



Energy spectrum of neutral pion at LHC proton-proton collisions measured by the LHCf experiment.

H. MENJO¹, O. ADRIANI^{2,3}, L. BONECHI², M. BONGI², G. CASTELLINI^{2,3}, R. D'ALESSANDRO^{2,3}, K. FUKATSU⁴, M. HAGUENAUER⁵, Y. ITOW^{1,4}, K. KASAHARA⁶, K. KAWADE⁴, D. MACINA⁷, T. MASE⁴, K. MASUDA⁴, G. MITSUKA⁴, Y. MURAKI⁴, M. NAKAI⁶, K. NODA⁸, P. PAPINI², A.-L. PERROT⁷, S. RICCIARINI^{2,9}, T. SAKO^{1,4}, Y. SHIMIZU⁶, K. SUZUKI⁴, T. SUZUKI⁶, K. TAKI⁴, T. TAMURA¹⁰, S. TORII⁶, A. TRICOMI^{8,11}, W. C. TURNER¹²

¹*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Japan*

²*INFN Section of Florence, Italy*

³*University of Florence, Italy*

⁴*Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan*

⁵*Ecole-Polytechnique, Palaiseau, France*

⁶*RISE, Waseda University, Japan*

⁷*CERN, Switzerland*

⁸*INFN Section of Catania, Italy*

⁹*Centro Siciliano di Fisica Nucleare e Struttura della Materia, Catania, Italy*

¹⁰*Kanagawa University, Japan*

¹¹*University of Catania, Italy*

¹²*LBNL, Berkeley, California, USA*

menjo@kmi.nagoya-u.ac.jp

DOI: 10.7529/ICRC2011/V03/1335

Abstract: The LHCf experiment is an LHC forward experiment dedicated to high energy cosmic-ray physics. The LHCf has completed the first phase of physics program, data taking at $\sqrt{s}=900$ GeV and 7 TeV proton-proton collisions, in July 2010. The LHCf detectors have capability of measurement of forward π^0 with more than 600 GeV by reconstruction from photon pairs measured by the two calorimeter towers. A data set taken by the Arm2 detector in 15 May 2010 was analyzed. In this paper, the measured π^0 energy spectrum is presented.

Keywords: LHCf, UHECRs, Hadron interaction model

1 Introduction

Recently the Pierre Auger Collaboration [1] and the Telescope Array Collaboration [2] are giving us exciting observational results of Ultra High Energy Cosmic Rays (UHECRs). They use the hybrid method of air shower arrays and fluorescence telescopes to observe air showers induced by UHECRs with huge effective areas and a high degree of accuracy. Although their efforts, the composition of UHECRs is not well understood yet because of uncertainty of the hadron interaction models used in air shower simulations.

The Large Hadron Collider (LHC), which is the largest and the most powerful hadron collider in the world, gives us an unique opportunity to study hadron interactions over 10^{16} eV. The design energy of proton-proton collisions is $\sqrt{s}=14$ TeV, which corresponds to 10^{17} eV in the laboratory frame. The LHC started operation with $\sqrt{s}=900$ GeV proton-proton collisions in November 2009 and now is in oper-

ation at $\sqrt{s}=7$ TeV. The LHCf experiment[3] is one of the LHC forward experiments. The aim is to provide a detailed calibration of hadron interaction models used in air shower simulation by measurement of energy and transverse momentum spectra of neutral particles (photons, neutrons and π^0 s) at the LHC forward region. The LHCf has already completed the physics operations for proton-proton collisions at $\sqrt{s} = 900$ GeV and 7 TeV in 2009 and 2010. Recently we have submitted the first physics paper about the forward photon energy spectra measured by the LHCf[4], which will be also presented in this conference[5]. In this paper, we will present the measured π^0 energy spectrum at $\sqrt{s}=7$ TeV proton-proton collisions.

