LHCf Status Report

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154th LHCC Meeting - OPEN Session
7 June 2023, CERN
Introduction
Ultra High Energy Cosmic Rays

Motivation
Understand mechanisms responsible for acceleration and propagation

Accurate measurements of UHECR flux and composition as a function of the energy

D’Enterria et al., 2011
Extensive Air Showers

Indirect measurement of UHECR energy flux and average composition by Extensive Air Showers

Measurement of average composition strongly relies on hadronic interaction models

Large uncertainties in interaction models due to the lack of high energy calibration data

$\langle X_{\text{max}} \rangle$: Small model discrepancy

$\ln <N_\mu>$: Large model discrepancy

Muon Puzzle
Hadronic interaction models

High energy calibration data are needed to properly tune hadronic interaction models

LHC is the best place where to study a system that is similar to the first CR-nucleus interaction

- Inelastic cross section
- Particle multiplicity
- $E/H$ Ratio $R = E_{\gamma} / E_h$
- Elasticity $k = p_{\text{lead}} / p_{\text{beam}}$
- Very forward particle spectra
  - Extrapolation to $E > 10^{17}\text{eV}$
  - Nuclear modification factor

$p-p$ at $\sqrt{s} = 14\text{ TeV} \rightarrow E_{\text{LAB}} = 10^{17}\text{ eV}$
The LHCf experiment

Detection of neutral particles having pseudorapidity $\eta > 8.4$

Two detectors installed in the TAN regions of IP1

Arm1

TAN (outside)

Arm2 inside TAN

Arm2
The LHCf detectors

**Arm1**

**Two sampling calorimeters**
- **Two towers**: 22 tungsten and 16 GSO scintillators layers
- **Depth**: 21 cm, $44 X_0$, $1.6 \lambda_i$
- **Energy resolution**: < 2% (photons)
  ~ 40% (hadrons)

- **Position resolution**: < 200 μm (photons)
  < 1 mm (hadrons)

**Tower Size**: 20 x 20 and 40 x 40 mm$^2$

**Imaging layers**: 4 x-y 1mm GSO bars

**Arm2**

**Two sampling calorimeters**
- **Tower Size**: 25 x 25 and 32 x 32 mm$^2$
- **Imaging layers**: 4 x-y 160μm Si microstrip

- **Position resolution**: < 40 μm (photons)
  < 800 μm (hadrons)
The LHCf acceptance

Neutron Event

Information on leading baryon and average inelasticity

Single Photon Event

Information on electromagnetic component

π⁰/η Event
Results from Run II
In $\eta > 10.75$ no model agrees with peak structure and production rate, whereas in the other regions, SIBYLL 2.3 and EPOS-LHC have better but not satisfactory agreement with the experimental measurements*

*:LHCf forward neutron spectra will be used for the next EPOS version!
Neutron Energy Flow & Inelasticity

$p$-$p \sqrt{s} = 13$ TeV

Most models reproduce the average inelasticity but not the distribution

$k = 2E/\sqrt{s}$

The energy flow is well described by EPOS-LHC

NB Elasticity/Inelasticity refers only to events where the neutron is the forward leading particle
Test of Feynman scaling using forward photons

First confirmation of Feynman scaling using zero-degree photons but no sensitivity to small $x_F$ dependency as in some models.
$\pi^0$ Production Rate

$p$-$p$ $\sqrt{s} = 13$ TeV

Different Arm1 and Arm2 geometries allows for a large $p_T$ vs $x_F$ coverage with an overlap to crosscheck results.

Good agreement between Arm1 and Arm2 data and between “Type-I” and “Type-II” events.
Among the large model variations, only QGSJETII-04 has good but not satisfactorily agreement with the experimental measurements.
The LHCf-ATLAS common operations leads to a much **higher degree of information** on processes responsible for forward production, allowing for accurate measurements of:

- Diffractive/Non-Diffractive production
- Multi-parton interaction process
- One-pion exchange process
- …

Forward photon production in \( \eta > 10.94 \)

Diffractive events can be distinguished from non-diffractive events by **ATLAS veto**:

Tracks=0 at \( |\eta|<2.5 \)
Operations in Run III
$p-p \sqrt{s} = 13.6$ TeV

Operations on September 24-26, 2022

Main Motivation

Thanks to the silicon DAQ upgrade and optimization of trigger scheme, significantly **enlarge the double-$\gamma$ event statistics** for more precise measurements of the production of $\pi^0$, $\eta$ and (possibly) $K^0_S$.

