IOP Conf. Series: Journal of Physics: Conf. Series **866** (2017) 012013 doi:10.1088/1742-6596/866/1/012013

Cosmic-ray physics at CERN

M. Rodríguez Cahuantzi

Faculty of Physics and Mathematics, Autonomous University of Puebla
Av. San Claudio y 18 Sur, Edif. EMA3-231, Ciudad Universitaria 72570, Puebla, México

E-mail: mrodriguez@fcfm.buap.mx / mario.rodriguez@correo.buap.mx

Abstract.
Accelerator experiments located underground are suitable for the study of atmospheric muons. The use of high-energy collider detectors for cosmic-ray physics was pioneered during the era of the Large Electron-Positron (LEP) collider at CERN by ALEPH, DELPHI and L3 collaborations. A development of these programs is possible at the Large Hadron Collider (LHC), where experiments like ALICE and CMS will operate for many years, with the possibility of recording a large amount of cosmic-ray data. In this proceedings, a review of the results obtained by LEP and LHC experiments is presented. This material was discussed along two sessions during the VI School on Cosmic-ray Physics and Astrophysics held at the Mesoamerican Center for Theoretical Physics (MCTP) located in Tuxtla Gutierrez, Chiapas, Mexico.

1. Introduction to accelerators and particle detectors

Since the invention of particle accelerators in the 1930s decade, they have been used for different purposes: basic research, applied sciences and industry. The energy of a beam of particles is increased by accelerators using electromagnetic fields to boost them to nearly the speed of light. At the same time, the total momentum of the particles is increased (wavelength decreases) and thus it is possible to inquire into the inside the atoms. The acquired energy by the particles within accelerators allows the production of massive particles which are studied by different experimental techniques involving the development of sophisticated particle detectors.

During the twentieth century, several accelerators complexes have been developed throughout the world to be used as colliders to carry out studies in particle physics (see table 1).

Table 1. List of some accelerator complexes

Name	Location	Main studies
SLAC	California-USA	discovery of charm quark and τ lepton
Fermilab	Illinois-USA	discovery of bottom and top quarks and τ neutrino
CERN	Swiss-France border	discovery of Z, W particles and Englert-Brout-Higgs Boson
BNL	NY-USA	discovery of charm quark simultaneously with SLAC
CESR	NY-USA	detailed studies of bottom quark
DESY	Hamburg-Germany	discovery of gluons
KEK	Tsukuba-Japan	B-mesons studies
IHEP	China	τ lepton and charm quark studies

Particle accelerators can be constructed as circular or linear arrangements to be able to provide two types of collisions:

- *fixed target*: accelerated charged particles collide with a specific target made by a solid, liquid or gas. The particles are produced in the forward direction. The detectors are cone shaped and placed downstream.
- *colliding beams*: two accelerated beams of charged particles collide by making them crossing to each other. Because the particles are produced in all directions (higher mass particles are easily produced in colliding beam arrays), most of the detectors are cylindrical or spherical.

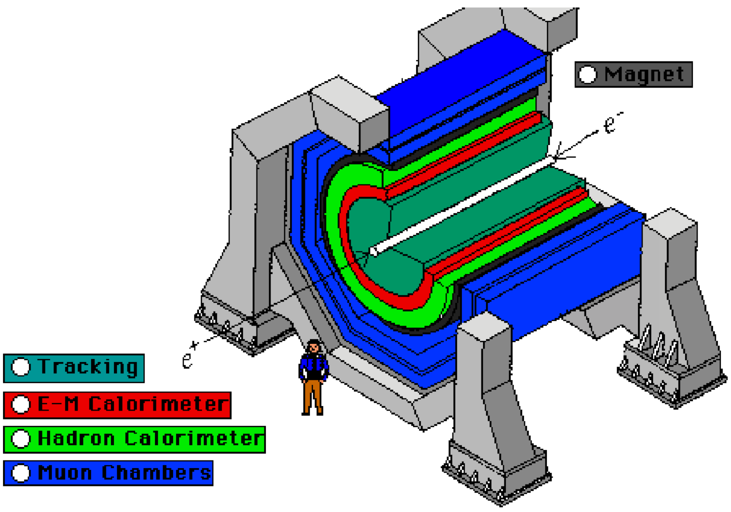

Figure 1. Schematic view of a particle detector arrangement. Figure taken from [1]

