The LHCf experiment: modelling cosmic rays at LHC

Alessia Tricomi
University and INFN Catania
on behalf of the LHCf Collaboration

- Aim of the experiment
- The LHCf detector
- Physics performance
- Installation and running plan
The LHCf Collaboration

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W. Turner

FRANCE
Ecole Politechnique Paris:
M. Haguenauer

SPAIN
IFIC Valencia:
A. Fauss, J. Velasco

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Firenze University and INFN:
O. Adriani, L. Bonechi, M. Bongi, G. Castellini, R. D’Alessandro, P. Papini, S. Ricciarini
Catania University and INFN:
A. Tricomi

JAPAN:
STE Laboratory Nagoya University:
Waseda University:
K. Kasahara, Mizuishi, Y. Shimizu, S. Torii
Kanagawa University Yokohama:
T. Tamura
Konan University:
Y. Muraki

CERN
D. Macina, A. L. Perrot
**Introduction: GZK cut off**

AGASA reports 18% systematic uncertainty in energy determination. 10% of systematic is due to interaction model.

Huge experiment (Auger, TA) will solve the statistics, but not for interaction model.

GZK cutoff: $10^{20}$ eV

20% correction on the absolute energy scale!!!

Accelerator calibration is necessary.

HOWEVER

Primary cosmic ray energy estimate relies on MC interaction models.

**GZK cutoff**

AGASA $\gamma=2.6$

$E>10^{20}$: 651

$E>10^{20}$: 42.82 ± 6.45

$E>10^{20}$: 2.25 ± 1.53
Introduction: cosmic ray composition

Not only GZK...

Different interaction models lead different conclusions about the composition of the primary cosmic rays.

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The LHCf experiment at LHC
Development of atmospheric showers

Correct simulation of interactions of primary cosmic rays with the atmosphere is essential to cosmic ray studies.

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University & INFN

The LHCf experiment at LHC

Cosmic ray spectrum

A 100 PeV fixed-target interaction with air has the cm energy of a pp collision at the LHC.

The dominant contribution to the energy flux is in the very forward region ($\theta \approx 0$).

In this forward region the highest energy available LHC measurements of $\pi^0$ cross section were done by UA7 ($E = 10^{14}$ eV, $y = 5-7$).

A 100 PeV fixed-target interaction with air has the cm energy of a pp collision at the LHC.

The LHCf experiment at LHC
The LHCf experiment at LHC

**LHCf location**

- **Detector I**
  - Tungsten
  - Scintillator
  - Scintillating fibers

- **Detector II**
  - Tungsten
  - Scintillator
  - Silicon mstrip

**INTERACTION POINT**
IP1 (ATLAS)

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**Beam line**

140 m

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Detectors will be installed in the TAN region, 140 m away from the Interaction Point 1, in front of the luminosity monitors.

- Here the beam pipe splits in 2 separate tubes.
- Charged particles are swept away by magnets!!!
- We will cover up to $y \to \infty$

The LHCf experiment at LHC
Detector #1

2 towers 24 cm long stacked vertically with 5 mm gap

Lower: 2 cm x 2 cm area
Upper: 4 cm x 4 cm area

Absorber
22 tungsten layers 7mm – 14 mm thick
(W: $X_0 = 3.5\text{mm}, \ R_M = 9\text{mm}$)

Impact point ($\eta$)

4 pairs of scintillating fiber layers for tracking purpose (6, 10, 32, 38 r.l.)

Energy

16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

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The LHCf experiment at LHC
Arm 1

Arm 1 completed in July 2006

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The LHCf experiment at LHC
Detector # 2

Impact point ($\eta$)

4 pairs of *silicon microstrip layers* (6, 12, 30, 42 r.l.) for tracking purpose (X and Y directions)

We used LHC style electronics and readout

16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

Energy

Absorber

22 tungsten layers 7mm – 14 mm thick (2-4 r.l.)

