PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International
Cosmic Ray Conference
12–23 July 2021

Status and Prospects of the LHCf and RHICf experiments

Hiroaki Menjo,[*] **on behalf of the LHCf and RHICf Collaboration**
(a complete list of authors can be found at the end of the proceedings)

Institute for Space-Earth Environmental Research, Nagoya University,
Nagoya, Aichi 464-8601, Japan
E-mail: menjo@isee.nagoya-u.ac.jp

Precise understanding of hadronic interactions at high energies is a key to improve mass composition measurements of very high energy cosmic-rays and to solve the muon excess issue observed in high energy cosmic-ray experiments using an air-shower technique. The LHCf and RHICf experiments measures the differential production cross sections of very forward neutral particle as photons, neutral pions and neutrons at LHC and RHIC, respectively. These data are critically important to test and tune hadronic interaction models used for air-shower simulations.

In this presentation, we introduce the recent results of both the experiments as well as our future operation plans. LHCf published an updated result of forward neutron measurement at pp, $\sqrt{s}$ = 13 TeV. From the observed neutron energy spectra, we also obtained the average inelasticity, which is one of the key parameters for air shower development, as 0.536 +0.031-0.037. In addition, several analysis are on-going; neutral pion measurement at pp, $\sqrt{s}$ = 13 TeV, central- forward correlation analysis with LHCf+ATLAS, photon measurement by RHICf. LHCf plans to have operations at pp and pO during the LHC-Run3 period. At pp collisions, new silicon readout system will be introduced to improve the read-out speed, and 10 times more statistics of the previous operation in 2015 will be obtained. Thanks to high statistics, rare particles such as η, K_s^0 and Λ will be addressed also. We also plan another operation at RHIC in 2024 with a new detector. The detector, a calorimeter composed of tungsten, Si pad and pixel layers, will have a much wider acceptance and higher sensitivity of K_s^0 measurement than the current detector.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

---

[*] Presenter

https://pos.sissa.it/

PoS(ICRC2021)301

1. Introduction

Precise understanding of hadronic interaction is an important key of very high energy cosmic-ray observations using extensive air shower technique. Mass composition of primary cosmic-rays is estimated from some shower parameters observed by ground detectors, for example, depth of maximum shower development X_{MAX}, muon production depth X^{μ}_{MAX}, and the number of muon on the ground N_{μ}. However the estimated average mass numbers from these parameters are not compatible with each other, and the results strongly depend on the choice of hadronic interaction model used in the air shower simulations. To improve or solve the situation, accelerator data at high energy hadronic collisions for testing and tuning hadronic interaction models are necessary.

The LHC forward (LHCf) [1] and RHIC forward (RHICf) [2] experiments were designed to measure energetic photons, π^0s and neutrons emitted in the very forward region of collisions, which play an important role in air shower developments, at LHC and RHIC. These accelerators provide collisions with a wide range of the center-of-mass collision energies $\sqrt{s}$ from 0.5 TeV up to 14 TeV, which correspond to 10^{14} - 10^{17} eV cosmic-ray interaction in the atmosphere. Both the experiments have obtained data in the last years, and several analysis results were published. In addition, they plan to have other operations near future. In this paper, we review recent results in Sec. 3 after briefly introducing the experimental setup in Sec. 2. In Sec. 4 we describe about the future operation plans, LHCf operations with pp and pO collisions and RHICf operation with a new detector, and then summarize in Sec. 5.

2. LHCf and RHICf experiments

The LHCf experiment consists of two independent detectors, called Arm1 and Arm2, installed ±140 m from the interaction point where the ATLAS detector installed as shown in Fig. 1. Each detector has two sampling and imaging calorimeter towers. Each tower is composed of tungsten plates, 16 GSO scintillator layers for sampling showers, and 4 position sensitive layers (GSO bar X-Y hodoscopes in Arm1 and X-Y silicon strip layers in Arm2) for imaging lateral shower distribution. The acceptances of the calorimeter towers are 20 mm × 20 mm and 40 mm × 40 mm in Arm1, and 25 mm × 25 mm and 32 mm × 32 mm in Arm2. The energy resolution for photos and neutrons are $< 5\%$ and 40%, respectively. More details of the detector performance can be found in [3, 4].