A view of a typical arrangement of particle detectors used in circular colliding beams is shown in figure 1. This type of detectors are usually constructed in four slices accordingly to the different particle species to be identified:

- *Tracking:* used to reconstruct the trajectories (tracks) and vertexes of the charged particles.
- *Electromagnetic calorimeter:* used to measure the energy of e^+, e^- pairs and photons
- *Hadron calorimeter:* used to measure the total energy of the produced hadrons.
- *Muon chambers:* used to detect muons. Neutrinos can be reconstructed as *missing energy*.
- *Magnet:* used to deflect the trajectories of produced charged particles. The radius of curvature is helpful to reconstruct the momentum and charge of the particles.

Electrons and protons are detected both in the tracking chamber and electromagnetic calorimeters. Neutral particles (neutrons and photons) can not be reconstructed by the tracking chambers. Photons are detected by the electromagnetic calorimeter and neutrons are evidenced by the deposited energy in the hadron calorimeter [1].

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2. Contribution of accelerators to cosmic-ray physics

Cosmic-rays (CR) are conformed by a beam of particles generated outside the Earth's atmosphere. The composition of primary cosmic-rays is 90% protons, 9% **He** nuclei and 1% heavier nuclei. The energy range of primary cosmic-rays that reach our planet starts from a few GeV per particle up to 10^{20} eV. At low energies the composition of the primary cosmic rays tends to be formed by protons with a few percentage of **He** nuclei, while at higher energies the nuclear contribution increases.

We can see in table 2 a clear contribution from the CR community to the discovery of elementary particles since early 1930's decade.

Table 2. Discovery of elementary particles

Particle	**Year**	**Discovered**	**Technique**
e^-	1897	Thomson	Discharge in gases
p	1919	Rutherford	Radioactivity
n	1932	Chadwik	Radioactivity
e^+	1933	Anderson	Cosmic-rays
$\mu^{+/-}$	1937	Neddermeyer, Anderson	Cosmic-rays
$\pi^{+/-}$	1947	Powell, Occhialini, Lattes	Cosmic-rays
$K^{+/-}$	1947	Rochester, Butler	Cosmic-rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic-rays
Λ^0	1950	Hopper	Cosmic-rays
anything else	1955 $\rightarrow$ today	various groups	Accelerators

In recent decades, the extensive air showers (EAS) created by the collisions between the primary cosmic-rays and the atmosphere nuclei components have been studied by several experimental arrays around the globe. The precise measurements of the energy spectrum of the primary cosmic-rays for energies between $10^{15}eV$ and 10^{17} eV bring us information related with their origin and acceleration mechanisms. The composition of the primary cosmic-rays for energies below 10^{14} eV can be measured directly by using satellites and balloons. For higher energies, large ground and underground experimental setups are used.

The interpretation of the data collected by dedicated cosmic-rays experiments depends on the extrapolation of theoretical models beyond the energy range where were they adjusted or they were tested for particle production. While some of the models converge in a common interpretation, these may lack some predictability at higher energies. Until now there are not experimental data from accelerators regarding the particle production at small angles in the forward region at energies around the region of the cosmic ray spectrum known as the *knee* (10^{15} eV). Furthermore, new physical phenomena in a very forward region at high energies in hadronic interactions, such as coherent photo-production of vector mesons or heavy flavor production, can significantly influence the measurements done with ground and underground experimental arrays. It is therefore necessary to carry out as much as possible measurements to achieve a good understanding of the forward production of particles and thus of the primary cosmic-rays flux energy. It is of particular interest the study of momentum of atmospheric muons as well as high muon multiplicity events collected with underground apparatus.

In a typical cosmic-ray experiment, the detection of atmospheric muons is usually done using large-area arrays on the surface of the Earth or with detectors deep underground. The main purpose of such experiments is to study the mass composition and energy spectrum of primary cosmic rays in an energy range above 10^{14} eV, which is not available through direct measurements using satellites or balloons. The big advantages of these apparatuses is the large size and, in the case of surface experiments, the possibilities for measuring different particles, such as electrons, muons and hadrons, created in extensive air showers. Because the detectors involved in collider experiments are tiny compared with the large-area arrays, the approach and the studies have to be different so that the remarkable performances of the detectors can be exploited [2].

