Status of the LHCf experiment

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on behalf of the LHCf collaboration
The LHCf collaboration


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Introduction

Air Shower Technique

Extensive air shower observation
- longitudinal distribution
- lateral distribution
- Arrival direction

Astrophysical parameters
- Spectrum
- Composition
- Source distribution

Air shower development

LHC experiments
Test the hadronic interaction models at $\sqrt{s}=13$ TeV, $E_{\text{lab}}=0.9 \times 10^{17}$ eV

Proton
Iron

Average depth of shower max. $\langle X_{\text{max}} \rangle$ ($\text{g/cm}^2$)

Energy per particle $E_{\text{prim}}$ (eV)

arxiv:1510.00568

SIBYLL 2.3rc3b
SIBYLL 2.1
EPOS LHC
QGSjetII-04

Proton
Iron

Haverah Park
Auger 2014
Yakutsk 2010
HiRes / MIA
Fly’s Eye

ALICE
CMS/TOTEM
LHCb/MoEDAL
ATLAS/LHC forward
Cross section
- If large $\sigma_{\text{ine}}$: rapid development
- If small $\sigma_{\text{ine}}$: deep penetrating

Very forward energy spectrum
- If softer shallow, development
- If harder deep, penetrating

Elasticity $k = \frac{E_{\text{lead}}}{E_{\text{avail}}}$
- If small $k$ ($\pi^0$s carry more energy): rapid development
- If large $k$ (baryons carry more energy): deep penetrating

Forward angular emission

Secondary particle multiplicity

Secondary interactions ($n, p, \pi$)

Multiplicity

Energy Flow

Pseudorapidity

\[ \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \]
Experimental Setup

**LHCf**

- Two independent detectors: **Arm1 and Arm2** in both sides of ATLAS interaction points
- Pseudorapidity coverage: \( \eta > 8.4 \)
- Measure neutral particles **Photon, Neutrons and \( \pi^0 \)**

Charged particles are swept out by the magnetic field of the dipole magnets

**ATLAS**

Interaction point

140 m

96 mm
The LHCf detectors

**Front Counter**
- thin scintillators with 80x80mm²
- To monitor beam condition.
- For background rejection of beam-residual gas collisions by coincidence analysis

**Sampling and Positioning Calorimeters**
- W (44 r.l, 1.7λ) and Scintillator x 16 Layers
- Four positioning sensitive layers
  - XY-Scintillator bars (Arm1) and XY-Silicon strip (Arm2)
- Each detector has two calorimeter towers, which allow to reconstruct π⁰

**Expected Performance**
- Energy resolution (> 100GeV)
  - < 5% for Photons
  - 40% for Neutrons
- Position resolution
  - < 200µm for Photons
  - a few mm for Neutrons
The LHCf detectors

Arm1 Detector

silicon strip detector

Detector in the LHC tunnel

GSO Scintillator
The LHCf history

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

Jan 2008
Installation
Sep
1st LHC beam

Aug 2007
SPS beam test

Dec 2009 - Jul 2010
0.9TeV & 7TeV p-p
(detector removal)

Dec 2012- Feb 2013
5TeV/n p-Pb, 2.76TeV p-p
Arm2 only
(detector removal and upgrade)

May-June 2015
13 TeV dedicated p-p
(detector removal)

Nov. 2016
5TeV/n & 8TeV/n p+Pb
Arm2 only
(detector removal)
## Status of analysis

<table>
<thead>
<tr>
<th>Run</th>
<th>$E_{\text{lab}}$ (eV)</th>
<th>Photon</th>
<th>Neutron</th>
<th>$\pi^0$</th>
</tr>
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<tbody>
<tr>
<td>p-p $\sqrt{s}=0.9\text{TeV}$</td>
<td>$4.3\times10^{14}$</td>
<td>PLB 715, 298 (2012)</td>
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<td>p-p $\sqrt{s}=2.76\text{TeV}$</td>
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<td>PRD 86, 092001 (2012)</td>
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<td>PBL 750 360 (2015)</td>
<td>PRC 86, 065209 (2014)</td>
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<td>p-p $\sqrt{s}=13\text{TeV}$</td>
<td>$9.0\times10^{16}$</td>
<td>Submitted to PBL</td>
<td>Preliminary</td>
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<td>p-Pb $\sqrt{s_{\text{NN}}}=5\text{TeV}$</td>
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<td>Operation in Nov. 2016</td>
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<tr>
<td>RHICf p-p $\sqrt{s}=510\text{GeV}$</td>
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Photon Energy Spectra

Figure 4: Comparison of the photon spectra obtained from the experimental data and MC predictions. The top panels show the energy spectra, and the bottom panels show the ratio of MC predictions to the data. The hatched areas indicate the total uncertainties of experimental data including the statistical and the systematic uncertainties.

