PROCEEDINGS OF SCIENCE

Zero degree neutron energy spectra measured by LHCf at $\sqrt{s}$ = 13 TeV proton-proton collision

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The Large Hadron Collider forward (LHCf) experiment is designed to measure the particle production in very forward region at LHC. Forward particle production in the hadronic interaction is one of the crucial points to understand the development of cosmic-ray air showers. We report the preliminary results of the neutron energy spectra measured by LHCf in $\sqrt{s}$ = 13 TeV proton-proton collisions in the pseudo-rapidity ranging from 8.81 to 8.99, from 8.99 to 9.22, and above 10.76. Analysis procedure such as particle identification, position and energy determinations are also discussed in this presentation.

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1. Introduction

Ultra High Energy Cosmic Rays (UHECRs) are studied by ground-based experiments, such as the Pierre Auger Observatory [1] and the Telescope Array [2]. These ground-based experiments must rely on the hadronic interaction models to reconstruct the incident cosmic-ray properties from the observed Extensive Air Shower (EAS) formed in the atmosphere. Because of the lack of calibration data relative to secondary particles produced in the forward region in high energy collisions, these models have different predictions.

The Large Hadron Collider forward (LHCf) experiment is designed to verify the hadronic interaction models used in the cosmic-ray physics [3]. LHCf measures neutral particles, mainly photons and neutrons, produced in very forward region from p-p collisions at LHC. The neutron spectra in $\sqrt{s} = 7$ TeV p-p collision have already been published by the collaboration [4][5]. In this paper we extend the analysis to data obtained in $\sqrt{s} = 13$ TeV p-p collisions.

2. The LHCf experiment and detectors

The LHCf experiment has two independent detectors named Arm1 and Arm2 [6]. These detectors are placed on the both sides of the LHC Interaction Point 1 (IP1), in the structure called Target Absorber Neutral (TAN) located 140 m far from IP1. Each detector consists of two calorimetric towers made up of 16 layers of sampling scintillation panels interleaved with tungsten plates and position sensitive detectors. The transverse dimensions of the calorimeter towers are 20 mm $\times$ 20 mm and 40 mm $\times$ 40 mm for Arm1, and 25 mm $\times$ 25 mm and 32 mm $\times$ 32 mm for Arm2. Position sensitive detectors are made of four pairs of X-Y position layers. These imaging layers are made up by 1 mm width scintillator bar bundles in Arm1 and by 0.16 mm read out pitch silicon micro-strip detectors in the case of Arm2. These detectors were upgraded for $\sqrt{s} = 13$ TeV operation. The performance of the detectors was investigated by using the accelerator beams and Monte Carlo (MC) simulations. The energy resolution and the position resolution for neutron are about 40 % and better than 1 mm, respectively [7].

3. Data analysis

In this section we present the analysis procedure to obtain the neutron energy spectra in $\sqrt{s} =$ 13 TeV p-p collisions.

3.1 Experimental data set

LHCf had an operation with p-p collisions in $\sqrt{s} = 13$ TeV from 10 to 13 June 2015. The data set analyzed in this work was taken from 22:32 of 12 June to 1:30 of 13 June, corresponding to the LHC Fill 3855, one of the special fills with low luminosity and high β^* optimized for LHCf data taking. In this fill 29 bunches collided at IP1 with beam crossing angle of 145 μrad. β^* was around 19 m and μ, the average number of collisions per bunch crossing, was 0.007 - 0.012. The instantaneous luminosity L was measured by the ATLAS experiment as 0.04 - 0.06 $\mu b^{-1}s^{-1}$ [8]. Considering the LHCf data acquisition live time, the recorded integral luminosity was 0.191 nb^{-1}. The number of inelastic collisions is estimated to be 1.5×10^7 with 5% systematic uncertainty.

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3.2 Monte Carlo simulation

Monte Carlo (MC) simulations relative to the same experimental configuration present at the LHC are necessary for four different purposes: estimation of correction factors, validation of the whole analysis procedure, energy spectra unfolding and comparison between the model predictions and the final experimental result. We separate MC in three different categories:

(a) Full simulation including the flight and decay of the particles in the beam pipe, interaction with the beam pipe and the magnetic field, and interaction in the detector

(b) Simulations requiring only generation of collisions

(c) Simulations requiring only interaction with the detector

All these three sets of simulations have been generated making use of the COSMOS (v7.645) and EPICS (v9.165) libraries [9]. Five different hadronic interaction models have been used to generate collisions: QGSJET II-04 [10], EPOS-LHC [11], DPMJET3-0.4 [12], PYTHIA 8.212 [13] and SIBYLL 2.1 [14].

