# Simulation Study for the performance of the LHCf experiment

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***Abstract*. The LHCf experiment aims to measure the neutral particles emitted in the forward region of LHC collisions. The two sampling and imaging calorimeters of a LHCf detector allow to measure energy and transverse momentum of $\pi^0$'s above 600GeV. We studied the performance of $\pi^0$ measurement with the Arm#1 detector by using a full MC simulation. $1.5 \times 10^4$ $\pi^0$ events were obtained from $2.3 \times 10^7$ p-p collisions at $\sqrt{s} = 14$TeV generated with DPMJET-3.03 for two detector positions. The reconstructed $\pi^0$ energy spectrum well reproduced the original production spectrum in the forward region.**

***Keywords*: HECRs, LHC, hadron interaction model**

## I. Introduction

The origin of high energy cosmic rays has been one of the most important themes in cosmic ray physics. Extensive air shower experiments have contributed to understand Ultra High Energy Cosmic Rays (UHECRs) physics. However the results are in some cases not fully in agreement because hadron interactions of high energy cosmic rays above $10^{15}$eV with atmospheric nuclei have not been fully understood. The energy spectrum of secondary $\pi^0$'s emitted in the forward region of the hadron interaction, which induce electromagnetic cascades in air showers, is one of the important parameters for air shower development. Given the same total cross section and inelasticity, a model with harder spectrum for secondary pions induces deeper penetration of air showers than other models [1]. The $\pi^0$ spectrum in the forward region at the most energetic hadron collision has been provided by the UA7 experiment with the S$p\bar{p}$S collider at the CERN for $2 \times 10^{14}$eV of the collision energy in "the laboratory frame" [2]. The Large Hadron Collider (LHC) will have proton-proton collisions at $\sqrt{s}$ =14TeV and push the laboratory equivalent collision energy up to $10^{17}$eV.

The LHCf experiment is one of the LHC physics experiments, and aims to measure energy and transverse momentum spectra of neutral particles, gamma-rays, $\pi^0$'s and neutrons, emitted in the forward region ($\eta >$ 8.4). The physics and detector performances of the LHCf experiment for gamma-ray and neutron measurements have been presented elsewhere [1], [3], [4], [5], [6], [7], [8], [9]. In this paper, we present the performance of $\pi^0$ measurements with one of the LHCf detectors (Arm#1) studied with a full MC simulation. More detail of the performance of $\pi^0$ measurements is found in [10].

## II. The LHCf Experiment

The LHCf experiment has two independent detectors (Arm#1 and Arm#2) with similar design but with slightly different configuration for background rejection and redundancy. The Arm#1 detector has two sampling and imaging calorimeters with the transverse cross section of $20 \times 20$mm and $40 \times 40$mm. Figure 1 shows the schematic view of the Arm#1 detector. Each calorimeter is composed of 22 tungsten plates of 7mm thickness (2r.l.), 16 plastic scintillators and 4 X-Y pairs of SciFi hodoscopes. The plastic scintillators are inserted by 2 or 4 r.l. step for shower sampling. The SciFi layers are inserted at 6, 10, 30 and 42 r.l. to measure the shower position and identify the multiple showers in one calorimeter. The total thickness is 44 r.l. and 1.7 interaction lengths.

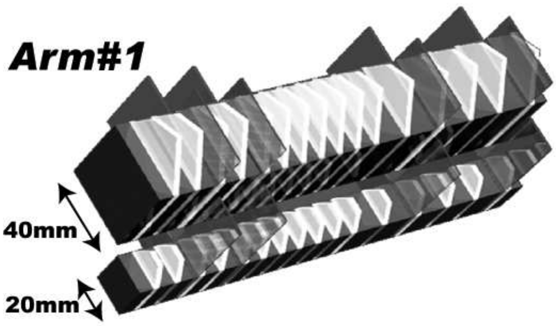


Fig. 1. Schematic view of the Arm#1 detector.

The calorimeters together with PMTs, MAPMTs and front-end circuits for the SciFi layers are packed in a aluminum box of $92\mathrm{mm}^w \times 280\mathrm{mm}^l \times 620\mathrm{mm}^h$.

The LHCf detectors have been inserted in each slot of TANs (zero degree neutral absorbers) which are installed at $\pm$140m from a LHC interaction point (IP1) and supported by manipulators mounted on the surface of the TANs. The manipulators allow the detectors to move vertically with 120mm stroke. During operations, the center of the smaller calorimeter will be normally set on the beam plane ("normal" position) but also on some other positions, for example, 10mm lower position than the "normal" position ("low" position), to cover the wide aperture. Since charged particles produced at p-p collisions are swept by magnetic field of dipole magnets installed at 60-80m from IP1, the LHCf detectors can measure only neutral particles. The pseudorapidity coverage at the location is $\eta >$8.7 and $\eta >$8.4 with zero and 140$\mu$rad beam crossing angles, respectively.

