







Study of high muon multiplicity cosmic-ray events with ALICE at the CERN Large Hadron Collider

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Plan of this talk

- Introduction
- Experimental setup / trigger configuration
- Atmospheric muon multiplicity distribution (MMD)
- Monte Carlo studies
- Summary

Introduction

LEP experiments were pioneers in the study of atmospheric muon bundles with underground apparatus used in particle accelerators: ALEPH, **Astroparticle Physics 19 (2003) 513–523 and** DELPHI, **Astro-particle Physics 28 (2007) 273–286**

- These muon bundles are well described at low intermediate multiplicity, but not the high muon multiplicity events.
- Delphi conclusion: "Even the combination of extreme assumptions of highest measured flux value and pure iron spectrum fails to describe the abundance of high multiplicity events".



Cosmic-ray energy coverage: 10¹³ - 10¹⁸ eV





Primary cosmic ray interacts with the atmosphere and creates an Extensive Air Shower (EAS)



The muons of the EAS crossing the rock and arriving in ALICE can be detected and analyzed. Muon threshold energy ~ 16 GeV



LHC

ALICE is designed to the study of strongly interacting matter in ultrarelativistic heavy-ion collisions at the CERN Large Hadron Collider (LHC)

Besides the heavy-ion physics program, ALICE has a dedicated physics group interested in Cosmicray physics.

ALICE









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Atmospheric muon multiplicity

- Between 2010 and 2013, ALICE collected 30.8 days of dedicated cosmic-ray data during downtime of LHC.
- A logical **OR** among the trigger signals of ACORDE, TOF and SPD was configured to generate the cosmic-ray trigger of ALICE.

Atmospheric muon multiplicity distribution (MMD): reconstruction of ALICE atmospheric muons

- The TPC reconstructs a single muon with two tracks (up and down).
- A specific algorithm has been worked out to obtain the whole track of the muon.
- Monte Carlo events and data of high multiplicity have been used to optimized the parameters of the matching algorithm.



Atmospheric muon multiplicity distribution (MMD)



We find a smooth distribution up to #µ < 70 and 5 events with more than 100 atmospheric muons (HMM)

Atmospheric muon multiplicity distribution (MMD): display of two HMM ALICE events



ALICE collected 5 events with more than 100 atmospheric muons during 30.8 days of data taking

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Monte Carlo studies



To study the MMD, simulated events equivalent to 30.8 days of live time were generated:

- Corsika 6990 with QGSJET-II-03 model
- Two independent samples: pure proton (lighter composition) and Fe (extremely heavy composition)
- Energy of the primary cosmic-ray: 10¹⁴ < E < 10¹⁸ eV
- Usual power law spectrum $E^{-\gamma}$ with $\gamma = 2.7$ for energies below the knee and $\gamma = 3.0$ for energies above the knee.
- Total (all-particle) flux of cosmic-rays with poly-gonato model taken from J. R. Hörandel, Astrop. Phys.19 (2003) 193-220
- The core of each shower was scattered with a random flat distribution at surface level, in an area of 205 x 205 m² centered around the ALICE apparatus.

Monte Carlo studies



To compare the data with MC, the simulated distributions obtained with proton and iron primary cosmic-rays were fitted with a power-law function.



The data approach the proton curve (low multiplicities). High multiplicity data lie closer to the iron curve. This suggests that the average mass of the primary cosmic-ray flux increases with increasing energy.

Monte Carlo studies



Our preliminary studies show that HMM events ($\#\mu > 100$) reconstructed by the ALICE-TPC are due to primary cosmic-rays with an energy larger than 10^{16} eV for both proton and iron.

To estimate the rate of these events with Monte Carlo models, a simulation of one year of effective data taking was done:

- Corsika 6990 (QGSJET II-03) and 7350 (QGSJET II-04 tuned with LHC data)*
- Energy of the primary cosmic-ray: 10¹⁶ < E < 10¹⁸ eV

* The significant differences between the two versions of QGSJET are the inclusion of Pomeron loops in the formalism of QGSJET II-04 and a retuning of the model parameters using early LHC data for the first time (Phys. Rev. D83 (2011) 014018)

Monte Carlo studies: comparison with data



	CORSIKA 6990		CORSIKA 7350		
HMM events	QGSJET II-03		QGSJET II-04		Data
	proton	iron	proton	iron	
Period [days per event]	15.5	8.6	11.6	6.0	6.2
Rate [×10 ⁻⁶ Hz]	0.8	1.3	1.0	1.9	1.9
Uncertainty (%) (syst + stat)	13	16	8	20	49

- Pure iron sample simulated with QGSJET II-04 model reproduces HMM event rate in close agreement with the measured value.
- Independent of the version model, the rate of HMM events with pure proton cosmicray composition is more difficult to reproduce.
- This result is compatible with recent measurements which suggest that the composition of the primary cosmic-ray spectrum with energies larger than 10¹⁶ eV is dominated by heavier elements: Phys. Rev. Lett. **107** (2011) 171104.

Monte Carlo studies: core

XZ plane: plan view as seen from above ALICE



 Distance between ALICE and the core of the shower for all the HMM events found in 5 years of simulated data.

 Shower core on average falls farther from ALICE location for primaries with E > 3 x 10¹⁷ eV

Summary



- The MMD of ALICE at low and intermediate multiplicities are well reproduced by Monte Carlo using Corsika 6990 (QGSJET II-03 model)
- Our results suggest a mixed-ion primary cosmic-ray composition with an average mass that increases with energy.
- This confirms the reliability of cosmic data taking and its explanation with simulation programs, allowing us to face the study of HMM events.

Summary



- In 30.8 days ALICE found 5 HMM events ($\#\mu > 100$). These type of events were also found by Aleph and Delphi.
- Observed rate of HMM events is consistent with the predicted by Corsika 7350 (QGSJET II-04 model) using pure Fe composition and primary energy larger than 10¹⁶ eV.
 - This is the first time that the rate of HMM events has been satisfactory reproduced using conventional hadron interaction models (an observation that places significant constraints on alternative, more exotic, production mechanisms)
 - Paper available in arXiv: http://arxiv.org/abs/1507.07577

Outlook



- ALICE will continue taking cosmic-ray data during pauses of LHC during Run 2. A dedicated trigger is also implemented to take cosmic HMM events during p-p collision runs (we acquired some experience with this trigger during Run 1)
- The idea is to study in more details HMM events. The study of different topics can be carried out with larger statistics, i.e., cosmic muon charge ratio for horizontal and near vertical muons.



Back-up

Trigger configuration for Cosmic-ray detection





back to back

back to back + 1, 2 or 3 pads

- TOF has an effective area of detection of 160 m².
- Full $\boldsymbol{\phi}$ and $45^{\circ} \leq \boldsymbol{\theta} \leq 135^{\circ}$ coverage.
- Time resolution less than 100 ps.
- Efficiency around 95%.

Trigger configuration for Cosmic-ray detection



 The SPD was incorporated into the trigger by requiring a coincidence between signals in the top and bottom halves of the outermost layer.

Trigger configuration for Cosmic-ray detection

Each module consists of two superimposed plastic scintillators paddles.



A requirement of 4-fold coincidence of ACORDE modules is required to generate the cosmic trigger.

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