LHCf: Status and short term prospects

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The LHC forward experiment (LHCf) is the dedicated experiment for the measurements of the cross section and energy spectrum of neutral pions and neutrons in the very forward region ($\eta > 8.4$) at the Large Hadron Collider (LHC) at CERN. The first physics data LHCf has taken on December 2009 at $\sqrt{s} = 900$ GeV. Data taking at $\sqrt{s} = 7$ TeV has been continued since March 2010. In this paper, analysis results with the first limited sample of data at 900 GeV and 7 TeV are presented.

1 Introduction

There have been highest energy cosmic-ray observations in the last decade which have dramatically improved the quality and quantity of the observation data [1, 2]. However, no consistent description is available about the nature of the very high-energy cosmic-rays among each observations. This still unsolved puzzle is mostly originated in the uncertainty of the interaction of primary cosmic ray off nuclei above 10^{18} eV where no experimental data is available from accelerators.

Even in the existing accelerator data, there have not been adequate measurements of the spectra of very forward secondary particles that are necessary to understand the air shower development. Among many hadron collider data, such information is obtained only from UA7 [3] for π^0 at $\sqrt{s} = 630$ GeV and ISR data [4] for neutrons at $\sqrt{s} = 70$ GeV. However, LHC makes it possible to study hadron interactions at $\sqrt{s} = 14$ TeV, corresponding to 10^{17} eV in a fixed target system. LHCf is designed for measurements of the spectra and cross section of very forward ($\eta > 8.4$) secondary neutral pions and neutrons at the LHC. These measurements can provide the stringent limits on many parameters unavoidable in hadron interaction models and set an anchor to extrapolate a description at low energies to the highest energy end.

2 The LHCf experiment

The LHCf detectors are installed in the slot of the TANs (target neutral absorbers) located ± 140 m away from the ATLAS interaction point (IP1) and measure secondary neutral particles arriving from the IP1. Inside the TAN, the beam vacuum chamber makes a Y shaped transition from the single copper beam-pipe facing the IP1 to the two separate beam pipes joining to the arcs of LHC. Charged particles from the IP1 are swept aside by the D1 dipole magnet before reaching the TAN. At this unique location the pseudo-rapidity η ranges from 8.4 to infinity (zero degrees).

The LHCf detector is a pair of two independent calorimeters, called *Arm1* and *Arm2* installed at the IP8 side and the IP2 side from the IP1, respectively. Both detectors consist of a combination of small sampling and imaging calorimeters, which is called a *tower*, essentially 16 layers of plastic scintillators (3 mm thickness) interleaved with tungsten absorber (7 mm for the first 11 layers and 14 mm for the rest), and 4 layers of position sensitive detectors. The longitudinal size of the sensitive area to neutral particles is 230 mm or $44X_0$ (1.7λ) in units of radiation length (hadron interaction length). The transverse size of each tower is 20 mm×20 mm and 40 mm×40 mm in Arm1, and 25 mm×25 mm and 32 mm×32 mm in Arm2. The smaller tower is designed to cover the range to zero degrees, and the detector position can be adjusted using the vertically movable manipulators. Four X-Y layers of position sensitive detectors, scintillating fiber (SciFi) belts in Arm1, and micro-strip silicon sensors in Arm2, are inserted at 6, 10, 30, and $42X_0$ to determine the incident shower position. The schematic views of the detectors are shown in Figure 1.

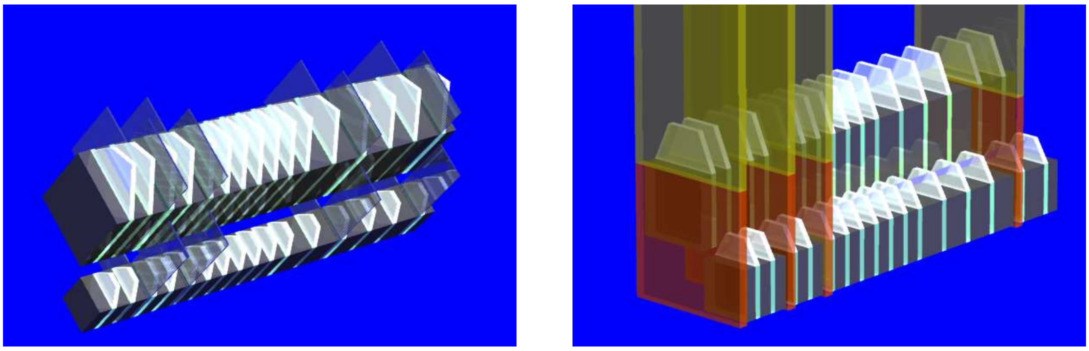

Figure 1: Schematic views of the LHCf detectors (Arm1 in the left panel and Arm2 in the right panel). Plastic scintillators (light green) are interleaved with tungsten layers (dark gray). Four layers of position sensitive layers (SciFi in Arm1 indicated by light gray and silicon strip detector in Arm2 indicated by brown) are inserted.