The performance of the LHCf detectors for particles below a few hundreds GeV were tested at CERN SPS by using electron, proton and muon beams [4], [3], [5], and has been well understood by using a Monte Carlo (MC) simulation [1], [4]. The performance for particles above a few hundreds GeV has been studied by using the MC simulation. The energy resolution is expected to be about 3% and 30% for 1TeV gamma-rays and hadrons, respectively. The position resolution for gamma-ray showers is expected to be better than 0.2mm.

## III. $\pi^0$ MEASUREMENTS WITH THE ARM#1 DETECTOR

Most of $\pi^0$'s produced at p-p collisions decay into gamma-ray pairs. The mass ($M_{\pi^0}$), the energy ($E_{\pi^0}$) and the momentum ($\mathbf{P}_{\pi^0}$) of $\pi^0$ can be reconstructed from energies and incident positions of a gamma-ray pair measured with each calorimeter by assuming the decay 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 gamma-ray pair detected in the 20mm and the 40mm calorimeter, respectively. $\mathbf{P_{g1}}$ and $\mathbf{P_{g2}}$ are momenta of the gamma-ray pair, $\theta$ is the opening angle of the gamma-ray pair. Assuming $\pi^0$ decays at IP1, $\theta$ is given by $\theta = R/140\mathrm{m}$, where $R$ is the distance between the incident positions of the gamma-ray pair at the detector plane. Figure 2 shows the geometrical acceptance of the Arm#1 detector for the $\pi^0$ measurements at the "normal" and the "low" position as functions of energy and transverse momentum of $\pi^0$. As shown in Fig.2, $\pi^0$'s with energy higher than 600GeV are detectable and the maximum value of detectable $\pi^0$ transverse momentum ($P_T^{max}$) depends on $\pi^0$ energy.

Backgrounds in $\pi^0$ measurements are mainly caused by interactions of secondary particles produced at p-p collisions with beam pipes and interactions of beam particles with residual gas in beam pipes. Since an event cut with the reconstructed mass is greatly helpful for the background rejection, the amount of the two backgrounds is expected to be less than 0.1% of the $\pi^0$ events and negligible [10].

## IV. MC SIMULATION

A full MC simulation, which treats overall physics processes of p-p collisions, transportation of secondary particles from IP1 to the TAN, and the LHCf detector response, has been implemented by EPICS [11]. In order to study the performance of the Arm#1 detector for $\pi^0$ measurement, $1.04 \times 10^7$ and $1.17 \times 10^7$ events of inelastic p-p collisions at $\sqrt{s}$ =14TeV were generated by the MC simulation with zero beam crossing angle and the two detector positions of "normal" and "low", respectively. Each statistics corresponds to approximately 20 minutes operation of the LHCf experiment at $10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity. Independent event sets with 4 times larger statistics were also generated to determine the correction functions shown in the following analysis section. For the generation of p-p collisions in the simulation, the hadron interaction model of DPMJET-3.03 [12] was used.

## V. $\pi^0$ MASS RECONSTRUCTION AND ENERGY SPECTRUM

In order to select events where each calorimeter has one gamma-ray incidence, the following event selections were carried out. *Hardware Trigger Cut:* The hardware trigger signals are generated by a coincidence of hit signals from any adjoining 3 scintillator layers in any one of the two calorimeters. The hit signals of each scintillator layer are formed by discriminators with the discrimination level equivalent to 150MeV energy loss. *Multi-hit Event Cut:* Approximately 10% of all the triggered events have multiple showers in one calorimeter ("multi hit events"). Approximately 93% of "multi gamma-rays hit events" were identified by using the lateral profiles measured by the first and the second SciFi layer and rejected. *Particle Identification(PID) Cut:* The expected flux of hadrons at the Arm#1 detector is comparable to

