PROCEEDINGS OF SCIENCE

Measurement of the forward η meson production cross section in p-p collisions at $\sqrt{s} = 13$ TeV with the LHCf Arm2 detector

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The LHC forward (LHCf) is a unique experiment designed to measure neutral particle production spectra in the forward region to provide high-energy data for tuning the hadronic interaction models used by ground-based cosmic rays experiments. These measurements are possible thanks to the excellent performance of this experimental apparatus, composed of two sampling calorimeters, Arm1 and Arm2, located at about ±140 m from the LHC interaction point 1 (IP1) at zero-degree angle. In this work, we would like to present the data analysis strategy and preliminary results for the measurement of η meson differential cross section as a function of the Feynman x_F variable, measured in p-p collisions at $\sqrt{s} = 13$ TeV with the Arm2 detector and compared with the predictions of four widely used hadronic interaction models. The importance of this observation relies on the fact that the strange quark contribution is one of the parameters characterizing the different models. Thus differences in this parameter induce a large discrepancy in the expected η production cross-section.

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1. Introduction

Despite the recent progress in the knowledge of ultra-high energy cosmic rays (UHECR) reached by extensive ground base experiments, like Pierre Auger Observatory[1] and the Telescope Array[2], the UHECRs mass composition measurements are still primarily affected by uncertainties related to the choice of the hadronic interaction model (HIM) used for crucial parts of the data analyses, which make difficult the interpretation of the result[3, 4]. HIMs treat the soft QCD interaction using several theoretical approaches, mainly based on Parton Model and Gribov-Regge theories[5, 6], that predict different results for particle productions. These differences induce significant errors in the MC simulations of the interaction between UHECR and Earth's atmosphere, which are fundamental for every experiment that performs indirect measurements of cosmic rays. High energy calibration data are required to tune and calibrate the HIMs. The Large Hadron Collider (LHC[7]) is the most suitable place to perform these measurements since a proton-proton collision at $\sqrt{s}$ = 14 TeV is equivalent to the interaction of about 10^{17} eV cosmic ray with the atmosphere. Soft processes are mainly equivalent to forward particle production in hadronic interactions, measured only at relatively low energies. The Large Hadron Collider forward (LHCf[8]) experiment extends these results by measuring forward neutral particles produced at the LHC to provide useful calibration data for model theorists. LHCf experimental setup consists of two independent sampling and imaging calorimeters, Arm1 and Arm2, located at about ±140 m from the Interaction Point 1 (IP1) of LHC. For this work, we used only the Arm2 detector, that is divided into two calorimetric towers, each composed of 17 tungsten plates, 16 Gd_2SiO_5 (GSO) scintillator layers for shower sampling, and 4 XY position sensitive layers made by silicon microstrips layers[9, 10]. LHCf has carried out measurements in proton-proton collisions at $\sqrt{s}$ = 0.9, 2.76, 7 and 13 TeV, and in proton-lead collisions at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV, measuring the production of photons, neutrons and π^0 [11–19]. LHCf can also reconstruct η meson[20], an important probe for the dependency of the HIMs on the strange quark contribution, a key parameter of the model. In this proceeding, we present the data analysis strategy and the preliminary results of the forward η meson production cross-section measurement in proton-proton collisions at $\sqrt{s}$ = 13 TeV.

2. Data analysis

The dataset used in the analysis has been taken during the LHCf operation in proton-proton collisions at $\sqrt{s}$=13 TeV in LHC fill #3855. It is obtained by merging two datasets with different pileup parameters μ, having integrated luminosities of 0.194 nb^{-1} and 1.9378 nb^{-1} for the datasets with pileup parameter μ = 0.01 and μ = 0.03, respectively. Transverse momentum and Feynman-x variable ($x_F = 2p_z/\sqrt{s}$) of η mesons were reconstructed from the kinematic variables of the incident photons coming from the decay channel $\eta \to \gamma\gamma$. The x_F distribution was extracted in only one bin of transverse momentum p_T < 1.1 GeV due to the dataset's limited η statistics.