3. LEP results

The use of high-energy physics detectors for cosmic-ray physics was pioneered by ALEPH (Cosmo-ALEPH) [3], DELPHI [4] and L3 (L3+C) [5] experiments during the Large Electron-Positron (LEP) collider era at CERN. In table 3 a summary of the topics in CR physics covered by each collaboration is shown.

Table 3. LEP experiments which contributed to Cosmic-ray physics. Table taken from [6]

Detector	**Depth (m)**	**Topics**
Cosmo-ALEPH	130	muon energy spectrum, μ^+/μ^- charge ratio, muon bundles, sources
DELPHI	100	muon bundles, source map
L3+C	50	angular dependence, μ^+/μ^- charge ratio, absolute muon spectrum

The main contribution of LEP experiments to the cosmic-ray physics was the measurement of the atmospheric muon momentum spectra and the detection of multi-muon bundles by the central barrel detectors. These results helped in the understanding of hadronic interaction models as well as the constrains of atmospheric neutrino fluxes. By measuring the atmospheric muon multiplicity distribution (MMD), LEP experiments concluded that the bulk of the data can be successfully described using standard hadronic production mechanisms, but the events with more than 100 reconstructed atmospheric muons occur with a frequency which is almost one order of magnitude above the simulation [7], even when assuming a combination of an extreme heavy composition with the higher measured flux values [8].

A nice and detailed discussion on LEP results on this topic can be found in [6].

4. LHC results

The Large Hadron Collider (LHC) is the largest particle accelerator ever built. It is placed in the same tunnel as LEP. The conditions at LHC allow the detailed study of $p-p$, $Pb-Pb$ and $p-Pb$ collisions:

- Large Quark Gluon Plasma temperature, volume, energy density and lifetime,
- Large cross section for hard probes: high p_T, jets, heavy quarks,
- Small net-baryon density at mid-rapidity corresponding to the conditions of early Universe,
- First principles methods more applicable (pQCD, Lattice Gauge Theory),
- New generation of particle detectors: ALICE, ATLAS, CMS and LHCb

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A development of CR Physics programs is possible at the LHC, where experiments operate for many years, with the possibility of recording a large amount of cosmic-ray data. In this context, the ALICE [9] and CMS [10] collaborations began separated programs to collect cosmic-ray data during pauses in LHC operations (see table 4).

Table 4. LHC experiments with Cosmic-ray physics programs.

Detector	Depth (m)	Topics
ALICE	50	multi-muon bundles, μ^+/μ^- charge ratio
CMS	89	μ^+/μ^- charge ratio

4.1. CMS contribution to CR Physics

The Compact Muon Solenoid (CMS) is a particle detector designed to study high energy $p-p$ collisions at LHC. It is composed by four slices: silicon tracker, calorimeters (electromagnetic and hadronic), superconducting solenoid and iron return yoke interspersed with muon chambers (see figure 2). The CMS apparatus is located 89 m. underground with 50 m. of moraines and 20 m. of molasse rock. The solenoid magnet of CMS provides a field of 4 teslas which allows the reconstruction of the momentum of the atmospheric muons that reach the central barrel of CMS spectrometer [10].

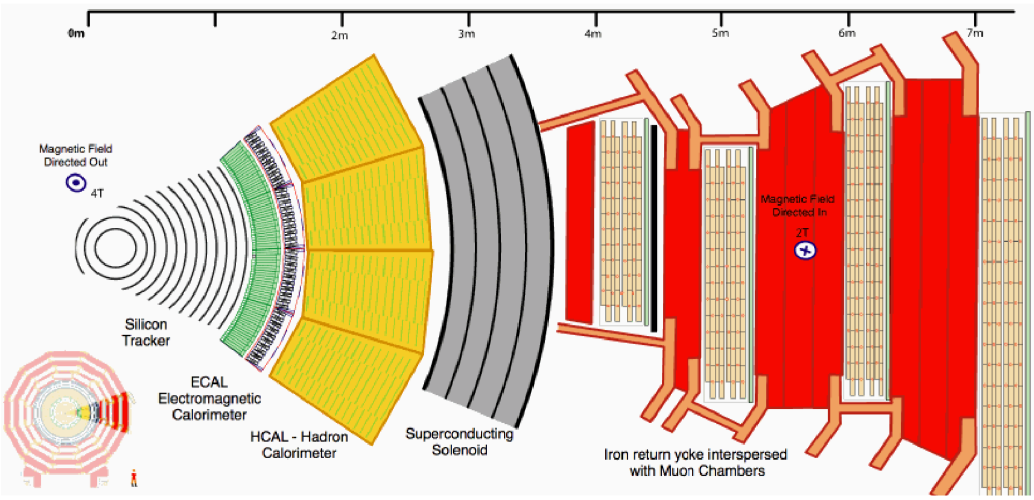

Figure 2. Schematic view of CMS detector. Figure taken from [11]

