Cosmic-ray studies using the ALICE detector at LHC

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Outline

- Motivations
- The ALICE Experiment and the atmospheric muons
  - Triggering and tracking detectors
- The Muon Multiplicity Distribution
- High Muon Multiplicity events
- Monte Carlo and data comparison
- Conclusions
Motivations

Use of collider detectors for cosmic-ray studies was pioneered by LEP experiments ALEPH, DELPHI and L3

✗ Small apparatus
✗ Muons crossing the rock
✔ High performance detectors
  – tracking
  – magnetic field
Motivations

- All LEP results were consistent with standard hadronic interaction models except the observation of high multiplicity muon bundles
  - even under the assumption of highest measured flux and pure iron spectrum


Detection of cosmic muons at LHC

- ALICE is located at LHC Point2
  52m underground (28m rock above)

- Muon energy threshold ~16 GeV
ALICE Experiment

ALICE is mainly devoted to the study of strongly interacting matter in $pp$, $pA$ and $AA$ collisions at ultra-relativistic energies.

Besides the Heavy-Ion Physics program, ALICE has a dedicated physics group devoted to cosmic-ray studies.
The ALICE detectors

Detectors used for cosmic-ray data taking in the central barrel:

- Trigger
  - ACORDE
  - TOF
  - SPD
- Tracking
  - TPC
Trigger detectors for cosmic muons

ACORDE
Array of 60 scintillator modules located in the three top octants of the magnet
Each module is made of two plastic scintillators with effective area of 0.38 m$^2$.
Configurable from 2-fold coincidence (1Hz) onward.

SPD
Two innermost coaxial cylinders of ITS, around the beam pipe.
10 M pixels segmented in 120 modules provide trigger and particle position.
Trigger detectors for cosmic muons

TOF

Array of 1638 MRPC pads (18 φ sectors with 5 modules each) around TPC.

Full φ coverage, $45^\circ < \theta < 135^\circ$, time resolution 100ps, ~95% efficiency

Back to back

Back to back ± 3 pads
Tracking detector for cosmic muons

TPC

- Main tracking device with excellent capabilities for high-track density
- 557k readout channels
- Moment resolution ~1% for $p_t < 2$ GeV/c
  ~20% for $p_t = 100$ GeV/c in HI collisions
- Tracking efficiency 90%
- $dE/dx$ resolution < 10%
Atmospheric muon reconstruction

- The TPC reconstructs a single muon as two tracks (up and down)
- A specific algorithm was worked out to match the two tracks as a single one
- Monte Carlo events and data of high multiplicity have been used to optimize the parameters of the matching algorithm
Analysis cuts

- To accept a track
  - > 50 space points in the TPC (out of a maximum of 159)
  - $p > 0.5$ GeV/c
  - if multi-muon, parallelism cut $\cos(\Delta\Psi) > 0.990$

- To match an up track with a down track
  - $d_{\text{ca}} < 3\text{cm}$ in the mid horizontal TPC plane

- Matched muon: up and down tracks matched

- Single-track muon: a track satisfying all cuts but distance $d_{\text{ca}}$
Efficiency of analysis cuts

- generate 1000 events for 20 different muon multiplicities (1 to 300)
- reconstruct with same algorithm as real data
- plot mean and RMS of

\[
\frac{(\# \text{ generated } \mu - \# \text{ reconstructed } \mu)}{\# \text{ generated } \mu}
\]
Data sample for cosmic-ray studies

- Data taken between 2010 and 2013 during no-beam periods
  - OR of ACORDE, TOF and SPD triggers
  - with and without magnetic field (0.5 T)
  - integrated live time 30.8 days
  - ~ 22.6M events with at least 1 reconstructed muon in TPC

- Multi-muon event: \( N_\mu > 4 \) in TPC
  - 7487 multi-muon events
Muon angular distribution

Data

ALICE

Muon angular distribution

May 26th, 2016

Vulcano Workshop 2016

Muon angular distribution

Data

ALICE

Muon angular distribution

May 26th, 2016

Vulcano Workshop 2016
Muon multiplicity distribution (MMD)

Smooth distribution up to $N_\mu \sim 70$

5 High Muon Multiplicity events (defined when $N_\mu > 100$)
High Muon Multiplicity (HMM) event with 276 muons

ALICE Coll., JCAP 01 (2016) 032
Location of HMM events
Monte Carlo simulation

- Simulated events equivalent to 30.8 days live time were generated
  - CORSIKA 6990 and QGSJET II-03 were used to model low-intermediate MMD and study HMM events
  - CORSIKA 7350 and QGSJET II-04 were used to check and confirm results for HMM events
  - two samples: pure $p$ (light composition) and pure Fe (extremely heavy composition)
  - primary cosmic-ray energy $10^{14} < E < 10^{18}$ eV
  - usual power law energy spectrum $E^{-\gamma}$ with $\gamma = 2.7$ below the knee ($3 \times 10^{15}$ eV) and $\gamma = 3.0$ above
Monte Carlo simulation

- the total (all-particle) absolute flux of cosmic rays was extracted from J. R. Hörandel, *Astrop. Phys.* **19** (2003) 193-220

- the core of each shower was scattered at surface level with a flat random distribution in an area of 205x205 m² centered around the ALICE apparatus
Comparison Data-MonteCarlo

Compare the MMD in the range $7 < N_\mu < 70$ with the simulated distributions fitted with a power-law function.