(W: $X_0 = 3.5\text{mm}, \ R_M = 9\text{mm}$)

2 towers 24 cm long stacked on their edges and offset from one another

Lower: 2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm

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The LHCf experiment at LHC
Arm 2

Arm 2 fully assembled in April 2007

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The LHCf experiment at LHC
LHCf Physics performance

1. Single photon spectrum
2. $\pi^0$ fully reconstructed (1 $\gamma$ in each tower)
3. n spectrum

$\pi^0$ reconstruction is an important tool for energy calibration ($\pi^0$ mass constraint)

Basic detector requirements:
✓ minimum 2 towers ($\pi^0$ reconstruction)
✓ Smallest tower on the beam (multiple hits)
✓ Dimension of the tower $\rightarrow$ Moliere radius
✓ Maximum acceptance (given the LHC constraints)

Simulation
Beam Test
LHCf performances: $\pi^0$ mass resolution

Arm #1
$\Delta E/E = 5\%$
$200 \mu m$ spatial resolution

$\Delta m/m = 5\%$
LHCf performances: Monte Carlo γ-ray energy spectrum
(5% Energy resolution is taken into account)

Gamma Energy Spectrum of 20mm square at Beam Center

10^6 generated LHC interactions → 1
Minute exposure@10^{29} cm^{-2}s^{-1}
luminosity

Discrimination between various models is feasible

Quantitative discrimination with the help of a properly defined \( \chi^2 \) discriminating variable based on the spectrum shape (see TDR for details)

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The LHCf experiment at LHC
LHCf performances: model dependence of neutron energy distribution

Original n energy

30% energy resolution

Neutron Energy Distributions

Counts [100GeV/10'/mea] vs Neutron Energy [GeV]

QGSJET
QGSJET II
DPMJET3
SIBYLL

Neutron Energy Spectrum of 20mm Calorimeter at beam center

particle/bin vs Neutron Energy [GeV]

DPMJET3
QGSJET
QGSJETII
SIBYLL

30% Energy Resolution
Now the real installation in LHC...

The idea is that installation takes place in 2 steps:
- Pre-installation: SUCCESSFULLY DONE
- Final installation: DATE TO BE FINALISED (JAN 2008?)

In between the 2 installation the baking out of the beam pipe will be done (200 °C), so the detectors should be removed.
LHCf possible running scenario

✓ Phase-I
- Parasite running during the early stage of LHC commissioning (summer 2008)
- Remove LHCf when luminosity reaches $10^{31}$ cm$^{-2}$s$^{-1}$ for radiation reason

✓ Phase-II
- Re-install the detector at the next opportunity of low luminosity run

✓ Phase-III
- Future extension for p-A, A-A run with upgraded detectors???
LHCf: conclusions and plans

✓ LHCf approved in June 2006 by the LHCC
✓ Physics performances:
  - able to measure $\pi^0$ mass with $\pm 5\%$ resolution.
  - able to distinguish the models by measurements of $\pi^0$
  - able to distinguish the models by measurements of $\gamma$
  - Beam crossing angle $\neq 0$ and/or vertical shifts of LHC by few cm will allow more complete physics measurements
✓ Detectors:
  - ARM1 and ARM2 fully ready
  - Performance measured in Test Beams
✓ Installation well advanced
  - ARM1 successfully pre-installed in January 07
  - ARM2 successfully pre-installed in April-May 07
  - Final installation date under discussion
✓ Running conditions:
  - Three foreseen phases
    - Phase I: low luminosity run during LHC commissioning
    - Phase II: low luminosity runs and possibly LHCf dedicated runs
    - Phase III: Heavy Ion runs?

Waiting for LHC beams!!!