The LHCf detectors measures only neutral particles, photons, π^0, and neutrons, produced at the very forward region including zero degree of collisions because charged particles are swept out due to magnetic field of dipole magnets located between the interaction point and the detectors. The pseudorapidity coverage is $|\eta| > 8.4$.

The LHCf operations have performed with pp collisions at several collision energies of $\sqrt{s}$ = 0.9, 2.76, 7 and 13 TeV in the past. The luminosity during the operations was approximately 10^{29} or less, which is 5 orders of magnitude less than the LHC nominal luminosity at pp. Operations with pPb collisions were also performed in 2013 and 2016. In the cases, only the Arm2 detector was installed into the beam line and measured particles produced in the proton-remnant side.

The RHICf experiment was performed using the LHCf Arm1 detector and the data acquisition (DAQ) system. The RHICf detector was installed at 18 m West from the STAR interaction point

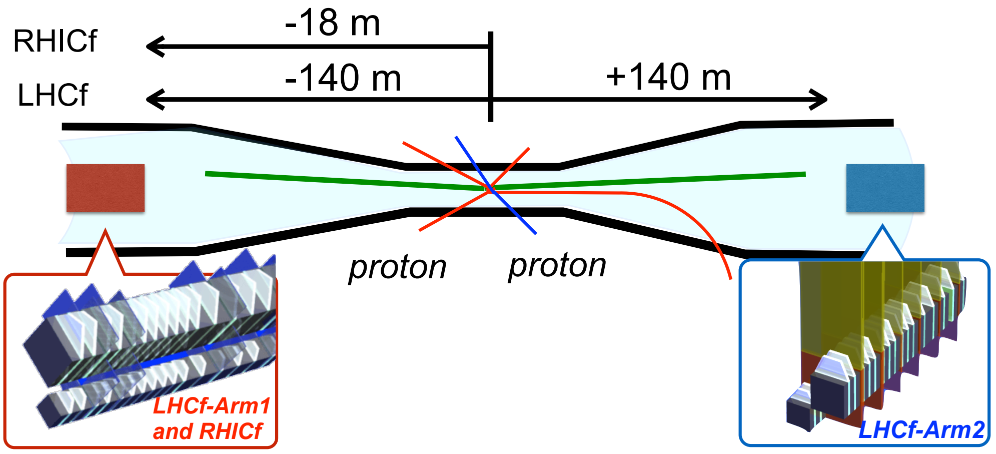

Figure 1: Location of the LHCf and RHICf detectors in the LHC/RHIC beam line. The LHCf detectors are located ±140 m far from the ATLAS interaction point. The RHICf (LHCf-Arm1) detector is installed at 18 m from the STAR interaction point. Only neutral particles generated at the interaction points can be reached because of magnetic field of dipole magnets located between the interaction point and the detector.

(Fig. 1). The operation was successfully completed with spin-polarized pp collisions at $\sqrt{s}$ = 510 GeV in June 2017. The luminosity in the RHICf operation was set to approximately 10^{31} cm^{2}s^{-1}, which is one order of magnitude lower than the nominal value of RHIC at pp collisions, to keep low collision pileup rate of 0.05 collision per bunch crossing.