The CMS collaboration used the cosmic-ray data collected during the commissioning of the detector to carry out studies related with the measurement of μ^+/μ^- cosmic charge ratio. The muon charge ratio reflects the excess of π^+ over π^- and K^+ over K^- in the forward fragmentation region of proton initiated interactions together with the fact that there are more protons than neutrons in the primary spectrum. The increase with energy of this quantity reflects the increasing importance of kaons in the TeV range and indicates a significant contribution of associated production by cosmic-ray protons. The same process is even more important for atmospheric neutrinos at high energy [12].

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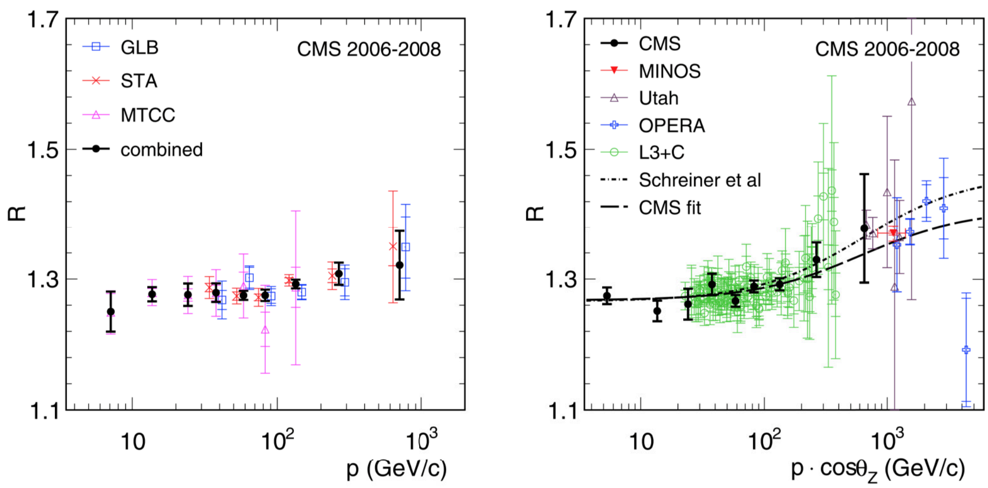
During the cosmic data taking in 2006 and 2008, CMS recorded around 295 million of events with a magnetic field ranging from 3.67 Teslas to 4 Teslas. The experimental data were treated in three different ways:

- *stand-alone muon track* (MTCC): reconstruction based only on hits from the muon chambers,
- *tracker track* (STA): reconstruction based only on hits from the silicon tracker,
- *global-muon track* (GLB): reconstruction based on hits from muon chambers and silicon trackers.

In figure 3 the results of each individual analysis are shown. The sources of systematic uncertainties are: trigger efficiency, charge misalignment and material description. In the region where the results overlap, CMS made a combination of them. For a momentum less than 100 GeV/c, the μ^+/μ^- cosmic charge ratio is 1.2766 ± 0.0032 (stat.) ± 0.0032 (syst.) which is in good agreement with the measurements made by previous experiments [13, 14, 15, 16].



(a) (b)

Figure 3. (a) The three CMS results, and their combination, as a function of the muon momentum. Data points are placed at the bin average, with the points from the standalone and global-muon analyses offset horizontally by ±10% to allow comparisons. (b) The CMS result, as a function of the vertical component of the muon momentum, together with some previous measurements and a fit of the pionkaon model to the CMS data [12]

CMS collaboration measured the flux ratio of positive to negative charge cosmic-ray muons as a function of the momentum and its vertical component. The result reported by CMS is in excellent agreement with previous measurements made by underground experiments. This is the most precise measurement of the charge ratio in the momentum region below 0.5 TeV/c. It is also the first measurement using muons with the complete CMS detectors. Details on this can be found in [12].