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The LHCf experiment at LHC
Back-up slides
LHCf performances: acceptance on $P_{T\gamma}$ - $E_\gamma$ plane

A vertical beam crossing angle $> 0$ will increase the acceptance of LHCf
LHCf performances: single $\gamma$ geometrical acceptance

Some runs with LHCf vertically shifted few cm will allow to cover the whole kinematical range
LHCf performances: $\gamma$ shower in Arm #2

Fluka based simulation

Position resolution of detector

500 GeV $\gamma$ shower

$7 \, \mu m$ for 1.8 TeV $\gamma$
SPS Beam Test

Test was successful

Analysis is under way for
- Energy calibration of the calorimeters
- Spatial resolution of the tracking systems

- CERN : SPS T2 H4
- 2006 Aug. 28 – Sep. 4
- Incident Particles
  - Proton  150,350GeV/c
  - Electron  100,200GeV/c
  - Muon  150GeV/c

Setup
- LHCf Detector
- Silicon Tracker
- Moving Table
- Trigger Scintillator
Performances of the LHCf Detector

Measured at the SPS

Beam Test in 2004

SciFi Position Resolution

Energy Resolution

LHCf can measure (and provide to LHC) the center of neutral flux from the collisions.

If the center of the neutral flux hits LHCf $\Rightarrow \ll 1$ mm resolution
Transverse projection of detector #1 in the TAN slot
Transverse projection of detector #2 in the TAN slot
Lateral view of ARM #2

Front scintillator:
Fixed position wrt to TAN

Silicon + Tungsten + Scintillator:
+/- 5 cm vertical excursion

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University & INFN

The LHCf experiment at LHC
**γ rate**

<table>
<thead>
<tr>
<th></th>
<th>20mm x 20mm</th>
<th>40mm x 40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sum E &gt; 100GeV</td>
<td>0.0674</td>
<td>0.0465</td>
</tr>
<tr>
<td>2. One Gamma Incident</td>
<td>0.0478</td>
<td>0.0353</td>
</tr>
<tr>
<td>3. One Hadron Incident</td>
<td>0.0146</td>
<td>0.0052</td>
</tr>
<tr>
<td>4. One Gamma in fiducial</td>
<td>0.0297</td>
<td>0.0272</td>
</tr>
<tr>
<td>5. One Neutron in fiducial</td>
<td>0.0006</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Table 3: Event rate of single γ's and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of beam-pipe and without beam crossing angle.

<table>
<thead>
<tr>
<th></th>
<th>20mm x 20mm</th>
<th>40mm x 40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sum E &gt; 100GeV</td>
<td>0.0674</td>
<td>0.0869</td>
</tr>
<tr>
<td>2. One Gamma Incident</td>
<td>0.0478</td>
<td>0.0623</td>
</tr>
<tr>
<td>3. One Hadron Incident</td>
<td>0.0145</td>
<td>0.0081</td>
</tr>
<tr>
<td>4. One Gamma in fiducial</td>
<td>0.0297</td>
<td>0.0511</td>
</tr>
<tr>
<td>5. One Neutron in fiducial</td>
<td>0.0006</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Table 4: Event rate of single γ's and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and with beam crossing angle of 140μrad.

<table>
<thead>
<tr>
<th></th>
<th>20mm x 20mm</th>
<th>40mm x 40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sum E &gt; 100GeV</td>
<td>0.0849</td>
<td>0.0721</td>
</tr>
<tr>
<td>2. One Gamma Incident</td>
<td>0.0654</td>
<td>0.0528</td>
</tr>
<tr>
<td>3. One Hadron Incident</td>
<td>0.0198</td>
<td>0.0078</td>
</tr>
<tr>
<td>4. One Gamma in fiducial</td>
<td>0.0445</td>
<td>0.0427</td>
</tr>
<tr>
<td>5. One Neutron in fiducial</td>
<td>0.0009</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Table 5: Event rate of single γ's and hadrons per inelastic collision for the Detector #2. Here the detector is at default position and without beam crossing angle.
**π⁰ rate**

<table>
<thead>
<tr>
<th></th>
<th>Event rate of π⁰ production per inelastic collision for Detector #1. Here the 2cm×2cm calorimeter is at the center of beam-pipe and the beam crossing angle is zero.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>One Particle Incident on each Calorimeter</td>
</tr>
<tr>
<td>2.</td>
<td>Gamma Incident on each Calorimeter</td>
</tr>
<tr>
<td>3.</td>
<td>Invariant mass cut (125 MeV &lt; M_{πγ} &lt; 145 MeV)</td>
</tr>
</tbody>
</table>

Table 6: Event rate of π⁰ production per inelastic collision for Detector #1. Here the 2cm×2cm calorimeter is at the center of beam-pipe and the beam crossing angle is zero.