3. Recent results and on-going analyses

Recently the neutron analysis at pp, $\sqrt{s}$ = 13 TeV was upgraded with extension of analysis region and the elasticity k_n (or inelasticity $1 - k_\mathrm{n}$) was measured [5]. The inelasticity is an energy fraction used for secondary particle productions, and it is one of the most important parameters for air shower development. The inelasticity can be calculated from energetic neutron energies E_n measured by the LHCf detector, which are leading particle in most cases, as $1 - k_\mathrm{n} = 1 - E_\mathrm{n}/E_\mathrm{beam}$ where E_beam is the beam energy of 6.5 TeV. Figure 2 shows the measured k_n distribution (left) and average inelasticity $< 1 - k_\mathrm{n} >$ (right). The obtained average inelasticity is $< 1 - k_\mathrm{n} > = 0.536^{+0.031}_{-0.037}$, and it shows good agreements with model predictions except PYTHIA.

Preliminary result of π^0 analysis at pp, $\sqrt{s}$ = 13 TeV was updated [6]. Using both the Arm1 and Arm2 data, a wide p_T region is covered. The other results, inclusive production cross sections of photon, π^0 and neutrons, published in the past can be found in [7–11]. In addition to them, joint analyses with ATLAS are on-going.

4. Future operations

LHCf plans to have two operations during LHC Run 3 (2022-2024) and RHICf will have an operation with a new detector in 2024. These future operations will provide not only increase of statistics, especially high energy π^0s and common events with ATLAS, but also measurement of η,

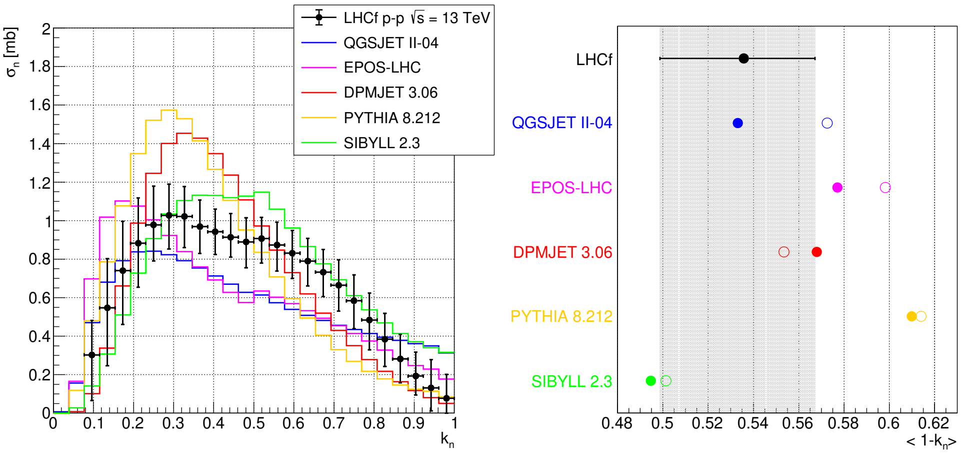

Figure 2: Inclusive production cross section as a function of elasticity k_n (left) and average inelasticity $< 1 - k_\mathrm{n} >$ (right) obtained from the neutron measurement at pp, $\sqrt{s} = 13$ TeV. Black markers represent the experimental data, and solid lines (left) and filled circle (right) refer to model predictions at the generator level, obtained using only the events where the leading particle is a neutron. Open circle in the right figure show the value of $< 1 - k_\mathrm{n} >$ obtained from any leading particles.

K_s^0 and Λ. K_s^0 is measured by detecting four photos from a K_s^0 decay; $K_s^0 \to 2\pi^0 \to 4\gamma$. The kaon measurement is also important for improving predictions of high energy atmospheric neutrino flux.

4.1 LHCf operation at pp, $\sqrt{s}$ = 14 TeV in 2022

The operation is scheduled for 2 days in the beginning of 2022. The collisions energy is requested to be $\sqrt{s} = 14$. The energy might be slightly lower than this value. The luminosity during the run is requested to be about 10^{30} cm^{-2}s^{-1}, which will be factor 10 higher than that of the last operation, to record factor 10 larger statistics of high energy π^0 events and several hundreds of K_s^0 events. In this operation, a joint operation with ATLAS ZDC detectors will be performed. The ZDC hadron module will be installed behind each LHCf detector, and it can measure the leaked-out particles of hadronic showers from the LHCf detector. Combining the data of two detectors the energy resolution for neutrons will be improved from 40% to 20%. This good resolution is important to select events of one-pion-exchange process, as discussed in [12], as well as improvement of the inclusive neutron measurements. The ATLAS roman pot detectors, ALFA and AFP, will join the operation also.

