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Measurement of η production rate in proton-proton collisions at 13 TeV with LHCf(*)

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Summary. — Indirect measurements of *Ultra High Energy Cosmic Rays* (UHECR) strongly depend on the hadronic interaction models used to simulate the interaction of a high energy cosmic ray with the atmosphere and thus the *Extensive Air Showers* (EAS). Different models bring to significantly different interpretations of the ground cosmic-ray measurements. The LHCf (*Large Hadron Collider forward*) experiment is a calorimetric experiment at LHC for the measurement of production rate of neutral particles in the forward region. The target of the experiment is to provide data in the forward region at high energy for testing and tuning the different hadronic models. In LHC Run 2, LHCf acquired data in proton-proton collisions at 13 TeV. With these data we have measured for the first time the production rate of η mesons in the forward region at high energy. In this paper we will present the η production rate measurement, and we will compare it with different hadronic models typically used by UHECR experiments.

1. – Introduction

The LHCf (*Large Hadron Collider forward*) experiment [1] is a calorimetric experiment at LHC designed to measure the production rate of neutral particles in the forward region in proton-ion collisions. These measurements are performed in order to provide high energy data in the forward region to test and tune the hadronic models that are used by *Ultra High Energy Cosmic Rays* (UHECR) ground experiments as the Pierre Auger Observatory [2] and Telescope Array [3]. Indeed, the interpretation of these measurements strongly relies on the simulation of UHECR interactions with the atmospheric nuclei. However, different models lead to different interpretations, limiting our understanding on the UHECR [4, 6].

The LHCf experiment is composed of two different detectors: Arm1 and Arm2. They are situated at about 141 m from the interaction point one (IP1) in the LHC tunnel. Precisely, they are positioned in the *Target Neutral Absorber* (TAN) region where the

(*) IFAE 2024 - "Energy Frontier" session beam pipe splits in an Y shape after the magnetic dipole D1, such that only neutral particles with $|\eta| > 8.4$ can reach the LHCf detector. Arm1 and Arm2 detectors are similar but with some differences. Since in this paper we will report measurements of Arm2 only, we will briefly describe the Arm2 design. As shown in fig. 1, the detector is a sampling and imaging calorimeter composed of two towers with square section: the Small Tower of side 25 mm and the Large Tower of side 32 mm. The calorimeter is composed of 16 GSO layers alternated to tungsten as passive material and four pairs of X-Y silicon strip detectors. In the first two couple the X and Y silicon detectors are in contact, while in the last two couples they are alternated with GSO and tungsten. The GSO is used to measure the energy released in the calorimeter, while the silicon strip detectors are used to measure the particle hit position on the tower in order to correct for the lateral leakage, the light collection efficiency and to distinguish different particles hitting the same tower in the same event. The calorimeter total length is about 44 radiation length or 1.6 hadronic interaction length.

During LHC Run 2, on June $12^{th} - 13^{th}$ 2015 there was a low luminosity fill dedicated to LHCf data taking. During this fill, two datasets have been acquired with integrated luminosities of about 0.194 nb^{-1} and 1.938 nb^{-1} respectively for a total of about 8.4 million of triggered events. In this paper we are going to discuss the production rate of the η meson as we have measured in this data taking. For a deeper discussion see [7], on which this paper is based.

2. – Measurement of η meson production rate

In this section we are going to discuss the event reconstruction and then the η meson production rate measurement analysis. Finally, we present our measurement of the η production rate in function of the Feynman-x variable $x_F = 2p_z/\sqrt{s}$.

2˙1. *Event reconstruction.* – We detect η mesons through their decay channel in γ pairs ($\eta \to \gamma\gamma$), which has a branching ratio of $(39.36 \pm 0.18)\%$ [8]. At the detector level, the event classification for neutral particles decaying in γ pairs like η and π^0 is the

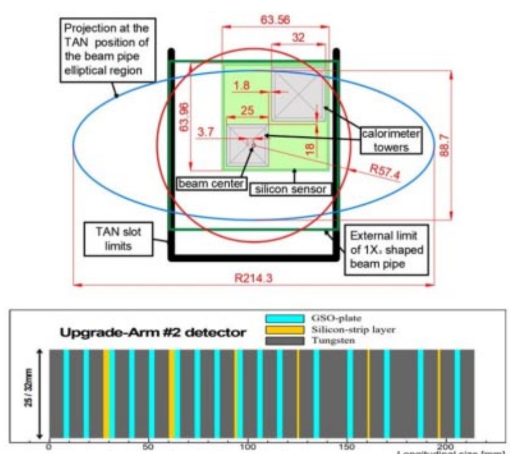

Fig. 1. – Schematic illustration of the LHCf-Arm2 detector. On the top a front view of the detector, while on the bottom a lateral view [7].