**Longest LHC Fill ever!**

September 24-26:
- Fill 8178 - 55h
- Fill 8179 - 2h

8 times larger statistics with respect to Run II

Much larger increase for the **double-$\gamma$ events** (Type-I and Type-II)

40 times larger statistics of **ATLAS common events** with respect to Run II

Data acquired in two different positions to completely cover the acceptance $\eta > 8.4$

- L$_{\text{int}} \sim 40$ nb$^{-1}$ per position

We expect a few **thousands of $\eta$ events** and a few **hundreds of $K^0_S$ events**
While the calibration of the detector is not yet completed, we started to make some preliminary check of the acquired data.

Accurate estimation of the projection of the beam center on the detector plane using hadron-like event hitmap reconstructed with the Arm2 silicon microstrip detector.

Data quality confirmed that the hardware was performing nicely; the hardware will be used as it is in the oxygen run (with the Arm2 detector only).
Preliminary studies
Collected statistics

While the calibration of the detector is not yet completed, we started to make some preliminary check of the acquired data.

LHCf-Arm2 Preliminary
pp $\sqrt{s}=13.6$ TeV 2022

- **Confirmation of the large increase in $\eta$ statistics** with respect to Run II data by roughly a **factor 10**:
  - $2.2 \times 10^4$ $\eta$ candidates

Type-II events will greatly improve the statistics thanks to dedicated trigger.
The large $\gamma\gamma$ event statistics collected in Run III allows for a precise measurement of forward $\pi^0$ and $\eta$ production with fine $p_T-x_F$ binning.

**LHCf Standalone analysis**
- Complete the calibration of Arm1 and Arm2 detectors
- Check preliminary spectra of forward $\gamma$ production
- Repeat the measurement of forward $\pi^0$ and $\eta$ production with much larger statistics
- Measure forward production of $K^0_s$ meson (using the decay $K^0_s \rightarrow 2\,\pi^0 \rightarrow 4\,\gamma$)

**ATLAS-LHCf joint analysis**
- Check the event alignment and the overall data quality
- Calibrate $\text{LHCf+ZDC}$ to reconstruct hadronic showers
- Measure the contribution of one pion exchange to forward neutron production

Differently from Run II, the presence of the ATLAS ZDC hadronic modules allows for an improvement of the LHCf energy resolutions to about 20%, which is necessary to accurately measure one pion exchange contribution.

Other interesting physics items, made possible by the jointly data taking with ATLAS, will be investigated on a longer time scale.
LHCf in Run III: p-O
Hopefully foreseen in 2024

Main Motivation
Both p-p and p-Pb collisions are not representative of the first interaction of a UHECR (which is a light nucleus) with an atmospheric nucleus (mainly N or O), hence the importance of p-O (and O-O) operations to avoid large extrapolation.

In addition, the main uncertainty in forward production from p-Pb collisions is due to contribution from Ultra-Peripheral Collisions (UPC background), which is irrelevant in the EAS case.

Run III is the last opportunity for LHCf!
A week of p-O (and possibly O-O) operations foreseen for 2024
The LHCf experiment highlighted *significant deviations* in forward production with respect to the current model expectations.

