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Comparison of hadron interaction models with measurement of forward spectra by the LHCf apparatus

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Summary. — The LHCf experiment is a forward experiment of LHC. The two LHCf detectors, each composed of a pair of sampling and imaging calorimeters, have been installed at the forward region of IP1 to measure energy and transverse momentum spectra of neutral particles emitted in the very forward region of LHC collisions ($\eta > 8.4$). The operation at 900 GeV and 7 TeV pp collisions has been completed in the middle of July 2010. We present some preliminary results in this paper.

PACS `13.85.Qk` – Inclusive production with identified leptons, photons, or other nonhadronic particles.
PACS `13.85.Tp` – Cosmic-ray interactions.

1. – Introduction

The Monte Carlo (MC) simulation is a part of essential tools for measurements of high-energy cosmic rays. However hadron interaction models used in air shower simulations have an uncertainty due to the lack of experimental data in the energy range over 10^{15} eV. The Large Hadron Collider (LHC), which is the largest and the most powerful hadron collider, started the operation in 2009. The design collision energy is $\sqrt{s} = 14$ TeV, which corresponds to 10^{17} eV in the laboratory system. The LHCf experiment is one of the LHC forward experiments. The aim is to measure the energy and transverse momentum spectra of gamma-rays, neutral hadrons and π^0's emitted in the very forward region of LHC and to provide critical data for calibration of hadron interaction models.

2. – The LHCf experiment

The LHCf apparatus is composed of independent detectors (Arm1 and Arm2) with similar design but with slightly different configuration for background rejection and redundancy. Each detector has two sampling and imaging calorimeters with the transverse cross-section of 20×20 mm and 40×40 mm in the Arm1 detector and 25×25 mm and 32×32 mm in the Arm2 detector. Figure 1 shows the schematic view of the Arm1 and Arm2 detectors. Each calorimeter is composed of 22 tungsten plates of 7 mm thickness (2 r.l.), 16 plastic scintillators and 4 position sensitive layers of X-Y SciFi hodoscopes and X-Y silicon strip detectors for Arm1 and Arm2, respectively. The plastic scintillators are inserted by 2 or 4 r.l. step for shower sampling. The position sensitive layers are inserted at 6, 10, 30 and 42 r.l. for the Arm1 calorimeters and at 6, 12, 30 and 42 r.l. for the Arm2 calorimeters to measure the shower position and identify the multiple showers in one calorimeter. The total thickness of each calorimeter is 44 r.l. and 1.7 interaction lengths. The calorimeters of each detector are packed together with PMT's and front-end circuits in the aluminum box of $92\,\text{mm}^w \times 280\,\text{mm}^l \times 620\,\text{mm}^h$. The energy resolution is expected to be $< 5\%$ and about 30% for gamma-rays with more than 100 GeV and hadrons, respectively. The position resolution for gamma-ray showers is expected to be better than 0.2 mm. These detector performances have been confirmed at the beam tests done in 2006 and 2007 at CERN SPS [1].

At $+/-$ 140 m from an LHC interaction point, IP1, zero degree neutral absorbers (TAN's) have been installed for preventing quenching of downstream superconducting magnets by neutral particles produced in *pp* collisions. Inside the TAN, the beam pipe

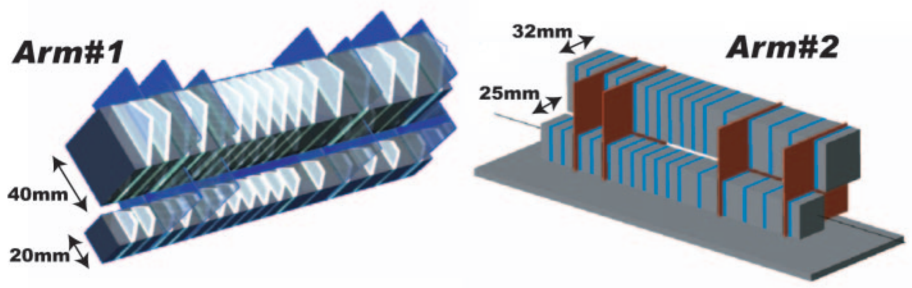

Fig. 1. – Schematic view of the Arm1 and Arm2 detectors.