The preparation for the operation is on-going. To obtain the high statistics data in the limited beam time, the readout system of Arm2 silicon detector is upgraded. In the old system, the silicon data sent from the tunnel is stored in a VME board and the readout time of one silicon event with 3k channels and 1.3 k byte is 0.8 msec via the VME bus, which mainly limited the total DAQ rate. In the new system, the data are directly read from a frontend computer via TCP/IP connections (Fig. 3), and the readout time will be dramatically reduced to 0.1 msec. Considering the readout of other devices the maximum DAQ rate will br improved from 800 Hz to 2 kHz. This upgrade also solves other issues like instability of optical connections due to radiation damage and aging of the

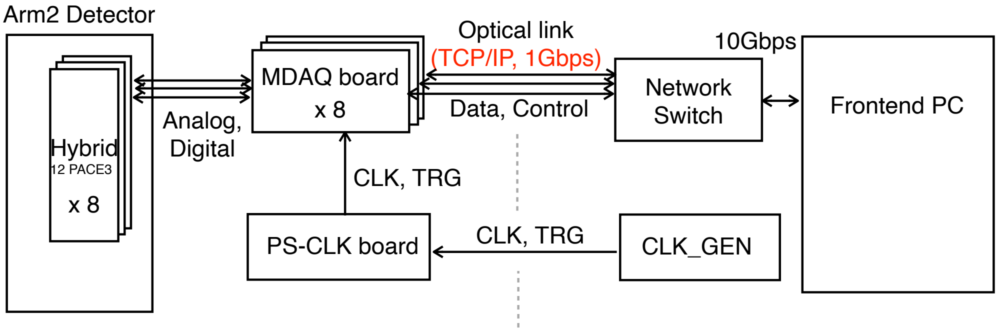

Figure 3: Schematic view of the new silicon readout system. The MDAQ boards and PS-CLK board are newly designed, which work for digitization and data transfer, and for clock and trigger distribution to the MDAQ boards, respectively. The CLK-GEN transfers clock and trigger signals from the central DAQ system and it is implemented on a FPGA board.

Figure 4: A photo of new MDAQ board. Analog signals transferred from PACE 3 chips are digitized in this board located near the Arm2 detector, and the data is sent to a counting room via 1 Gbps optical link with TCP/IP protocol.

system. Figure 4 shows a photo of new MDAQ board. We are now doing final tests of produced boards.

4.2 LHCf operation with pO collisions

Proton and Oxygen nucleus collisions are the best and ideal condition to study the hadronic interaction by high-energy cosmic-rays happened in the atmosphere. As a first approximation, a high energy proton-ion or ion-ion collisions is described as a supper-position of well studied pp collisions at LHC. It it not enough to describe the energy spectra of particle productions precisely, and the forward particle production is suppressed due to shadowing of nucleons located behind and interactions of produced particles in the nucleus matter, so called nuclear effect. LHC have provided pPb collisions during Run 1 and 2, and LHCf measured the nuclear effect at pPb collisions for forward π^0 production [10]. However, Pb is too heavy to estimate the nuclear effect and there was a large background of photons and neutrons in the forward region due to interactions between a proton and electromagnetic field of a Pb nucleus.

LHCf have continuously requested to have proton-ion collisions at LHC since several years ago. While a few technical discussions about oxygen beam were done in workshops, these was little progress to realize the pO collisions. We strongly requested them again to LHC committee because the beam line configuration will be changed to improve the radiation protection in LHC high luminosity phase, and the LHCf detectors cannot be inserted to the beam line after that. The LHCf operation with pO collisions is also strongly supported by people of the cosmic-ray and hadron communities. The technical and physics studies and discussions between LHC machine and experimental people were accelerated in last some months, and currently a short special run with pO and OO collisions becomes a new physics program during Run 3.