The data acquired in $p$-$p \sqrt{s} = 13.6$ TeV will improve our knowledge:

- High precision measurement on *forward $\pi^0$ and $\eta$ production*
- First event measurement of *$K^0_s$ production* in the forward region
- Insight into different production mechanisms (*LHCf-ATLAS*)

Of fundamental importance for CR are *$p$-$O$ runs* in 2024:

Run III is the *last chance* for LHCf experiment to take this data!
Thank you for the attention!
# Publication table

<table>
<thead>
<tr>
<th></th>
<th>$\gamma$</th>
<th>neutron</th>
<th>$\pi^0$</th>
<th>$\eta^0$</th>
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</table>
| Detector Calibration | NIM A, 671, 129 (2012)  
                          | JINST 12 P03023 (2017)  
                          | JINST 9 P03016 (2014) |                                             |          |
| p+Pb 5.02 TeV    |                                              |                                           |                                              |          |
| **Focus of this presentation** | | | | |
                          | JHEP 07 (2020) 16 | Analysis ongoing | submitted to JHEP |
| p+Pb 8.1 TeV     | Analysis ongoing |                                           |                                              |          |
Photons $d\sigma/dE$

$p-p\ \sqrt{s} = 13\ \text{TeV}$

**QGSJET II-04** is in good agreement for $\eta>10.94$, otherwise softer

**EPOS-LHC** is in good agreement below 3-5 TeV, otherwise harder
Test of Feynman scaling using $\pi^0$

Different collision energies at LHC/RHIC allows to test the Feynman scaling hypothesis using $\pi^0$ in $\sqrt{s}=2.76$ and 7 TeV

Feynman scaling holds at $\pm 20\%$ level

D’Enterria et al., 2011
Diffractive and non-diffractive production

$\sqrt{s} = 13 \text{ TeV} - \eta > 10.94$

LHCf measures the total production rate in the forward region

Different models lead to different contributions to diffractive and non-diffractive events

How to separate diffractive and non-diffractive production?

LHCf-ATLAS joint analysis
LHCf-ATLAS joint analysis

Preliminary result for photons in p-p $\sqrt{s} = 13$ TeV

After a preliminary test in 2013, in 2015 and 2016 LHCf and ATLAS experiments had common operation.

Diffractive events can be distinguished from non-diffractive events by ATLAS veto: tracks=0 at $|\eta|<2.5$
LHCF-ATLAS joint analysis
On-going analysis

Study of **mechanism of multiparton interaction** using neutron events in LHCF as proposed by S. Ostapchenko et al., Phys. Rev. D 94, 114026

**Strong central-forward correlation (QGSJET, EPOS)**
Initial part of parton cascade modeled as superposition of partons

**Weak central-forward correlation (SIBYLL, PYTHIA)**
Initial part of parton cascade modeled as universal state

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$d\sigma_{\text{neutron}}/dE$ (LHCF)

- $E_{\text{true}} > 4500 \text{ GeV}$
- $500 \text{ GeV} < E_{\text{true}} < 1500 \text{ GeV}$
- SIBYLL 2.3
- PYTHIA 8.212 DL
- EPOS-LHC
- QGSJET II-04

$N_{\text{charged}}$ (ATLAS)
GOAL: Increase the statistics for LHCf-ATLAS common analyses

GOAL: Identification of single diffractive events + measurements of:
- $\Delta$ resonance $(p+p \rightarrow p+\Delta \rightarrow p+p+\pi^0)$
- Bremsstrahlung $(p+p \rightarrow p+p+\gamma)$

GOAL: Indirect measurement of $p-\pi$ cross section via the contribution from one-pion exchange (OPE) with better hadron energy resolution

Operation with ALFA+AFP roman pots

Operation with ZDC ($\sigma_E/E = 40\% \rightarrow 20\%$)

using MC true information

LHCf-ATLAS joint analysis
Foreseen analysis with Run III data

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<th>Neutron Energy [GeV]</th>
<th>Bkg.</th>
<th>OPE</th>
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<tr>
<td>$</td>
<td>n</td>
<td>&lt;2.5$</td>
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$N_{\text{charged}} > 60 \quad r < 6\ mm$
Additional motivations for Run III: Operations with ATLAS ZDC

Indirect measurement of p-π cross section via one-pion exchange

Operation with ZDC (σ/E = 40% → 20%)