makes a transition from a single common beam pipe facing IP1 to two separate beam pipes joining to the arcs of LHC (Y-chamber). In the crotch of the Y-chamber, there is an instrumentation slot with dimensions $96\,\mathrm{mm}^w \times 1000\,\mathrm{mm}^l \times 607\,\mathrm{mm}^h$ for detectors of beam monitors and forward physics experiments. The LHCf detectors have been inserted in the slots of both the TAN's. The instrumentation slot allows to measure neutral particles produced at the interaction point at zero degree of collisions but not charged particles because they are swept away by the magnetic field of the beam separation dipoles located between IP1 and the TAN. The aperture is limited by the size of the TAN instrumentation slot and the aperture of the beam pipes located between IP1 and the TAN. The pseudo-rapidity coverage of the LHCf detectors is $\eta > 8.7$ and $\eta > 8.4$ with zero and $140\,\mu$rad beam crossing angles, respectively.

3. – Operation in 2009 and 2010

LHC had the first *pp* collision with 450 GeV beams on 23 November 2009. After some commissioning, LHC had delivered stable *pp* collisions with $\sqrt{s} = 900\,\mathrm{GeV}$ at each interaction point in December 2009. In the beginning of the LHC operation, we have completed the commissioning of the DAQ system in 2.6 hours and then have taken data with 900 GeV collisions for 27.7 hours during the LHC operation in 2009. In total, we got about 2800 and 3700 shower events for Arm1 and Arm2, respectively, in about 0.5 million *pp* collisions at IP1.

After the shutdown of LHC in the beginning of 2010, on 30 March 2010, LHC became the energy frontier of the particle accelerators by colliding beams with energy of 3.5 TeV. The collision energy of $\sqrt{s} = 7\,\mathrm{TeV}$ is equivalent to $2.6 \times 10^{16}\,\mathrm{eV}$ in the laboratory system. From that day, LHC is delivering stable *pp* collisions at 7 TeV continuously with increasing the luminosity. The acceptance of the LHCf detectors at 7 TeV *pp* collisions is much higher than that at 450 GeV. About 8% of collisions at 7 TeV produce energetic secondaries with energy above 100 GeV which are incident on the LHCf detector. During the period between 30 March and 5 June, LHC has delivered $14\,\mathrm{nb}^{-1}$ collisions at IP1 without beam crossing angle and the LHCf experiment took 5.1×10^7 and 5.4×10^7 shower events in 223 hour operation by the Arm1 and Arm2 detectors, respectively. After that, beams are collided with $100\,\mu$rad beam crossing angle at IP1. It means that the pseudorapidity coverage of the LHCf detectors increases from > 8.7 to > 8.4. 1.7×10^8 and 1.6×10^8 shower events have been taken in Arm1 and Arm2, respectively, in about 150 hours operation with $100\,\mu$rad beam crossing angle. In addition to operations at 7 TeV, LHC delivered 900 GeV *pp* collisions again on 2, 3 and 27 May 2010. The LHCf experiment has taken 15 times more statistics data than that taken in 2009.

We have completed our physics operation at the collision energies of 900 GeV and 7 TeV in the middle of July 2010. The LHCf detectors have been removed from the LHC tunnel on 20 July. We will have a beam test at CERN SPS with the detectors to confirm radiation damage of the scintillator layers in 2010. Then the detectors will be upgraded with replacing the plastic scintillators to GSO scintillators and will be re-installed to the LHC tunnel for operations with *pp* collisions at the LHC designed energy of $\sqrt{s} = 14\,\mathrm{TeV}$ in 2013.

4. – Results

4.1. *Particle identification.* – Electromagnetic showers induced by gamma-rays are discriminated from hadronic showers by using the shapes of longitudinal shower

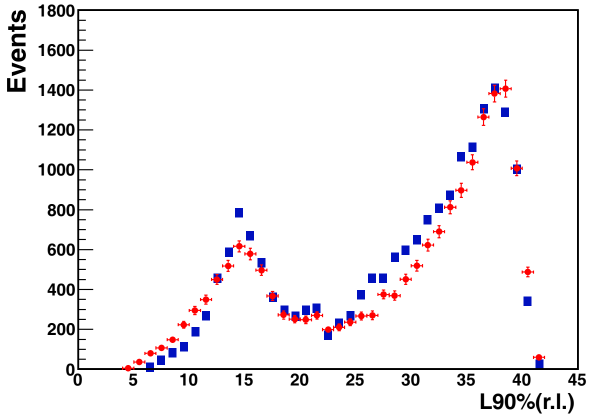

Fig. 2. – (Color online) L90% distributions measured by the Arm1 smaller calorimeter at 900 GeV collisions. L90% is defined for the particle identification as the longitudinal position in the calorimeter with the radiation length (r.l.) unit containing 90% of the summation of the shower particles. The red and blue points indicate results of data and MC generated by the QGSJET2 model, respectively.

