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Recent results from the LHCf experiment

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The LHCf experiment is an unique dedicated experiment for measurement of very forward particle production relevant to cosmic-ray air shower developments. The LHCf measured the spectra for forward photons, neutral pions and neutrons at $\sqrt{s} = 7\,\mathrm{TeV}$ *p*-*p* collisions and the nuclear modification factor for forward neutral pions at $\sqrt{s} = 5\,\mathrm{TeV}$ *p*-Pb. No hadronic interaction models used in air shower developments of very high energy cosmic-rays is able to reproduce all LHCf data reasonably while some of models are able to reproduce LHCf data partially.

KEYWORDS: LHCf, UHECR, hadronic interaction

1. Introduction

Energy of cosmic-rays is widely distributed from 10^9 eV to 10^{20} eV and the flux is able to be well fitted with a power raw function of index about 2.7. The highest energy about 10^{20} eV exceeds the LHC collision energy of 10^{17} eV in the laboratory frame. The sources of Ultra-High Energy Cosmic-Rays (UHECRs), which should be much more powerful accelerators than LHC in the universe, are being searched for a long time however we have no clear answer yet. The observation of UHECRs is not an easy task because of its very poor flux as 1 event per $100\,\mathrm{km}^2$ and a year at the cosmic ray energy of 10^{20} eV. However the air shower technique allows us to observe UHECRs with huge acceptance of detector. High energy cosmic-rays collide with atmospheric nuclei and produce lots of secondary particles. The energetic photons mainly produced from decays of secondary π^0s induces electromagnetic showers and the other hadrons make hadronic interactions with atmospheric nuclei again. Continuing these interactions, air showers develop and shower particles fall on the ground. Experiments measure air showers with particle detectors on the ground and fluorescence telescopes and reconstruct information of primary cosmic-rays, energy, chemical composition and arrival direction, from the observed data. This technique is very powerful to effectively increase the acceptance by using a huge volume of atmosphere as a part of detector. However, for precise measurement, the knowledge of hadronic interaction between cosmic-rays and atmospheric nuclei is necessary. Average and RMS of the measured X_{MAX}, which is the depth at the maximum development of each air shower, are a well-used indicators of the composition. However the predictions of X_{MAX} by air shower simulations depend on the hadron interaction model used in the simulation.

The largest particle collider, Large Hadron Collider (LHC), started the operation in 2009. The designed collision energy of p-p is $\sqrt{s} =$ 14 TeV which is equivalent to 10^{17} in the laboratory frame. The LHC is providing lots of exciting results and the LHC data is critical to verify and improve hadronic interaction models used in the air shower simulation.

In this paper, we quickly introduce the LHC experimental results with focusing important parameters for air shower development in Section 2. Then the recent LHCf results with p-p collisions at $\sqrt{s} =$ 7 TeV and with p-Pb collisions at $\sqrt{s_{NN}} =$ 5 TeV are reviewed in Section 3. Finally we summarize in Section 4.

2. LHC results and air shower development

Here, the key parameters of hadronic interaction are listed.

- **Inelastic cross section** is the most important parameter for air shower development. Larger inelastic cross section induces deeper shower development, which means increase of $< X_{MAX} >$. Because the fluctuation of X_{MAX} is mainly due to the fluctuation of depth of collisions between primary cosmic ray and atmospheric nuclei, RMS of X_{MAX} become larger with smaller inelastic cross section. TOTEM, ATLAS, CMS and ALICE experiments published inelastic cross section of p-p collisions. Especially TOTEM, which is a dedicated experiment to the precise measurement of cross section at p-p, provided the precise total and the inelastic cross sections at $\sqrt{s} =$ 7 and 8 TeV [1,2].

- **Inelasticity** is a parameter to give you an idea of total energy used for production of secondaries. Smaller inelasticity induces deeper shower development because the leading baryons are able to penetrate to deeper atmosphere with making interactions. The inelasticity k can be estimated with measurement of leading baryons in collisions, which provides $1-k$ or elasticity. Not only the total energy of secondaries but also energy spectrum of energetic secondaries must be measured. Both leading baryons and energetic secondaries are emitted to the forward region of collisions. The right figure of Fig. 1 shows energy flux distribution at $\sqrt{s} =$ 14 TeV p-p as a function of pseudorapidity. The energy flux concentrates on the large pseudorapidity region. The region is covered by the LHCf experiment as well as ZDCs and Roman pot detectors.

- **Multiplicity** at the central region of collisions are so high. The left figure of Fig. 1 shows the multiplicity distribution as a function of pseudorapidity. Higher multiplicity induces larger number of muons on the ground. The central region of collisions are fully covered by so many trackers of ATLAS, CMA, LHCb and ALICE.