The schedule and operation condition is still under discussion. Currently the special run is scheduled for 7 days in 2023 or 2024 including the beam setup time. The beam energy is requested to 7 TeV/Z for the pO run, which corresponds to the center-of-mass collisions energy per nucleon of $\sqrt{s}$ = 10 TeV. The expected performances of LHCf at pO collisions can be found in [13].

4.3 RHICf II in 2024

The RHICf experiment also plans to have a next operation, called RHICf II. The main motivation of the operation is to increase statistics of high-X_F π^0 events and measurement of strange hadrons K_s^0 and Λ at pp collisions. We are also requesting an operation with proton and light collisions.

For the RHICf II operation a new detector will be used instead of the LHCf-Arm1 detector used in the last operation, and it is being developed using ALICE FoCal-EM technology [14]. The new detector consists of tungsten layers, silicon pad (one pad size of 1 cm^2 × 1 cm^2) and silicon pixel (one pixel size of 30 μmm^2 × 30 μmm^2) detectors as shown in Fig. fig:rhicf2, which are for shower absorbers, longitudinal shower sampling, and precise shower core determination. The acceptance of the detector is 8 cm$^\mathrm{W}$ × 18 cm$^\mathrm{H}$, which is much larger than one of the old RHICf detector. The fine segmentation of each layer and wide acceptance of the detector allow us to precisely measure energies and impact positions of multi-particles in one event, for example four photons from a K_s^0 decay, and they are essential to improve the sensitivity for K_s^0 and Λ as well as for π^0. Figure 6 shows the geometrical acceptance of the new detector for π^0, K_s^0 and Λ. The acceptance values are much higher than those of the old detector, and the energy threshold of detection is also improved. For example, the detection threshold of π^0s is improved from 60 GeV to 20 GeV.

The RHICf II operation is requested for RHIC Run in 2024. Thanks to good radiation hardness and fast DAQ system, a dedicated beam time with a special condition like low luminosity for the RHICf II operation is not requested, and the operation will be performed as a parasitic operation to other RHICf physics programs. The operation side, installation of STAR or sPHENIX interaction points, is under discussion. Currently an operation with pp collisions at $\sqrt{s}$ = 200 GeV is scheduled for Run 2024, and possibly pA collisions will be done also.

5. Summary

The LHCf and RHICf experiment measured forward neutral particles at LHC and RHIC to study hadronic interaction for cosmic-ray air showers. Inelasticity at pp, $\sqrt{s}$ = 13 TeV was measured using forward neutron data. Some other analyses, for example π^0 measurement at pp, $\sqrt{s}$ = 13 TeV

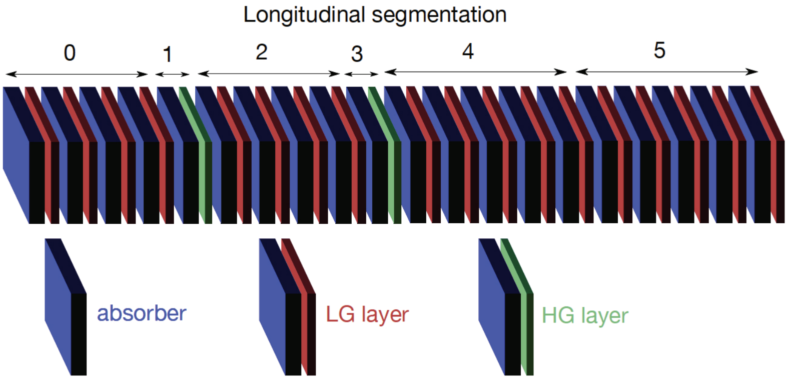

Figure 5: Schematic of the FoCal-E electromagnetic calorimeter. The blue absorber is tungsten, the red low granularity silicon layers of silicon pad with $1cm^2$ segmentation are used for energy measurement while the green high granularity layers of silicon pixel detectors give precise position information.

