The results and the future prospects from a LHC forward experiment

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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

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

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

Uncertainty of hadron interaction models

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

![HECRs](image_url)
The Large Hadron Collider (LHC)

- **pp 7TeV+7TeV** → $E_{lab} = 10^{17}eV$ (2014-)
- **pp 3.5TeV+3.5TeV** → $E_{lab} = 2.6 \times 10^{16}eV$
- **pp 450GeV+450GeV** → $E_{lab} = 2 \times 10^{14}eV$

### Key parameters for air shower developments

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

LHCf, ZDCs
The LHCf experiment

LHCf Detector (Arm#1)

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

Beam pipe

Protons

Charged particles (+)

Neutral particles

Charged particles (-)

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

96mm

140m
The LHCf Detectors

**Sampling and Positioning Calorimeters**
- $W (44 \text{ r.l} , 1.7\lambda_I)$ 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 $\pi^0$

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

**Front Counter**
- thin scintillators with 80x80mm$^2$
- To monitor beam condition.
- For background rejection of beam-residual gas collisions by coincidence analysis
LHCf can measure

Energy spectra and Transverse momentum distribution of

- Gamma-rays ($E>100\text{GeV}, \text{d}E/E<5\%$)
- Neutral Hadrons ($E>a$ few $100\text{ GeV}, \text{d}E/E\sim30\%$)
- $\pi^0$ ($E>600\text{GeV}, \text{d}E/E<3\%$)

at pseudo-rapidity range $>8.4$

Low multiplicity !!

High energy flux !!

Energy Flux @14TeV

Front view of calorimeters @ 100µrad crossing angle

Simulated by DPMJET3
Status of the LHCf experiment

2008
- First data taking

2009
- First full data taking with $\sqrt{s} = 900$ GeV p-p collisions.

2010
- Physics programs with $\sqrt{s} = 900$ GeV and 7 TeV p-p collisions has been completed.

2012
- Calibration of detectors with beams at SPS (Aug.)
- Operation with p-Pb collisions (Nov.)

2014
- Operation with $\sqrt{s} = 14$ TeV p-p collisions

Published results:
- Forward photon spectra at $\sqrt{s} = 900$ GeV and 7 TeV
- Forward $\pi^0$ spectra at $\sqrt{s} = 7$ TeV

On going analysis:
- Forward neutron spectra (Next talk)
- Mesons ($\eta$, $K^0$, $\Lambda$)

Future operations
- Nuclear effect
- Energy dependency
Results from $\sqrt{s} = 900$ GeV and 7 TeV p-p data

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

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

“Measurement of forward neutral pion transverse momentum spectra for $\sqrt{s} = 7$TeV proton-proton collisions at LHC”
- Pseudo-rapidity, $\eta > 10.94$ and $8.81 < \eta < 8.9$
- The spectra of two detectors are consistent within the errors.

![Graphs of photon spectra at $\sqrt{s} = 7$ TeV]
Photon spectra at $\sqrt{s} = 7$ TeV $p-p$

- No model can reproduce the LHCf data perfectly.
- DPMJET and PYTHIA are in good agreement $E_\gamma < 1.5$ 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.
Photon spectra at $\sqrt{s} = 900$ GeV $p-p$

- Both of Data and MC show little $\eta$ dependency.
- The tendencies of MC against Data are very similar to one of 7 TeV in $\eta > 10.94$. 
**DATA : Comp. 900GeV/7TeV**

**Coverage of 900GeV and 7TeV results in Feynman-X and \( P_T \)**

900GeV vs. 7TeV with the same \( P_T \) region

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**Good agreement of \( X_F \) spectrum shape between 900 GeV and 7TeV. ➔ weak dependence of \(<p_T>\) on \( E_{CMS} \)**

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\[
\frac{1}{\sigma_{inel}} \frac{d\sigma}{dX_F} \bigg|_{\eta<\text{limited}} \propto \frac{1}{\sigma_{inel}} \frac{d\sigma}{p_T dp_T dX_F} \langle p_T \rangle dp_T
\]

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**Note :** No systematic error is considered in both collision energies. 21% of the luminosity determination error allows vertical shift.
Mass, energy and transverse momentum are reconstructed from the energies and impact positions of photon pairs measured by each calorimeter:

\[ M_{\pi^0} = \sqrt{E_{\gamma_1} E_{\gamma_2} \theta^2}, \]

\[ E_{\pi^0} = E_{\gamma_1} + E_{\gamma_2}, \]

\[ P_{T\pi^0} = P_{T\gamma_1} + P_{T\gamma_2}. \]

