Test of hadronic interaction models by a LHC forward experiment; LHCf

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Lots of hadronic interaction models were developed.

For studies of universe
For detector simulations
For Cosmic-rays

Wide energy range from $10^9$ to $10^{20}$ eV
All processes
p-A, π-A as well as p-p
Energy Spectrum of Cosmic-rays

Very wide energy range

\[10^9 \sim 10^{20} \text{ eV}\]

Kinks in the spectra

- Knee \(\sim 10^{15}\) eV
- Ankle \(\sim 10^{18}\) eV
- Cut-off \(\sim 10^{19.5}\) eV

The goal of CR-studies is to understand the **sources** and the **acceleration mechanism**.

Observation of not only “charged” cosmic-rays but also X-rays/gamma-rays and neutrinos.
Observation of CRs

Direct Measurement by Balloon and Satellite

- 1 particle/m²/sec
- 1 particle/m²/year
- 1 particle/km²/year
- 1 particle/km²/century

Air shower technique
Air showers are observed by
- Particle detector array (SD)
- Florescence telescopes (FD)

### Extensive air shower observation
- Longitudinal distribution
- Lateral distribution
- Arrival direction

### Air shower development

### Astrophysical parameters
- Spectrum
- Composition
- Source distribution
UHECR experiments

Pierre Auger Observatory
SD + FD
3,000km² in Argentina

Telescope Array
SD+FD
700km² in USA

AGASA, HiRes and JEM-EUSO
A PAO hybrid event

Hybrid detector

Coihueco

Loma Amarilla

Los Morados

Los Leones

Various detection technique = energy scale independent of hadronic inter. models

\[ E_{\text{cal}} = \int \text{d}X \frac{dE}{dX} \]

\[ \sigma_{\text{sys}} \approx 14\% \]

\[ \sigma_{\text{max}} < 20 \text{ g/cm}^2 \]

\[ \Delta_{\text{sys}} \approx 15 \text{ g/cm}^2 \]

\[ X_{\text{max}} \]

\[ S_{1000} \]

\[ E_{\text{surface}} = f(S_{1000}, \theta) \]
A PAO hybrid event

Hybrid detector

Estimator of composition

Estimator of energy

From R. Ulrich (KIT)

Hydrogen

Carbon

Helium

Nitrogen

Oxygen

Estimator of composition

Various detection technique = energy scale independent of hadronic inter. models

Various detection technique = energy scale independent of hadronic inter. models

\[ S_{1000} \]

\[ E_{\text{surface}} = f(S_{1000}, \theta) \]

\[ E_{\text{cal}} = \int dX \frac{dE}{dX} \]

\[ \sigma_{X_{\text{max}}} < 20 \text{ g/cm}^2 \]

\[ \Delta_{\text{sys}} \approx 15 \text{ g/cm}^2 \]

\[ X_{\text{max}} \]

\[ \sigma_E/E \sim 8\% \]

\[ \Delta_{\text{sys}} \approx 14\% \]
Composition measurement of UHECRs

Composition of UHECRs is one of important observable.

\[ \Delta X_{\text{max}} \] indicates the different primary mass composition

\[ \text{Altitude (km)} \]

- 10 km (600g/cm\(^2\))
- 4.3 km (600g/cm\(^2\))
- 1.4 km (875g/cm\(^2\))
- Sea level (1100g/cm\(^2\))

\[ X_{\text{max}} \] distribution measured by AUGER

- EPOS-LHC
- QGSJetII-04
- Sibyll2.1

Uncertainty of hadron interaction models

Error of \(<X_{\text{max}}\>\) measurement

0690 Ahn
0751 De Souza
ICRC 2013
X_{max}
the depth of air shower maximum.
An indicator of CR composition

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

Air shower development

Astrophysical parameters
- Spectrum
- Composition
- Source distribution

X_{max} distribution measured by AUGER

Uncertainty of hadron interaction models

V

Error of \langle X_{max} \rangle measurement

0690 Ahn
0751 De Souza

ICRC2013
Composition at Knee \( (10^{15-16}\text{eV}) \)

- Spectrum mass decomposition by KASCADE collaboration:

![Graphs showing flux vs. primary energy for different particle types and models (QGSJET 01 and SIBYLL 2.1)].

**Change in spectrum slope due to mass composition (large uncertainties due to models) or change in hadronic interactions.**

ref. T.Pierog in HESZ2015
Hadronic interaction

QCD theory can calculate well all process

NO

The model has been checked very well with collider data.

Yes, but few data in the very forward region

pQCD can calculate only the process with the hard interaction (high $Q^2$). For other processes, exp., diffractive process, decay of remnants, jet production., phonological model is needed.

