Recent results from LHCf

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On behalf of the LHCf collaboration

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Large Hadron Collider
- The most powerful accelerator on the earth-

Ultra High Energy Cosmic Rays
What is the most powerful accelerator in the Universe?
The LHCf collaboration


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**Introduction**

**HECRs**

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

Air shower development

Astrophysical parameters
- Spectrum
- Composition
- Source distribution

**$X_{\text{max}}$ distribution measured by AUGER**

*$X_{\text{max}}$* is the depth of air shower maximum. An indicator of CR composition

Uncertainty of hadron interaction models

Error of $<X_{\text{max}}>$ measurement
Air Shower development

- **Total cross section**
  - Large $\sigma \rightarrow$ rapid development
  - Small $\sigma \rightarrow$ deep penetrating

- **Multiplicity (N)**
  - Large $N \rightarrow$ rapid development
    - large number of muons
  - Small $N \rightarrow$ deep penetrating
    - small number of muons

- **Inelasticity ($k$)/Secondary spectra**
  - Large $k$, Softer spectra
    - rapid development
  - Small $k$, harder spectra
    - deep penetrating
The Large Hadron Collider (LHC)

\[
\begin{align*}
pp & \quad 7\text{TeV}+7\text{TeV} & \rightarrow & \quad E_{\text{lab}} = 10^{17}\text{eV} & \quad 2014- \\
pp & \quad 3.5\text{TeV}+3.5\text{TeV} & \rightarrow & \quad E_{\text{lab}} = 2.6 \times 10^{16}\text{eV} \\
pp & \quad 450\text{GeV}+450\text{GeV} & \rightarrow & \quad E_{\text{lab}} = 2 \times 10^{14}\text{eV}
\end{align*}
\]
Whole pseudo-rapidity is covered by the LHCf experiments

**Key parameters for air shower developments**

- **Total cross section**: ↔ TOTEM, ATLAS, CMS
- **Multiplicity**: ↔ Central detectors
- **Inelasticity/Secondary spectra**: ↔ Forward calorimeters

LHCf, ZDCs

D. d”Enterria, (2007)
The LHCf experiment

LHCf Detector (Arm#1)

Two independent detectors at either side of IP1 (Arm#1, Arm#2)

TAN - Neutral Particle Absorber-
transition from one common beam pipe to two pipes
Slot: 100mm(w) x 607mm(H) x 1000mm(T)
The LHCf Detectors

Sampling and Positioning Calorimeters

- W (44 r.l, 1.7λ₁) and Scintillator x 16 Layers
- 4 positioning layers
  - XY-SciFi(Arm1) and XY-Silicon strip(Arm#2)
- Each detector has two calorimeter towers, which allow to reconstruct π⁰

Expected Performance
- Energy resolution (> 100GeV)
  - < 5% for photons
  - 30% for neutrons
- Position resolution
  - < 200µm (Arm#1)
  - 40µm (Arm#2)

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

\( \eta > 8.7 \) @ zero crossing angle

\( \eta > 8.4 \) @ 140urad

Shadow of beam pipes between IP and TAN
LHCf can measure

Energy spectra and Transverse momentum distribution of:
- Gamma-rays ($E > 100$ GeV, $dE/E < 5\%$)
- Neutral Hadrons ($E > a$ few 100 GeV, $dE/E ~ 30\%$)
- $\pi^0$ ($E > 600$ GeV, $dE/E < 3\%$)

at pseudo-rapidity range $> 8.4$

Energy Flux @14TeV

Low multiplicity !!