2 The LHCf experiment

The LHCf experiment has two independent detectors (Arm1 and Arm2). Each detector has two sampling and imaging calorimeter towers with the transverse cross sec-

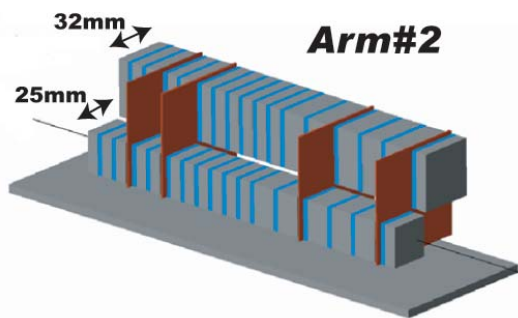


Figure 1: The schematic view of LHCf Arm2 detector.

tion 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 Arm2 detector. Each calorimeter tower is composed of 22 tungsten plates of 7 mm thickness (2 radiation length: r.l.), 16 plastic scintillators and 4 position sensitive layers of X-Y SciFi hodoscopes for Arm1 and X-Y silicon strip detectors for Arm2. The detector performances have been well studied by beam tests at CERN SPS [6, 7, 8, 9]. The energy resolution for photons is $< 5\%$ and the position resolution is $< 200 \mu\text{m}$ and $< 60 \mu\text{m}$ for Arm1 and Arm2, respectively. At $\pm 140\text{m}$ from an LHC interaction point (IP1), the beam pipe makes transition from a single big beam pipe facing IP1 to two separate beam pipes jointing to the LHC arc (Y-chamber). The small gap of 96 mm between the beam pipes allows us to install the LHCf detectors to view exact zero degree of LHC collisions. Because there are dipole magnets between IP1 and the Y-chamber, charged secondaries generated at proton-proton collisions are swept away and only neutral particles hit the LHCf detectors. The aperture is limited by the narrowest beam pipe between IP1 and the detector. The pseudo-rapidity coverage of the LHCf detectors is $|\eta| > 8.7$ and $|\eta| > 8.4$ with zero and $140 \mu\text{rad}$ beam crossing angles, respectively.

The LHCf had successfully taken data with proton-proton collisions at $\sqrt{s}=900$ GeV and $\sqrt{s}=7$ TeV in 2009 and 2010 [10]. The LHCf detectors have been removed from the LHC tunnel in July 2010 and they will be upgraded to improve radiation hardness [11, 12] for future operations at the LHC designed collision energy of $\sqrt{s}=14$ TeV in 2014 and at proton-ion and ion-ion collisions.

3 Capability of π^0 reconstruction

Most of π^0 s produced in proton-proton collisions decay into photon pairs (the branching ratio of 98.8%). The mass (M_{π^0}), the energy (E_{π^0}) and the momentum (\mathbf{P}_{π^0}) of π^0 can be reconstructed from measurements of the energies and incident positions of photon pairs detected one photon in each calorimeter of one detector, by assuming the decay

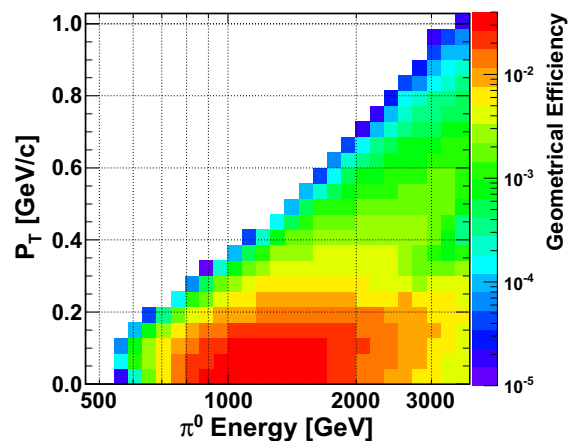


Figure 2: The geometrical efficiency of the Arm2 detector for π^0 measurements at the normal operation position.

