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Latest LHCf results and preparation to the LHC run for 13 TeV proton–proton interactions

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Abstract. The LHCf experiment is a CERN experiment dedicated to forward physics which is optimized to measure the neutral particle flow at extreme pseudo-rapidity values, ranging from 8.4 up to infinity. LHCf results are extremely important for the calibration of the hadronic interaction models used for the study of the development of atmospheric showers in the Earth atmosphere. Starting from the recent run of proton-Lead nucleus interactions at LHC, the LHCf and ATLAS collaborations have performed a common data taking which allows a combined study of the central and forward regions of the interaction. The latest results of LHCf, the upgrade of the detectors for the next 6.5 TeV + 6.5 TeV proton–proton run and the status of the LHCf-ATLAS common activities are summarized in this paper.

1 Introduction

The LHCf experiment is based on two independent sampling and imaging calorimeters (called Arm1 and Arm2), each composed of two separated calorimeter towers. Each tower is made of 16 tungsten

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layers and 16 plastic scintillator layers for energy measurement. Four position sensitive layers complete each calorimeter, complementing the energy measurement with the measurement of the particle impact position. The position sensitive layers are different for Arm1 and Arm2. X-Y scintillating fiber (SciFi) hodoscopes are used in Arm1 and X-Y silicon strip detectors in Arm2. The transverse cross sections of calorimeter towers are 20×20 mm^2 and 40×40 mm^2 in Arm1 and 25×25 mm^2 and 32×32mm^2 in Arm2. The detectors are installed 140 m away from the IP1 (Atlas) LHC interaction point, inside a massive absorber (Target Neutral Absorber, TAN) whose purpose is to protect the downstream cryogenic devices and magnets from the intense flux of neutral particle debris produced at IP1. In fact charged particles coming from the IP are swept away by the inner beam separation dipole before reaching the TAN, so that only photons, mainly from π^0 decays, neutrons and neutral kaons reach the LHCf location.

Being the LHCf detectors positioned along the beam line, they are able to measure neutral particles in the pseudo-rapidity range from $\eta = 8.4$ to infinity (zero degree). Details of the detector performance are published in [1, 2]. The energy resolution of the detectors for photons and hadrons is approximately 5% and 35%, respectively, while the position resolution in their impact point reconstruction is better than 200μm for photons and about 1 mm (or better at high energy) for neutrons.

The experiment has taken data during different periods, between 2009 and 2013, both in p-p and p-Pb collisions. In the next year p-p collisions with a total energy of 13 TeV in the center of mass frame will allow completing the LHCf physics program at the LHC. The detectors have been upgraded and installed on the TAN absorber in November 2014 to be ready for data taking on spring 2015, when a new common data taking with the ATLAS experiment is also planned.

The latest analysis results, including the neutron inclusive energy spectra in 7 TeV p-p collisions and the p_T vs η π^0 spectra in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are reported in section 2.

2 Latest results

Main results by the LHCf experiment are published in papers [3–6]. In this section we will present some preliminary results for the inclusive neutron spectra measured in p-p collisions at $\sqrt{s}$ = 7 TeV (paragraph 2.1) and for the p_T vs η π^0 spectra in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (paragraph 2.2.

2.1 Neutron spectra in p-p collisions at $\sqrt{s}$ = 7 TeV

The data used in this analysis were taken in 2010 in low luminosity conditions, that are optimal for the LHCf experiment due to the reduced event pile-up effect. Performance of detectors for hadron measurements have been carefully studied by Monte Carlo simulations. A comparison between these simulations and results from a test beam at CERN-SPS, where 350 GeV protons were used, can be found in [7].

The data analysis method for neutron energy spectra closely follows that used for the photon component, which is described in [3]. The luminosity has been measured with the help of the LHCf front counter rates, properly normalized with the Van der Meer LHC scan. Particle identification has been carried out by looking at the longitudinal shower development, using two dimensional cuts in the $L20_{\%}$ and $L90_{\%}$ plane, where $L20_{\%}$ and $L90_{\%}$ are the longitudinal depths containing 20% and 90% of the total deposited energy, respectively. Hit position has been evaluated by using the transverse shower distribution, measured with the position sensitive layers, to allow measuring particle pseudo-rapidity and correcting the energy measured for the leakage effects.