- **Nuclear effect** is also important because primary cosmic-rays interact with atmospheric nuclei as Nitrogens and Oxygens. LHC provided p-Pb collisions in 2013. Lead is much heavier than Nitrogen and Oxygen. So strong nuclear effect can be expected at p-Pb collisions and the nuclear effect at light ions may be extrapolated from the results at p-p and at p-Pb.

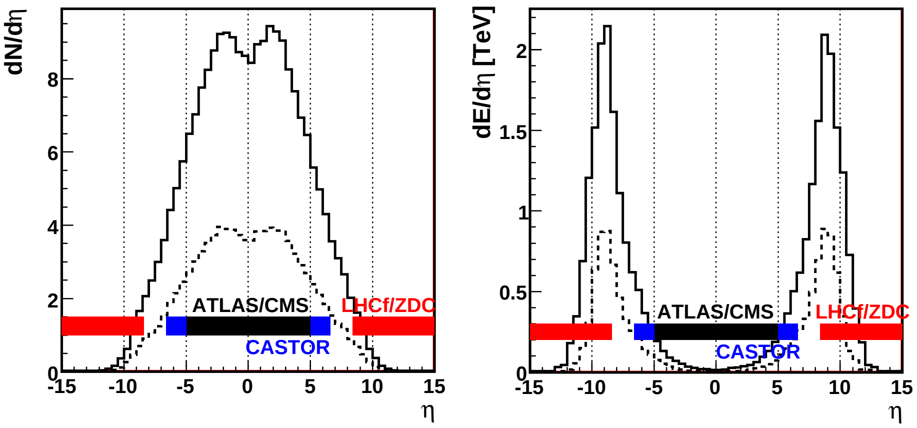

Fig. 1. Multiplicity (left) and energy flux (right) distributions generated with DPMJET3.05 at $\sqrt{s} = 14$ TeV p-p as a function of pseudorapidity. The solid and the dashed lines show for all particles and for neutral particles, respectively.

3. The LHCf experiment

The LHCf experiment is one of the forward experiments at LHC [3]. The aim is to measure the production cross section of energetic secondaries at very forward regain of LHC collisions and to provide critical data for improving hadronic interaction models used in air shower simulation. The LHCf has two independent detectors, so called Arm1 and Arm2. The detectors were installed +/- 140m from a LHC interaction point (IP1) where the ATLAS detector is installed. The detectors were inserted into experimental slots of beam separation chambers (Y shape chambers), which is a unique position to allow the detectors viewing zero degree of collisions. Because the charged particles are swept out due to the magnetic field of dipole magnets which are located between IP1 and the LHCf detectors, only neutral particles, photons and neutrons, are able to be detected by the LHCf detectors. Each detector has two sampling and imaging calorimeters that are consisted of 22 tungsten layers (2 radiation length), 16 plastic scintillators and 4 position sensitive layers of X-Y scintillation fiber (SciFi) hodoscopes (Arm1) and X-Y silicon strip detectors (Arm2). The transverse cross sections of calorimeters are 20×20 mm^2 and 40×40 mm^2 in Arm1 and 25×25 mm^2 and 32×32 mm^2 in Arm2. The center of smaller calorimeter in each detector was located near the zero degree of collisions during the operation. The energy resolution of detectors are about 5 % for photons and 40 % for neutrons. The position resolution is better than 200 μm for photons and a few mm for neutrons. More details of the detector performance were reported elsewhere [4–8].

3.1 Results at p-p collisions $\sqrt{s} = 7$ *TeV*

The LHCf experiment had a operation with p-p collisions at $\sqrt{s} = 7$ TeV from March until July 2010. The operation has been successfully done and have taken more than 200 M shower events in total. The energy spectrum of photons and the transverse momentum spectra of π^0s were already published [9, 10]. Figure 2 shows the transverse momentum spectrum of π^0s measured by LHCf (black dots) with predictions of several hadronic interaction models (colored lines) [11–15]. The best agreement with LHCf data is given by EPOS1.99 in the models.