Energy Flux @14TeV

High energy flux !!
Contribution of diffractive events

Multiplicity of $\pi^0$ @ 7TeV, $p$-$p$

Energy flux of $\pi^0$ @ 7TeV, $p$-$p$

Double diffractive $\pi^0$

Single diffractive $\pi^0$ (one side)

Generated by PYTHIA 8.145
Operation in 2009-2010

At 450GeV+450GeV p-p
• 06 Dec. – 15 Dec. in 2009
  27.7 hours for physics, 2.6 hours for commissioning
  ~2,800 and ~3,700 shower events in Arm1 and Arm2
• 02 May – 27 May in 2010
  ~15 hours for physics
  ~44,000 and ~63,000 shower events in Arm1 and Arm2

At 3.5TeV+3.5TeV p-p
• 30 Mar. – 19 July in 2010
  ~150 hours for physics with several setup
  With zero crossing angle and with 100µrad crossing angle.
  ~2x10^8 and ~2x10^8 shower events in Arm1 and Arm2

Operation at $\sqrt{s} = 900$GeV and 7TeV has been completed successfully. The detectors has been removed from the LHC tunnels at July 2010, and will be upgraded for the future operations.
Forward photon spectrum at $\sqrt{s} = 7$TeV p-p collisions

“Measurement of zero degree single photon energy spectra for $\sqrt{s} = 7$ TeV proton-proton collisions at LHC“

DATA
- 15 May 2010 17:45-21:23, at Low Luminosity $6 \times 10^{28} \text{cm}^{-2}\text{s}^{-1}$
- 0.68 nb-1 for Arm1, 0.53 nb-1 for Arm2

MC
- DPMJET3.04, QGSJETII03, SYBILL2.1, EPOS1.99
- PYTHIA 8.145 with the default parameters.
- $10^7$ inelastic p-p collisions by each model.

Analysis Procedure
- Energy Reconstruction from total energy deposition in a tower with some corrections, shower leakage out etc.
- Particle Identification by shape of longitudinal shower development.
- Cut multi-particle events.
- Two Pseudo-rapidity selections, $\eta > 10.94$ and $8.81 < \eta < 8.9$.
- Combine spectra between the two detectors.
Event sample

Longitudinal development measured by scintillator layers

- 25mm Tower ➔ 600GeV photon
- 32mm Tower ➔ 420GeV photon

Total Energy deposit ➔ Energy Shape ➔ PID

Lateral distribution measured by silicon detectors

- X-view
- Y-view

Hit position, Multi-hit search.

π⁰ mass reconstruction from two photon.

\[ M_{\pi^0} = \sqrt{E_{\gamma1} E_{\gamma2}} \cdot \theta \]
Event selection and correction

- Select events < $L_{90\%}$ threshold and multiply $P/\varepsilon$
  - $\varepsilon$ (photon detection efficiency) and $P$ (photon purity)
- By normalizing MC template $L_{90\%}$ to data, $\varepsilon$ and $P$ for certain $L_{90\%}$ threshold are determined.

Calorimeter Depth

- Elemag: 44r.l.
- Hadronic: 1.7$\lambda$

Particle Identification

- dE
- Shower development
- Photons
- Hadrons
- Calorimeter layers
- Integral of dE
- Calorimeter layers

$L_{90\%}$ Distribution

- LHCf \( \sqrt{s} = 7 \text{ TeV} \)
- 500 GeV < $E_{\text{jet}}$ < 1 TeV
- $\eta > 0.94$, $\Delta \phi = 360$
- Arm1, Data 2010, $L_{\text{int}} = 0.68 \text{ nb}^{-1}$
- Arm1, QGSJET II-03 (Photon)
- Arm1, QGSJET II-03 (Hadron)
Multi-hit identification

- Event cut of multi-peak events,
  - Identify multi-peaks in one tower by position sensitive layers.
  - Select only the single peak events for spectra.

An example of multi peak event

Single hit detection efficiency

Double hit detection efficiency

Arm 1

Arm 2
Comparison between the two detector

- Pseudo-rapidity selection, $\eta>10.94$ and $8.81<\eta<8.9$
- Normalized by number of inelastic collisions with assumption as inelastic cross section of 71.5mb
- Spectra in the two detectors are consistent within errors.
  - Combined between spectra of Arm1 and Arm2 by weighted average according to errors

![Comparison between Arm1 and Arm2 detectors](image_url)
Comparison between MC’s

DPMJET 3.04  QGSJETII-03  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145

