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# Status and Prospects of the LHCf Experiment

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The Large Hadron Collider forward (LHCf) experiment at the Large Hadron Collider (LHC) measures neutral particle production in the very forward region of proton-proton and proton-ion collisions, aiming to improve hadronic interaction models (HIMs) used in ultra-high-energy cosmic ray (UHECR) simulations. This paper presents recent experimental activities of LHCf. Results from Run II, where neutron energy spectra and forward $\eta$ meson production were measured at $\sqrt{s}$ = 13 TeV, are discussed in detail. Discrepancies between the data and HIM predictions, particularly in neutron elasticity distributions and $\eta$ meson production rates, highlight the need for refinement of these models. In Run III, LHCf collected about ten times more data, enabling more precise measurements of neutral mesons, including $\pi^0$, $\eta$, $K^0_s$, and $\Lambda^0$. Collaborative operations with the ATLAS experiment permitted combined analyses, enhancing studies of diffractive processes and the one-pion exchange mechanism. Future prospects include proton-Oxygen collisions in 2025, providing direct insights into cosmic ray interactions with atmospheric nuclei and reducing uncertainties associated with previous extrapolations from proton-proton and proton-Lead data.

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## 1. Introduction

The study of ultra-high-energy cosmic rays (UHECR) and their interactions with Earth atmosphere is fundamental to astroparticle physics, offering insights into astrophysical processes and particle physics at energies unreachable in laboratories. However, uncertainties in the hadronic interaction models (HIMs) used to simulate the extended air showers (EAS) generated when UHECRs collide with atmospheric nuclei complicate the interpretation of cosmic ray data. A notable challenge is the "Muon Puzzle," referring to the discrepancy between the observed number of muons in EASs and the predictions made by current HIMs, especially at ultra-high energies [1]. At the LHC [2], proton-proton collisions at $\sqrt{s} = 14$ TeV correspond to about $10^{17}$ eV in the laboratory frame, providing a unique opportunity to study hadronic interactions relevant to UHECRs. The LHCf experiment [3] measures neutral particles in the very forward region ($\eta > 8.4$), aiming to improve HIMs crucial for simulating UHECR interactions with the atmosphere. The LHCf detectors, Arm1 and Arm2, are sampling calorimeters located ±140 meters from IP1, each comprising two tungsten/GSO towers with position-sensitive layers for precise energy and trajectory measurements [4]. Arm1 uses GSO bar-bundle hodoscopes, while Arm2 employs silicon microstrip detectors. This paper discusses the recent LHCf results: Section 2 presents Run II analyses, including neutron inelasticity and $\eta$ meson production; Section 3 covers Run III operations and ongoing analyses, highlighting increased statistics and collaboration with ATLAS; Section 4 outlines future prospects, particularly the proton-Oxygen collisions planned for 2025.

## 2. Run II Results and Analysis

In 2015, LHCf collected data during Run II at $\sqrt{s} = 13$ TeV with a low-luminosity beam configuration, featuring a luminosity range of $0.4 \div 1.4 \times 10^{29}$ $\text{cm}^{-2}\text{s}^{-1}$ and a $\beta^*$ value of 19 m. Key results include measurements of forward neutron energy spectra, average inelasticity, and forward $\eta$ meson production rates.

### 2.1 Neutron energy spectra and average inelasticity

Figure 1 shows the neutron energy spectra measured in various pseudorapidity regions [5]. In the zero-degree region ($\eta > 10.75$), the data exhibit a peak structure not reproduced by current HIMs, which also underestimate the neutron yield by at least 20%. In other pseudorapidity intervals, models like SIBYLL 2.3 and EPOS-LHC better agree with the data. From the spectra, the neutron elasticity distribution, $k_n = 2E_n/\sqrt{s}$, was extracted (Figure 2, left). The average inelasticity $\langle 1 - k_n \rangle$ is shown in the right panel. While models predict average values close to the data, they fail to reproduce the detailed $k_n$ distribution.

### 2.2 Production of forward $\eta$ mesons

The first forward $\eta$ meson production measurement at $\sqrt{s} = 13$ TeV was conducted using the LHCf-Arm2 detector [6]. Figure 3 shows the $\eta$ meson production rate compared to various HIMs. While no model fully reproduces the results, QGSJET II-04 performs better at high $x_F$ ($x_F > 0.7$). With this result, measuring the $\eta/\pi^0$ production ratio is possible.

