MEXT of Japan, the Mitsubishi Foundation in Japan and Istituto Nazionale di Fisica Nucleare (INFN) in Italy. The receipt of JSPS Research Fellowship (HM and TM), INFN fellowship for non Italian citizens(HM and KN) and the LGS Leadership Development Program of Nagoya University 'QFPU' from JSPS and MEXT of Japan (GM) are also acknowledged. A part of this work was performed using the computer resource provided by the Institute for the Cosmic-Ray Reseach (ICRR), University of Tokyo.

References
[1] O.Adriani, Phys.Lett.B 703 (2011) 128-134
[2] LHCf Collaboration, Phys. Rev. D 86, 092001 (2012)
[3] T.Mase et al., Nuclear Instruments and Methods in Physics Research A 671 (2012) 129-136
[4] HAMAMATSH,Technical information, Metal package photomultiplier tubes R7400U series and subminiature photosensor modules