### Mass reconstructed from photon pairs

- **LHCf-Arm1** \( \sqrt{s}=7\) TeV, \( \int L dt=2.53\text{nb}^{-1} \)
- \( 9.0 < y < 9.2 \)

### Acceptance 

#### Rapidity - \( P_T \)

- **LHCf Arm1**
- **LHCf Arm2**
\[ \pi^0 \text{ spectra at } \sqrt{s} = 7 \text{ TeV } p-p \]

- EPOS1.99 show the best agreement with data in the models.
- DPMJET and PYTHIA have harder spectra than data ("popcorn model")
- QGSJET has softer spectrum than data. (only one quark exchange is allowed)
1. Thermodynamics

\[
\frac{1}{\sigma_{\text{inel}}} \frac{E}{d^3 \sigma} = A \cdot \exp\left(-\sqrt{p_T^2 c^2 + m_{\pi^0}^2 c^4 / T}\right)
\]

\[
\langle p_T \rangle = \sqrt{\frac{\pi m_{\pi^0} c^2 T}{2} \frac{K_2(m_{\pi^0} c^2 / T)}{K_{3/2}(m_{\pi^0} c^2 / T)}}
\]

2. Numerical integration

\[
\langle p_T \rangle = \int_0^\infty 2\pi p_T f(p_T) dp_T
\]

actually up to the upper bound of histogram

Systematic uncertainty of LHCf data is 5%.

Compared with the UA7 data (\(\sqrt{s}=630\)GeV) and MC simulations (QGSJET, SIBYLL, EPOS).

Two experimental data mostly appear to lie along a common curve

→ no evident dependence of \(\langle p_T \rangle\) on \(E_{CMS}\).

Smallest dependence on \(E_{CMS}\) is found in EPOS and it is consistent with LHCf and UA7.

Large \(E_{CMS}\) dependence is found in SIBYLL
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

**p-Pb operation (Nov. 2012)**

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

**p-p at 14TeV (2014)**

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

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

**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 $\sqrt{s} = 7\text{TeV}$ p-p 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
Shadow of beam pipes between IP and TAN

Pseudo-rapidity range.

$\eta > 8.7$ @ zero crossing angle

$\eta > 8.4$ @ 140urad
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 distribution in different $\eta$ intervals at $\sqrt{s_{NN}} = 7$ TeV

- Comparison of p-p / p-N / p-Pb

QGSJET II-04

SIBYLL 2.1

Courtesy of S. Ostapchenko
Analysis for photon at 7TeV

- **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

- **Lateral distribution measured by silicon detectors**
  - X-view
  - Y-view

- **Total Energy deposit ➔ Energy Shape ➔ PID**

- **Hit position, Multi-hit search.**

- **π⁰ mass reconstruction from two photon.**
  \[ M_{\pi^0} = \sqrt{E_{\gamma1}E_{\gamma2}} \cdot \theta \]
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
The LHCf combined results in general for the rapidity range larger than 9 show the smallest dependence of hadronic interaction models. Shaded areas indicate the range of total uncertainties of the combined spectra, namely larger than 9 for EPOS 1.99, SIBYLL 2.1, and QGSJET II-03. At 8 GeV, SIBYLL 2.1 gives softer hadronic interaction models. Shaded areas indicate the range of total uncertainties of the combined spectra, namely smaller than 9 for DPMJET 3.04.

The average transverse momentum, \( p_T \), versus rapidity that is independent of the center of mass energy, in agreement with the expectation of soft QCD processes. Comparison between the LHCf and UA7 results indicate an agreement with typical values for soft QCD processes. Combinations of the Arm1 and Arm2 detectors to the predicted spectra of the Arm1 and Arm2 detectors have been compared, and give consistent results. The experimental data of various models have been measured by two independent LHCf detectors in the early 2010. Transverse momentum spectra of neutral pions have been measured at different centrality bins of LHC proton-proton collisions in the rapidity range larger than 9 at LHC and SpS, respectively. It should be remarked that of the three models the predictions by EPOS 1.99 shows the best agreement with the LHCf and UA7 results except for the mass energy among three models, and this tendency is consistent with the LHCf, UA7, and LHCf combined data.

Fig. 10 that amongst the three models the best agreement with the LHCf data is obtained by EPOS 1.99.