4.2. ALICE contribution to CR Physics

ALICE is one of four large experiments at the CERN Large Hadron Collider. Located 52 meters underground with 28 meters of overburden rock, it has also been used to detect atmospheric muons produced by cosmic-ray interactions in the upper atmosphere. In this section, the muon multiplicity distribution of these cosmic-ray events and their comparison with Monte Carlo simulation is discussed. The analysis made by ALICE exploits the large size and excellent tracking capability of its Time Projection Chamber (TPC). They gave a special emphasis to the study of high multiplicity events containing more than 100 reconstructed muons and corresponding to a muon areal density larger than 5.9 m^{-2}. The ALICE measurement on the rate of these events shows that they stem from primary cosmic-rays with energies above 10^{16} eV. The frequency of these events can be successfully described by assuming a heavy mass composition of primary cosmic-rays in this energy range and using the most recent hadronic interaction models to simulate the development of the resulting air showers.

ALICE is located at Point 2 of the LHC accelerator tunnel, in a cavern placed 52 m underground and with 28 m overburden of rock, at 450 m above the sea level. The rock absorbs all of the electromagnetic and hadronic components of an EAS, while near vertical muons with a surface energy greater than 16 GeV can reach the detectors. ALICE is a typical collider experiment, with a solenoid magnet housing the central barrel detector, and a forward muon arm, consisting of absorbers, a large dipole magnet, and fourteen planes of tracking and triggering chambers located outside the ALICE magnet. A complete description of the apparatus is given in [9].

The ALICE TPC was used to reconstruct the trajectory of cosmic-ray muons passing through the active volume of the detector. For the purpose of detecting cosmic-ray muons, the effective area of the detector considering its horizontal cylindrical geometry is approximately 17 m^2.

Specific triggers have been implemented to detect atmospheric muons crossing the central barrel of the ALICE apparatus (see Fig.4). To trigger and measure cosmic-ray events, three detectors were used: ACORDE (Alice COsmic Ray DEtector), TOF (Time of Flight) and SPD (Silicon Pixel Detector).

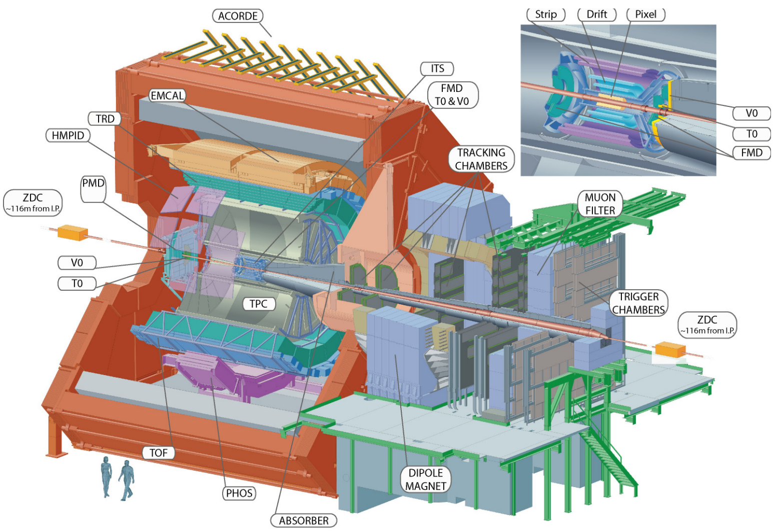


Figure 4. The ALICE detector at P2-LHC. ACORDE, TOF, TPC and SPD are used to trigger and measure cosmic-ray events.

ACORDE consists of an array of 60 scintillator modules located on the three top octants of the ALICE magnet. Each module is composed of two superimposed plastic scintillator paddles with an effective detection area of 0.37 m^2 (see Fig. 5). The trigger is given by the coincidence of the signals in n different modules (n-fold coincidence) in a 100 ns time window. A typical

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configuration of ACORDE is $n = 4$.

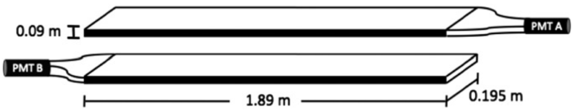

Figure 5. Schematic view of one ACORDE module. The light produced in the scintillator plastic is driven by two optical guides to one PMT per paddle. The information of the pulse is sent to the FEE (front end electronics) to generate the ACORDE cosmic-ray trigger.

