Correction for PMT temperature dependence of the LHCf calorimeters

E. Matsubayashi
STEL Nagoya Univ. in Japan
for LHCf collaboration
Outline

• Introduction and physics motivation
• Energy scale problem
• Method of gain correction for PMT temperature & result
• Summary
Physics motivation

• Analysis of high energy cosmic-ray observations relies on the MC simulation of air shower development.
• MC simulation depend on the choice of hadron interaction model.
• Cause large systematic uncertainty to HECR measurement result.

LHCf experiment reveal the forward neutral particle production ($\gamma$, $\pi^0$, $\eta$, …) in hadron collision.

High energy particles are emitted forward → effective for shower development

Forward energy spectrum
If softer → shallow development
If harder → deep penetrating

Inelasticity $k = 1 - p_{\text{lead}}/p_{\text{beam}}$
If large $k$ ($\pi^0$s carry more energy) → rapid development
LHCf Detector

- Two independent LHCf detectors (Arm1, Arm2)
- Each detector has two calorimeters (Small Tower, Large Tower)

<table>
<thead>
<tr>
<th>Absorber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten layer 44 $X_0$ (1.7 $\lambda_i$)</td>
</tr>
<tr>
<td>16 energy sampling layers</td>
</tr>
<tr>
<td>Plastic scintillators (EJ260)</td>
</tr>
<tr>
<td>4 imaging layers</td>
</tr>
<tr>
<td>XY-Scifi (Arm1) / XY-Silicon strip (Arm2)</td>
</tr>
</tbody>
</table>

Located the 140 m forward position from IP in LHC
pseudo-rapidity range $>8.4$
Detector performance

Energy resolution

- Beam test
- Simulation

$\Delta E / E$ [%]

Energy [GeV]

$< 5\%$ (>50 GeV)

Resolution [μm]

- Beam test
- Simulation

$< 200\,\mu m$ (Arm1)
$< 40\,\mu m$ (Arm2)

Hadron Shower

$\pi^0$ reconstruction

$E_{\gamma_1}$

$E_{\gamma_2}$

$\theta$

$M_{\pi^0} = \sqrt{E_{\gamma_1}E_{\gamma_2}\theta^2}$

135 MeV

EM shower

PID

by shower shape

400 GeV photon

1 TeV neutron

Energy scale determination

Calibration in 2007@SPS
Charge measured in each scintillator \( (Q_i) \rightarrow \) energy deposit \( (dE_i) \)
Conversion factors \( (A_i) \) obtained from SPS electron test beam data taken below 150 GeV.

\[
dE_i = A_i \cdot Q_i
\]

calibration error is 3.5 %

Test by the data @LHC

Energy scale of calorimeter was tested by using reconstructed \( \pi^0 \) mass.

Measures energy and position of two gamma generated by the decay of \( \pi^0 \).
Reconstruct the invariant mass

\[
M_{\gamma\gamma} \approx \sqrt{E_{\gamma_1} E_{\gamma_2} \theta^2}
\]

Compare with \( \pi^0 \) rest mass 135 MeV

140m
LHCf had an operation at the $\sqrt{s} = 7$ TeV p-p collision in 2010.

energy scale problem

$M_{\gamma\gamma}$ in Fill 1104 are ...
Arm1 $145.8\pm0.1^{\text{stat}}$ MeV $+8.1\%$
Arm2 $139.9\pm0.1^{\text{stat}}$ MeV $+3.8\%$

Taken into account as a part of the systematic errors of the energy.

$M_{\gamma\gamma}$ correlates with PMT holder temperature.

influence of temperature dependence of PMT gain $(-0.25\%/^\circ\text{C})$
In order to correct the PMT gain changed effect by temperature, Correction term $G_i(T_{PMT})$ is included in $dE_i$ function.

$$dE_i = G_i(T_{PMT}) \cdot A_{i,SPS} \cdot Q_i$$

$$G_i(T_{PMT}) = \frac{1}{1 - a \cdot (T_{PMT}^{calib} - T_{PMT})}$$

But $T_{PMT}$ was not measured while the time of 7 TeV p-p collision and calibration. So estimate $T_{PMT}$ by the elapsed time from HV ON and HV as the below

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

$t$: elapsed time from HV ON  
$\tau$: time constant  
$\Delta T$: rise temperature  
$T_{ref}$: ambient temperature
Correction A

Correct the temperature that changed at time in LHC because of Joule heat from PMT divider

$$T_{UP}(t) = \Delta T \exp\left(-t / \tau\right)$$

Correction B

Correct the temperature difference between at LHC and at SPS.

$$T_{SPS-LHC} = T_{PMT}^{\text{calib}} - T_{PMT}^{LHC}$$

So,

$$G_i = \frac{1}{1 - a \cdot \{T_{SPS-LHC} + T_{UP}(t)\}}$$

135MeV

change of $T^{LHC}$

difference between $T^{\text{calib}}$ and $T^{LHC}$

raw

time
In order to measure \( \Delta T \) & \( \tau \) by Arm2 ...

1. put Pt thermometer on PMT
2. fit PMT in acrylic PMT holder.
3. apply HV (500 V or 600V)

\[
T_{PMT}(t, v) = T_{ref} + \Delta T(v)\{1 - \exp(-t / \tau)\}
\]

\( \bar{\tau} = 3428 \pm 41 \) (sec)
Correction B (T LHC vs T SPS)

PMT temperature in LHC

The voltage is 500V in LHC

Ambient temperature = the temperature besides a detector

PMT temperature in SPS

The voltage is 600V in SPS

Ambient temperature = the temperature on the rack beside beam line

Ambient temperature = the temperature on the rack beside beam line

use the thermometer in this box

use some temperature at the time of RUN which use for derivation of $A_i$
In the Fill1104 ...
M_{gg} 139.9 MeV → 137.4 MeV
disagreement 3.8 % → 1.8 %

Energy scale shift become smaller than
calibration error (3.5%).
Summary & Future

• LHCf results have large systematic errors resulting from the energy scale shift.