The calorimeters are designed to have energy and position resolutions better than 5% and 0.2 mm, respectively, for electromagnetic showers with energies above 100 GeV. Thanks to the small aperture of a tower, the multiplicity of secondary particles in a single tower is reduced to a reasonable level even at $\sqrt{s} = 14$ TeV. The two towers are positioned to detect a gamma-ray pair from the π^0 decay with one electromagnetic shower in each towers. By reconstructing the invariant mass of gamma-ray pairs, π^0 can be identified among gamma-like events and hence the energy spectrum of π^0 is measured. Even with a short operation at the commissioning of LHC, statistically sufficient physics data can be recorded to deeply investigate the existing interaction models on the market. Please see other documents for the scientific goal and the details of the detectors [5, 6].

3 Operations in 2009 and 2010

LHC has succeeded first physics collisions (*stable beams*) on 6 December 2009 at $\sqrt{s} = 900$ GeV. They provided a total of 0.5M collisions at IP1 in 2009. After a winter shutdown, the LHC succeeded to have collisions at $\sqrt{s} = 7$ TeV on 30 March 2010 and is gradually increasing the luminosity. The integrated luminosity reached ~ 14 nb^{-1} at the end of May. Meanwhile the LHC provided 15 times more collisions at $\sqrt{s} = 900$ GeV than 2009. LHCf has successfully started data taking at the first collisions and is accumulating data at all runs with stable beam conditions.[1] LHCf has accumulated 113k and 100M high energy shower events (approximately above 10 GeV) at 900 GeV and 7 TeV collisions, respectively. The trigger of the LHCf detectors is based on the signals from one of the beam monitors (BPTX) and the existence of a high energy shower in any of the calorimeters. During the 2009–2010 runs, the LHC was always operated with at least one non-crossing bunch (having no pair bunch in the other beam) in both beams. Any high energy particles associated with passage of such bunches at IP1 are thought to be collision products of the beam and residual gas in the beam pipe, thus background in our measurement.

4 Analysis

4.1 Event reconstruction and particle identification

One half of the secondary particles reaching the TAN is expected to be from gamma rays and the rest is from hadrons (mainly neutrons). Here a parameter called "$L_{90\%}$" is introduced to identify whether an incident particle of a shower is a gamma or a hadron. $L_{90\%}$ is defined as the longitudinal position of the first tungsten layer in units of radiation length where 90% of the total energy is deposited.

4.2 Analysis results at $\sqrt{s} = 900$ GeV

Energy spectra of gamma-ray-like and hadron-like events after applying the particle ID criteria are shown in Figure 2. The data is from the Arm1 detector after combining the results of two towers. With this limited statistics, no significant difference is found between Arm1 and Arm2. Considering the statistical error and the conservative systematic uncertainty related to the energy scale, the measured spectra and the prediction by QGSJET2 [7] have a good agreement.

4.3 Analysis results at $\sqrt{s} = 7$ TeV

The energy spectra of gamma-ray-like and hadron-like events are shown in Figure 3. Here the spectra measured in the Arm2 detector are separated in the results of two different towers. The red (upper) and blue (lower) squares are events associated with the crossing and non-crossing bunches, respectively. The contamination of the beam-gas background was two orders of magnitude below the signal level and can be neglected in the analysis. A comparison of the spectra between each tower shows the harder spectra in the small tower (covering the range to zero degrees) in gamma-ray like and hadron like spectra. This tendency indicates a strong beaming of the high energy very forward particles that was not observed in the 900 GeV data.

Furthermore, in the case of 7 TeV collisions, gamma-ray pairs from π^0 decays may hit two towers in the same event due to the small opening angle. Using the energy and position

[1] LHCf has finished operation at this energy in the middle of July 2010 and removed the detectors from the LHC tunnel.

