LHCf: Very forward measurement at LHC p-p and p-Pb

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The LHCf experiment is an LHC experiment dedicated to measurement of very forward neutral-particle spectra with the aim of improving hadronic interaction model used in MC simulation of cosmic-ray induced air showers. The LHCf have completed the physics plans for $\sqrt{s}$ = 0.9 and 7 TeV p-p collisions in 2010 and for $\sqrt{s_{NN}}$ = 5.02 p-Pb collisions in 2013. The LHCf have another operation with the increased collision energy of 13 TeV in 2015. The recent LHCf result of forward neutron energy spectra at 7 TeV p-p and forward π^0 spectra at p-Pb are presented in this paper.

1 LHCf experiment

The LHCf experiment is one of the LHC forward experiments. The aim is to provide critical calibration data of hadronic interaction models used in MC simulation of air showers induced by cosmic-rays with measuring the production spectra of neutral secondary particles at the very forward region of LHC collisions. The most of energetic particles produced at collisions emit into the forward region and the energy flux of secondaries concentrates on the region although the multiplicity concentrates on the central region of collisions which are covered by the central

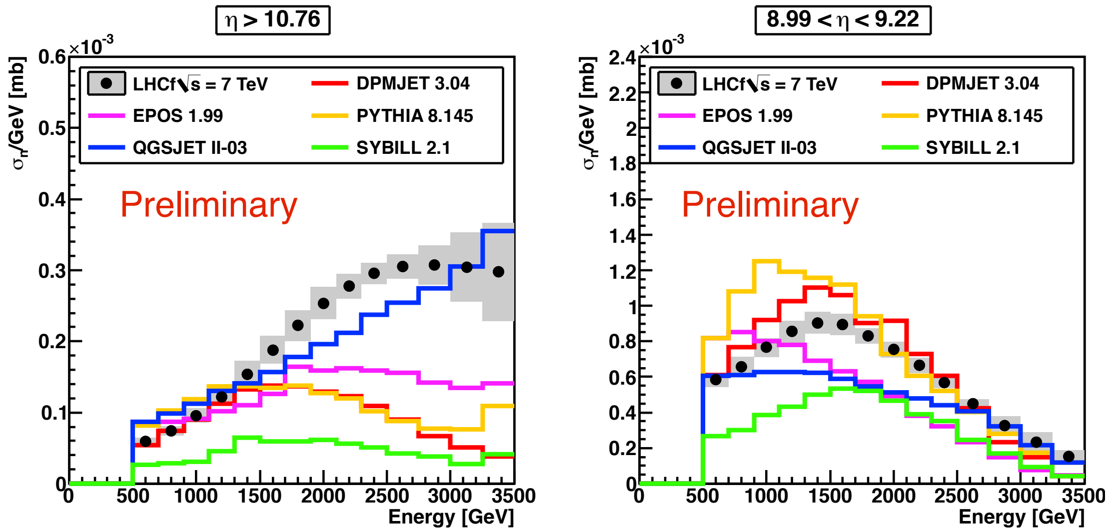

Figure 1: Forward neutron energy spectra at $\sqrt{s}$ = 7 TeV p-p collisions measured in $\eta > 10.76$ (left) and $8.99 < \eta < 9.22$ (right) [6]. The black dots and the shaded area show LHCf data and the uncertainties. The color lines indicate the predictions by several hadron interaction models[7, 8, 9, 10, 11].

detectors like ATLAS.

The LHCf have two independent detectors, so called Arm1 and Arm2, which were installed +/- 140m from the ATLAS interaction point (IP1). Each detector has two sampling and imaging calorimeter towers which are consisted of tungsten plates, 16 scintillator layers for shower sampling and four position sensitive layers for measurement of shower position. The position sensitive layers were developed with deferent techniques of X-Y scintillating fiber hodoscopes and X-Y silicon strip detectors for Arm1 and Arm2, respectively. The transverse cross sections of calorimeters are $20\times20\,\mathrm{mm}^2$ and $40\times40\,\mathrm{mm}^2$ in Arm1 and $25\times25\,\mathrm{mm}^2$ and $32\times32\,\mathrm{mm}^2$ in Arm2. The energy resolution of detectors are about 5 % for photons and 40 % for neutrons. The position resolution is better than $200\,\mu$m for photons and a few mm for neutrons. More details of the detector performance were reported elsewhere [1, 2].