350 GeV proton

Preliminary

σ/E = 21%

Energy measured in Arm1+ZDC [GeV]

Operation with ZDC

LHCf

ATLAS ZDC

neutron

1.6 λ₁

1.1 λ₁ × 3

TAN (absorber for neutrals)

D1 dipole magnet

ATLAS INTERACTION REGION

D1 dipole magnet

TAN

Arm1

IP1

140 m

140 m

Arm2
Additional motivations for Run III: Operations with ATLAS AFP

Identification of single diffractive events
+ possible measurements of:
  • $\Delta$ resonance ($p+p \rightarrow p+\Delta \rightarrow p+p+\pi^0$)
  • Bremsstrahlung ($p+p \rightarrow p+p+y$)
Upgrade for Run III operations:
Upgrade of the silicon microstrip DAQ

Old electronics based on 100 Mbit/s Fiber Optical Transmitter/Receiver Interface (FOXI) transmitters

New electronics based on 1 Gbit/s fast optical links
The time necessary for readout+transmission of silicon data reduces from 370 μs to 200 μs

Dead time of Arm2 is now dominated by VME to read out GSO scintillators
In Run III, the maximum DAQ speed of the Arm2 detector increased from 0.5 to 1.5 kHz
Upgrade for Run III operations: Optimization of the trigger scheme

The different trigger schemes enhance different event categories

Small Tower

Photon energy small tower Arm2 run 80305

Large Tower

Photon energy large tower Arm2 run 80305
p-p $\sqrt{s} = 13.6$ TeV:
Hadron-like candidate in Small Tower
p-p $\sqrt{s} = 13.6$ TeV:
Type-I candidate
$p-p \sqrt{s} = 13.6$ TeV:
Type-II candidate in Small Tower
Higher collision energy is preferred because of larger LHCf acceptance

Expected luminosity
L\textsubscript{int} \sim 1.4 \text{ nb}^{-1} for p-O
L\textsubscript{int} \sim 0.7 \text{ nb}^{-1} for O-O

NeutronMultiplicity in one Tower
O-O

Nominal Position

15 mm Higher

Due to large multiplicity we will operate:
- p-O: with Arm2 on the proton-remnant side
- O-O: with Arm2 @ 15 mm higher than nominal
p-O and O-O operations:
Collision conditions

2022 conditions for p-p @ 13.6 TeV:
- $N_{\text{bunch}} = 144/500$
- $\Delta t_{\text{bunch}} = 525 \text{ ns}$
- $L < 10^{30} \text{ cm}^{-2}\text{s}^{-1}$
- $\theta_{\text{crossing}} = 290 \mu\text{rad}$
  - $\mu = 0.01 - 0.02$
  - $\beta^* = 19.2 \text{ m}$

Ideal conditions for p-O @ 9.9 TeV:
- $N_{\text{bunch}} = 24/43$
- $\Delta t_{\text{bunch}} = 2 \mu\text{s}$
- $L < 10^{29} \text{ cm}^{-2}\text{s}^{-1}$
- $\theta_{\text{crossing}} = 290 \mu\text{rad}$
  - $\mu = 0.01 - 0.02$
  - $\beta^* = 10 \text{ m}$

For each detector position
$L_{\text{int}} \sim 40 \text{ nb}^{-1}$

Higher collisions energy increases the LHCf detector acceptance

( Expected )

$E_{\text{int}} \sim 0.7 \text{ nb}^{-1}$ for p-O
nominal position
$L_{\text{int}} \sim 0.7 \text{ nb}^{-1}$ for p-O
+5 mm higher position
$L_{\text{int}} \sim 0.7 \text{ nb}^{-1}$ for O-O
p-O and O-O operations:
Main experimental challenge

**Neutron Multiplicity in Small Tower**

**Proton remnant side**

LHCf can safely operate on proton-remnant side since it can separately reconstruct two particles in same tower and less than 10% of events have more than a particle.

**Oxygen remnant side**

Due to high multiplicity, LHCf can operate on oxygen remnant side only 15 mm higher ($\eta<11$).