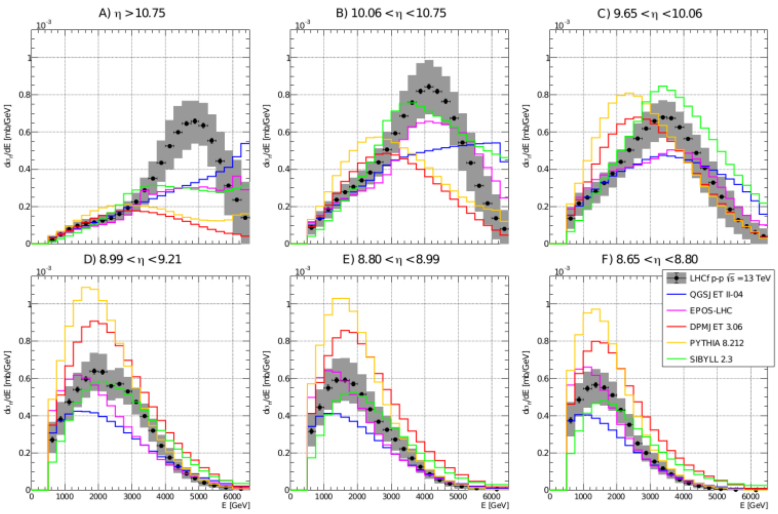

**Figure 1:** Neutron energy spectra measured in different pseudorapidity regions at $\sqrt{s}$ = 13 TeV, compared with predictions from various hadronic interaction models. The models fail to reproduce the peak structure observed in the data, particularly in the zero-degree region ($\eta$ > 10.75).

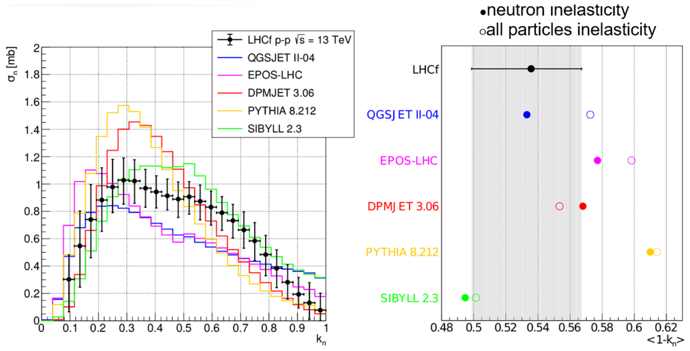

**Figure 2:** Left: Neutron elasticity ($k_n$) distribution measured at $\sqrt{s}$ = 13 TeV, compared with various hadronic interaction models. Right: Average inelasticity $\langle 1 - k_n \rangle$. While models predict average values close to the data, they fail to reproduce the detailed $k_n$ distribution.

## 3. Run III operations and ongoing analyses

In September 2022, LHCf collected over 300 million events during Run III at $\sqrt{s}$ = 13.6 TeV [7], about a tenfold increase over Run II data-taking.

### 3.1 Key physics targets

Run III focuses on increasing statistics for $\pi^0$ and $\eta$ mesons, and the first forward measurements of $K_s^0$ and $\Lambda^0$ mesons. With about 22,000 $\eta$ events collected (vs. 2,000 in 2015), uncertainties in spectra and the $\eta/\pi^0$ ratio are significantly reduced. Figure 4 shows the invariant mass distribution for two-photon events, highlighting $\pi^0$ and $\eta$ peaks. The enhanced statistics allow more precise measurements of the $\pi^0$ and $\eta$ spectra.

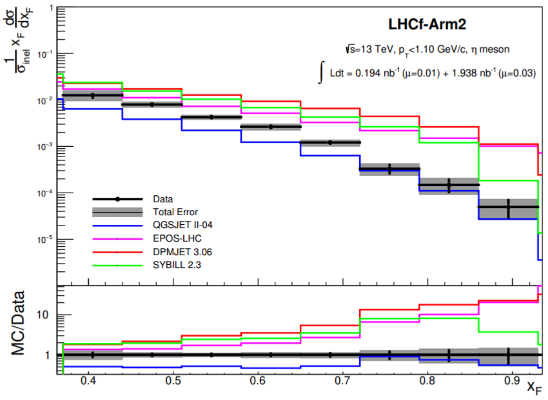

**Figure 3:** Forward $\eta$ meson production rate measured by LHCf at $\sqrt{s} = 13$ TeV, compared with predictions from HIMs. No model can reproduce the results in the whole $x_F$ range, QGSJET II-04 performs better at $x_F > 0.7$.

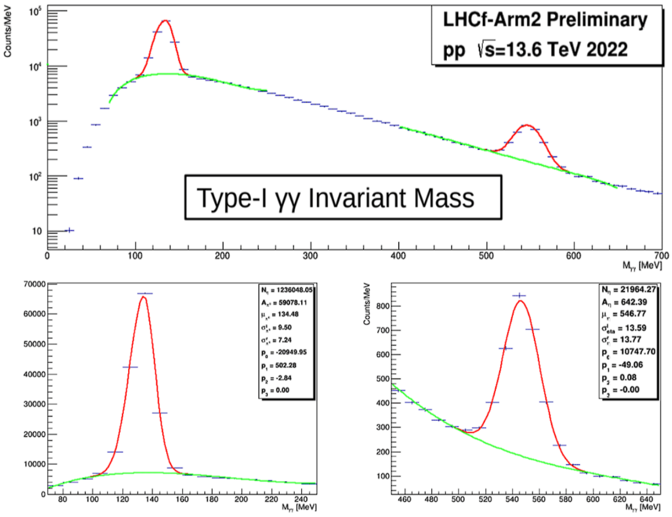

**Figure 4:** Invariant mass distribution of two-photon events collected during LHC Run III in 2022, showing clear peaks corresponding to $\pi^0$ and $\eta$ mesons. The increased statistics improve the experimental sensitivity.

