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Study of the forward emission of neutral particles in proton-proton interactions with the LHCf experiment

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Summary. — The most recent results published by different experiments about the atmospheric cosmic-ray showers at very high energy are in disagreement and point to different scenarios, both for the composition of cosmic rays beyond the "knee" region and for the possible excess of particles with energy beyond the GZK cut-off. An important contribution to the systematic uncertainty in the reconstruction of the type and kinematics of the primary particles by the analysis of cosmic-ray showers is due to the poor knowledge of the hadronic interactions at extreme energies. The LHCf experiment, briefly described in this paper, is an important tool to calibrate the hadronic interaction models at high energy through a dedicated study at the LHC accelerator.

PACS 13.75.Cs – Nucleon-nucleon interactions.
PACS 13.85.Ni – Inclusive production with identified hadrons.
PACS 13.85.Qk – Inclusive production with identified leptons, photons, or other nonhadronic particles.

1. – Physics and goals of LHCf

Important questions about the mechanisms which govern the Universe have been left open by the last generation of cosmic-ray experiments. In particular the ground-based detector arrays located all around the world have drawn in the last decades different conclusions based on the interpretation of data collected at energies beyond the so-called "knee" region of the cosmic-ray spectrum (around 10^{15}–10^{16} eV), up to the highest investigated energies (around 10^{20}–10^{21} eV). At these energies the hadronic interaction is almost unknown and all the simulations are based on a calibration done at the CERN SPS by the UA7 Collaboration [1] at much lower energy. The greatest part of the energy contained in an atmospheric shower induced by extreme energy cosmic rays is

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transported by the forwardly emitted cone of particles which constitutes the core of the shower. For this reason it is fundamental to study the emission of particles at very low angle in proton-proton, proton-nucleus or nucleus-nucleus collisions at the highest possible energy at accelerator facilities, where the type of particles, their kinematics and several other parameters are known and kept under control. The LHCf experiment [2, 3] is designed to achieve this aim by providing a detailed study of the production of neutral particles in the very-forward region of the proton-proton interaction at the LHC energy. The LHC machine allows making these measurements at 14 TeV in the center-of-mass frame, the greatest energy ever reached by a particle accelerator. The primary aim of these measurements is a strong improvement in the calibration of the Monte Carlo codes which are used to simulate the development of the atmospheric showers induced by cosmic rays of energies exceeding the "knee" energy. The different models which are commonly used to simulate hadronic interactions at very high energy give different results for the production of particles at small angles. These differences affect not only the production probability of different particles, but also the dependence of the cross-sections on the transverse momenta of the outgoing particles, that is the angular dependence of the cross-sections for the different processes. For these reasons the LHCf experiment will study the transverse momentum dependence of gamma-ray, neutral pion and neutron fluxes in the pseudo-rapidity region beyond 8.5, which is not accessible by the central detectors installed all around the interaction points (IP). The detector will take data during the low luminosity runs of the collider, below $10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This study will be achieved by means of two independent detectors located on the beam line, 140 m far from IP1, on both sides. These measurements will also provide the possibility to determine the absolute cross-sections once the luminosity of the LHC machine, measured by other experiments, is known.

2. – The detectors

Each of the two LHCf detectors is made of a couple of square-section $44\,X_0$ deep sampling electromagnetic calorimeters, called "towers", with an impact surface of a few cm^2. Each tower consists of alternating tungsten and scintillator layers, used as absorber and sampling materials respectively. In spite of the small transverse size of the towers, comparable with the Moliere radius in Tungsten (~ 9 mm), the high longitudinal granularity results in a good energy resolution for electromagnetic showers and give also the possibility of doing a detailed study of the longitudinal development of energy release for particle identification. The transverse development, particularly important for determining the particle impact point and its distance from the calorimeter edge (to reject events with high energy loss outside the calorimeter), is studied by means of four X-Y tracking layers made of 1 mm diameter scintillating fibres for detector I and $160\,\mu$m readout pitch micro-strip silicon sensors for detector II [2, 4]. The division of one detector into two separate calorimeters is required to minimize the overlap of signals due to the different simultaneous showers when detecting the two gamma-rays produced in a neutral pion decay. The different geometries of the two detectors [5] have been carefully studied to maximize the accessible kinematic region and exploit the different characteristics of the position sensitive detectors. The projection of the beam pipe material from the IP to the detector location, which strongly limits the useful volume available for the experiment, has been taken into account for correctly dimensioning and shaping the detectors.