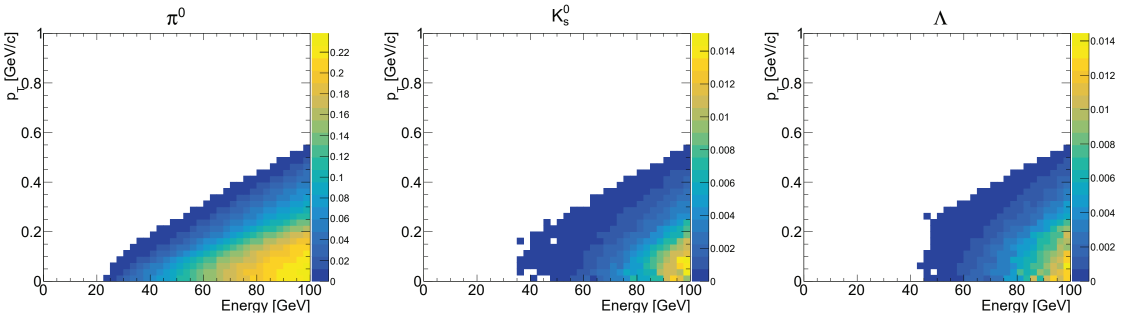

Figure 6: Expected geometrical acceptance of the RHICf II detector for π^0, K_s^0 and Λ as functions of the energy and transverse momentum. The color shows the geometrical acceptance defined as a fraction of the detected events in the generated events of MC simulation.

and joint analyses with ATLAS, are on-going. Both the experiments plan to have next operations, pp in 2022 and pO + OO in 2023 or 2024 by LHCf, and pp (+ pA) in 2024 by RHICf. These focus more on studying detail physics processes, strange hadron measurements, and pA collisions with higher statistics data and better performance by a joint operation with ATLAS ZDC and roman pots, new detector in RHICf.

References

[1] L. Collaboration, *LHCf experiment: Technical Design Report*. Geneva: CERN, 2006.

[2] Y. Itow *et al.*, "Letter of intent; Precise measurements of very forward particle production at RHIC," 1 2014.

[3] Y. Makino *et al.*, "Performance study for the photon measurements of the upgraded LHCf calorimeters with Gd_2SiO_5 (GSO) scintillators," *Journal of Instrumentation*, vol. 12, p. P03023, Mar. 2017.

[4] K. Kawade *et al.*, "The performance of the LHCf detector for hadronic showers," *Journal of Instrumentation*, vol. 9, p. P03016, Mar. 2014.

[5] O. Adriani *et al.*, "Measurement of energy flow, cross section and average inelasticity of forward neutrons generated in $\sqrt{\text{s}}$ = 13TeV proton-proton collisions with the LHCf Arm2 detector," *JHEP*, vol. 07, p. 016, 2020.

[6] A. Tiberio *et al.*, "Very-forward π^0 production cross section in proton-proton collisions at $\sqrt{s}$ = 13 TeV measured with the LHCf experiment," *Proc. of ICRC 2021*.

[7] O. Adriani *et al.*, "Measurement of zero degree inclusive photon energy spectra for $\sqrt{s}$ = 900GeV proton-proton collisions at LHC," *Physics Letters B*, vol. 715, pp. 298–303, Sept. 2012.

[8] O. Adriani *et al.*, "Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 7 TeV proton-proton collisions at LHC," *Physics Letters B*, vol. 703, pp. 128–134, Sept. 2011.

[9] O. Adriani *et al.*, "Measurement of forward photon production cross-section in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the LHCf detector," *Phys. Lett.*, vol. B780, pp. 233–239, 2018.