### 3.2 Joint operations with ATLAS

A significant feature of Run III is the collaborative effort between LHCf and ATLAS [8]. LHCf and ATLAS exchanged triggers during dedicated runs, enabling combined analyses. Main targets include studies of photon spectra in diffractive events [9] and multiparton interactions using neutron events [10]. The integration of the ATLAS Zero Degree Calorimeter (ZDC) and Roman Pots (RP) improves the energy resolution of forward neutrons and allows the tagging of scattered protons. One key study is investigating the one-pion exchange (OPE) process in proton-proton collisions (Figure 5, left) [11], providing insights into high-energy pion-proton interactions. The right panel of Figure 5 shows neutron energy spectra predicted by various HIMs and the OPE contribution. Joint operation with ATLAS ZDC enhances neutron energy resolution from approximately 40% to 20% [12], improving OPE event selection.

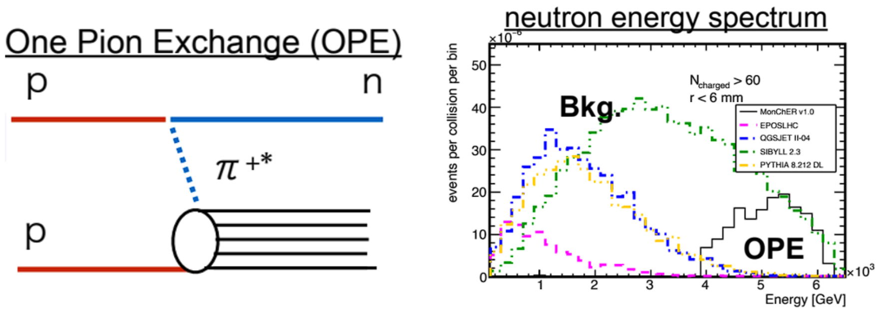

**Figure 5:** Left: Diagram illustrating the one-pion exchange (OPE) process contributing to forward neutron and pion production in proton-proton collisions. Right: Neutron energy spectra predictions by several HIMs, highlighting the OPE contribution.

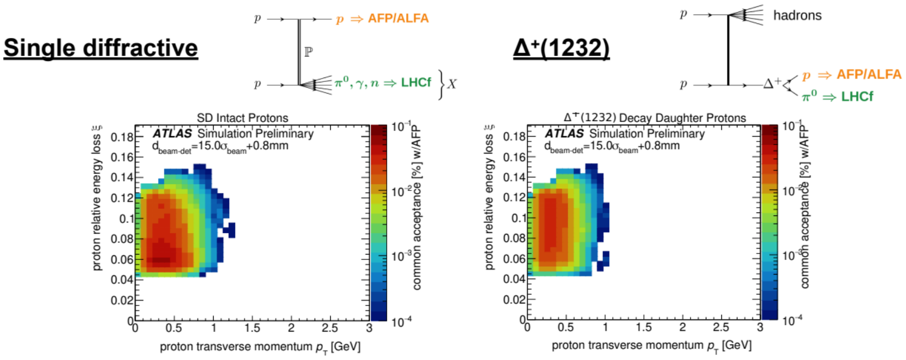

**Figure 6:** Acceptance maps for protons in the transverse momentum space from simulated single diffractive processes (left) and $\Delta^+(1232)$ resonance production (right) in the joint LHCf and ATLAS Roman Pot detectors.

Joint analyses with the RPs allow studies of $\Delta^+(1232)$ resonance production by detecting a $\pi^0$ meson with LHCf and a proton with RPs on the same side, and single diffractive processes by measuring scattered protons with RPs and diffractive products with LHCf on the opposite side. Figure 6 shows the LHCf+RP acceptance maps for protons in these processes.

## 4. Future prospects: proton-Oxygen collisions in 2025

In 2025, the LHC will perform proton-Oxygen (p-O) and Oxygen-Oxygen (O-O) collision runs, providing a direct way to study interactions between cosmic rays and atmospheric nuclei. Unlike previous runs requiring large extrapolations, p-O collisions allow precise measurements of cross-sections and particle production relevant to UHECRs physics. For LHCf, p-O collisions reduce systematic uncertainties since ultra-peripheral collision contributions are negligible compared to main QCD processes. In previous p-Pb measurements, UPC effects introduced significant uncertainties. LHCf will focus on the proton-remnant side in p-O runs, ensuring controlled particle multiplicity and higher-quality data. Combined data collection with ATLAS is also planned [13].

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