The SPD is part of the Inner Tracking System located inside the inner field cage of the TPC. It is composed of two layers of silicon pixel modules located at a distance of 39 mm and 76 mm from the LHC beam axis, respectively. The layers have an active length of 28.3 cm, centered upon the nominal interaction point of the LHC beams. The SPD was incorporated into the trigger by requiring a coincidence between signals in the top and bottom halves of the outermost layer.

TOF detector is a cylindrical MRPC (Multi-gap Resistive Plate Chamber) array, completely surrounding the TPC. The trigger requires a signal in a read-out channel (a pad) in the upper part of the TOF and another in a pad in the opposite lower part forming a back-to-back coincidence with respect to the central axis of the detector.

A logical OR among the trigger signals of ACORDE, TOF and SPD was configured to generate the cosmic-ray trigger of ALICE. Most events were classified as either single muon events or multi-muon events, with a small percentage of "interaction" events where very energetic muons have interacted with the iron yoke of the magnet producing a shower of particles that pass through the TPC.

The atmospheric muons that cross the ALICE central barrel are reconstructed as two tracks (see Fig. 6). In order to quantify the muon multiplicity per event, a dedicated algorithm was developed by ALICE to match both reconstructed tracks and to obtain the full length of the muon track crossing the TPC (*up* and *down* tracks). However, the tracking algorithm has not been optimized for very inclined (quasi horizontal) tracks. Therefore, to avoid reconstruction inaccuracies associated with the most inclined showers, ALICE restricted the zenith angle of all events to the range $0° < \theta < 50°$.

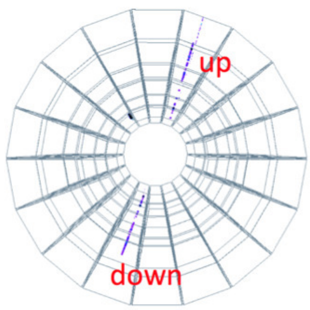

Figure 6. Track reconstruction of one single atmospheric muon with the TPC of ALICE.

Each TPC track can be reconstructed with up to 159 clusters (space points). In this analysis, tracks with at least 50 clusters in the TPC and a momentum larger than 0.5 GeV/c were required.

Since the atmospheric muons coming from the same EAS event arrive almost parallel at ground level, all the analyzed tracks per event should be parallel between them.

Finally, each *up-track* is matched to the closest *down-track* when the distance in the transverse plane (XZ) between them is less than 3 cm. A muon reconstructed with two tracks is called "matched muon". If the matching condition is not fulfilled the track is anyway accepted as a muon and called "single-track muon". Most of the single-track muons originate from particles crossing the TPC close to its edge, where part of the muon trajectory may fall outside the detector.

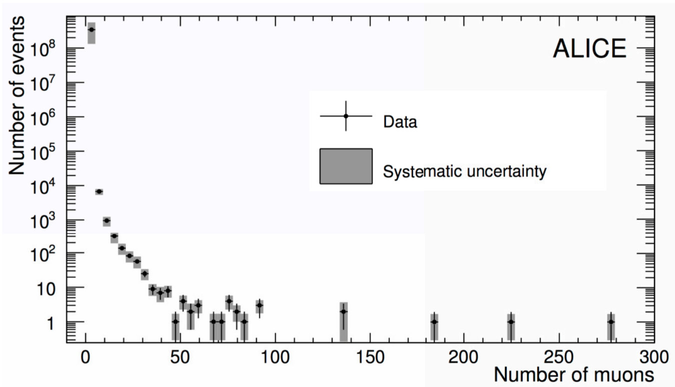

Figure 7. Atmospheric-muon multiplicity distribution taken from [17]

The main topic related to cosmic-ray physics investigated by ALICE is the study of the muon-multiplicity distribution (MMD) and in particular of events with high density of muons. The MMD measured by ALICE is shown in Fig. 7. There are 5 events with a number of muons greater than 100. As expected, a smooth distribution can be observed up to a muon multiplicity around 70. The MMD reconstructed by ALICE is very similar to that obtained by the LEP experiments [4, 5], which could not be explained by Monte Carlo models.