As expected the data are between the pure $p$ composition (approaching it at low multiplicity) and the pure Fe composition (at higher multiplicity).
Monte Carlo study of HMM events

- In 30.8 days, 5 HMM events were recorded, corresponding to a rate of $1.9 \times 10^{-6}$ Hz.
- To estimate the rate of these events:
  - A simulation of 1 year of live time was performed.
  - Simplified Monte Carlo simulations show that only primaries with $E > 10^{16}$ eV contribute to HMM events reconstructed in the ALICE TPC.
  - So only primaries with $10^{16} < E < 10^{18}$ eV are generated, and $\theta < 50^\circ$.
  - Samples for both $p$ and Fe primaries.
Monte Carlo results

Number of HMM events in 365 days of data taking

<table>
<thead>
<tr>
<th></th>
<th>Simplified MC</th>
<th></th>
<th>Full MC</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>proton</td>
<td>iron</td>
<td>proton</td>
<td>iron</td>
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<tr>
<td>CORSIKA 6990</td>
<td>40</td>
<td>61</td>
<td>27</td>
<td>51</td>
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<tr>
<td>QGSJET II-03</td>
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<tr>
<td>CORSIKA 7350</td>
<td>41</td>
<td>72</td>
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<td>52</td>
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<tr>
<td>QGSJET II-04</td>
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</table>

To reduce the statistical fluctuations, four additional simulations were performed, reusing the EAS sample and randomly assigning the core of each shower over the 205x205 m² area.
Monte Carlo results

- Averaging the 5 samples
  - estimate the number of HMM in 1 year
  - reduce the statistical fluctuations
- Uncertainties are dominated by
  - statistical errors on real data
  - systematic errors on MC data
- Two sources of systematic errors in MC
  - the uncertainties in the generation parameters
  - the muon reconstruction algorithm
HMM: comparison data-MC

<table>
<thead>
<tr>
<th>HMM events</th>
<th>CORSIKA 6990</th>
<th>CORSIKA 7350</th>
<th>Data</th>
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<tr>
<td></td>
<td>QGSJET II-03</td>
<td>QGSJET II-04</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>Fe</td>
<td>p</td>
<td>Fe</td>
</tr>
<tr>
<td>Period [days per event]</td>
<td>15.5</td>
<td>8.6</td>
<td>11.6</td>
</tr>
<tr>
<td>Rate [x10^{-6} Hz]</td>
<td>0.8</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Uncertainty (syst+stat) (%)</td>
<td>25</td>
<td>25</td>
<td>22</td>
</tr>
</tbody>
</table>

- The rate of HMM events can be reproduced using the latest hadronic interaction models and a reasonable CR primary flux.
- Pure Fe primary composition (i.e. heavy nuclei composition) seems to better reproduce the HMM events.
  - though the large uncertainty in the measured rate prevents a firm conclusion about the origin of these events.
- Consistent with the fact that HMM events are generated by primaries with $E > 10^{16}$ where the composition is dominated by heavier elements.
Core location of simulated EAS giving $> 100$ muons in the ALICE TPC, for Fe primaries with $10^{16} < E < 10^{18}$ eV corresponding to 5 years of data taking.

- On average shower core falls farther from ALICE location for $E > 3 \times 10^{17}$ eV.
Conclusions – I

- In 2010-2013 ALICE took 30.8 days of cosmic-ray data
- The MMD at low and intermediate multiplicity is well reproduced by Monte Carlo simulations using CORSIKA 6990 with QGSJET II-30 model
- ALICE results suggest a mixed ion primary CR composition with an average mass increasing with energy
Conclusions – II

- 5 HMM events ($N_\mu > 100$) were recorded in the same 30.8 days data taking period.
- The observed rate is consistent with the predictions of CORSIKA 7350 with QGSJET II-04 model using a pure Fe primary composition and energy $> 10^{16}$ eV.
- For the first time the rate of HMM events has been well reproduced using conventional hadronic interaction models.
Outlook

- ALICE will continue to take cosmic data during LHC Run2 (2015 onward)
  - during no-beam periods
  - a dedicated trigger to select HMM events during $pp$ collision runs has been implemented (and tested during Run1)
    - in 2015 about 40 days of live time were collected
- The aim is to study HMM events in greater detail
- Other cosmic-ray topics (e.g. cosmic muon charge ratio) could also be performed with larger statistics
BACKUP
ACORDE and SPD triggers

The SPD cosmic trigger requires a coincidence between top and bottom halves of outer layer.

The ACORDE cosmic trigger requires a 4-fold coincidence of modules.
TOF trigger efficiency
Monte Carlo results

Number of HMM events in 365 days of data taking

<table>
<thead>
<tr>
<th>Run</th>
<th>CORSIKA 6990 QGSJET II-03</th>
<th>CORSIKA 7350 QGSJET II-04</th>
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<tr>
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<td>Simple MC</td>
<td>Full MC</td>
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<tr>
<td>4</td>
<td>26</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>33</td>
<td>22</td>
</tr>
</tbody>
</table>

Two sources of systematic errors:
- the muon reconstruction algorithm
- the uncertainties in the generation parameters