The LHCf have successfully completed the operation with proton-proton collisions at $\sqrt{s}$ =0.9, 7 TeV in 2010 and the operation with proton-lead collisions at $\sqrt{s_{NN}}$ =5.02 TeV in 2013. The forward photon and π^0 spectra at proton-proton collisions has been published [3, 4, 5].

2 Neutron spectrum in $\sqrt{s}$ = 7 TeV p-p collisions

The measurement of neutron energy spectum is a way to access one of the key parameters for air-shower development, inelasticity of hadronic interaction. The parameter is estimated from the energy of leading baryons in collisions. The LHCf detectors are able to measure neutral hadrons, mostly neutrons, with 40% energy resolution and 1 mm position resolution. Events with hadron induced showers are well identified with parameters calculated from longitudinal developments of showers. Figure 1 shows the preliminary result of neutron energy spectra after

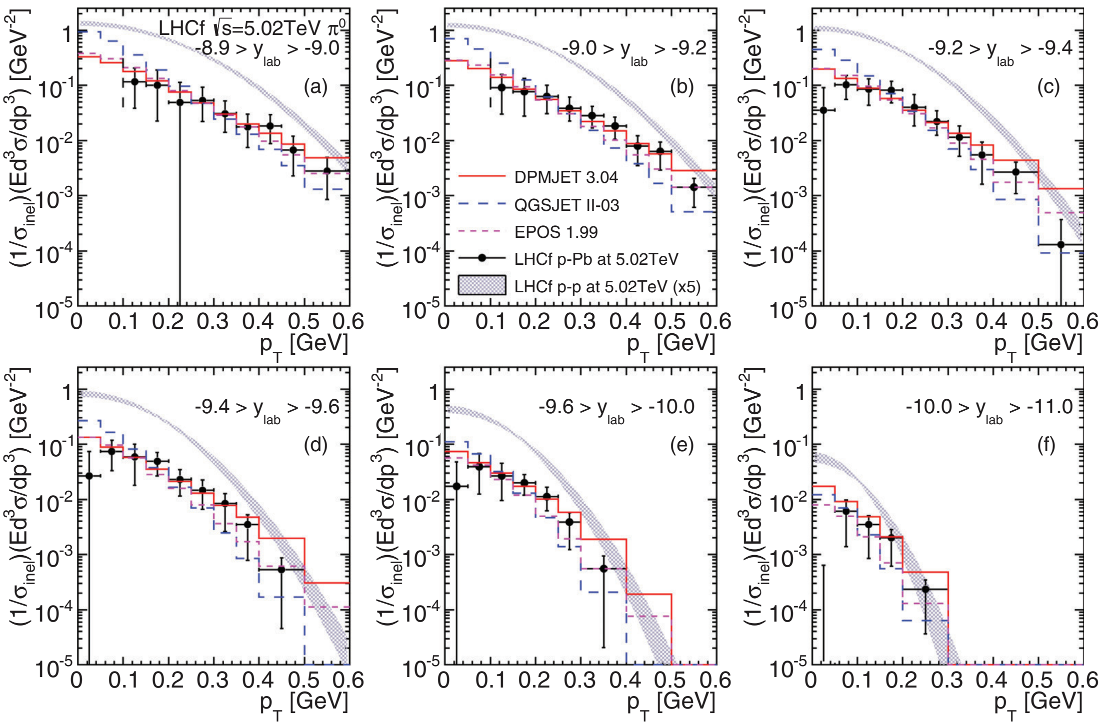

Figure 2: Transverse momentum spectra of forward π^0s at p-Pb [12]. The black dots and the shaded area show LHCf data and the uncertainties. The color lines indicate the predictions by several hadron interaction models[7, 8, 9, 10, 11].

unfolding procedure for detector response [6]. The left and the right figures are for the pseudo-rapidity bins of $\eta > 10.76$ and $8.99 < \eta < 9.22$, respectively. The colored lines indicate the predictions of several hadronic interaction models [7, 8, 9, 10, 11]. We found that the spectrum in $\eta > 10.76$ was very hard like QGSJET2 and the spectrum in $8.99 < \eta < 9.22$ was in the middle of model predictions.