Acknowledgments
We thank the CERN staff and the ATLAS Collaboration for their essential contributions to the successful operation of LHCf. This work was partly supported by JSPS KAKENHI Grant Numbers JP26247037, JP23340076 and the joint research program of the Institute for Cosmic Ray Research (ICRR), University of Tokyo. This work was also supported by Istituto Nazionale di Fisica Nucleare (INFN) in Italy. Parts of this work were performed using the computer resource provided by ICRR (University of Tokyo), CERN and CNAF (INFN).

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References


EPOS-LHC Good agreement in < 3,4 TeV of both high/low-\(\eta\)
QGSJET II-04 Very nice overall agreement in the high-\(\eta\)
Softer in the low-\(\eta\)
SIBYLL 2.3 Very nice overall agreement in the high-\(\eta\)
Harder in the low-\(\eta\)
Photon Energy Flow

Energy Flow Calculation:

\[
\frac{dE}{d\eta} = C_{\text{thr}} \frac{1}{\Delta \eta} \sum_{E_j > 200\,\text{GeV}} E_j F(E_j)
\]

F(Ej) : Measured differential cross-section
\(\Delta \eta\) : The pseudo-rapidity range
\(C_{\text{thr}}\) : Correction factor for the threshold 200 GeV → 0 GeV.

Ref: Y. Makino CERN-THESIS-2017-049

EPOS-LHC, SIBYLL2.3  Good agreement
QGSJET II-04 ~ 30% lower than data
Neutron Analysis

Motivation

- Inelasticity measurement $k_{\text{inela}}$
  \[ k_{\text{inela}} = 1 - \frac{E_{\text{leading}}}{E_{\text{beam}}} \]
- Large discrepancies between data and model prediction were found in the previous analysis of p-p, $\sqrt{s}=7\text{TeV}$

Analysis

- Particle Identification
  EM shower $\rightarrow$ develop in shallow layers
  Hadronic showers $\rightarrow$ develop in deep layers
- Energy resolution of 40%
- Contamination of $\Delta^0$, $K^0$

Poster by M. Ueno; CRI185
Figure 5.3: Unfolded neutrons energy spectra for p-p collisions at $p_{\text{s}} = 13$ TeV measured by the LHCf Arm2 detector. Black markers are experimental data with statistical uncertainty, whereas gray bands represent the quadrature sum of statistical and systematic uncertainty. Histograms refer to generators spectra simulated using CRMC. Top are energy distributions expressed as $\frac{dN}{dE}$ and bottom are the ratios of these distributions to the experimental data.

Ref: E.Berti CERN-THESIS-2017-035
Neutron Energy Spectra

Figure 5.3: Unfolded neutrons energy spectra for p-p collisions at $p_s = 13\,\text{TeV}$ measured by the LHCf Arm2 detector. Black markers are experimental data with statistical uncertainty, whereas gray bands represent the quadrature sum of statistical and systematic uncertainty. Histograms refer to generators spectra simulated using CRMC. Top are energy distributions expressed as $\frac{dN}{dE}$ and bottom are the ratios of these distributions to the experimental data.

- $\eta > 10.76$
  - QGSJET II-04
  - EPOS-LHC
  - Best agreement in $\eta > 10.76$

- $8.99 < \eta < 9.22$
  - QGSJET II-04
  - EPOS-LHC
  - Good Agreement in $8.81<\eta<8.99$ and $8.99<\eta<9.22$

- $8.81 < \eta < 8.99$
  - QGSJET II-04
  - EPOS-LHC
  - Preliminary

Data (Arm2)
- QGSJET II-04
- EPOS-LHC
- DPMJET 3.06
- PYTHIA 8.212
- SIBYLL 2.1
**Short summary of p-p, 13TeV analyses**

### Photon Results

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<thead>
<tr>
<th>Model</th>
<th>$\eta &gt; 10.94$</th>
<th>$8.81 &lt; \eta &lt; 8.99$</th>
<th>Energy flow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPOS-LHC</strong></td>
<td>Good in &lt; 4 TeV</td>
<td>Good in &lt; 3 TeV</td>
<td>Good</td>
</tr>
<tr>
<td><strong>QGSJET II-04</strong></td>
<td>Good</td>
<td>Softer than data</td>
<td>30% lower</td>
</tr>
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<td><strong>SIBYLL 2.3</strong></td>
<td>Good</td>
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### Neutron Results

