Recent results from the LHCf experiment

Alessio Tiberio

*University of Florence*

on behalf of the LHCf Collaboration

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Outline

- Physics motivations of LHCf
- Experimental setup
- Latest analysis:
  - neutron energy spectra in 7 TeV p-p collisions
  - $\pi^0 P_T$ spectra in 5.02 TeV p-Pb collisions
- Upgrades for 13 TeV operations in 2015
The LHCf collaboration

Y. Itow\textsuperscript{1,2}, K. Kawade\textsuperscript{1}, Y. Makino\textsuperscript{1}, K. Masuda\textsuperscript{1}, Y. Matsubara\textsuperscript{1}, E. Matsubayashi\textsuperscript{1}, H. Menjo\textsuperscript{3}, Y. Muraki\textsuperscript{1}, T. Sako\textsuperscript{1}, N. Sakurai\textsuperscript{1}, Y. Sugiura\textsuperscript{1}, Q. D. Zhou\textsuperscript{1}

\textsuperscript{1} Solar-Terrestrial Environment Laboratory, Nagoya University, Japan
\textsuperscript{2} Kobayashi-Maskawa Institute, Nagoya University, Japan
\textsuperscript{3} School of Science, Nagoya University, Japan

K. Kasahara, Y. Shimitsu, T. Suzuki, S. Torii \textit{RISE, Waseda University, Japan}

T. Tamura \textit{Kanagawa University, Japan}

K. Yoshida \textit{Shibaura Institute of Technology, Japan}

M. Haguenauer \textit{Ecole Polytechnique, France}

W. C. Turner \textit{LBNL, Berkeley, USA}


\textit{INFN, Università di Firenze, Italy}

A. Tricomi \textit{INFN, Università di Catania, Italy}

A-L. Perrot, D. Pfeiffer \textit{CERN, Switzerland}
High energy cosmic rays

Very low flux at high energies

Only indirect measurements

Flux of Cosmic Rays

1 particle per m² – second

Knee (1 particle per m² – year)

Indirect

Direct

Ankle (1 particle per km² – year)

(source: Swordy – U.Chicago)

Credit: ASPERA/G.Toma/A.Saftoiu
Indirect measurements

Air showers measurements:
- Longitudinal distribution
- Lateral distribution
- Arrival direction

Astrophysical parameters:
- Spectrum
- Composition
- Sources distribution

Monte Carlo simulations of air showers with accurate hadronic interaction models are needed
Contributions from accelerator experiments

- **Inelastic cross section**
  - Large → rapid development
  - Small → deep penetrating

- **Inelasticity** $k = 1 - \frac{p_{\text{lead}}}{p_{\text{beam}}}$
  - Large → rapid development
  - Small → deep penetrating

- **Forward energy spectrum**
  - Softer → rapid development
  - Harder → deep penetrating

- **Nuclear effects**

  Contributions from accelerator experiments

  - Soft interactions dominate (non-perturbative QCD)
  - Several phenomenological models proposed

Inputs from experimental data are important
Two detectors are located 140m away from ATLAS (Interaction Point 1) along the beam line.
Experimental setup

- **Two independent detectors**
- **Two sampling calorimeters** ("towers") in each detector: tungsten and 16 plastic scintillators (EJ-260)
- Depth: $44 \times 0.1, 1.6 \lambda$
- Energy resolution < 5% photons ~ 40% neutrons

- **Arm1**
  - 20 x 20 mm$^2$ & 40 x 40 mm$^2$ calorimeters
  - 4 x-y SciFi tracking layers
  - Position resolution: < 200 μm

- **Arm2**
  - 25 x 25 mm$^2$ & 32 x 32 mm$^2$ calorimeters
  - 4 x-y silicons microstrip tracking layers
  - Position resolution: 40 μm

LHCf is located in TAN slots very forward particles

Charged particles are deviated by D1 dipole magnet

Only neutral particles (photons and neutrons)

IP8 (LHCb)

~ 8 cm

IP1 (ATLAS)

140 m

Beam line

IP2 (ALICE)

~ 6 cm

LHCf is located in TAN slots very forward particles

Charged particles are deviated by D1 dipole magnet

Only neutral particles (photons and neutrons)

Arm1

Arm2

Beam line

INCOMING NEUTRAL PARTICLE BEAM
Arm1 & Arm2 detectors

290mm
Arm#1 Detector

90mm

Arm#2 Detector
Forward energy flux @ LHC

p-p collisions @ $\sqrt{s} = 14$ TeV

E$_{cr} = 10^{17}$ eV

LHCf pseudo-rapidity range: $\eta > 8.4$
(with 140 $\mu$rad beam crossing angle)

LHCf covers the peak of energy flow

Pseudo-rapidity

$\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$
## Status of analysis

<table>
<thead>
<tr>
<th></th>
<th>$E_{\text{CR}}$ [eV]</th>
<th>Photons</th>
<th>Neutrons</th>
<th>$\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-p @ 2.76 TeV</td>
<td>$4.1 \times 10^{15}$</td>
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<tr>
<td>p-Pb @ 5.02 TeV</td>
<td>$1.3 \times 10^{16}$</td>
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Neutrons analysis in p-p collisions at 7 TeV