3 π^0 P_T spectrum in $\sqrt{s_{NN}} = 5.02\,$TeV p-Pb collisions

In the bingeing of 2013, LHC had proton-lead collisions at the center-of-mass collision energy per nucleus of $\sqrt{s_{NN}} = 5.02\,$TeV. LHCf have installed one of the LHCf detectors (Arm2) into the LHC tunnel and had an operation. In the most of our operation time, the Arm2 detector was located on the p-remnant side where proton beams passed from IP1. The LHCf had an operation at the Pb-remnant side only for some hours. In that time, the detector was located 4 cm up from zero degree of collisions to avoid too high multiplicity on the calorimeter towers. Figure 2 shows the transverse momentum spectra of π^0s in p-Pb collisions (the p-remnant side) [12]. The expected contribution of ultra peripheral collisions (UPCs) was already subtracted in these spectra. The thin lines indicate the predictions from the hadronic interaction models, DPMJET3, QGSJET2 and EPOS1.99. The transverse momentum spectra at proton-

proton collisions with the equivalent energy of $\sqrt{s} = 5.02\,\mathrm{TeV}$ were derived from the LHCf data taken at $\sqrt{s} =$ 0.9 2.76 and 7 TeV proton-proton collisions and are shown as the gray hatched lines in Fig.2. Comparing the measured transverse momenta with the estimated spectra in proton-proton collisions give us new information of nuclear modification effect. The nuclear modification factor, $\mathbf{R_{pPb}}$, was defined as the ratio of the p-Pb result to the p-p result. $\mathbf{R}_{pPb}$ varies from 0.1 at P_T 0.1 GeV/c to 0.3 at P_T 0.3 GeV/c. This tendency is found in the all rapidity bins of Fig2. The hadronic interaction model reproduce the small factor of $\mathbf{R_{pPb}}$ 0.1 constantly in the P_T range. They are in good agreement with the LHCf result within the errors.

4 Future prospects

The LHC will restart the operation in 2015. In the beginning of LHC physics run, a run with very low-luminosity of $10^{30} cm^2 s^{-1}$ is planed. The LHCf will have an operation for one week in that period at proton-proton collisions with $\sqrt{s} = 13\,\mathrm{TeV}$. The collision energy is about 10^{17} eV. It will be unique data point of forward spectra at the highest collision-energy of collider experiment in the next decades. Comparing with the date taken at proton-proton collisions of $\sqrt{s} = 0.9$, 2.76 and 7 TeV in the past operations, the energy scaling of forward particle production can be checked. The test with the wide collision energy of $10^{14} - 10^{17}$ eV in the laboratory frame is important because it covers the energy of well-known Knee kink of the cosmic-ray spectrum around 10^{15} eV. Additionally the operation in 2015 will be important to study the diffractive physics thanks to the common operation with the ATLAS experiment. The LHCf sends its final trigger signals to ATLAS trigger system and they trigger ALTAS after pre-scaling of the signals. It was confirmed by a simple simulation study that an event cut with the number of particle tracks in the ATLAS central tracker works well to select only diffractive events. Forward production spectra with such event categorization help us to understand the particle production mechanism in the soft hadronic interactions.
After the operation in 2015, we are proposing to bring one of the detectors to RHIC and to have an operation at proton-proton collisions with $\sqrt{s} = 0.5\,\mathrm{TeV}$. It provides an opportunity of measuring forward production spectra with much wider P_T coverage than the operation at LHC 0.9 TeV proton-proton collisions. It will be much useful to test the energy scaling.

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