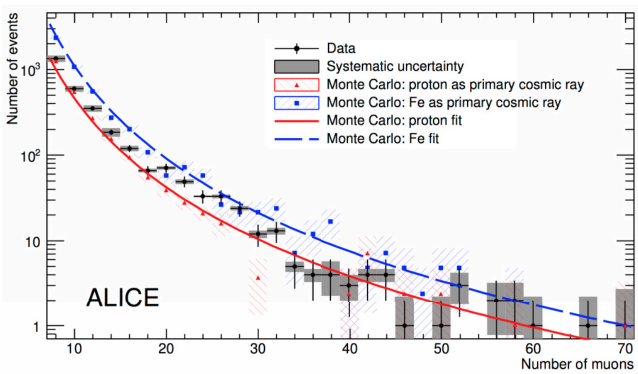

Figure 8. Atmospheric-muon multiplicity distribution of the data compared with the fit obtained with CORSIKA 6990 for proton (red line) and Fe (blue line). Figure taken from [17]

The data points shown in figure 8 are, as expected, in between the pure proton composition (light elements) and pure Fe (heavy elements). The lower multiplicities (lower primary

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Table 5. Comparison of the HMM event rate obtained with the full simulation and from measurement. Table taken from [17]

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

energies) are closer to pure proton. At lower multiplicities, corresponding to lower primary energies, ALICE reported that the data approach the proton curve, which represents a light ion composition of the primary cosmic ray flux, while higher multiplicity data lie closer to the iron curve, representing a heavier composition. The limited statistics for a number of muons larger than 30 does not allow for a precise, quantitative study of the composition, but the distribution below this multiplicity suggests that the average mass of the primary cosmic ray flux increases with increasing energy [17].

Events with more than 100 atmospheric muons (HMM) reconstructed by the ALICE-TPC are due to primary cosmic-rays with an energy larger than 10^{16} eV [18]. To estimate the rate of the high muon-multiplicity events with the Monte Carlo models, ALICE simulated one year of effective data taking with Corsika 6990 (QGSJET II-03) and Corsika 7350 (QGSJET II-04, calibrated with TOTEM results on $\sigma_{pp}^{tot/el}$ [19]):

- energy of the primary cosmic-ray: $10^{16} < E < 10^{18}$ eV,
- zenith angle range $0^0 - 50^0$

The fluctuations of these rare events are relatively small in the Monte Carlo (which corresponds to 1 year of data) but are quite large in the real data (31 days of data taking). Within the large uncertainties quoted in table 5, there is agreement between the HMM rate observed in data and in the Monte Carlo calculation which makes use of CORSIKA supposing a heavy composition at these energies ($E > 10^{16}$ eV) [18].

5. Conclusions

LEP experiments provided important results in the field of cosmic-rays physics. The muon spectra obtained by Cosmo-ALEPH and L3+C helped to better constrain atmospheric neutrino fluxes and also to improve the knowledge of the ν_μ neutrino induced background in neutrino astronomy telescope. Measurements on multi-muon events were used to test hadronic interactions models at high energies: at low multiplicities a light component of the primary cosmic ray is favored while at higher multiplicities the interaction models failed to describe the data [6].

LHC experiments are continuously taking cosmic-ray data since 2006. The CMS experiment measured the μ^+/μ^- cosmic charge ratio as a function of the muon momentum and its vertical component. The result is in agreement with previous measurements by underground experiments. This is the most precise measurement of this quantity in the momentum region below 0.5 TeV/c [12].

On the other hand, the ALICE experiment collected about 31 days of dedicated cosmic-ray data. The analysis of the collected data on the measurement of MMD and its comparison with the Monte Carlo simulations suggest a mixed composition with an increasing average mass of the primary cosmic ray at higher energies. The obtained MMD is in agreement with most experiments working in the energy range around the knee. Using CORSIKA 6990/7350 (QGSJET II-03/04) as hadronic interaction model, ALICE was able to simulate these events and to reproduce,within relatively large uncertainties, their rate. It seems that most of the HMM are due to iron or heavy nuclei with an energy greater than 10^{16} eV and a shower core located near ALICE [18]. This is the first time that the rate of HMM events, observed at the relatively shallow depth of ALICE, has been satisfactorily reproduced using a conventional hadronic model for the description of extensive air showers; an observation that places significant constraints on alternative, more exotic, production mechanisms.

5.1. Acknowledgements
This work was supported by CONACyT México Basic Science projects under grant number 24408 (CB-2015-2018) and SEP-PRODEP project under grant number PTC-431, DSA/103.5/15/7449. The author also thanks to the organizers of the VI School on Cosmic-ray Physics and Astrophysics held in the Mesoamerican Center for Theoretical Physics (MCTP) for their kind invitation.

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