<table>
<thead>
<tr>
<th></th>
<th>Event rate of π⁰ production per inelastic collision for Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and the beam crossing angle is 140μrad.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>One Particle Incident on each Calorimeter</td>
</tr>
<tr>
<td>2.</td>
<td>Gamma Incident on each Calorimeter</td>
</tr>
<tr>
<td>3.</td>
<td>Invariant mass cut (125 MeV &lt; M_{πγ} &lt; 145 MeV)</td>
</tr>
</tbody>
</table>

Table 7: Event rate of π⁰ production per inelastic collision for Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and the beam crossing angle is 140μrad.

<table>
<thead>
<tr>
<th></th>
<th>Event rate of π⁰ production per inelastic collision for Detector #2. Here the 2.5cm×2.5cm calorimeter is at the center of neutral particle flux and the beam crossing angle is 0μrad.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>One Particle Incident on each Calorimeter</td>
</tr>
<tr>
<td>2.</td>
<td>Gamma Incident on each Calorimeter</td>
</tr>
<tr>
<td>3.</td>
<td>Invariant mass cut (125 MeV &lt; M_{πγ} &lt; 145 MeV)</td>
</tr>
</tbody>
</table>

Table 8: Event rate of π⁰ production per inelastic collision for Detector #2. Here the 2.5cm×2.5cm calorimeter is at the center of neutral particle flux and the beam crossing angle is 0μrad.
γ ray energy spectrum for different positions

Gamma Energy Spectrum of 20mm calorimeter at Center

Gamma Energy Spectrum of 20mm calorimeter at 30mm shift

QGSJETII: used model
QGSJET: $c^2/DOF=107/125$
DPMJET3: $c^2/DOF=224/125$
SYBILL: $c^2/DOF=816/125$
The CERN test beam on August 2004

Detector Setup
LHCf CERN 2004
(side view)

Before correction
After correction

2 mm

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Monte Carlo

Leak Correction

MC predicts that the leakage is energy independent!

Prototype Experiment

- Monte Carlo
- Distance from Edge

Graphs showing the number of particles as a function of distance from the edge for different energies.

- MC Leak Normalised
- MC Leak Normalised to 200 GeV/c

Graphs showing the ratio of the number of particles to the number of particles at 200 GeV/c as a function of distance from the edge.

Distance from Edge

Graphs showing the distribution of particles as a function of distance from the edge for different energies.
Estimate of the background

✓ **beam-beam pipe**

→ $E_\gamma$(signal) > 200 GeV, OK

background < 1%

✓ **beam-gas**

→ It depends on the beam condition

background < 1% (under $10^{-10}$ Torr)

✓ **beam halo-beam pipe**

→ It has been newly estimated from the beam loss rate

Background < 10% (conservative value)
The effect of LHCf on BRAN measurements has been studied in the last months by simulation.

- **Reduction of shower particles at BRAN**
- **Position dependence on beam displacement**

(question from machine peoples: if we shift by 1 mm the real beam, does the center of the measured neutral energy shifts by 1 mm?)
BRAN response vs beam position

Relative change of the reduction factors for BRAN with respect to the nominal value (center of the beam: nominal one)

If the position of beam center stays within a few mm from the beam-pipe center, the reduction factors do not change more than 10%.
LHCf performances: $\pi^0$ geometrical acceptance