Due to the limited energy resolution for the neutron sample (≃30-40%), the measured spectra should be properly unfolded to get the realistic neutron spectra. We used a multidimensional-spectra unfolding method based on Bayesian theory, relying on the two measured variables Energy and P_T.

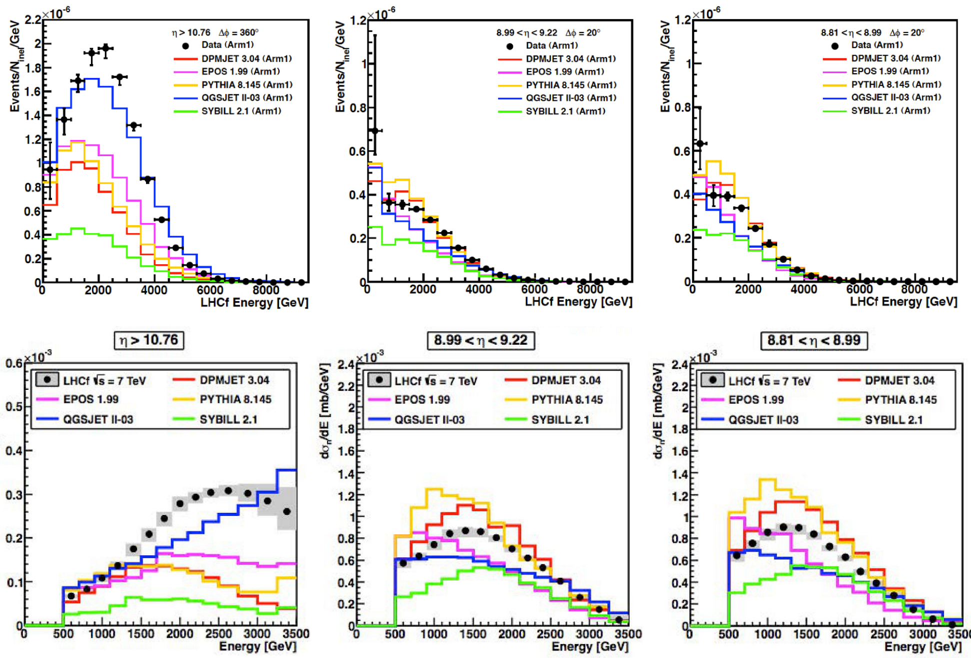

Figure 1. Top: preliminary neutron spectra measured by LHCf Arm1 in the $\sqrt{s} = 7$ TeV p-p collisions in three different rapidity regions. Bottom: preliminary unfolded neutron spectra measured by LHCf in the $\sqrt{s} = 7$ TeV p-p collisions in three different rapidity regions, compared with the models predictions.

Top graphs in figure 1 show preliminary energy spectra of neutrons measured by the Arm1 detector compared with MC predictions; the three panels correspond to a classification of spectra in terms of the pseudo-rapidity variable: $\eta > 10.76$ in the first plot (center of the small tower), $8.99 < \eta < 9.22$ in the second plot and $8.81 < \eta < 8.99$ in the third plot (latter two cases correspond to different regions of the large tower). The effect of the limited energy resolution for hadrons is evident from these plots, ranging from 0 up to more than 8 TeV in the neutron reconstructed energy. The preliminary neutron physics spectra obtained after the unfolding procedure are presented in the bottom graphs on the same figure. A combination of the Arm1 and Arm2 spectra in the three above defined rapidity regions was exploited to obtain these spectra.

A pronounced high energy neutron peak in the very forward region ($\eta > 10.76$), that is predicted only by the QGSJET-II model, is evident from these results. The presence of this peak is a clear indication of small inelasticity in the very forward direction of the p-p collision. We therefore expect that the baryons produced in the first interaction of a primary cosmic ray with the atmosphere carry on a large fraction of the primary energy, leading to deeply penetrating VHECR induced atmospheric showers.

