LHCf results and perspectives

Raffaello D'Alessandro*

on behalf of the LHCf collaboration

*Università di Firenze & INFN-Firenze
Outline

- Introduction and physics case
- The detector
- Photon and $\pi^0$ analysis
- Status of LHCf and future prospects
- Conclusions
The physics case lies in cosmic ray energy spectrum and composition

- AGASA and HiRes showed a marked discrepancy in results 10 years ago
- Recent results Auger, HiRes (final), and TA indicate the presence of GZK cutoff
- Absolute values differ between experiments and between detection methods used.
- \( X_{\text{max}} \) gives information of the primary particle
- Results are different between experiments
- Interpretation relies on the MC prediction and has quite strong model dependence

Composition too .....
LHCf : a bridge between cosmic ray physics and accelerators

- Use the colliding beams at LHC to study the interaction of UHE primary cosmic rays in the atmosphere.

\[ E_{CM} \sim (2 \times E_{lab} \times M_p)^{1/2} \]

- \( \sqrt{s} = 14 \text{TeV} \) collision at LHC → \( 10^{17} \text{eV} \) cosmic ray impacting on the atmosphere

1. Inelastic cross section (ex. by TOTEM)
2. Forward energy spectrum
3. Inelasticity...
Where does the energy flow?

- Most of the energy flows in the very forward direction.
- Particles with $X_F > 0.1$ contribute to 50% of the air shower.
- Very important to study what's happening at high eta.

### Multiplicity

- All particles
- Neutral

### Energy Flux

- $8.4 < \eta < \infty$

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LHC Days in Split – 2012
Split, Croatia

R. D'Alessandro
Università di Firenze & INFN-Firenze
The LHCf experiment

- Here the beam pipe splits in the two separate tubes that circle LHC
- Charged particles (and the proton beams) are channelled away by the magnets
- Unique configuration (better than SppS) that allows the LHCf calorimeters to extend their coverage to $|\eta| > 8$
The LHCf detectors (1)

- Two “tiny” E.M. calorimeters with precise reconstruction of transverse and longitudinal shower profiles

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

**Interaction Point**
- IP1 (ATLAS)

**Detector II**
- Tungsten
- Scintillator
- Silicon μstrips

8 cm 140 m 6 cm

Front Counter

44\(X_0\), 1.6 \(\lambda_{int}\)

\(\pi^0\) \(\gamma\)
LHCf operations @900 GeV & 7 TeV

- With Stable Beam at 900 GeV Dec 6th – Dec 15th 2009
- With Stable Beam at 900 GeV May 2nd – May 27th 2010

<table>
<thead>
<tr>
<th></th>
<th>Shower</th>
<th>Gamma</th>
<th>Hadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm1</td>
<td>46,800</td>
<td>4,100</td>
<td>11,527</td>
</tr>
<tr>
<td>Arm2</td>
<td>66,700</td>
<td>6,158</td>
<td>26,094</td>
</tr>
</tbody>
</table>

- With Stable Beam at 7 TeV March 30th - July 19th 2010
- We took data with and without 100 μrad crossing angle for different vertical detector positions

<table>
<thead>
<tr>
<th></th>
<th>Shower</th>
<th>Gamma</th>
<th>Hadron</th>
<th>n0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm1</td>
<td>172,263,255</td>
<td>56,846,874</td>
<td>111,971,115</td>
<td>344,526</td>
</tr>
<tr>
<td>Arm2</td>
<td>160,587,306</td>
<td>52,993,810</td>
<td>104,381,748</td>
<td>676,157</td>
</tr>
</tbody>
</table>
Single photon spectrum analysis

- Analysis Procedure
  - Energy Reconstruction from total energy deposition in a tower (corrections for shower leakage, light yield etc.)
  - Particle Identification by analysis of the longitudinal shower development
  - Remove multi-particle events by looking at transverse energy deposit
  - Two Pseudo-rapidity regions selections, $\eta > 10.94$ and $8.81 < \eta < 8.9$
  - Combine spectra between the two detectors
  - Compare data with the expectations from the models
Energy and Particle ID