2.1 Event selection

Several criteria were applied to select the η candidates:

- **Event Type:** Only events with one photon per tower (Type I) were considered since the acceptance for events with both photons hitting a single tower (Type II) was too low.

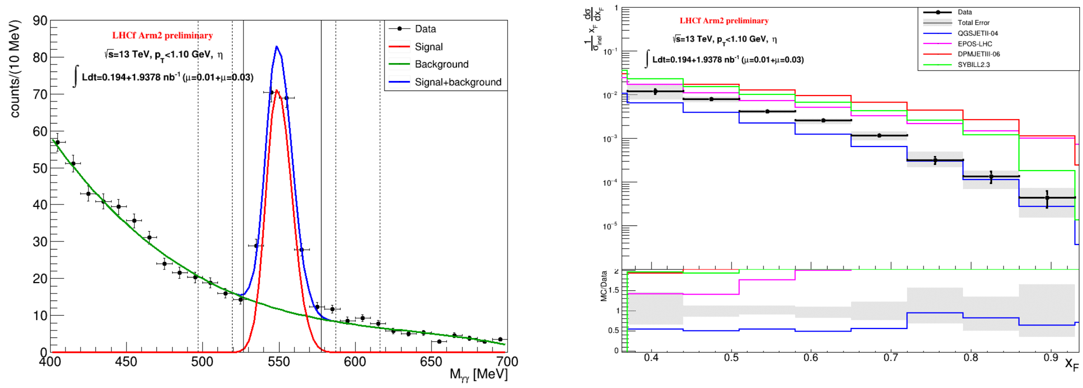

Figure 1: *Left*: Invariant mass distribution of selected Arm2 events with $p_T < 1.1$ GeV. Solid vertical lines border the signal window, while the dashed are the background windows. *Right*: Preliminary production cross-section of η mesons compared with several hadronic interaction model results. None of the models can reproduce the experimental distribution in the whole x_F range. The experimental data are obtained by merging the two datasets with different pileup parameter μ, having integrated luminosities of 0.194 nb^{-1} ($\mu = 0.01$) and 1.9378 nb^{-1} ($\mu = 0.03$).

- **Number of hits:** Events with at least a background particle in addition to the two photons (multihit events) were rejected.
- **Energy threshold:** To ensure the 100% trigger efficiency, only photons with energy greater than 200 GeV were selected.
- **Position cut:** Only photons hitting the calorimeter within 2 mm of the edges of the towers were considered to reduce the impact of the shower leakage on the energy reconstruction.
- **Particle identification:** The discrimination between photons and neutral hadrons was performed by using an energy-dependent cut function on the $L_{90\%}$ variable, defined as the depth within 90% of the energy deposit is contained. The cut function was calculated using MC simulation and imposing 90% selection efficiency for each energy bin.

2.2 Signal extraction

Candidates for η events are selected using the characteristic peak in the di-photon invariant mass ($M_{\gamma\gamma}$) distribution corresponding to the η rest mass. We used a sideband method to extract the x_F distribution and subtract the background, mainly composed of residual hadron and combinatorial contamination. First, the $M_{\gamma\gamma}$ distribution was fitted with a composite model function, consisting of an asymmetric Gaussian for the signal component and a third-order Čebyšëv polynomial function for the background component. Then a signal window is defined as the $M_{\gamma\gamma}$ region within 3σ from the signal peak, while two background windows are defined in the regions $[\pm 4\sigma, \pm 7\sigma]$. After background subctraction we found about 1500 η candidates. Left panel of Figure 1 shows the $M_{\gamma\gamma}$ distribution.