Fix target experiment:
$E_{CR} < 450$ GeV

Collider experiment:
Very difficult to have a measurement at the very forward region (close to zero degree of collisions)
The general approach is the same in different programs but the models and approximations used are different.
Hadronic interaction
Large Hadron Collider
The Large Hadron Collider (LHC)

pp 6.5TeV+6.5TeV  →  $E_{\text{lab}} = 9 \times 10^{16}$ eV  2015-
pp 3.5TeV+3.5TeV  →  $E_{\text{lab}} = 2.6 \times 10^{16}$ eV  2010-2011
pp 450GeV+450GeV  →  $E_{\text{lab}} = 2 \times 10^{14}$ eV  2009,2010
$+ \sqrt{s}=2.76$TeV, 8TeV
A-A/p-A PbPb  $\sqrt{s_{NN}}=2.76$TeV  2011-
A-A/p-A PbPb  $\sqrt{s_{NN}}=2.76$TeV  2011-
p-Pb  $\sqrt{s_{NN}}=5$TeV  2012-

Energy Flux
@p-p $\sqrt{s}=14$TeV, DPMJET3

ATLAS/LHCf
LHCb/MoEDAL
CMS/TOTEM
ALICE
Energy Flow in the forward region

Challenge of limited phase space coverage

- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

Electron Profile

$\eta = -\ln \tan \frac{\theta}{2}$

More than 50% of shower from $\eta > 8$
Key Parameters

- Inelastic Cross Section
  → TOTEM, ATLAS, CMS, ALICE
- Forward Energy Spectrum
  → LHCf, ZDC and etc.
- Inelasticity $k = 1 - p_{\text{lead}}/p_{\text{beam}}$
  → LHCf, ZDC and etc.
- Secondary interactions

+Nuclear Effect @ CR-Air
The LHCf collaboration involves ~30 members at 10 institutions.

The calibration of GSO plates at HIMAC

Purpose
Make the position maps of light yield of GSO for all GSO plates before assembling the detector.

Experiment
HIMAC: An Ion accelerator in Chiba, Japan.
Beam: 400 MeV/n 12C
Beam Time: 23rd to 25th July 2013 (3 nights)

Jul. 2011
Feb. 2009
Jul. 2013
Apr. 2013
Two LHCf detectors (Arm1 & Arm2) are installed into the very forward region of the LHC interaction point (IP1). LHCf can measure neutral particles ($\gamma$, n) at the rapidity range $\eta > 8.4$. 
The LHCf detectors

**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 (Arm#2)
- **Each detector has two calorimeter towers, which allow to reconstruct π⁰**

**Expected Performance**

- Energy resolution (> 100 GeV)
  - < 5% for Photons
  - 40% for Neutrons
- Position resolution
  - < 200μm for Photons
  - a few mm for Neutrons

**Front Counter**

- thin scintillators with 80x80mm²
- To monitor beam condition.
- For background rejection of beam-residual gas collisions by coincidence analysis
The LHCf detectors

Arm1 Detector

silicon strip detector

Detector in the LHC tunnel

GSO Scintillator
LHCf physics operation with pp $\sqrt{s}=13$TeV has been completed!!

- LHCf detectors were installed in Nov. 2014
- Special physics operation with low pile-up in 9 - 13 June 2015.
- After the operation, LHCf detectors were removed on 15 June during TS1.

Photo @ CERN
Most of collaborators were in the front of the LHCf control room.
Operation in Run II

- 26.6 hours of operation with DAQ rate of 200 - 500 Hz
- 39 M shower events and 0.53 M $\pi^0$ events were obtained.
- The final triggers of LHCf were sent to ATLAS for common operation.

Table of Statistics

<table>
<thead>
<tr>
<th></th>
<th>Arm1</th>
<th>Arm2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower Events</td>
<td>18 M</td>
<td>21 M</td>
</tr>
<tr>
<td>$\pi^0$ Events</td>
<td>0.22 M</td>
<td>0.31 M</td>
</tr>
</tbody>
</table>
Arm2 Event Display