2.2 π^0 spectra in p-Pb collision at $\sqrt{s} = 5.02$ TeV

At the beginning of 2013 the LHCf Arm2 detector was used to take data during p-Pb collisions at the nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV. Data were collected mainly on the proton remnant side, but a short data taking on the nucleus remnant side was also performed. The spectra measured in the p-remnant side provide new information on the effect of the dense nuclear matter in the forward particle production, which is particularly important for HECR Physics, since heavy nuclei (projectiles) and light nuclei (projectiles and targets) can be involved in the the primary interactions of cosmic rays in the Earth atmosphere [8].

Neutral pion P_T spectra have been measured in different rapidity ranges, and the results have been compared to the predictions of different hadronic interaction models. Results are published in [6].

The invariant mass spectrum of the photons pairs is shown in Figure 2 for events where each calorimeter tower is hit by one photon. This distribution demonstrates the excellent performance of the detector in the reconstruction of a clean π^0 sample. A clean peak corresponding to the neutral pion events is prominent over a small background due to pairs of uncorrelated photons. Once the π^0 events are identified, transverse momentum and rapidity are evaluated, allowing the costruction of the transverse momentum vs rapidity spectra.

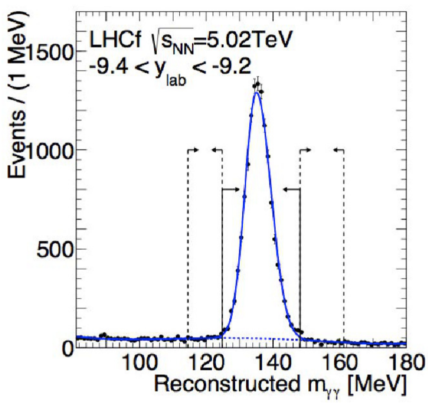

Figure 2. Invariant mass distribution of the reconstructed photon pairs in the rapidity region $-9.4 < y_{lab} < -9.2$.

According to preliminary simulations, approximately half of the forward produced π^0 arise from Ultra-Peripheral Collisions (UPC) of the proton in the electromagnetic (e.m.) field produced by the Lead nucleus. To obtain pure QCD spectra the effect of the UPC is subtracted. For this purpose the Weizsacher-Williams approximation is used to estimate the energy distribution of the virtual photons emitted by the fully ionized Pb nucleus, and finally the e.m. interactions between the virtual photons and the proton is simulated with the SOPHIA model [9]. Final spectra have been compared with the spectra in p-p collisions at 5.02 TeV, estimated by interpolating the LHCf results at 2.76 TeV and 7 TeV [6] (see Figure 3). Results are also compared with expectations by different models. From the comparison of p-p and p-Pb results the nuclear modification factor R_{pPb} at very high rapidity has been also derived, which is an indication of the strength of the effect of the dense nuclear medium on forward particle production. Figure 4 shows the measured R_{pPb} compared with the predictions by different models. Although with a large uncertainty, LHCf data show a strong suppression for neutral pion production for rapidity values $y_{lab} > 8.9$: R_{pPb} varies from 0.1 at $p_T \approx 0.1$ GeV to 0.3 at $p_T \approx 0.6$ GeV. Hadronic interaction models predict small values of R_{pPb}, showing an overall agreement with the LHCf data within the experimental uncertainty.

3 Upgrade of detectors for the 13 TeV p-p run

Both the LHCf detectors have been upgraded for the 2015 run, when p-p interactions will be produced at $\sqrt{s} = 13\,TeV$. This run will allow LHCf to complete the physics program that was conceived in the proposal. At this energy it will be possible to provide measurements of neutral particle production at extreme rapidity values at the highest interaction energy ever reached.

The main upgrades concerned the replacement of the scintillator material and the silicon microstrip sensors, that is basically all the sensitive part of detectors. The original plastic scintillator material was completely replaced by GSO because of the high dose rate foreseen in the next run at