developments measured by the 16 scintillator layers. To parameterize the transition shape of a shower, we defined L90%, which is the longitudinal position containing 90% of the summation of the shower particles. Figure 2 shows the L90% distribution of data measured by the smaller calorimeter of the Arm1 detector at 900 GeV pp collisions. There are two peaks at around 15 r.l. and 38 r.l. made by electromagnetic showers and hadronic showers, respectively. For the moment, we set the criteria of L90% to discriminate between gamma-ray–like events and hadron-like events as a function slightly depending on total energy deposit (dE) in the calorimeter, $16 + 0.0002 \times \mathrm{d}E$ r.l. dE is the total energy deposit normalized by MIP and is about 4000 if 100 GeV gamma-ray hits the calorimeter.

4·2. *Results at* 900 GeV *pp collisions*. – In total, 4.7×10^4 and 6.7×10^4 shower events have been taken in 2009 and 2010 operations at 900 GeV pp collisions by the Arm1 and Arm2 detectors, respectively. About 1% of the events are background events due to the collisions between beams and residual gas in the beam pipe (the beam-gas background). The beam-gas background can be estimated and monitored by using the events with non-colliding beams at IP1. Figure 3 shows the measurement spectra of gamma-ray–like and hadron-like events after subtraction of the beam-gas background. The colored dots indicate MC results generated by the hadron interaction models, DPMJET3 [2], QGSJET1 [3], QGSJET2 [4,5], SYBILL2.1 [6] and EPOS1.99 [7,8], which are normalized by total entries of gamma-ray–like and hadron-like events. In the spectra for hadron-like events, for the moment, the gamma-ray equivalent energy is used instead of reconstructed hadron energy because the detector response for hadrons is still under study. Only statistical errors are shown in the figures and systematic errors are under study.

4·3. *Results at* $\sqrt{s} = 7\,\mathrm{TeV}$. – Figure 4 shows the energy spectra of gamma-ray–like and hadron-like events measured by the Arm1 and Arm2 detectors at 7 TeV pp collisions. Even though only 2% of all data were used for the spectra, small statistical errors are given up to a few TeV energy bin. The comparison with MC is in progress.

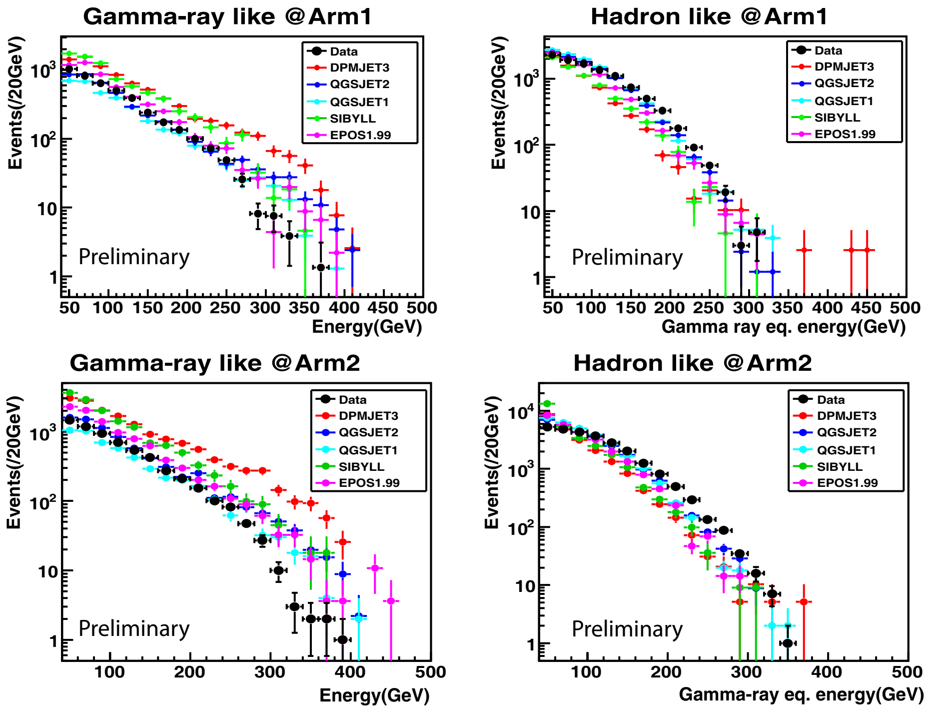

Fig. 3. – (Color online) The energy spectra for gamma-ray–like and hadron-like events measured by Arm1 (upper) and Arm2 (bottom) at 900 GeV collisions. The black dots indicate the measured spectra. The colored dots indicate MC generated by several hadron interaction models, which are normalized by total entries of the gamma-ray– and hadron-like events.