The preliminary result of forward neutron spectrum was shown in the 33rd international cosmic-ray conference [16]. The reconstructed energy spectrum, which was spared with the detector resolution of 40%, seems to be harder than any model predictions at zero degree of collisions. A paper

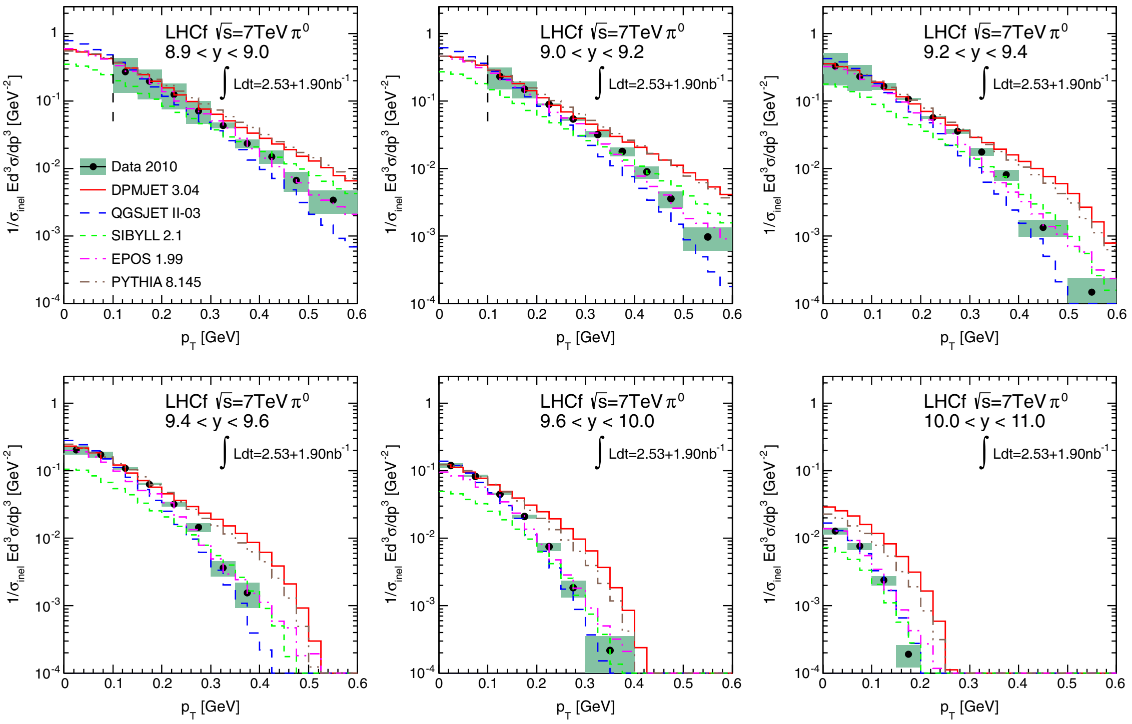

Fig. 2. Transverse momentum spectra of forward π^0s in each rapidity bin [10]. The black dots and the shaded area show LHCf data and the uncertainties. The color lines indicate the predictions by several hadron interaction models [11–15].

for LHCf neutron measurement at $\sqrt{s} = 7$ TeV p-p collisions including unfolded energy spectra is in preparation.

3.2 Results at p-Pb collisions $\sqrt{s_{NN}} = 5$ TeV

One of the LHCf detectors, Arm2, had been installed for an operation with p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the beginning of 2013. The transverse momentum spectra of forward π^0s has been published [17]. Comparing with the spectra derived for p-p collision at $\sqrt{s} = 5.02$ TeV from experimental data at $\sqrt{s} = 0.9$ TeV, 2.76 TeV and 7 TeV, the nuclear modification factor of 0.1-0.4 was found in the pseudo rapidity range of $-8.9 > y > -11.0$ and the transverse momentum range of $P_T < 0.6$ GeV/c. Such small factor is well reproduced with the hadronic interaction models of DPMJET3.03, EPOS1.99 and QGSJETII-03.

4. Summary

LHC provided unique data for verifying and improving hadronic interaction models that are used in the air shower simulation for UHECRs. The LHCf experiment had operations at $\sqrt{s} = 0.9$, 2.76 and 7 TeV p-p collisions and at $\sqrt{s_{NN}} = 5$ TeV p-Pb collisions. The measured spectra of forward photons and π^0s favor the EPOS1.99 model although these models are not able to reproduce the measured spectra of forward neutrons. The nuclear modification factor of forward π^0s at $\sqrt{s_{NN}} = 5$ TeV p-Pb collisions was measured as between 0.1 and 0.4, which was well reproduced with DPMJET3.03, EPOS1.99 and QGSJETII-03. While some of models can reproduce some of experimental data, no hadronic interaction models is able to reproduce all experiment data consistently yet.

The LHC will be restarted in 2015 with increasing the collisions energy of *p*-*p* to $\sqrt{s} = 13\,\mathrm{TeV}$. The LHC physics experiments including the LHCf will restart their data taking also. The LHCf detector are being upgraded for improving radiation hardness with replacing the plastic scintillators and the SciFi layers with GSO scintillator and GSO bar bundles [18, 19]. Data taken in 2015 will be so important for understanding discrepancies between data and model predictions and for testing energy scaling of key parameters for air shower developments.

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