Gray hatch: Systematic Errors
Blue hatch: Statistics errors of MC

LHCf √s=7TeV
Gamma-ray like

\eta > 10.94, \Delta\phi = 360°

8.81 < \eta < 8.99, \Delta\phi = 20°
Comparison between MC’s

DPMJET 3.04  QGSJETII-03  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145

Gray hatch : Systematic Errors
Blue hatch: Statistics errors of MC

No model are able to reproduce the LHCf results perfectly
Forward photon spectrum at $\sqrt{s} = 900\text{GeV}$ $p$-$p$ collisions

“Measurement of zero degree inclusive photon energy spectra for $\sqrt{s} = 900$ GeV proton-proton collisions at LHC“

900GeV photon analysis

- **DATA**
  - 2,3 and 27 May 2010, Low Luminosity $3-12 \times 10^{28}$ cm$^{-2}$s$^{-1}$
  - 0.30 nb$^{-1}$ (DAQ Live time. Arm1:99.2%, Arm2:98.0%)

- **MC**
  - DPMJET3.04, QGSJETII03, SYBILL2.1, EPOS1.99 PYTHIA 8.145 with the default parameters.
  - ~$3 \times 10^7$ inelastic p-p collisions by each model.

- **Analysis Procedure**
  - Energy Reconstruction from total energy deposition in a tower with some corrections, shower leakage out etc.
  - Particle Identification by shape of longitudinal shower development.
  - Cut multi-particle events. Few multi-particle events are expected
  - Two Pseudo-rapidity selections, $\eta > 10.15$ and $8.77 < \eta < 9.46$.
  - Combine spectra between the two detectors.
900GeV photon analysis

Two pseudo-rapidity ranges
- $\eta > 10.15$
- $8.77 < \eta < 9.46$

Arm1 and Arm2 data show an overall good agreement within their systematic uncertainties.

Arm1 data vs Arm2 data
900GeV photon analysis

Cross section of LHCf detectors

Beam pipe shadow

Arm1

Arm2

Two pseudo-rapidity ranges
- $\eta > 10.15$
- $8.77 < \eta < 9.46$

Arm1 and Arm2 data show an overall good agreement within their systematic uncertainties.
900GeV photon analysis

Two pseudo-rapidity ranges
- $\eta > 10.15$
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Arm1 and Arm2 data show an overall good agreement within their systematic uncertainties.
900GeV photon analysis

Combined data vs MC simulations

LHCf $\sqrt{s} = 900$GeV, Photon like

$\eta > 10.15$ ($\langle \eta \rangle = 39$ $\mu$rad)

$8.77 < \eta < 9.46$ ($\langle \eta \rangle = 234$ $\mu$rad)
DATA-MC : comp. 900GeV/7TeV

MC/Data

η > 10.94

LHCf \sqrt{s}=900\text{GeV}, Photon like
η > 10.15 (\langle \theta \rangle = 39 \text{ mrad})

LHCf \sqrt{s}=900\text{GeV}, Photon like
8.77 < η < 9.46 (\langle \theta \rangle = 234 \text{ mrad})
**Coverage of 900GeV and 7TeV results in Feynman-X and \( P_T \)**

- 900GeV vs. 7TeV with the same PT region

*Normalized by the number of entries in \( X_F > 0.1 \)*
*No systematic error is considered in both collision energies.*

**Good agreement of \( X_F \) spectrum shape between 900GeV and 7TeV. ➔ Checking more for the Feynman scaling now.**
Forward \( \pi^0 \) spectra at \( \sqrt{s} = 7\text{TeV} \) p-p collisions

“It will be submitted soon.”
Mass, energy and transverse momentum are reconstructed from the energies and impact positions of photon pairs measured by each calorimeter

\[ M_{\pi^0} = \sqrt{E_{\gamma 1}E_{\gamma 2}\theta^2}, \]
\[ E_{\pi^0} = E_{\gamma 1} + E_{\gamma 2}, \]
\[ P_{T\pi^0} = P_{T\gamma 1} + P_{T\gamma 2}. \]

**Analysis Procedure**

- Standard photon reconstruction
- Event selection
  - one photon in each calorimeter
  - reconstructed invariant mass
- Background subtraction by using outer region of mass peak
- Unfolding for detector response.
- Acceptance correction.