[10] O. Adriani *et al.*, "Measurements of longitudinal and transverse momentum distributions for neutral pions in the forward-rapidity region with the LHCf detector," *PRD*, vol. 94, p. 032007, Aug. 2016.

[11] O. Adriani *et al.*, "Measurement of very forward neutron energy spectra for 7 TeV proton-proton collisions at the Large Hadron Collider," *Physics Letters B*, vol. 750, pp. 360–366, Nov. 2015.

[12] K. Ohashi *et al.*, "A simulation study for one-pion exchange contribution on very forward neutron productions in ATLAS-LHCf common events," *Proc. of ICRC 2021*.

[13] E. Berti *et al.*, "LHCf plan for proton-oxygen collisions at LHC," *Proc. of ICRC 2021*.

[14] ALICE Collaboration, "Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment," *CERN-LHCC-2020-009, LHCC-I-036*, Jun 2020.

Full Authors List:

LHCf Collaboration

O. Adriani[a,b], E. Berti[a], L. Bonechi[a], M. Bongi[a,b], R. D'Alessandro[a,b], G. Castellini[c], M. Haguenauer[d], Y. Itow[ef], K. Kasahara[g], M. Kondo[e], Y. Matsubara[e], H. Menjo[e], Y. Muraki[e], K. Ohashi[e], P. Papini[a], S. Ricciarini[a,c], T. Sako[h], N. Sakurai[i], K. Sato[e], Y. Shimizu[j], T. Tamura[k], A. Tiberio[a,b], S. Torii[k], A. Tricomi[l,m,n], W. C. Turner[o], M. Ueno[e], K. Yoshida[g]

[a] INFN Section of Florence - Florence, Italy
[b] University of Florence - Florence, Italy
[c] IFAC-CNR - Florence, Italy
[d] Ecole-Polytechnique - Palaiseau, France
[e] Institute for Space-Earth Environmental Research, Nagoya University - Nagoya, Japan
[f] Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University - Nagoya, Japan
[g] Faculty of System Engineering, Shibaura Institute of Technology - Saitama, Japan
[h] Institute for Cosmic Ray Research, University of Tokyo - Kashiwa, Japan
[i] Tokushima University - Tokushima, Japan
[j] Kanagawa University - Kanagawa, Japan
[k] RISE, Waseda University - Shinjuku, Tokyo, Japan
[l] INFN Section of Catania - Catania, Italy
[m] University of Catania - Catania, Italy
[n] CSFNSM - Catania, Italy
[o] LBNL - Berkeley, California, USA

RHICf Collaboration

O. Adriani[a,b], E. Berti[a], L. Bonechi[b], R. D'Alessandro, Y. Goto[c,d], B. Hong[e], Y. Itow[f,g], K. Kasahara[h], M. H. Kim[c,d], H. Menjo[f], I. Nakagawa[c,d], T. Sako[i], N. Sakurai[j], K. Sato[f], R. Seidl[c,d], K. Tanida[k], S. Torii[l], A. Tricomi[m,n,o]
[a] University of Florence - Florence, Italy
[b] INFN Section of Florence - Florence, Italy
[c] RIKEN Nishina Center for Accelerator-Based Science - Wako, Japan
[d] RIKEN BNL Research Center, Brookhaven National Laboratory - Upton, USA
[e] Korea University - Seoul, Korea
[f] Institute for Space-Earth Environmental Research, Nagoya University - Nagoya, Japan
[g] Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University - Nagoya, Japan
[h] Shibaura Institue of Technology - Saitama, Japan
[i] Institute for Cosmic Ray Research, University of Tokyo - Kashiwa, Japan
[j] Tokushima University - Tokushima, Japan
[k] Advanced Science Research Center, Japan Atomic Energy Agency - Tokai-mura, Japan
[l] RISE, Waseda University - Shinjuku, Tokyo, Japan
[m] University of Catania - Catania, Italy
[n] INFN Section of Catania - Catania, Italy
[o] CSFNSM - Catania, Italy