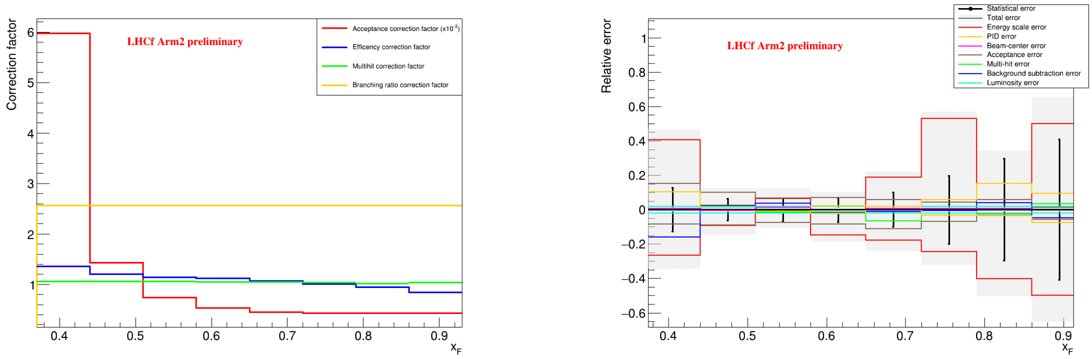

Figure 2: *Left:* Distributions of correction factors applied to final x_F distribution. The acceptance correction factor is scaled to a factor 10^{-2}. *Right:* List and distributions of experimental uncertainties.

2.3 Corrections and uncertainties

We applied several correction factors to the obtained x_F distribution:

- **Efficency correction:** Calculated using MC simulation based on the QGSJETII-04 model[21], looking at the differences between the MC reconstructed spectrum and the MC truth.
- **Acceptance correction:** To obtain the inclusive x_F spectrum, a geometrical acceptance correction is calculated using the QGSJETII-04 and EPOS-LHC[22] models, taking the ratio between the predicted spectrum of η that hit the Arm2 detector and the total distribution.
- **Multihit correction:** The fraction of events lost due to the multihit rejection was corrected using the QGSJETII-04 MC model.
- **Branching ratio correction:** The inefficiency due to the limited branching ratio of the decay $\eta \to \gamma\gamma$ (39.41%) has been compensated for with a constant correction.

The left panel of Figure 2 shows the distributions of the correction factors. We considered several sources of systematical uncertainties, mainly related to the indetermination of the energy scale, the particle identification, the beam-center position and luminosity. We also calculate errors connected to the experimental corrections described in this section. Right panel of Figure 2 shows a summary of error sources.

3. Results

The preliminary η production cross section is shown in the right panel of Figure 1, together with the prediction of four widely used hadronic interaction models: QGSJETII-04[21], EPOS-LHC[22], DPMJETIII-06[23], and SYBILL2.3[24, 25]. None of the models can reproduce the experimental distribution in the whole x_F range. QGSJETII-04 works well for high values of x_F, but a factor 2 of difference remains for lower values. Thanks to the detector read-out upgrade, the new data-taking during LHC Run III, scheduled for September 2022, will increase the η mesons statistics and improve the measurement's precision [26].

References

[1] The Pierre Auger cosmic ray observatory, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 798 (2015) 172.

[2] M. Fukushima, Telescope Array Project for Extremely High Energy Cosmic Rays, Progress of Theoretical Physics Supplement 151 (2003) 206.

[3] Pierre Auger Collaboration collaboration, Depth of maximum of air-shower profiles at the pierre auger observatory. i. measurements at energies above $10^{17.8}$ eV, Phys. Rev. D 90 (2014) 122005.

[4] R. Abbasi, M. Abe, T. Abu-Zayyad, M. Allen, R. Anderson, R. Azuma et al., Study of ultra-high energy cosmic ray composition using telescope array's middle drum detector and surface array in hybrid mode, Astroparticle Physics 64 (2015) 49.

[5] V.N. Gribov. A reggeon diagram technique. Sov. Phys. JETP, 26(414-422):27, 1968.

[6] T Regge. Nuovo Cimento 14 951 Regge T 1960. Nuovo Cimento, 18:947, 1959.

[7] L. Evans, The Large Hadron Collider, New Journal of Physics 9 (2007) 335.

[8] O. Adriani, L. Bonechi, M. Bongi, G. Castellini, R. D'Alessandro, D.A. Faus et al., The LHCf detector at the CERN large hadron collider, Journal of Instrumentation 3 (2008) S08006.