Arm #1

<table>
<thead>
<tr>
<th>Pi0 Energy</th>
<th>Geometrical Acceptance</th>
<th>Direction [μrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 TeV</td>
<td>[Graph]</td>
<td>0</td>
</tr>
<tr>
<td>2.0 TeV</td>
<td>[Graph]</td>
<td>50</td>
</tr>
<tr>
<td>5.0 TeV</td>
<td>[Graph]</td>
<td>450</td>
</tr>
</tbody>
</table>

Arm #2

<table>
<thead>
<tr>
<th>Pi0 Energy</th>
<th>Geometrical Acceptance</th>
<th>Direction [μrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 TeV</td>
<td>[Graph]</td>
<td>0</td>
</tr>
<tr>
<td>2.0 TeV</td>
<td>[Graph]</td>
<td>50</td>
</tr>
<tr>
<td>5.0 TeV</td>
<td>[Graph]</td>
<td>450</td>
</tr>
</tbody>
</table>
LHCf performances: energy spectrum of $\pi^0$

Typical energy resolution of $\gamma$ is 3% at 1TeV
## Optimal LHCf run conditions

<table>
<thead>
<tr>
<th>Beam parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td># of bunches</td>
<td>≤ 43</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>&gt; 2 μsec</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>0 rad</td>
</tr>
<tr>
<td></td>
<td>140 μrad downward</td>
</tr>
<tr>
<td>Luminosity per bunch</td>
<td>&lt; $2 \times 10^{28}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>&lt; $0.8 \times 10^{30}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$4 \times 10^{10}$ ppb ($\beta^* = 18$ m)</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{10}$ ppb ($\beta^* = 1$ m)</td>
</tr>
</tbody>
</table>

✓ Beam parameters used for commissioning are good for LHCf!!!

( No radiation problem for 10kGy by a “year” operation with this luminosity )
**Parameter evolution and rates**

From R. Bailey presentation at January 2007 TAN workshop

**Optimal conditions for LHCf running**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 (and 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p$</td>
<td>$N$</td>
<td>$\beta$</td>
<td>$I_{beam}$ (mJ)</td>
</tr>
<tr>
<td>43</td>
<td>$4 \times 10^{10}$</td>
<td>11</td>
<td>1.7 $10^{12}$</td>
</tr>
<tr>
<td>43</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>1.7 $10^{12}$</td>
</tr>
<tr>
<td>156</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>6.2 $10^{13}$</td>
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<tr>
<td>156</td>
<td>$9 \times 10^{10}$</td>
<td>2</td>
<td>1.4 $10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>11</td>
<td>3.7 $10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>3.7 $10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$6 \times 10^{10}$</td>
<td>2</td>
<td>5.6 $10^{13}$</td>
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<tr>
<td>936</td>
<td>$9 \times 10^{10}$</td>
<td>1</td>
<td>8.4 $10^{13}$</td>
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<tr>
<td>2808</td>
<td>$4 \times 10^{10}$</td>
<td>11</td>
<td>1.1 $10^{14}$</td>
</tr>
<tr>
<td>2808</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>1.1 $10^{14}$</td>
</tr>
<tr>
<td>2808</td>
<td>$5 \times 10^{10}$</td>
<td>1</td>
<td>1.4 $10^{14}$</td>
</tr>
<tr>
<td>2808</td>
<td>$5 \times 10^{10}$</td>
<td>0.55</td>
<td>1.4 $10^{14}$</td>
</tr>
</tbody>
</table>

From R. Bailey, January 2007
### Beyond 2007

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage I</th>
<th>II</th>
<th>III</th>
<th>Shutdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Hardware commissioning 7TeV</td>
<td>Machine checkout 7TeV</td>
<td>Beam commissioning 7TeV</td>
<td>43 bunch operation</td>
</tr>
<tr>
<td></td>
<td>No beam</td>
<td>Beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Shutdown</td>
<td>Machine checkout 7TeV</td>
<td>Beam setup</td>
<td>25ns ops</td>
</tr>
<tr>
<td></td>
<td>No beam</td>
<td>Beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R. Bailey, January 2007

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The LHCf experiment at LHC