Dedicated part for \( \pi^0 \) analysis
7TeV $\pi^0$ analysis

Signal window : $[-3\sigma, +3\sigma]$
Sideband : $[-6\sigma, -3\sigma]$ and $[+3\sigma, +6\sigma]$

Remaining background spectrum is estimated using the sideband information, then the BG spectrum is subtracted from the spectrum made in the signal window.

$$\text{Signal} = f(E, P_T)^{signal} - f(E, P_T)^{BG} \frac{\int_{\hat{M}-3\sigma_i}^{\hat{M}+3\sigma_u} L_{BG} dM}{\int_{\hat{M}-6\sigma_i}^{\hat{M}-3\sigma_i} L_{BG} dM + \int_{\hat{M}+3\sigma_u}^{\hat{M}+6\sigma_u} L_{BG} dM}$$

Detector responses are corrected by an unfolding process that is based on the iterative Bayesian method.

(G. D’ Agostini NIM A 362 (1995) 487)

Detector response corrected spectrum is proceeded to the acceptance correction.
7TeV π⁰ analysis

Arm1 data vs Arm2 data vs MC generator

- No energy-scale systematic uncertainty quoted.
- Consistent spectra are obtained between Arm1 and Arm2.
  ➔ Going to combine between results of the Arms.
Future operations

$p$-Pb operation (Nov. 2012)

Install the one of the LHCf detector.
Nuclear effect at the proton remnant side.

Courtesy of S. Ostapchenko
Future operations

\textbf{p-Pb operation (Nov. 2012)}

Install the one of the LHCf detector.
Nuclear effect at the proton remnant side.

\textbf{p-p at 14TeV (2014 or 2015)}

Measurement at the LHC design energy.
Energy scaling by comparison with 900GeV and 7TeV data
TDR, O.Adriani, et al. CERN-LHCC-2006-004

\textbf{LHCf covers the peak}
Future operations

**p-Pb operation (Nov. 2012)**
Install the one of the LHCf detector.
Nuclear effect at the proton remnant side.

**p-p at 14TeV (2014 or 2015)**
Measurement at the LHC design energy.
Energy scaling by comparison with 900GeV and 7TeV data.
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**Operations at RHIC (after 2015?)**
Lower collision energy, ion collisions.
Starting discussion with RHIC people.
LHCf has measured the energy and transverse momentum spectra at the very forward region of $\sqrt{s} = 900\text{GeV}$ and $\sqrt{s} = 7\text{TeV}$ proton-proton collisions in 2010.

We showed the results,
- Single photon spectra at $\sqrt{s} = 7\text{TeV}$ p-p collisions.
- Inclusive photon spectra at $\sqrt{s} = 900\text{GeV}$ p-p collisions.
- $\pi^0$ spectra measured at $\sqrt{s} = 7\text{TeV}$ p-p collisions.

Many analyses are ongoing,
- Hadron analysis
- $P_T$ spectrum of photons

Future operations will provide many data at the forward region.
- p-Pb collisions (the end of this year.)
- p-p collisions at $\sqrt{s} = 7\text{TeV}$ (2014 or 2015)
- operations at RHIC
Backup slides
7TeV $\pi^0$ analysis

- Photon analysis and $\pi^0$ analysis compensate each missing information.
  - High energy photon originates from large $P_T$ $\pi^0$ events.
  - Photon spectrum includes a contribution from other hadrons/baryons.
$P_T$ distribution for photons

pp 7TeV, EPOS
Photons on the p-remnant side

- Photon energy distrib. in different $\eta$ intervals at $\sqrt{s_{NN}} = 7$ TeV
- Comparison of p-p / p-N / p-Pb

QGSJET II-04

SIBYLL 2.1

All $\eta$s
8.81 $< \eta < 8.99$
$\eta > 10.94$

Courtesy of S. Ostapchenko