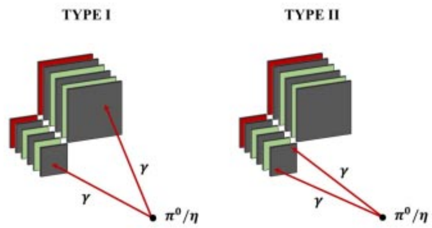

Fig. 2. – Illustration of event classification in LHCf Arm2 for η and π^0 decay in $\gamma\gamma$: for *type I* events the two photons hit different towers, while for *type II* events the two photons hit the same tower [7].

following (see fig. 2):

- *type I* events in which the two photons hit different towers;
- *type II* events in which the two photons hit the same tower.

For η mesons we perform the analysis only for *type I* events, since *type II* η are kinematically suppressed. The analysis strategy is similar to the one carried out for π^0 [9, 10].

After the selection of *type I* events only, events where a particle hit the tower by 2 mm from any edge are rejected, in order to avoid large position dependent correction (lateral leakage and light collection efficiency). Then, we reconstruct the energy from the GSO signals, applying the position dependent correction. In addition, we have a neutral hadron background due to hadron neutral particle hitting the detector, mainly neutrons. To discriminate photons from this background we perform a selection based on the longitudinal profile of the shower. The good performances on the photon-hadron discrimination using this selection are discussed in [9].

2·2. *Data analysis*. – To identify the η mesons we build the invariant mass of the two photons:

$$M_{\gamma\gamma} = \sqrt{2E_1E_2 \cdot (1 - cos(\theta))} \tag{1}$$

with E_1 and E_2 the energies of the photons and θ the opening angle between the photons in the laboratory reference system. Looking at the invariant mass spectra in the η meson mass region we obtain the distribution shown in fig. 3. We select the events in the peak of fig. 3 with a sideband method [9] in order to disentangle η mesons from background. Indeed, since in the dataset the η statistics is low, we can not extract the x_F distribution and remove the background for every x_F bin using a template fit. Specifically, to separate the background we perform a fit of the invariant mass distribution (the blue line in fig. 3) with the sum of a Gaussian function for the signal and a third$-$order Chebyshev polynomial function for the background. Then, using the expected mean and standard deviation of the Gaussian extracted from the fit we define a signal region (defined by vertical continuous black lines in fig. 3) and a background region (defined by vertical dotted black lines in fig. 3). Finally, we estimate the background component in the signal region as the sum of the x_F distributions in the background regions scaled for the ratio between the integrals of the fitted Chebyshev polynomial function in the signal and background regions.

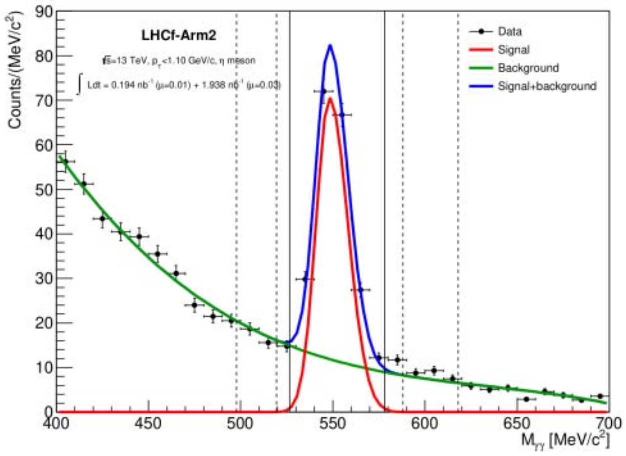

Fig. 3. – Invariant mass spectrum of the two selected photons in the η meson mass region. Through a sideband method we separate η mesons from the background: the blue line is the method result which describes signal+background, the green line the background and the red one the signal. [7]