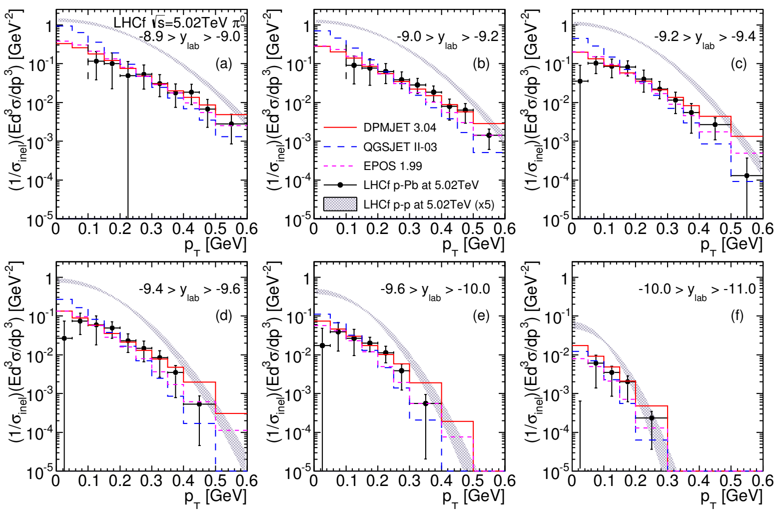

Figure 3. p_T spectra measured by LHCf in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV after subtracting the UPC contribution (filled circles); hadronic interaction models predictions and derived spectra for p-p collisions at 5.02 TeV are also shown. Error bars include both statistical and systematic uncertainties. Figures from [6]

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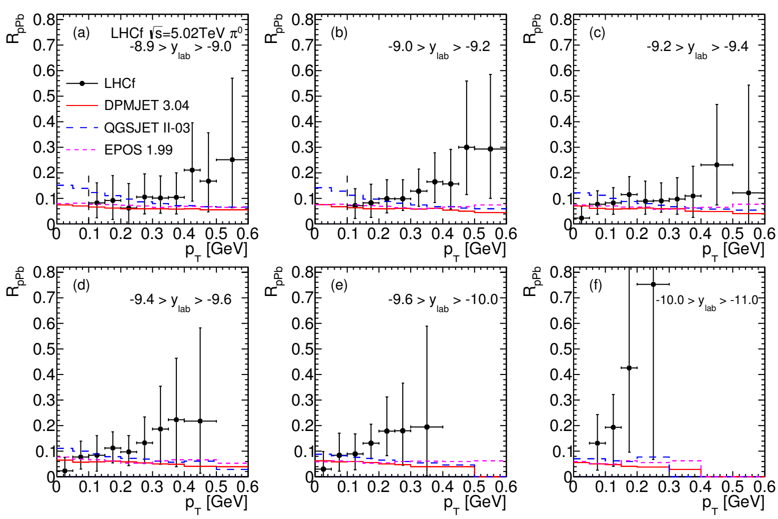

Figure 4. Measured nuclear modification factor for π^0 (black solid circle) compared with the expectation of different models. Error bars include both statistical and systematic uncertainties. Figures from [6]

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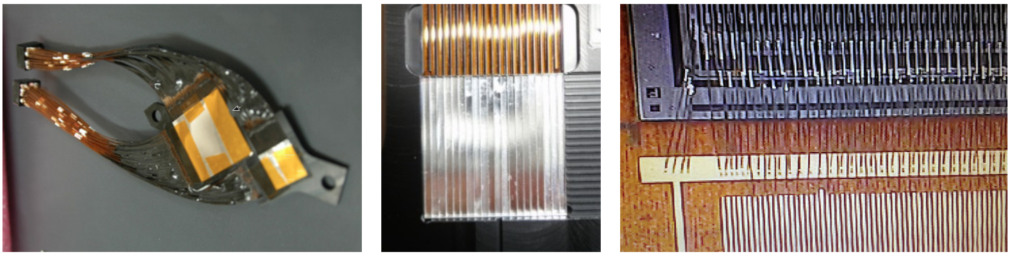

Figure 5. Left: upgraded Arm1 tracking plane made of square 1 mm × 1 mm GSO fibers. Center: detail of an Arm1 tracking plane. Right: detail of the upgraded Arm2 tracking layer, showing one microstrip silicon sensor (top of the figure) connected to a fanout circuit (lower part of the figure) with one strip every two connected to the fanout lines and the others to a large ground pad (horizontal in the figure).