3.3 Event reconstruction

The event reconstruction algorithm used in this analysis is summarized in this section. Firstly, we applied the selection which required the energy deposit of more than 600 MeV for any successive three layers to reject low energy background events. For each event passed the selection we reconstruct the quantities: the impact point on the detector, energy, and particle identification. The impact point was determined by fitting the lateral distribution measured by the position sensitive layer on which the energy deposit was maximum in the four layers. The incident particle energy was determined by the summation of energy deposits from the 3rd to the 16th sampling layers in the calorimeter tower. After correction for lateral leakage of shower particles, the summation of energy deposit was converted to the incident particle energy using calibration driven by a simulation study. Particle identification was performed by using the shower-transition shape measured by the sampling layers. Electromagnetic showers develop in the shallow part of the calorimeters while hadronic showers develop deeply. We defined a parameter L_{2D} as

$$L_{2D} = L_{90\%} - 0.25 \times L_{20\%} \tag{3.1}$$

where $L_{20\%}$ and $L_{90\%}$ represent the calorimeter depth containing 20% and 90% of the total deposited energy in the detector, respectively. Figure 1 shows the L_{2D} distribution for the experimental data and MC simulation. In this analysis, we selected the events meeting the criterion $L_{2D} > L^{th}_{2D}$ with L^{th}_{2D} about 20 considering a weak energy dependence.

4. Results

Preliminary results are discussed below. More detailed description of the Arm2 analyses is found in [15].

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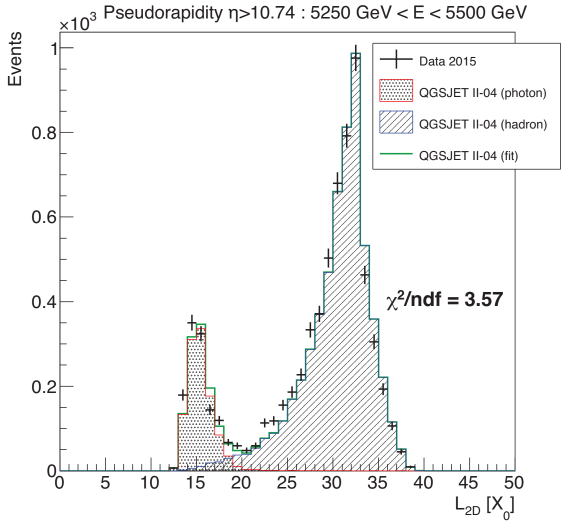

Figure 1: The L_{2D} distribution measured by the LHCf Arm2 detector. QGSJETII-04 hadrons (blue) and photons (red) distributions were fitted to experimental data (black) in order to estimate PID correction factor. The result of the fit is shown in green.

4.1 Comparison between Arm1 and Arm2 detectors

For cross-check of the analysis, we compared the obtained results between the Arm1 and Arm2 detectors. Figure 2 shows the folded neutron energy spectra for the rapidity region $\eta > 10.76$ measured by the Arm1 and the Arm2 detectors. The spectra have long tail over the beam energy of 6.5 TeV because of 40% energy resolution. Experimental errors including the statistical and the systematic uncertainties are shown only in the Arm2 spectra in Fig. 2. Two spectra are consistent within errors.

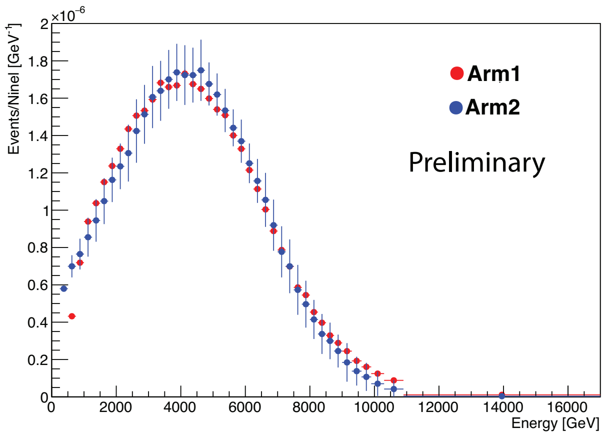

Figure 2: The folded neutron energy spectra measured for the rapidity region $\eta > 10.76$. The red and the blue points represent the results by the Arm1 and the Arm2 detectors, respectively. Only the Arm2 result shows the experimental errors including the statistical and the systematic uncertainties.