Once we have selected the η meson events and subtracted the background, we can use the measured η mass to check the absolute energy scale. Particularly, we measure an η mass shifted of $(-2.65 \pm 0.20)\%$ with respect to the η world average $(547.862 \pm 0.017)\ MeV/c^2$ [8]. In addition with the same dataset and similar analysis we measure a π^0 invariant mass shifted of $(-2.57 \pm 0.04)\%$ with respect to the world average. Since the two shifts are compatible, we have shifted the energy scale of -2.65% so that the η mass measured is the same of the world average. This procedure is taken into account when estimating the systematic errors. Indeed, the absolute energy scale uncertainty results to be the largest systematic error of the measurement. In addition, we correct the number of η mesons for the branching ratio and the detector geometric acceptance.

Finally, the η inclusive production rate is defined as:

$$\frac{1}{\sigma_{inel}} \cdot x_F \cdot \frac{d\sigma}{dx_F} \tag{2}$$

with σ_{inel} the inelastic cross-section for proton-proton collisions at $\sqrt{s} = 13\ TeV$ [11], and $x_F \cdot d\sigma/dx_F$ is the η production differential cross-section. The η meson inclusive production rate measured by LHCf is shown in fig. 4. The grey band in the figure represents the total uncertainty of the measurements, whose largest contribution is the statistical error, while the most important systematic error is the one on the energy scale due to the -2.65% shift discussed before. In addition, several systematic errors have been considered, such as the ones on beam center stability, luminosity value, background subtraction and Monte Carlo related corrections.

In fig. 4 the η inclusive production rate is compared with the predictions of some of the most common hadronic models used by UHECR experiments: QGSJETII-04 [12], EPOS-LHC [13], DPMJET 3.06 [14], SYBILL 2.3 [15]. None of the cited hadronic models reproduces well the data, only QGSJETII-04 reproduces the data for x_F larger than 0.7. Thus, with this new measurement a new dataset for calibration of these models in the

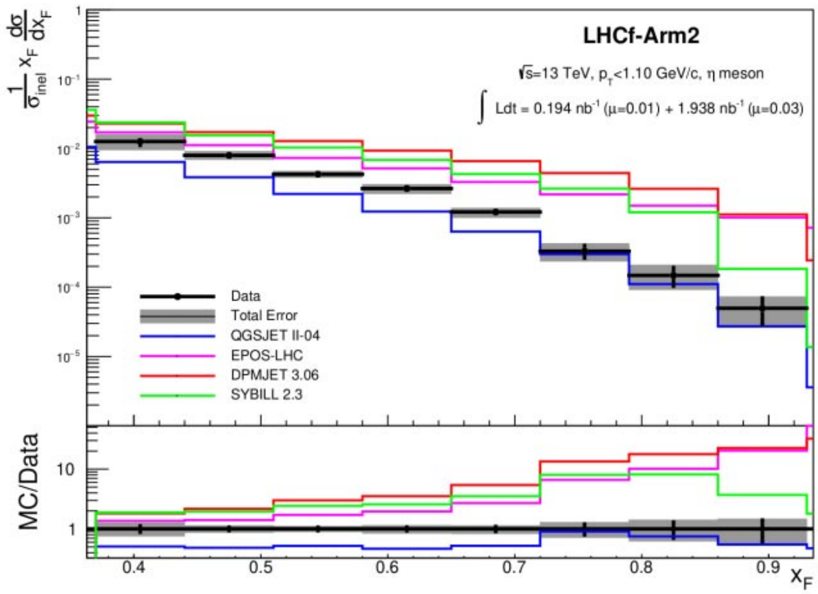

Fig. 4. – η meson inclusive production rate measured by LHCf, compared with the prediction of some of the most common hadronic models used by UHECR experiments. [7]

forward region at high energy is provided, which could help in tuning the models and doing a step forward in the interpretation of UHECR measurements. Moreover, during LHC Run 3 in 2022 we have acquired data increasing the η meson statistics of a factor about 8, with which we will provide more precise measurements.

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