LHC, of the order of 4 Gy/nb^{-1}. Because the amount of statistics required by LHCf is around 40 nb^{-1}, the total integral dose expected for the LHCf run at low luminosity in 2015 is less than 200 Gy. While the original scintillator tiles begin to show a sensible signal reduction already at 100 Gy, the replacement of plastic scintillator with GSO allows extending the life of the LHCf detectors up to 10^6 Gy, even if at 10^3 Gy it shows already an increase of 20% in the light emission. Basic target is to complete operations well before reaching 10^3 Gy.

From the hardware point of view, both the calorimeter tiles and the tracking planes made of scintillating fibers were replaced in Arm1 (see left and center pictures in figure 5) and the calorimeter tiles were replaced also in Arm2.

In addition completely new silicon layers and relative front-end boards were installed in Arm2. This choice was driven mainly by one reason: the definition of a new strip connection scheme to reduce the saturation effect of electronic channels observed during the development of e.m. showers produced by high energy photons. In the original scheme one strip was read-out every two and the others were left floating, in such a way that the charge collected on the unread strips could be partly spread on the adjacent strips, thanks to their capacitive coupling.

It has been verified during the previous runs that the channels connected to the strips located near the center of an e.m. showers begin to saturate already for 500÷600 GeV photons. This is not problematic for the reconstruction of the photon impact point, because only a few strips are affected by this problem, while the shower profile is much larger and allows anyway the reconstruction of the center of the shower with almost unchanged precision. Nonetheless the situation at $\sqrt{s} = 13\,TeV$ will be obviously worse, because the interaction energy is higher and higher energy photons are expected. In the new scheme, shown in the right picture in figure 5, all the strips which were originally floating are now connected to ground. In this way all the charge which is collected by these strips is lost towards ground and the signal developing on the read-out strips is reduced. During a beam test at the CERN SPS accelerator the performance of the new silicon modules and the saturation effect have been investigated. The threshold energy for this effect increased of a factor of $1.5 \div 1.7$ approximately, that correspond to an incoming photon energy of around 1 TeV.

4 LHCf and ATLAS common activity

Since the 2013 p-Pb run the LHCf and ATLAS collaborations have begun a joint activity motivated by discussions with several theoretical physicists and developers of hadronic interaction models. Focusing on the cosmic ray field, the measurement of neutral particle production at high rapidity, provided by the LHCf experiment, can be complemented by the simultaneous measurement of the activity in the low rapidity region, covered by the ATLAS detector. This allows for example to classify the collected events into diffractive and non diffractive. These two classes of events are usually treated independently from each other by hadronic interaction models and have therefore very different characteristics. The verification of predictions for the forward particle production given by models for these two types of event cannot be performed with the LHCf detector only, but information from the ATLAS detector are needed.

For this reason in 2013 an agreement between the two collaborations has allowed to use the LHCf trigger signal to trigger the ATLAS detector in such a way to have a set of events triggered by LHCf, for which the status of the activity in the central region is known. The 600 Hz LHCf trigger signal was included, downscaled to 20÷40 Hz, in the ATLAS minimum bias trigger. A few million common events in the proton remnant side of the p-Pb interaction at $\sqrt{s_{NN}} = 5.02$ TeV were collected and the analysis of these data in currently ongoing.

The same trigger configuration is foreseen for the 2015 p-p run at $\sqrt{s} = 13$ TeV. A one week dedicated low luminosity run for LHCf is foreseen on May 2015. Due to the short available time for common data taking, discussions are underway to define the details of trigger sharing and the requirements for collecting a sufficient amount of data allowing the previously discussed studies.

References

[1] O. Adriani *et al.*, JINST **3**, S08006 (2008)
[2] O. Adriani *et al.*, JINST **5**, P01012 (2010)
[3] O. Adriani *et al.*, PLB **703**, 128 (2011)
[4] O. Adriani *et al.*, PRD **86**, 092001 (2012)
[5] O. Adriani *et al.*, PLB **715**, 298 (2012)
[6] O. Adriani *et al.*, PRC **89** 065209 (2014)
[7] K. Kawade *et al.*, JINST **9**, P03016 (2014)
[8] O. Adriani, *et al.*, CERN-LHCC-2011-015, LHCC-I-021 (2011)
[9] A. Mucke *et al.*, Computer Physics Communications **124**, 290 (1999)