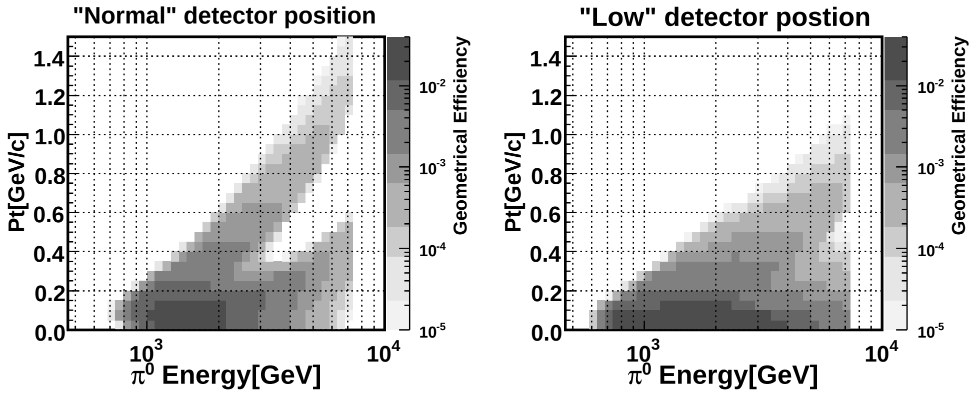


Fig. 2. Geometrical acceptance of the Arm#1 detector for $\pi^0$ measurements at the "normal" (left) and the "low" (right) detector position as functions of $\pi^0$ energy and transverse momentum. Only gamma-rays with energy above 100GeV and incident on 2mm inside from the calorimeter edge are taken into account.

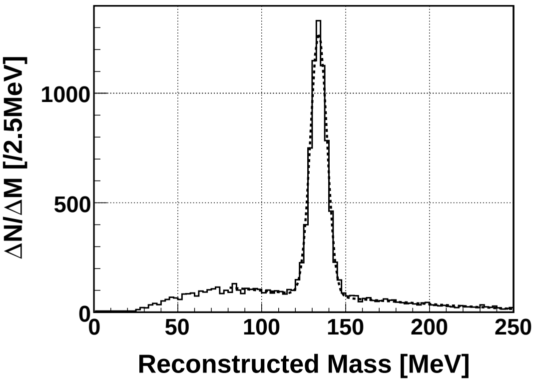


Fig. 3. The reconstructed mass distribution calculated with $1.04\times10^7$ events of p-p collisions for zero beam crossing angle and at the "normal" detector position. The dashed line shows the fitting result with a function combining Gaussian and 2nd-order polynomial function. The center of the Gaussian is 134MeV, while the sigma of Gaussian is 4.9MeV.

the expected flux of gamma-rays. More than 98% of the hadron events were identified by using the longitudinal profile measured by the plastic scintillator layers and rejected. *Reconstructed Mass Cut:* The distribution of the reconstructed mass from the event set for the "normal" detector position with equation (1) is shown in Fig.3. There is a clear peak at 134MeV with spread of 5MeV width on the broad distribution caused by wrong combinations of gamma-rays which accidentally hit the calorimeters simultaneously. In order to discriminate pure $\pi^0$ events, we required the reconstructed mass between 125MeV and 145MeV.

The numbers of events at each stage of the event selection are summarized in Table I. As a result, 6,231 and 10,602 events were selected from about $10^7$ p-p collision events for the "normal" and the "low" detector position, respectively. Figure 4 shows the reconstructed $\pi^0$ energy spectrum for the events selected from the event set for the "normal" detector position. The selected events include background events caused by wrong combinations of gamma-rays (combinatorial backgrounds) as shown in Fig.3. The amount of the background events is about 10% of the total selected events and is estimated by fitting the reconstructed mass distribution. The shape of the energy spectrum for the background events can be also estimated by using the distributions reconstructed from two gamma-rays picked up from two different events.

TABLE I
SUMMARY OF NUMBER OF EVENTS.

| Detector position | "Normal" | "Low" |
|---|---|---|
| Total event | $1.04 \times 10^7$ | $1.17 \times 10^7$ |
| Triggered event | $1.41 \times 10^6$ | $2.03 \times 10^6$ |
| Before mass cut | 12,328 | 23,817 |
| After mass cut | 6,231 | 10,602 |
| Estimated background | 600±25 | 1,277±36 |

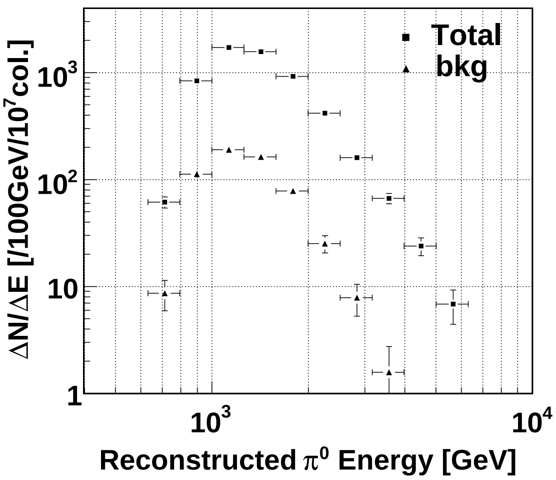


Fig. 4. The expected $\pi^0$ energy spectrum at the "normal" detector position. The squares show reconstructed energy spectra from all selected events with statistical errors. The triangles show estimated background spectra due to wrong combinations of gamma-rays.