LHCf Arm2 Detector

$\pi^0$ Candidate Event

LHC p-p, $\sqrt{s} = 13$ TeV Collisions

$E_{\gamma} = 1.01$ TeV

$E_{\gamma} = 1.02$ TeV
## LHCf Results

<table>
<thead>
<tr>
<th>Photon</th>
<th>π⁰</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-p $\sqrt{s}=0.9$ TeV</td>
<td>PLB 715 (2012) 298-303</td>
<td>-</td>
</tr>
<tr>
<td>p-p $\sqrt{s}=2.7$ TeV</td>
<td>arXiv:1507.08764</td>
<td></td>
</tr>
</tbody>
</table>
| p-p $\sqrt{s}=7$ TeV  | PLB 703 (2011) 128-134 | PRD86(2012)092001  
                           |                     | arXiv:1507.08764  
                           |                     | PLB 750 (2015) 360-366 |
| p-p $\sqrt{s}=13$ TeV | Preparing      | On-going                  |
| p-Pb $\sqrt{s}=5$ TeV | PRC 89 (2014) 065209  |                           |
| (p-Pb $\sqrt{s}=8$ TeV) |             |                           |
- No model can reproduce the LHCf data perfectly.
- Data points are on the middle of MC predictions except $E < 500\text{GeV}$. 

Data


DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145
Neutral Pions at 7TeV p-p

\[ \pi^0 \rightarrow 2\gamma \]

**P_{T} spectra**

- **9.0 < y < 9.2**
  - MC/Data
  - $\int L dt = 2.53 \pm 1.90 \text{nb}^{-1}$

- **9.2 < y < 9.4**
  - MC/Data
  - $\int L dt = 2.53 \pm 1.90 \text{nb}^{-1}$

**Reconstructed Mass**

MC/Data

- **9.0 < y < 9.2**
  - $\times \sqrt{s} = 7 \text{TeV}$, $\int L dt = 2.53 \text{nb}^{-1}$

Consistent with Photon results
For neutron analysis, the events with deeply developed showers were used.

### Longitudinal development of showers

**Shower development**

- **Photon**
- **Hadron**

**Calorimeter layers**

- **Energy [GeV]**
- **Number of MPFs**

**θ > 10.76**

**8.99 < θ < 9.22**

**0.81 < θ < 0.99**

---

**Event selection and correction**

- **Integral of**
  - **Arm1 + Syst + Unfold**
  - **Arm2 + Syst + Unfold**

**Photon**

- **θ > 10.76**
- **Large tower A (8.99 < θ < 9.22)**
- **Large tower B (8.81 < θ < 8.99)**

---

**LHCf experiment**

- **2. LHCf experiment**
- **D1 bending magnets**, **LHCf** can measure only neutrons.

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**In this paper, we report the results of analyzing the**

- **0-6% of other hadrons, i.e.,**
- **0-6% of other hadrons, i.e.,**

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**Conclusion**

- **For neutron analysis, the events with deeply developed showers were used.**

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**Longitudinal development of showers**

- **θ > 10.76**
- **Large tower A (8.99 < θ < 9.22)**
- **Large tower B (8.81 < θ < 8.99)**

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**Beam pipe shadow**

- **Beam center**
Phonons, $p-p \sqrt{s}=13\text{TeV}$

**$\eta > 10.94, \Delta \phi=180^\circ$**

$LHCf \sqrt{s}=13\text{TeV}$ photon

$\eta > 10.94, \Delta \phi=180^\circ$

$\int Ldt=0.191\pm0.191\text{nb}^{-1}$

**$8.81<\eta<8.99, \Delta \phi=20^\circ$**

$LHCf \sqrt{s}=13\text{TeV}$ photon

$8.81<\eta<8.99, \Delta \phi=20^\circ$

$\int Ldt=0.191\pm0.191\text{nb}^{-1}$
Comparison with 7TeV result

$\eta > 10.94$

$\sqrt{s}=13\text{TeV}$ photon

$\eta > 10.94$, $\Delta\phi=180^\circ$

Preliminary

$\int L dt =0.191 \pm 0.191\text{nb}^{-1}$

$1/N_\text{e} \cdot dN/dE \ [\text{GeV}]$

LHCf $\sqrt{s}=13\text{TeV}$ photon

$8.81<\eta<8.99$, $\Delta\phi=20^\circ$

Preliminary

$\int L dt =0.191 \pm 0.191\text{nb}^{-1}$

$1/N_\text{e} \cdot dN/dE \ [\text{GeV}]$

LHCf $\sqrt{s}=13\text{TeV}$ photon

$\eta > 10.94$, $\Delta\phi=360^\circ$

Preliminary

$\int L dt =0.191 \pm 0.191\text{nb}^{-1}$

$1/N_\text{e} \cdot dN/dE \ [\text{GeV}]$

LHCf $\sqrt{s}=7\text{TeV}$

Gamma-ray like

$\eta > 10.94$, $\Delta\phi=360^\circ$

Preliminary

$\int L dt =0.68 \pm 0.53\text{nb}^{-1}$

$\text{Events}/N_{\text{inv}}/\text{GeV}$

LHCf $\sqrt{s}=7\text{TeV}$

Gamma-ray like

$8.81 < \eta < 8.99$, $\Delta\phi=20^\circ$

Preliminary

$\int L dt =0.68 \pm 0.53\text{nb}^{-1}$

$\text{Events}/N_{\text{inv}}/\text{GeV}$

LHCf $\sqrt{s}=7\text{TeV}$
LHCf results (comparison with model predictions) ⇒ No model can reproduce data perfectly.