- Impact position from lateral distribution
- Position dependent corrections
- Light collection non-uniformity
- PID criteria based on transition curve
- L90%

L90 is the longitudinal distance in radiation lengths measured from the entrance to a calorimeter to the position where 90% of the total shower energy has been deposited.
Single photon (continued)

- Reject events with multi-peaks
  - Identify peaks in one tower with position sensitive layers
  - Select only single peak events for spectra
  - Efficiency evaluated from MC and Data (artifical samples)
Acceptance and Energy scale

- \( R1 = 5\text{mm}, R2-1 = 35\text{mm}, R2-2 = 42\text{mm}, \theta = 20^\circ \)
- Small Tower \( \rightarrow \eta > 10.94 \)
- Large Tower \( \rightarrow 8.81 < \eta < 8.99 \)

- Energy scale checked by \( \pi^0 \) identification from two separate tower events.
- Mass shift observed both in Arm1 (+7.8%) and Arm2 (+3.7%)
- No energy scaling applied, but shifts assigned in the energy scale systematic error

![Energy spectra graphs showing peaks at 140.0 ± 0.1 MeV for Arm2 Data and 135.0 ± 0.2 MeV for Arm2 MC.](image)
7TeV single photon comparisons.

DPMJET 3.04  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145  QGSJET II-03
900 GeV results

- Data sets used in the analysis were taken on 2, 3 and 27 May 2010 during the LHC operations with proton-proton collisions at $\sqrt{s} = 900$ GeV, (Fill ID = 1068, 1069 and 1128)

- Monte Carlo (MC) used the hadronic interaction models, QGSJET II-03, PYTHIA 8.145, SIBYLL 2.1, EPOS 1.99 and DPMJET 3.04

- The detector response was calculated by using the EPICS 8.81/COSMOS 7.49 simulation package

- No multi hit cut applied (inclusive spectra).
  - less than 1% of showers above 40 GeV affected by more than 2% $\Delta E$. 
• Ratio of MC spectra divided by data.

Normalized by the number of entries in XF > 0.1
No systematic error is considered in both collision energies.

Good agreement of XF spectrum shape between 900 GeV and 7 TeV.
⇒ weak dependence of $<p_T>$ on ECMS

LHCf Arm1 Photon Like

Preliminary

Data 2010 at $\sqrt{s}=900$GeV
(Normalized by the number of entries in XF > 0.1)
Data 2010 at $\sqrt{s}=7$TeV ($\eta>10.94$)
LHCf 7TeV $\pi^0$ analysis

- Analysis finalised and paper accepted by Physics Review D
- PID with L90
- Mass peak used for selection
- More $P_T$ bins (2\(\gamma\) in one tower)
- $P_T$ spectra
Acceptance and unfolding

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

Bifurcated Gaussian distribution for the signal component and a 3rd order Chebyshev polynomial function for the background component.

Raw distributions are corrected for detector responses 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 then corrected for acceptance.
LHCf 7TeV $\pi^0$ spectra

Sideband subtraction method to treat the background
BKG from hadrons or 2 photons coming from unrelated decays
\( \pi^0 \) spectra vs MC

- EPOS shows the best agreement
dpmjet 3.04 & pythia 8.145 show overall agreement with LHCf data for 9.2<y<9.6 and pT <0.25 GeV/c, while the expected π0 production rates by both models exceed the LHCf data as pT becomes large.

- sibyll 2.1 predicts harder pion spectra than data, but the expected π0 yield is generally small.

- qgsjet II-03 predicts π0 spectra softer than LHCf data.

- epos 1.99 shows the best overall agreement with the LHCf data.

- behaves softer in the low pT region, pT < 0.4GeV/c in 9.0<y<9.4 and pT <0.3GeV/c in 9.4<y<9.6.

- behaves harder in the large pT region.
π⁰ spectra continued ....

- Fit of the $p_T$ spectra, exponential distribution with the form:

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

- from which the average $\langle p_T \rangle$:

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

- $K$ is the modified Bessel function, $T$ from the fit is consistent with 100 MeV typical of soft QCD.