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<th>$8.81 &lt; \eta &lt; 8.99$, $8.99 &lt; \eta &lt; 9.22$</th>
<th>Energy flow</th>
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<tr>
<td><strong>EPOS-LHC</strong></td>
<td>lower flux than data</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td><strong>QGSJET II-04</strong></td>
<td>Best in the models</td>
<td></td>
<td>Good</td>
</tr>
</tbody>
</table>
On-going analyses

Recent activities

New data

Joint analysis with ATLAS
On-going analyses

With p-p, $\sqrt{s} = 13$TeV data

- Complete the neutron analysis.
- $\pi^0$ analysis
- $\eta$ meson analysis

$\eta \rightarrow 2\gamma (39\%)$
- $\rightarrow 3\pi^0 (33\%)$
- s̅s contribution

$\eta \rightarrow 2\gamma (39\%)$
- $\rightarrow 3\pi^0 (33\%)$
- s̅s contribution

Invariant mass distribution of photon pairs

V.A. Khoze et al., arXiv:1705.03685
Joint Analysis with ATLAS

ATLAS (Central region)  +  LHCf (Very Forward region)  \[\Rightarrow\]

Common operation scheme

- Common operation with ATLAS in 2013 (p-Pb 5 TeV, p-p, 2.76 TeV), 2015 (p-p, 13 TeV) and 2016 (p-Pb, 5TeV, 8TeV)
- Joint analysis of p-p 13TeV data is ongoing with ATLAS soft-QCD group.

Powerful tool to understand the processes of forward particle production:
- Detailed tests of models
- Providing some parameters as the low-mass diffractive cross section
Joint Analysis with ATLAS - Selection of Diffractive interactions -

Non-diffraction event view

Proton

LHCf

Diffraction

Δη

Rapidity gap

Proton

LHCf

EPOS-LHC

QGSJET II-04

SIBYLL2.3

PYTHIA

Poster by Q. Zhou; CRD131
New data

The LHC tunnel again

- **p+Pb $\sqrt{s_{NN}} = 8.1$ TeV**
  - Operation in November 2016
  - Measurement of the nuclear modification factor at the highest energy
  - Common operation with ATLAS

RHIC at BNL (The RHICf experiment)

- **p+p $\sqrt{s} = 510$ GeV**
  - (polarized beam)
  - Operation in June 2017.
  - Test of energy scaling with the wide $p_T$ range.
    - (The XF-$p_T$ coverage is almost same as LHCf @ $p+p \sqrt{s}=7$TeV)
  - Common operation with STAR

Poster by T. Sako, CRI086
Both operations were successfully completed.
Summary

- Forward energy spectra for photons and neutrons measured at p-p, $\sqrt{s}=13$TeV were presented.
  - EPOS-LHC showed overall good agreement with data for photons.
- LHCf continues the activities to provide critical data to test and tune the hadronic interaction models.
  - On-going analyses; neutrons, $\pi^0, \eta$
  - LHCf-ATLAS joint analyses.
  - New data; p-Pb collisions, RHICf at p-p, $\sqrt{s}=510$GeV.
- The final goal of the LHCf experiment is the measurement at p-light A, light A-A (p-N, N-N)
Backup
Operation with $p+p, \sqrt{s}=13\text{TeV}$

- **Physics Motivation**
  - Test the hadronic interaction models at the highest collision energy. $E_{\text{Lab}}=0.9 \times 10^{17}\text{eV}$
  - Energy Scaling
  - Enlarge the $p_T$ acceptance.

- **Operation**
  - Dedicated run with low pile-up in 9 - 13 June 2015
  - Common operation with ATLAS.
No model can reproduce the LHCf data perfectly.  
**DPMJET** and **PYTHIA** are in good agreement at high-$\eta$ for $E_\gamma < 1.5$ TeV, but harder in $E > 1.5$ TeV.  
**QGSJET** and **SIBYLL** shows reasonable agreement of shapes in high-$\eta$ but not in low-$\eta$.  
**EPOS** has less $\eta$ dependency against the LHCf data.
Neutron energy spectra at p+p, 7 TeV

The motivation of forward neutron measurement is for inelasticity measurement, k = 1 - p_{leading}/p_{beam}

**QGSJET II-04** predicted the high energy peak at high-\(\eta\) but lower flux in the lower-\(\eta\)

**DPMJET3.04** nice agreement in middle/low-\(\eta\)
$\pi^0$ $p_T$ spectra at $p+p$, 7TeV

- **QGSJETII-04**: best agreement
- **EPOS-LHC**: harder than data for large $p_T$
- **SYBILL**: good agreement only for small $\gamma$
π⁰ p_z (≈ E) spectra at p+p, 7TeV

DPMJET and Pythia overestimate over all E-p_T range

PRD 94 (2016) 032007