Energy resolution ~40% above 500 GeV (due to high leakage)

True spectrum is smeared by detector response

Unfolding is needed to extract physics results

Energy resolution

\[ \sigma_E/E \sim 40\% \text{ because of } 1.6\lambda \]

- Neutron measurements are important to explain the "muon excess" observed in ground based experiments
Inclusive neutron energy spectra in p-p at 7 TeV

- Large amount of high energy neutrons for $\eta > 10.76$ (only predicted by QGSJET)
- Small inelasticity in the very forward region

Before unfolding

After unfolding
π^0 analysis in p-Pb collisions at 5.02 TeV

- Only Arm2 installed (better position resolution than Arm1)
- Data taken both at p-side and Pb-side (swapping beams)

Soft-QCD processes

- Central collision
- Peripheral collision

Ultra peripheral collisions (UPC)

About half of the observed π^0 originates from UPC, another half is generated in soft-QCD processes

Dominant channel for forward π^0 production:
p + γ^* → Δ(1232) → p + π^0

UPC contribution to P_T spectra is estimated from MC simulations (using Weizsacker Williams approximation for γ^* spectrum and SOPHIA model for p-γ^* collision)
π^0 reconstruction

π^0 candidate: one photon in each tower

π^0 detection efficiency
p-Pb √s=5.02 TeV

Unfolding the smeared P_T spectra and correction for geometrical inefficiency

BG subtraction by sideband

UPC subtraction

LHCf data
UPC MC (x0.5)
Inclusive $\pi^0$ $P_T$ spectra in p-Pb

- Data (filled circles) are in good agreement with DPMJET and EPOS MC
- p-Pb spectra are harder than p-p spectra (shaded area, multiplied by 5)
- p-p spectra at 5.02 TeV are interpolated from results at 2.76 and 7 TeV
Nuclear modification factor in p-Pb

Both data and MC shows strong suppression
NMF grows with $P_T$ as expected
(p-Pb spectra are harder than p-p spectra)

$$R_{pPb}(p_T) \equiv \frac{\sigma_{\text{pp}}^{\text{inel}}}{\langle N_{\text{coll}} \rangle \sigma_{\text{PbPb}}^{\text{inel}}} \frac{E d^3 \sigma_{PbPb}^{\text{pp}}/dp^3}{E d^3 \sigma_{\text{pp}}/dp^3}$$

$\langle N_{\text{coll}} \rangle = 6.9$
Upgrades for 13 TeV operations

- More radiation damage is expected: 0.2 Gy/nb @7 TeV, 2-3 Gy/nb @13 TeV
  - All plastic scintillators have been substituted with GSO scintillators (can survive up to $10^6$ Gy)
  - In Arm1, scintillation fibers were replaced with GSO bars (1 x 1 x 20 mm$^3$ and 1 x 1 x 40 mm$^3$ for small and large tower respectively)
- In old configuration, silicons detectors in Arm2 saturate for photons with energy > 1.5 TeV
  - Signal reduced (~ 60%) by using a new bonding scheme: half of the silicon strips now are grounded, while in the old configuration were floating
- Silicon detectors positions were changed to better catch E-M and hadronic showers
Summary

- LHCf can contribute to reduce systematic uncertainties on hadronic interaction models
- Data in p-p and p-Pb collisions were taken to study QCD processes and nuclear effects
- Measurements of spectra of leading barions (neutrons) and leading mesons ($\pi^0$) were done
- Detectors are ready to operate at $\sqrt{s} = 13$ TeV in 2015
Backup slides
Models tuning after LHC data

\[ X_{\text{MAX}} \equiv \text{depth of air shower maximum in atmosphere} \]

Depends on energy and type of primary particle

Uncertainty in hadronic interaction models

Uncertainty in \( X_{\text{MAX}} \) interpretation

Smaller differences between different models after LHC operations
Photons spectra in p-p at 7 TeV
Photons spectra in p-p at 900 GeV
Feynman X scaling

- Comparison in the same $P_T$ range ($P_T < 0.13 \times X_F$ GeV/c)
- Normalized by # of events with $X_F > 0.1$
- Statistical error only
Photons selection

- **L90%**: depth in $X_0$ where 90% of the deposited energy is contained

- Energy-dependent threshold to keep photon detection efficiency at 90%

- Events with L90% less than threshold are recognized as photons
Neutrons selection

- A 2D method based on longitudinal shower development is used.
- \( L_{20\%}(L_{90\%}) \): depth in \( X_0 \) where 20\% (90\%) of the deposited energy is contained.
- \( L_{2D} = L_{90\%} - 0.25 \cdot L_{20\%} \)
- Mean purity in the 0-10 TeV range: 95\%
- Mean efficiency: \(~90\%\)
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\[ m_{\pi^0} = \sqrt{E_1 E_2 \theta} \]