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Averaged $p_T$ for the 6 $y$ regions

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>$\chi^2$ (dof)</th>
<th>$T$ [MeV]</th>
<th>$\langle p_T \rangle$ [MeV/c]</th>
<th>Total uncertainty [MeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[8.9, 9.0]$</td>
<td>0.7 (7)</td>
<td>84.5</td>
<td>201.4</td>
<td>8.8</td>
</tr>
<tr>
<td>$[9.0, 9.2]$</td>
<td>17.8 (7)</td>
<td>75.5</td>
<td>184.1</td>
<td>3.5</td>
</tr>
<tr>
<td>$[9.2, 9.4]$</td>
<td>71.1 (8)</td>
<td>65.0</td>
<td>164.0</td>
<td>1.9</td>
</tr>
<tr>
<td>$[9.4, 9.6]$</td>
<td>138.0 (6)</td>
<td>53.8</td>
<td>142.4</td>
<td>1.4</td>
</tr>
<tr>
<td>$[9.6, 10.0]$</td>
<td>20.0 (5)</td>
<td>44.2</td>
<td>123.5</td>
<td>1.7</td>
</tr>
<tr>
<td>$[10.0, 11.0]$</td>
<td>14.8 (2)</td>
<td>21.9</td>
<td>77.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Why neutron measurements are important for CR physics

- Auger hybrid analysis
  - event-by-event MC selection to fit FD (fluorescence) data (top plot)
  - comparison with SD (shower) data vs MC (bottom plot)

- Clear muon excess in data even for Fe primary MC
  - The number of muons increases with the increase of the number of baryons!

=> importance of direct baryon measurement
Energy and Position Resolution

We are trying to improve the energy resolution by looking at the ‘electromagneticity’ of the event.

Neutron incident at \((X,Y) = (8.5\text{mm}, 11.5\text{mm})\)

~1mm position resolution

Weak dependence on incident energy
K^0 analysis

- Vertex of a K^0 \rightarrow 2\pi^0 decay is unknown due to the longer flight path of K^0: 
  - Vertex must be estimated using likelihood of K^0 \rightarrow 2\pi^0 decay with the rest mass constraints.

- Precise understanding of so called Type-II \pi^0 events is crucial for the reconstruction of K^0s.

\begin{itemize}
  \item K^0_s \\
  \pi^0 \rightarrow \pi^0 \rightarrow Large tower \\
  \pi^0 \rightarrow Small tower
\end{itemize}
$K^0$ acceptance

- Two “Type-II $\pi^0$s” on small and large tower.
- $E > 100\text{GeV}$ is required for each photon.
- Detector position of Arm1 is assumed to be -14mm.
• **Physics goals:**
  - model discrimination from a cosmic-ray point of view, by photons, neutral pions & neutrons
  - nuclear modification factor
  - inelasticity and others?

• **LHCf measurement for p-Pb interactions at 3.5TeV proton energy could be easily and finely integrated in the LHCf global campaign.**

<table>
<thead>
<tr>
<th>Period</th>
<th>Type</th>
<th>Beam energy</th>
<th>LAB proton Energy (eV)</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>p - p</td>
<td>450+450 GeV</td>
<td>$4.3 \times 10^{14}$</td>
<td>Arm1+Arm2</td>
</tr>
<tr>
<td>2009/2010</td>
<td>p - p</td>
<td>3.5+3.5 TeV</td>
<td>$2.6 \times 10^{16}$</td>
<td>Arm1+Arm2</td>
</tr>
<tr>
<td>2012</td>
<td>p – Pb</td>
<td>3.5 TeV proton E</td>
<td>$10^{16}$</td>
<td>Arm2</td>
</tr>
<tr>
<td>2014</td>
<td>p - p</td>
<td>7+7 TeV</td>
<td>$10^{17}$</td>
<td>Arm1+Arm2 upgraded</td>
</tr>
</tbody>
</table>
What LHCf can measure in the p+Pb run: E, pT, \( \eta \) spectra of neutral particles