[9] Y. Makino, A. Tiberio, O. Adriani, E. Berti, Bonechi, M. Bongi et al., Performance study for the photon measurements of the upgraded LHCf calorimeters with Gd_2SiO_5(GSO) scintillators, Journal of Instrumentation 12 (2017) P03023.

[10] O. Adriani, L. Bonechi, M. Bongi, G. Castellini, R. Ciaranfi, R. D'Alessandro et al., The construction and testing of the silicon position sensitive modules for the LHCf experiment at CERN, Journal of Instrumentation 5 (2010) P01012.

[11] O. Adriani et al., Measurement of zero degree inclusive photon energy spectra for $\sqrt{s}$=900 GeV proton–proton collisions at LHC, Physics Letters B 715 (2012) 298.

[12] 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 703 (2011) 128.

[13] O. Adriani, E. Berti, L. Bonechi, M. Bongi, R. D'Alessandro, M. Haguenauer et al., Measurement of forward photon production cross-section in proton–proton collisions at $\sqrt{s}$=13 TeV with the LHCf detector, Physics Letters B 780 (2018) 233.

[14] 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 750 (2015) 360.

[15] O. Adriani, E. Berti, L. Bonechi, M. Bongi, R. D'Alessandro, S. Detti et al., Measurement of inclusive forward neutron production cross section in proton-proton collisions at $\sqrt{s}$=13 TeV with the LHCf Arm2 detector, Journal of High Energy Physics 2018 (2018) 73.

[16] O. Adriani, E. Berti, L. Bonechi, M. Bongi, R. D'Alessandro, S. Detti et al., Measurement of energy flow, cross section and average inelasticity of forward neutrons produced in $\sqrt{s}$=13 TeV proton-proton collisions with the LHCf Arm2 detector, Journal of High Energy Physics 2020 (2020) 16.

[17] The LHCf Collaboration collaboration, Measurement of forward neutral pion transverse momentum spectra for $\sqrt{s}$=7 TeV proton-proton collisions at the LHC, Phys. Rev. D 86 (2012) 09200.

[18] The LHCf Collaboration collaboration, Measurement of forward neutral pion transverse momentum spectra for $\sqrt{s}$=7 TeV proton-proton collisions at the LHC, Phys. Rev. D 86 (2012) 092001.

[19] LHCf collaboration, Measurements of longitudinal and transverse momentum distributions for neutral pions in the forward-rapidity region with the LHCf detector, Phys. Rev. D94 (2016) 032007 [1507.08764].

[20] G. Piparo et al., Preliminary measurement of the forward meson production cross section in p-p collisions at $\sqrt{s}$ = 13 TeV with the LHCf Arm2 detector - Poster for 148 LHCC meeting, 17-18/11/2021. https://indico.cern.ch/event/1091653/contributions/4619513/attachments/2348131/4004594/LHCf_poster.pdf

[21] S. Ostapchenko, Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: QGSJET-II model, Phys. Rev. D 83 (2011) 014018.

[22] T. Pierog, Iu. Karpenko, J. M. Katzy, E. Yatsenko, and K. Werner, EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider, Phys. Rev. C 92 (2015) 034906.

[23] F. W. Bopp, J. Ranft, R. Engel, and S. Roesler, Antiparticle to particle production ratios in hadron-hadron and d-Au collisions in the DPMJET-III Monte Carlo model, Phys. Rev. C 77 (2008) 014904.

[24] E.-J Ahn, R. Engel, T.K. Gaisser, P. Lipari, and T. Stanev, Cosmic ray interaction event generator SIBYLL 2.1, Phys. Rev. D 80 (2009) 094003.

[25] R. Engel, T.K. Gaisser, F. Riehn, T. Stanev, Proceedings of the 34th International Cosmic Ray Conference, The Hague, p. 1313 (2015)

[26] K. Ohashi et. al., Prospects of the LHCf Operation in 2022, in this proceedings.