## VI. Reconstruction of $\pi^0$ production spectrum

In order to reconstruct the production spectrum, we consider the following corrections;

- geometrical acceptance,
- $\pi^0$ survival efficiency in the event selection,
- multi hit contamination to the $\pi^0$ sample,
- subtraction of the combinatorial background, and
- branching ratio $\pi^0 \to 2\gamma$ (98.8%).

The corrections of the geometrical acceptance and the survival efficiency in the event selection have been carried out in the 2-dimensional plane of the energy and the transverse momentum of $\pi^0$. The correction functions for the $\pi^0$ survival efficiency and the multi hit contamination were made from independent event sets with 4 times larger statistics. The correction function for the multi-hit contamination depends on the multiplicity of the hadron interaction model in the forward region. The uncertainty of the multiplicity in the forward region causes a systematic error.

Figure 5 shows the reconstructed $\pi^0$ production spectrum by combining both of the event sets for the "normal" and the "low" detector position with statistical and systematic errors. In Fig.5, the dashed and solid lines show $\pi^0$ production spectra given by the DPMJET3.03 model with and without the $P_T^{max}(E_{\pi^0})$ cut, respectively. Except the data for the lowest energy bin, where the correction of the geometrical acceptance is sensitive to the reconstructed $\pi^0$ energy, the reconstructed spectrum is in good agreement with the production spectrum with the $P_T^{max}(E_{\pi^0})$ cut. The $\chi^2$ value between these spectra is 12.9 with D.O.F. of 9 (the $\chi^2$ probability is 0.187) when only statistical errors are taken into account. It indicates that the LHCf experiment can reproduce the production spectrum of $\pi^0$'s in the forward region. The systematic errors of the reconstructed spectrum are mainly caused by the uncertainties of the energy scale of the calorimeters and the correction function for the multi hit contamination. As shown in Fig.5, the systematic error due to the energy scale error is dominant in all the errors for the reconstructed spectrum. In this calculation, the energy scale error was assumed to be conservatively $\pm 5\%$. However, the uncertainty of the energy scale can be improved with a calibration by using the peak position in the $\pi^0$ mass distribution reconstructed from data itself.

## VII. Summary

We have studied the performance of one of the LHCf detectors installed at 140m from IP1 for the $\pi^0$ measurement by using a full MC simulation. The two sampling and imaging calorimeters of each LHCf detector allow to reconstruct invariant mass, energy and transverse momentum of $\pi^0$'s above 600GeV from gamma-ray pairs measured by the calorimeters. Since the reconstructed mass helps to reject background events caused by beam-gas and secondaries-beam pipes interactions, the amount of the backgrounds is expected to be $\sim$0.1% of $\pi^0$ events. In order to verify the performances for the $\pi^0$ measurement, MC simulations for $1.04 \times 10^7$ and $1.17 \times 10^7$ p-p collisions, each corresponding to an about 20 minutes operation during the LHC beam commissioning with 43 bunches and $10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ of luminosity, were carried out with the DPMJET3.03 model for the "normal" and the "low" detector position, respectively. With the event selections of the simulated hardware trigger, the multi-hit event rejection, the PID and the reconstructed mass cut, 6,231 and 10,602 events were selected including backgrounds of about 10% due to wrong combinations of gamma-rays. The reconstructed $\pi^0$ energy spectrum well reproduced the original production spectrum. The LHCf experiment will hence provide a critical calibration point at $10^{17}$eV for the hadron interaction models and will help a better understanding of ultra high energy cosmic rays through the improvement of the air shower simulation.

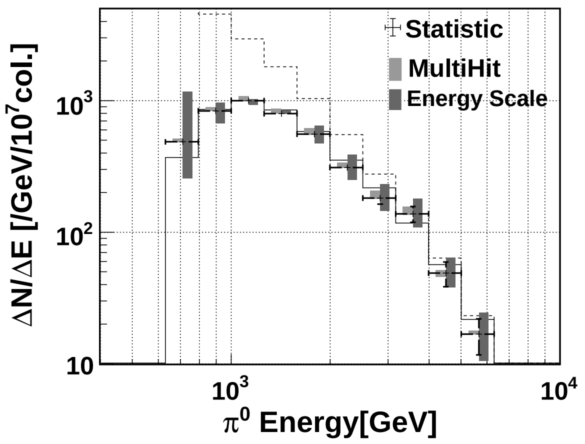


Fig. 5. The reconstructed $\pi^0$ production spectrum with statistic and systematic errors. The crosses show the reconstructed $\pi^0$ production spectrum with statistic error. The bray and the dark gray bars show the systematic errors due to the uncertainties of the energy scale and the correction function for the multi hit contamination, respectively. The solid and the dashed lines shows $\pi^0$ production spectra provided by the DPMJET3.03 model with and without the $P_T^{max}(E_{\pi^0})$ cut, respectively.

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