- Simulating protons with energy \( E_p = 3.5 \) TeV
  
  \[
  E_N = \frac{Z}{A} E_p = 1.38 \text{ TeV/nucleon} \quad \sqrt{s_{NN}} = 4.4 \text{TeV}
  \]

- “Arm2” geometry considered on both sides of IP1 to study both p-remnant side and Pb-remnant side

- Results are shown for DPMJET 3.0-5 and EPOS 1.99, \( 10^7 \) events each
A word of caution

- Results are shown for DPMJET 3.0-5 and EPOS 1.99
  - EPOS 1.99 does not consider Fermi motion and Nuclear Fragmentation. Problems for the Pb-remnant side results.
- QGSJET2 can be used for p-Pb collisions. Works in progress.
- Public version of other models (Sybill, HIJING, Pythia etc.) cannot be used for p-Pb collisions.
Proton-remnant side: multiplicity

Small tower

Big tower

\[ \gamma \text{-rays, small tower} \]
\[ \text{EPOS} \quad \text{DPMJET III} \]

\[ \gamma \text{-rays, big tower} \]
\[ \text{EPOS} \quad \text{DPMJET III} \]

\[ \text{n, neutrons, small tower} \]
\[ \text{EPOS} \quad \text{DPMJET III} \]

\[ \text{n, neutrons, big tower} \]
\[ \text{EPOS} \quad \text{DPMJET III} \]

multi-hit events are \(<\sim1\%\) of single events
Lead-remnant side - multiplicity

Small tower

Big tower

There might be too many neutrons =>

Use of Arm2 which has finer pitch Si μ-strip detectors

First p-remnant side, then Pb-side by swapping beams
Proton-remnant side: photon spectrum

Small tower

Big tower

\( \frac{1}{N_{\text{int}}} \frac{dN}{dE} \text{ (GeV)}^{n} \)

\( 10^{-9} \)

\( 10^{-8} \)

\( 10^{-7} \)

\( 10^{-6} \)

\( 10^{-5} \)

\( 10^{-4} \)

\( 10^{-3} \)

\( 10^{-2} \)

\( 10^{-1} \)

\( 10^{0} \)

\( 10^{1} \)

\( 10^{2} \)

\( 10^{3} \)

\( 10^{4} \)

\( 10^{5} \)

\( 0 \)

\( 500 \)

\( 1000 \)

\( 1500 \)

\( 2000 \)

\( 2500 \)

\( 3000 \)

\( 3500 \)

\( \gamma\text{-rays, small tower} \)

\( \gamma\text{-rays, big tower} \)

\( 1 \)

\( 2 \)

\( 3 \)

\( 4 \)

\( 0 \)

\( 0.5 \)

\( 1 \)

\( 1.5 \)

\( 2 \)

\( 2.5 \)

\( 3 \)

\( 3.5 \)

\( 4 \)

\( 0 \)

\( 500 \)

\( 1000 \)

\( 1500 \)

\( 2000 \)

\( 2500 \)

\( 3000 \)

\( 3500 \)

\( \frac{DPMJET \text{ III}}{EPOS} \) ratio

\( \frac{DPMJET \text{ III}}{EPOS} \) ratio

\( p\text{-remnant side} \)

\( p\text{-remnant side} \)
Conclusions

- Thanks to this Conference for the opportunity given to present our results and future ideas.

- LHCf photon and $\pi^0$ analysis has been completed
  - Many detailed systematic checks
  - First comparison of various hadronic interaction models with experimental data in the most challenging phase space region ($8.81 < h < 8.99, h > 10.94$)
  - Large discrepancy especially in the high energy region with all models
  - Implications on UHECR Physics under study in strict connection with relevant theoreticians and model developers

- Other analyses are in progress (hadrons, PT distributions, ….)

- LHCf was removed from the tunnel on July 20, 2010

- We will come back in the TAN for the p-Pb run end of 2012

- We are upgrading the detectors to improve their radiation hardness (GSO scintillators and rearrangement of the silicon layers)

- We will anyway come back in LHC for the 14 TeV run with upgraded detector.