The independent two calorimeter towers in each detector allow us to reconstruct energy, momenta and mass of π^0's from measurements of the energies and incident positions of gamma-ray pairs. Figure 5 shows the reconstructed invariant mass and the reconstructed energy of π^0's from a data set of the Arm2 detector. In the mass distribution, there is a very sharp peak corresponding to the π^0 mass. The mass resolution is 2.3%.

5. – Conclusions

The LHCf experiment is a LHC forward experiment with calorimeters viewing zero degree of collision. The aim is to measure the energy and transverse momentum spectra of the most energetic neutral secondaries produced in the very forward region of LHC. The LHCf operation at 900 GeV and 7 TeV *pp* collisions has been completed in the middle of July 2010. The detector will be upgraded and reinstalled to the LHC tunnel for operation at the LHC design collision energy of 14 TeV in 2013.

Some preliminary results, the measured energy spectra of gamma-ray–like and hadron-like events at 900 GeV and 7 TeV *pp* collisions, the reconstructed mass and energy spectra of π^0, are presented in this paper. The results at 900 GeV are almost final and are going to be submitted. The analysis for 7 TeV data is processing quickly.

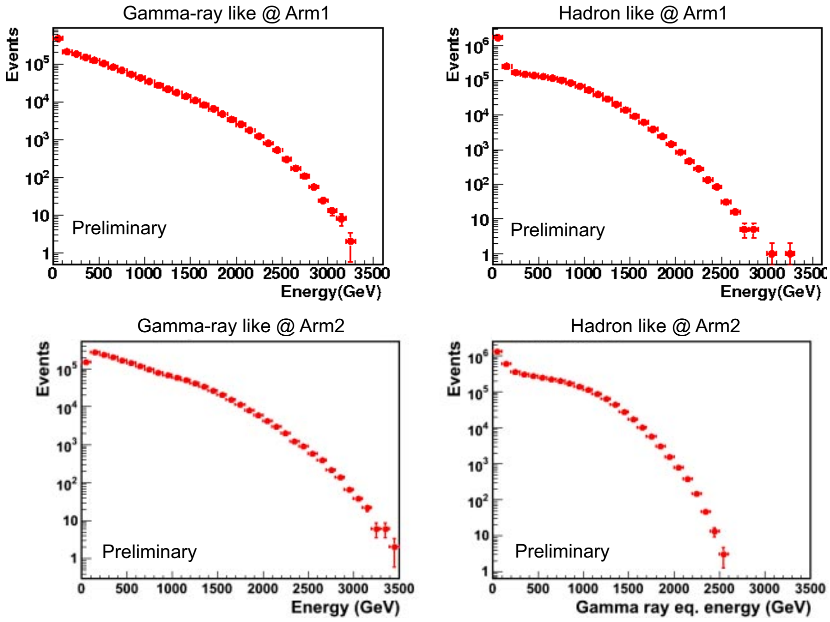

Fig. 4. – The energy spectra for gamma-ray–like and hadron-like events measured by Arm1 (upper) and Arm2 (bottom) at 7 TeV collisions.

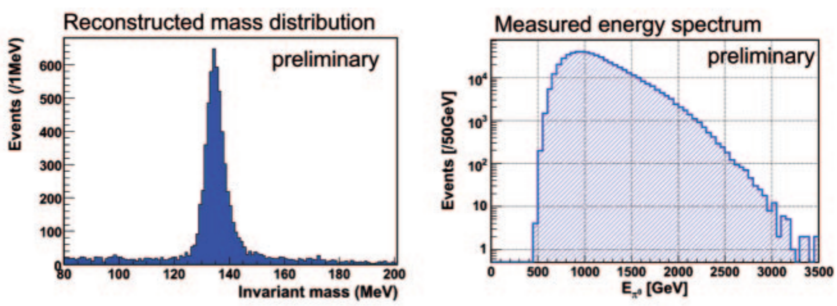

Fig. 5. – The reconstructed mass (left) and energy of π^0 from measurements of gamma-ray pairs at the Arm2 detector.

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