vertex at IP1 as,

$$M_{\pi^0} = \sqrt{E_{g1} \cdot E_{g2} \cdot \theta^2} \quad (1)$$

$$E_{\pi^0} = E_{g1} + E_{g2} \quad (2)$$

$$\mathbf{P}_{\pi^0} = \mathbf{P}_{g1} + \mathbf{P}_{g2}, \quad (3)$$

where E_{g1} and E_{g2} are energies of the photon pair detected in one calorimeter and the other calorimeter, respectively. \mathbf{P}_{g1} and \mathbf{P}_{g2} are momenta of the photon pair and θ is the separation angle of the photon pair. Assuming π^0 decays at IP1, θ is given by $\theta = R/141.05\text{m}$, where R is the distance between the incident positions of the gamma-ray pair at the detector plane. The detectability of π^0 s strongly depends on the π^0 energy, the transverse momentum and the geometry of the calorimeters. The minimum separation angle is $\theta_{min} = 2M_{\pi^0}/E_{\pi^0}$ when $E_{g1} = E_{g2} = E_{\pi^0}/2$, while the maximum value of θ (θ_{det}) is determined by the maximum distance R_{max} in the detectable area, i.e., $\theta_{det} = 58\text{mm}/141.05\text{m}$ at the normal operation position of Arm2. It corresponds to the limitation of energy range of detectable π^0 to $E_{\pi^0} > 600\text{GeV}$. Figure 2 shows the geometrical efficiency of the Arm2 detector for π^0 measurements at the normal operation position as functions of the energy and the transverse momentum of π^0 . The geometrical efficiency is defined as the fraction of events which have a pair of gamma-rays one each hitting one of the calorimeters with respect to all produced π^0 s. As shown in Fig.2, the maximum value of detectable π^0 transverse momentum is given as a function of π^0 energy.

4 Analysis

Data used in this analysis has been taken by the Arm2 detector for 3 hours on 15 May 2010 during proton-proton collisions at $\sqrt{s}=7$ TeV with zero degree crossing angle. Because the luminosity of $(6.3 - 6.5) \times 10^{28} \text{cm}^{-2}\text{s}^{-2}$ in

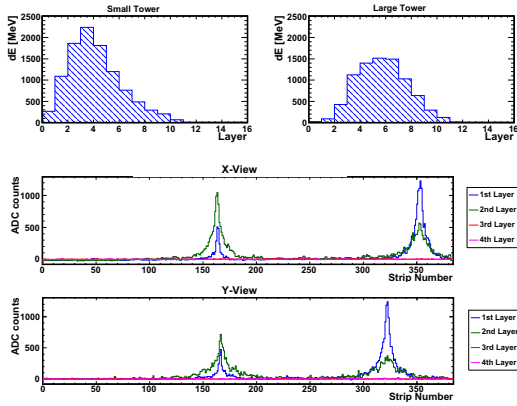


Figure 3: A π^0 candidate event measured by Arm2. The top figures show the longitudinal shower developments for two photons measured by the scintillator layers. The middle and bottom figures show the lateral distributions of X and Y measured by the silicon micro-strip detectors. Each silicon detector covers both the calorimeter towers.

this period [13] was not high, the pile-up of collisions per one bunch crossing was not effective on this analysis. In this period, the DAQ livetime of Arm2 was 67.0 % and the integral luminosity was 0.53 nb^{-1} .

Figure 3 shows a sample of π^0 candidate event. The longitudinal and the lateral shower developments were measured clearly by the 16 scintillator layers in each tower and the 4 silicon micro-strip detectors, respectively. The energy of an incident photon on a calorimeter tower was reconstructed from the total energy deposit between 2nd and 13th scintillator layers after some corrections for gain of PMT's, light yield and shower leakage effect. The shape of measured longitudinal shower development also helps us to identify the particle type (electromagnetic or hadronic). Because the longitudinal length of calorimeter towers is thick for electromagnetic interaction (44 r.l.) but thin for hadronic interaction (1.7λ), electromagnetic showers and hadronic showers have quite different shower shapes. To parameterize this, we defined a simple parameter, $L_{90\%}$, as the longitudinal distance measured from the entrance to a calorimeter to the position where 90 % of the total shower energy has been deposited. We set the selection criteria in $L_{90\%}$ to keep 90 % of efficiency for photons as a function of the reconstructed energy. Impact positions of photons were easily reconstructed from measured lateral distributions as you can see the two beautiful peaks in Fig.3 which correspond to two electromagnetic showers in both the calorimeter towers. We required impact position of 2mm inside from the edge of a calorimeter to avoid degradation of the energy resolution. The lateral distributions also help us to identify events with more than two incident particles in a calorimeter (multi-hit events). In this analysis, we cut the multi-hit events.

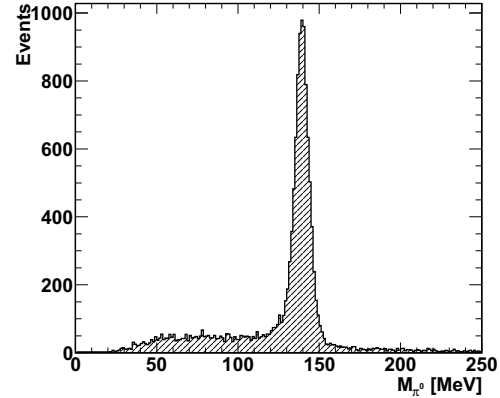


Figure 4: The reconstructed invariant mass distribution.