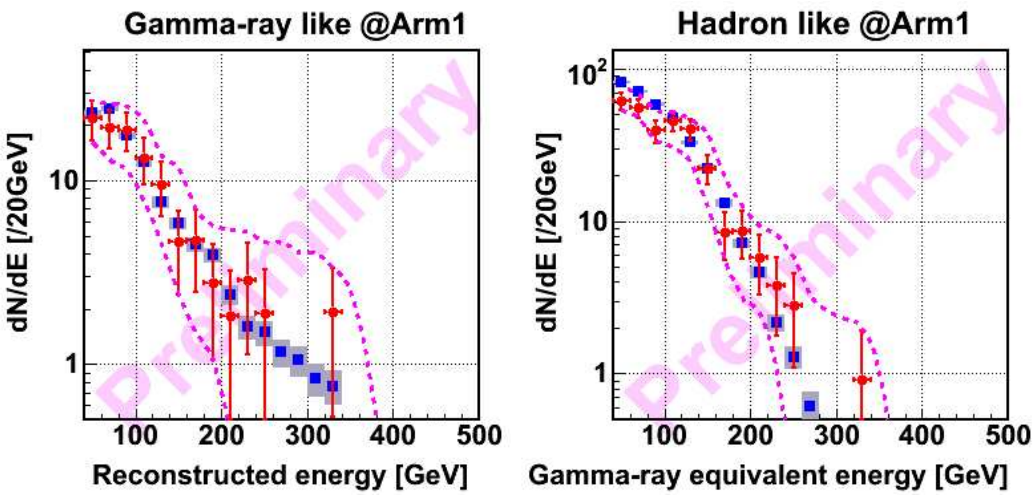

Figure 2: Energy spectra at $\sqrt{s} = 900$ GeV. The red points indicate the data taken in 2009 and its statistical error. The blue squares and the gray hatched area indicate the MC simulation with QGSJET2 and its statistical error, respectively. The systematic uncertainty related to the energy scale is drawn as a dashed curve (+15%, −10%).

information of these gamma-rays and assuming that its vertex is IP1, the invariant mass of the gamma-ray pairs can be reconstructed. The observed π^0 mass is reasonably distributed around 135 MeV.

5 Conclusions

No significant trouble has happened at the operation of LHC since last year and data taking has been stably continued.

As for the analysis at 900 GeV, the energy spectra of the data taken in 2009 seem to be agreeable with QGSJET2 although they have small statistics and a large statistical and systematic uncertainty.

The analysis at 7 TeV indicates harder spectra in the small tower than in the large tower even with the limited number of events. This can be understood by strong beaming of high energy secondary particles.

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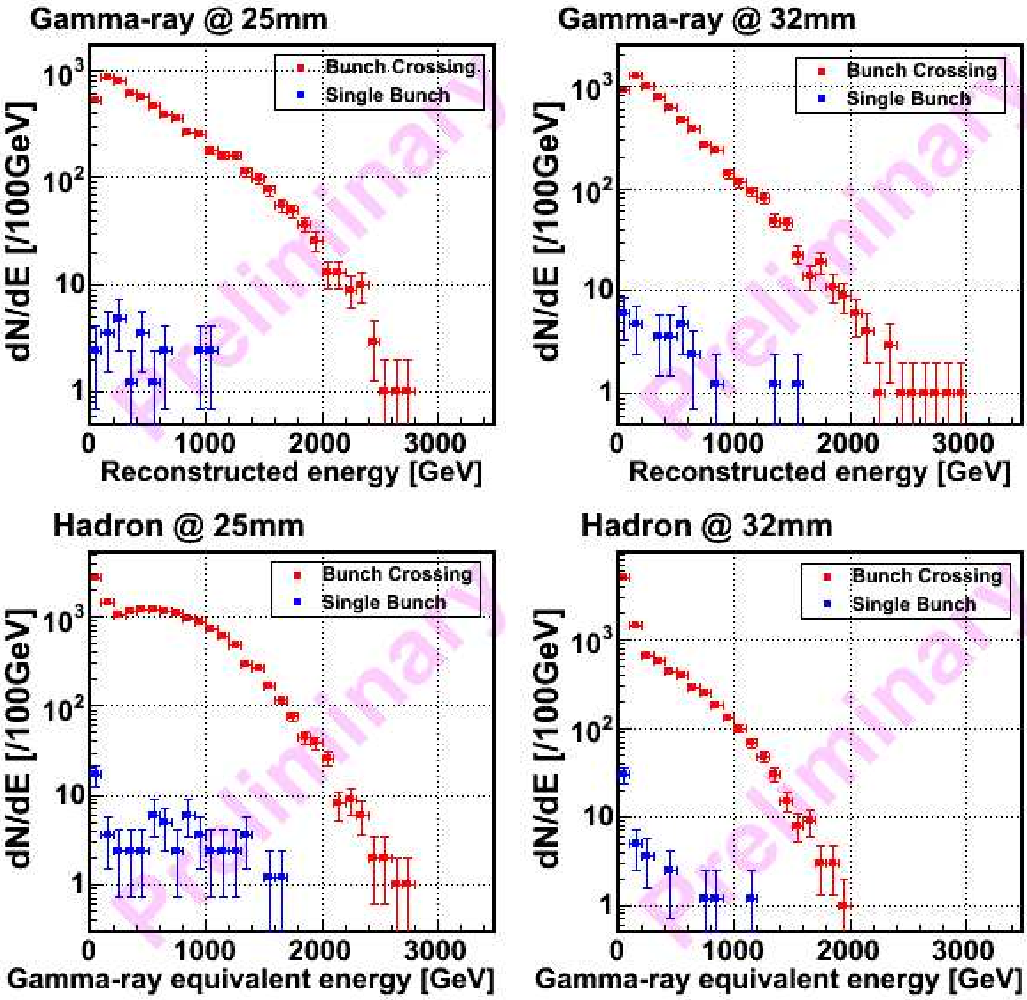

Figure 3: Energy spectra at $\sqrt{s} = 7$ TeV. The red (upper) squares indicate the crossing bunch data and its statistical error, while the blue (lower) squares show non-crossing bunch data.