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4.2 Comparison with MC simulations

Figure 3 shows the unfolded neutron energy spectra for the pseudo-rapidity regions, $\eta > 10.76$, $8.99 < \eta < 9.22$, and $8.81 < \eta < 8.99$, measured by the LHCf Arm2 detector. The obtained spectra were compared with the model predictions of QGSJET II-04, EPOS-LHC, DPMJET3-0.6, PYTHIA 8.212 and SIBYLL 2.1. The vertical axis is the differential cross section of neutron production as shown in Eq.4.1,

$$\frac{d\sigma_n}{dE} = \frac{1}{L}\frac{2\pi}{\Delta\phi}\frac{\Delta N}{\Delta E} \tag{4.1}$$

where L is the integrated luminosity corresponding to the data, and $\Delta N = \Delta N(\Delta\eta, \Delta E)$ is the number of neutrons observed for each pseudo-rapidity interval $\Delta\eta$ in each energy bin of width ΔE, and $\Delta\phi$ is the azimuthal interval of analysis region on the Arm2 detector plane .

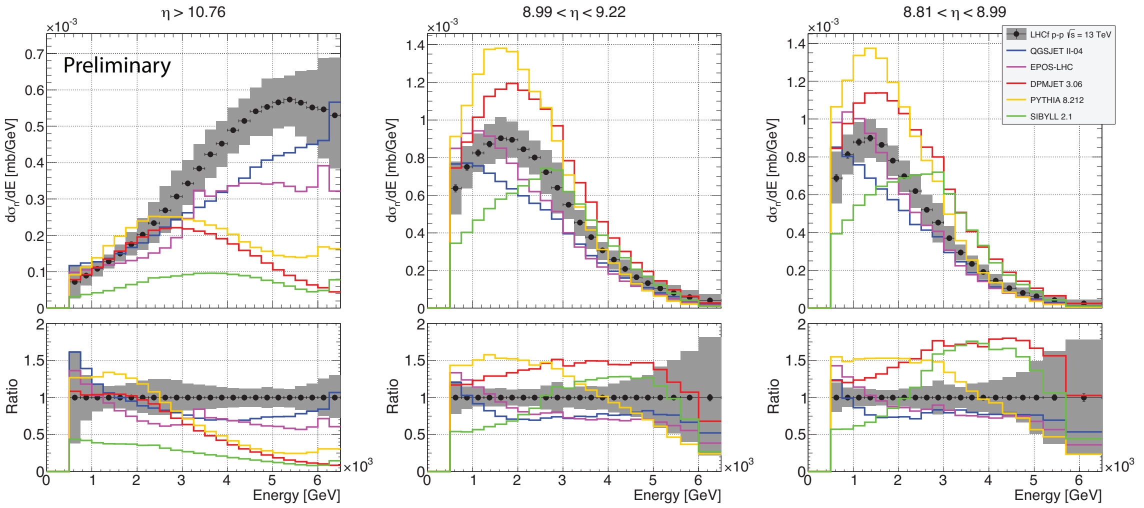

Figure 3: The unfolded neutron energy spectra for p-p collisions in $\sqrt{s} = 13$ TeV measured by the LHCf Arm2 detector.

In the pseudo-rapidity $\eta > 10.76$, we found that only QGSJET II-04 and, in part, EPOS-LHC qualitatatively reproduce the increase of the number of neutron production rate in the high energy region. All the other model predictions do not exhibit high energy peak as observed in the experimental data.

The results in the pseudo-rapidity regions, $8.99 < \eta < 9.22$, and $8.81 < \eta < 8.99$, are characterized by a good overall agreement of EPOS-LHC and QGSJET II-04 with experiment. Especially, EPOS-LHC has a good agreement in the region around 1.5 TeV.

5. Summary

The LHCf experiment measured the particle production in very forward region in $\sqrt{s} = 13$ TeV p-p collisions. Using the Arm2 detector we obtained the preliminary neutron energy spectra in the pseudo-rapidity ranging from 8.81 to 8.99, from 8.99 to 9.22, and above 10.76. These spectra were compared with the model predictions and we found the big difference in the pseudo-rapidity region, $\eta > 10.76$.

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In this presentation, we showed the unfolded spectra only for Arm2. The same analysis for Arm1 data is on going. The final results with combining the two detectors' result will be shown soon.

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