The invariant mass can be calculated in the events with photon pair each hitting on each calorimeter tower according to Eq.(1). In the event of Fig.3, the invariant mass was reconstructed as $M_{\pi^0}=139 \text{ MeV}$ from $E_{g1}=599 \text{ GeV}$, $E_{g2}=419 \text{ GeV}$ and $R=39.2 \text{ mm}$. Figure 4 shows the distribution of the reconstructed invariant mass. There is a very clear peak at $140.0 \pm 0.1 \text{ MeV}$, which is slightly shifted from the true π^0 invariant mass of 135.0 MeV . This 3.7 % difference can be explained by the systematic error of energy scale that we estimated as 3.5 %. However we did not apply the correction of energy scale for safety. We selected the events with the reconstructed mass between 130 MeV and 150 MeV. As a result, 8,429 events were selected as π^0 candidates.

5 Measured π^0 energy spectrum

Figure 5 shows the preliminary result of measured π^0 energy spectrum. The error bars indicate the statistical errors. We will add comparisons with simulation results calculated by several interaction models and will present them in a poster session of 32nd ICRC.

6 Summary

The LHCf experiment is an LHC forward experiment and the aim is to provide a detailed calibration of hadron interaction models which are used in air shower simulation. The LHCf had operations with $\sqrt{s}=900 \text{ GeV}$ and 7 TeV proton-proton collisions in 2009 and 2010 and they have been successfully completed in July 2010. Each LHCf detector has two calorimeter towers to measure π^0 s by reconstruction from photon pairs. The minimum energy of detectable π^0 s is about 600 GeV. We analyzed a data set taken by the Arm2 detector in 15 May 2010 at $\sqrt{s}=7 \text{ TeV}$ proton-proton collisions. After the cuts, multi-hit cut, PID cut and invariant mass cut, 8,429 events were selected as

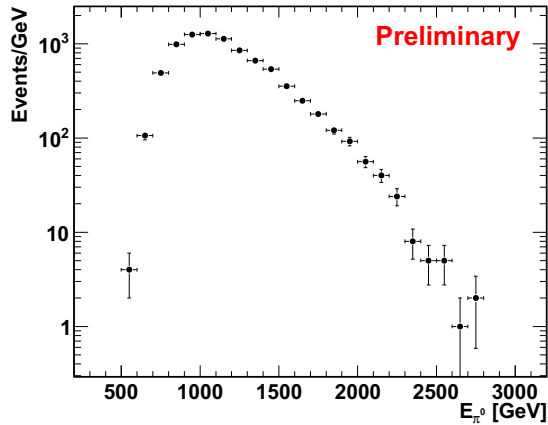


Figure 5: π^0 energy spectrum measured by the Arm2 detector.

π^0 candidate events. The measured π^0 energy spectrum was presented. We will compare it with the simulation results calculated by several hadron interaction models and will present it in a poster session of this conference.

References

- [1] Pierre Auger Collaboration : Proceedings of 31st ICRC, arXiv0906.2189 and arXiv0906.2319.
- [2] H. Sagawa, et al., Proceedings of ‘ the Symposium on the Recent Progress of Ultra-High Energy Cosmic-Ray Observation 2010, ’ Nagoya, AIP in press, 2011
- [3] LHCf Technical Design Report, CERN-LHCC-2006-004
- [4] O. Adriani, et al., arXiv:1104.5294, 2011
- [5] G. Mitsuka, et al., Proc. 32nd Int.Cosmic Ray Conf., Beijing, 2011
- [6] O. Adriani, et al., JINST, 2008, **3**, S0800
- [7] O. Adriani, et al., JINST, 2010, **5**, P01012
- [8] K. Noda, et al., Proc. 32nd Int.Cosmic Ray Conf., Beijing, 2011
- [9] T. Mase, et al., Proc. 32nd Int.Cosmic Ray Conf., Beijing, 2011
- [10] T. Sako, et al., Proc. 32nd Int.Cosmic Ray Conf., Beijing, 2011
- [11] K. Kawade, et al., Proc. 32nd Int.Cosmic Ray Conf., Beijing, 2011
- [12] T. Suzuki, et al., Proc. 32nd Int.Cosmic Ray Conf., Beijing, 2011
- [13] K. Taki, et al., Proc. 32nd Int.Cosmic Ray Conf., Beijing, 2011