3. – Simulation results

Two main simulations of the detectors have been set up and are currently used to study the detector response in details. The main one is based on the EPICS [6] simulation tool and is under development since the first proposal of the experiment in 2004. The second one, which was used at the beginning only to understand the performance of micro-strip silicon layers, uses the FLUKA simulation tool [7] and has been recently developed to check and validate the results of the EPICS simulation. The lists of secondary particles produced at 14 TeV in the proton-proton interaction, used as input for the simulations, are generated by using the DPMJET, QGSJET, and SYBILL models. Comparison of the predictions of the different models has shown that a good discrimination of the SYBILL model with respect to the others can be achieved by measuring the energy distribution and transverse momentum dependence of single gamma events [2]. Improvements in discrimination can be obtained by moving the LHCf detector up thus extending the accessible kinematic region. This is possible thanks to a homemade motorized system which can be remotely controlled allowing a maximum displacement of 120 mm between a bottom and a top positions. The latter one, the so-called "garage" position, is taken as the safe position where the detectors will be stored during potentially dangerous operations like the beam injection phase. Moreover the possibility to detect both the gamma-rays produced in the neutral pion decay at the IP allows the reconstruction of the neutral pion invariant mass, in such a way to have an important calibration point for the energy measurement and a clean sample of events with very low background. Although the detectors are optimized to study the electromagnetic showers, LHCf allows also to study the neutron component, thanks to its consistent depth, corresponding to 1.7 nuclear interaction length. Obviously the sample of neutrons has to be selected among those particles which interact in the first part of the calorimeter to allow a good energy resolution. Particle identification can be then easily performed by exploiting the longitudinal and transverse segmentation of the sensible layers. Simulations show that 30% energy resolution is expected for 1 TeV neutrons interacting in the first layers of tungsten, that is within a few X_0 depth. Even if such a resolution is assumed over a wide energy range, it is found that the expected distributions of energy releases by neutrons coming from the proton-proton interactions at IP are very different depending on the hadronic interaction model which is used. All of these different measurements will constitute an important set of points for calibrating the Monte Carlo codes which are used for the study of the atmospheric showers.

4. – Status and perspectives

Since 2008 the complete LHCf apparatus has been ready for data taking. The first data, a few events due to the interaction of beam particles with residual gas in the beam pipe, were registered on September 10, 2008, during the first inaugural running of the LHC machine. Unfortunately a long delay in the commissioning of the LHC machine has been imposed due to important problems arose during this short run for some cryogenic system serving the superconductive magnets. Since then the LHCf detector have been intensively tested from the electronics and software point of view. DAQ software, slow control monitor and data analysis have been improved with the aim to have a fast, light and safe system for any condition or failure during real run. A remotely controlled mechanical device has been implemented jointly by LHC and LHCf to help technicians moving the detectors from their locations to some safe locations outside the beam line, thus minimizing the time needed for the removal of the detectors when required.

While until September 2008 the experiment was supposed to run at the beginning of the beam commissioning, at low luminosity and 7 TeV + 7 TeV beam energy, being removed after a few days of data taking, the most recent LHC running schedule [8] has imposed a careful revision of the running strategy. Discussion between the LHCf Collaboration and the LHC Committee is still open. The achievement of the primary physics goals of LHCf requires running for a few days with the initially foreseen conditions (maximum energy at low luminosity). Because according to the new plan the beam energy will increase gradually from 450 GeV to 5 TeV in the running period between 2009 and 2010, the LHCf strategy is now under consideration, to evaluate the possibility to start data taking since the beginning and then move the detectors at some times from their run location to the safe "garage" positions, to preserve them for successive measurements at different energies. This new plan implies however a greater adsorbed dose for the LHCf detectors, leading to a worsening of the apparatus performance before reaching the nominal running conditions. New solutions to improve the radiation hardness of the detectors, mainly limited by the scintillating materials, are therefore under investigation. The possibility of replacing the current detectors with stronger ones during some long shutdown will be soon discussed.

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