• It was found that one of the major sources of energy shift is the temperature dependence of PMT.

• In order to correct the variation of the PMT gain by temperature, two types of temperature variation were considered.

• By correction, Arm2 energy scale shift was improved from 3.8 % to 1.8 %.

• By this improvement, systematic error caused by energy scale was improved by 30 %.
Figure 4: Comparison of the single photon energy spectra between the experimental data and the MC predictions. Top panels show the spectra and the bottom panels show the ratios of MC results to experimental data. Left (right) panel shows the results for the large (small) rapidity range. Different colors show the results from experimental data (black), QGSJET II-03 (blue), DPMJET 3.04 (red), SIBYLL 2.1 (green), EPOS 1.99 (magenta) and PYTHIA 8.145 (yellow). Error bars and gray shaded areas in each plot indicate the experimental statistical and the systematic errors, respectively. The magenta shaded area indicates the statistical error of the MC data set using EPOS 1.99 as a representative of the other models.
The effect of hadron interaction

出典：Y. Tameda, http://indico.cern.ch/contributionDisplay.py?contribId=75&confId=152124
Temperature dependence of PMT Gain

The cathode behavior decide by a semiconductor that is used.
(the cathode of LHCf detectors are bialkali)

-0.25 %
cathode thermal behavior
(λ dependence)
+ dynode thermal behavior
verification of temperature dependence
Check the temperature dependence of detector at SPS collider in 2012.
✓ Change the temperature whole the detector by chiller (Fig.5)
✓ inject 200GeV/c e⁻ beams

![Diagram of detector system]

The temperature dependency coefficient is consistent with the PMT (R7400U) catalog value (-0.20% / degree)
We could confirm that there is the dependency of energy scale on the temperature.
However, to explain the energy scale shift found by pi⁰ mass peak, we must think carefully about it.

Confirm the temperature dependence of detectors (Fig.6)
エネルギー由来の系統誤差

エネルギースペクトルの模式図

- オリジナル
- Energy +10%
- Energy −10%

Arm1, Small tower

- energy scale

- data
- statistical error + systematic error
- statistical error
エネルギ再構成
先行研究により以下を検証

ADC値
エネルギ損失換算係数
→より厳しいイベント選択
集光効率補正
シャワー漏れ出し・漏れ込み補正
→測定データを用いて導出

エネルギ再構成
→有意な変化なし
解析手法に問題なし

放出角度決定

$M_{\gamma\gamma} \approx \sqrt{E_{\gamma1}E_{\gamma2}\theta^2}$

入射位置
位置検出器の工作精度で数十μmに制限
←Arm1のずれを説明するには1.8mmものオフセットが必要

IP1からの距離
140mに対して数十μmの精度で決定
←Arm1のずれを説明するには10mのずれが必要

原因と考えにくい
systematic error of Energy scale

Set the large size error which include reconstructed mass and $\pi^0$ mass (135 MeV).

Error of $M_{\gamma\gamma} \equiv \sqrt{E_{\gamma1}E_{\gamma2}\theta^2}$ is decided as follow.

1. $\pm 3.5\%$ (calibration error) Gaussian probability
2. $\pm 8.1\%$ (energy scale shift) flat probability

\[ \begin{align*}
\text{Quadratic sum}
\end{align*} \]
π⁰が空気シャワーに与える影響

青は緑より前方にπ⁰を生成しやすいモデル

電磁シャワーを生成するπ⁰は、シャワー発達に与える影響が大きい

最大発達高度が大きく変わる
LHCf situation

**p-p collision**  \((\rightarrow \text{lab})\)

- ✓ \(\sqrt{S} = 900\, GeV \rightarrow 2 \times 10^{14}\, eV\)  \((2009\, \text{-}2010)\)
- ✓ \(\sqrt{S} = 2.76\, TeV \rightarrow 1.5 \times 10^{16}\, eV\)  \((2012)\)
- ✓ \(\sqrt{S} = 7\, TeV \rightarrow 2.6 \times 10^{16}\, eV\)
- □ \(\sqrt{S} = 13\, TeV \rightarrow 9 \times 10^{16}\, eV\)
The knowledge of

Equivalent center of mass, $\sqrt{s_{pp}}$ (GeV)

$10^2$ $10^3$ $10^4$ $10^5$ $10^6$

$10^19$ $10^{18}$ $10^{17}$ $10^{16}$ $10^{15}$ $10^{14}$ $10^{13}$

- RHIC ($pp$)
- Tevatron ($pp$) 7 TeV 14 TeV
- LHC ($pp$)
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande 2009
- ATIC
- PROTON
- RUNJOB
- Auger 2009
- Tibet ASg (SIBYLL 2.1)

Cosmic ray energy & mass composition

LHCf Detectors

ARM1

ARM2

Front view of calorimeter

pseudo-rapidity range >8.4

beam pipe shadow

beam center

Detector#2

25, 32 mm

Longitudinal size (mm)

Vertical size

Thermometers at PMT holder and tungsten holder
Shower leakage

typical size of lateral shower is 9 mm
In order to ADC $\rightarrow$ dE (MeV), the dE histograms of each layer obtained

1 from beam test (ADC value)
2 from MC data (dE $\rightarrow$ particle)

were compared by $\chi^2$.

1 particle = 0.453 MeV