- $\gamma, \pi^0$: data is located in the band of model predictions.
- $n$: higher flux at zero degree than any models.

**Short summary of results**

- Energy [GeV]
  - $s=13$ TeV photon
  - $\eta > 10.94$, $\Delta\phi = 180^\circ$
  - $\int L dt = 0.191 \pm 0.191 \text{nb}^{-1}$

**Photons, p-p $\sqrt{s}=13$TeV**

- Preliminary

**Neutrons, p-p $\sqrt{s}=13$TeV**

- $\eta > 10.76$

- Events/N [GeV]
  - $d\sigma/dE$ [mb/GeV]
  - $\eta$, $\phi$, $\Delta\phi$

<table>
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<tr>
<th>Model</th>
<th>LHCf $\sqrt{s}=7$ TeV</th>
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<th>SYBILL 2.1</th>
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<td>EPOS-LHC</td>
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<td>DPMJET 3.06</td>
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LHCf results (comparison with model predictions) ⇒ No model can reproduce data perfectly.

- $\gamma, \pi^0$: data is located in the band of model predictions.
- $n$: higher flux at zero degree than any models.
What are sources of discrepancies between data and models predictions?

The LHCf data, inclusive spectra of photons, $\pi^0$, neutrons, clearly requires the tuning/modification of models. To understand the discrepancy, process-related data are really helpful for the model developers.

- Diffractive / non-diffractive selection by ATLAS information.

What data are additionally needed to test/tune the models?

- QGSJET2 and EPOS has been tuned with several data taken at $p-p \sqrt{s}=7$TeV. However issues related to UHECRs are not solved yet.
  => Additional data are needed.

- Production cross section of other mesons, $\eta$, $\rho$, $K$ and etc.
  LHCf can access the production cross section of $\eta$ in the forward region.

- $p-\pi$ interaction in the air-shower development.
  LHCf+ATLAS can measure $p-\pi$ collisions at LHC

- Test of models at a lower collision energy
  LHCf goes to RHIC($p-p \sqrt{s}=500$GeV) at BNL
Event categorization with non-diffractive and diffractive collisions.

Diffractive processes

- **Single-diffraction**
  
- **Double-diffraction**

- **Central-diffraction**
Investigation of photon spectrum

Inclusive spectrum: contribution from diffraction + non-diffraction

The excess of PYTHIA8 at E>3TeV due to over contribution from diffraction

Slides from Q.Zhou @ Low-X 2016
Contribution of diffractive collisions

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

Inclusive spectra:
QGSJET2 $\sim$ EPOS-LHC

Contribution of Diffraction
QGSJET2 $<$ EPOS-LHC

The common operation with ATLAS has been successfully done in 2015. The event selection by using number of tracks measured by ATLAS is a powerful tool to identify diffractive or non-diffractive events

Common analysis is on-going
Peaks corresponding to $\pi^0$, $\eta$

$\pi^0$ peaks are observed at lower invariant mass values, while $\eta$ peaks are observed at higher values.

Energy thresholds for $\pi^0$ and $\eta$ detections:
- For $\pi^0$: $E_{\pi^0} > 600$ GeV
- For $\eta$: $E_\eta > 2.2$ TeV

$\eta \rightarrow 2\gamma$ ($\sim 30\%$)
LHC is p-π collider also? proton may collide the pion cloud around coming proton. The pion-exchange events are tagged with the detection of one high energy neutron in the very forward region.

\[ p+p \rightarrow n + (\pi^+ + p) \rightarrow n + X \]
\[ p: 6.5 \text{ TeV}, \pi: \sim 1.0 \text{ TeV} \rightarrow \sqrt{s}_{p\pi} = 6 \text{ TeV} \]

Measurement of π+p interactions is very important as the hadronic interaction of secondaries in Air showers.
Hadronic interaction models is one of the keys for precise measurement of UHECRs.

LHCf is a forward experiment of LHC. LHCf published the results of photons, $\pi^0$ and neutrons at p-p with several collision energies of 0.9, 2.76, 7 and 13 TeV.

New data from LHCf, diffractive studies, p-$\pi^0$ collisions, measurement at RHIC, will be provided and hadronic interaction models will be improved.
Measurement at RHIC