First Observation of High-Energy Cosmic-Ray Events Obtained in Coincidence between EAS-TOP and LVD at Gran Sasso.

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(a) EAS-TOP Collaboration.
(b) LVD Collaboration.
Summary. — We present the first results of the combined measurements of the EAS-TOP and LVD collaborations. We demonstrate the first observations of UHE cosmic rays and their interactions. Examples of different classes of events and their significance in high-energy and astrophysical studies are discussed.

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1. Introduction.

We present the first results of the combined measurements of the EAS-TOP and LVD collaborations, the former operating at the surface and the latter deep underground, as a combined telescope to study the ultrahigh-energy (UHE) cosmic-ray interactions.

A detailed multicomponent study of EAS is essential for the understanding of cosmic-ray events at high energies in order to disentangle the main basic properties of
the UHE "cosmic-ray physics": i) primary spectra and composition; ii) hadronic (protons and heavy nuclei) interactions at UHE energies \((E_0 \gg 1000\text{ TeV}, \text{i.e. above present accelerator energies})\), iii) search for astrophysical sources, as well as the various open problems in the "underground" physics.

The experimental set-ups have therefore to include surface and deep underground detectors. The surface detectors, located at mountain level, measure the electromagnetic, muonic and hadronic components. The deep underground detectors measure the high-energy (TeV) muons, their interactions (giving essential information on the highest energies), and the neutral penetrating component.

Detectors have to combine large acceptance (to operate with primary fluxes \(= (10^{-10} \div 10^{-9}) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\)) with high resolving powers (in energy and geometry) and versatility of operation. The Italian Gran Sasso Laboratory\([3]\) provides the best opportunity, due to the possibility of operating a multicomponent\([4]\) surface array as EAS-TOP (at 2000 m a.s.l.) with deep underground detectors as LVD (\(= 3000\text{ m w.e. underground}\)).

In this note we show typical examples of different classes of events obtained through the simultaneous observation by the telescope of the two detectors.

2. – The detectors.

The two apparatus are separated by \(\approx 1000\text{ m}\) in altitude, and \(\approx 500\text{ m}\) on the horizontal projection, the average relative zenith angle being 25 degrees. The overall geometric acceptance is \(I \approx 10^8 \text{cm}^2 \text{sr}\).

EAS-TOP\([1]\) includes:

\(a)\) The e.m. detector\([5]\), in operation since the beginning of 1989, consisting of 37 scintillator modules \(10\text{ m}^2\) each, distributed over an area \(A \approx 10^5\text{m}^2\). The triggering condition is provided by the coincidence of four contiguous detectors (at the level of 0.3 m.i.p. each). During the run in which the data under discussion were taken, 29 such modules were in operation.

\(b)\) The muon-hadron detector\([6]\): 9 active layers \((12 \times 12\text{ m}^2\); 5 in operation during the run under discussion\) made of a double plane of streamer tubes for muon tracking and a single plane of proportional tubes for hadron calorimetry interleaved with 13 cm thick iron absorbers.

\(c)\) The atmospheric Cherenkov light system\([7]\): 8 telescopes separated by \(= 100\text{ m}\) from each other, equipped with three mirrors, of 90 cm diameter, seen by two large aperture \((9^\circ\) during the run here discussed\) devices and an imaging one, based on a multianode photomultiplier. The first telescope is now in operation.

LVD\([2, 8]\) is a compact large-volume apparatus \((40 \times 13 \times 12\text{ m}^3)\) with a modular structure made of 190 identical modules, located in hall A of the underground Gran Sasso Laboratory.

LVD includes:

\(a)\) The liquid scintillator detector: 1520 counters of \(1.5\text{ m}^2\) each; the total thickness at 25° from the zenith is 740 g cm\(^{-2}\) of scintillator, and 180 g cm\(^{-2}\) of Fe. The threshold for triggering the data acquisition is given by an energy deposit
\[ \Delta E > 7 \text{MeV} \] in a single counter; the electronics allows a linear measurement of the energy deposit in a single counter up to \( \approx 1 \text{TeV} \).

b) The tracking system: 190 L-shaped modules arranged as a grid of eight horizontal and five vertical double layers of limited streamer tubes. The digital read-out of orthogonal coordinates gives a spatial resolution of \( \approx 1 \text{cm} \).

The data reported here were collected when one "tower" (i.e. 1/5 of the full detector) was in operation.

The different characteristics of the surface and underground detectors allow a large variety of coincidences between the various components of the two arrays, giving the possibility of facing different problems of HE and e.m. physics.

3. – Examples of the various classes of coincidences.

This analysis refers to data taken during the period June-August 1992 for a total of 1214.7 hours of combined live time.

Coincidences are performed off-line from the timing of the events, obtained by using two rubidium oscillators, with accuracy \( 1 \mu \text{s} \), following the technique already tested for the e.m. [9] and the Cherenkov [10] detectors.

The peak of the time coincidences between the triggers of the two apparatus (for a subset of data) is shown in fig. 1, and can be easily identified. In the present run 2725 events are concentrated inside \( \Delta t = 5 \mu \text{s} \), vs. 220 expected from background. Such back-

![Fig. 1. – Delay time distribution of the EAS-TOP (e.m. detector) and LVD triggers; the peak identifies the correlated events.](image-url)
Fig. 2. - The correlated event with largest muon multiplicity detected in LVD: a) the LVD front view with hits in the tracking system and reconstructed tracks; the energy losses (MeV) in the scintillators are also indicated; b) the EAS-TOP data: black squares correspond to scintillation counters, the numbers of detected particles are shown. The cross indicates the shower core location as reconstructed from the e.m. detector data; the stars indicate the projection of the 9 muons detected in coincidence in the LVD detector. Notice that two muons have overlapping stars.

Ground can be reduced by requiring that the projection of the shower axis is within a definite distance, $d_{\text{max}}$, from the center of LVD. For example, for EAS-TOP, internal events—[5], making a cut at $d_{\text{max}} = 100$ m and without any selection on the LVD events, the background is reduced by a factor $\approx 80$ while the loss of signal is $\approx 20\%$.

A few examples of the different classes of coincidences are considered in the following:

i) The e.m. EAS-TOP detector and LVD.

The coincident event with the largest multiplicity muon bundle detected by LVD ($N_\gamma = 9$) is shown in fig. 2a) together with the corresponding e.m. component as
Fig. 3. - Observation of the three components of an event: (a) electromagnetic; the cross indicates, as in fig. 2a); the shower core. MHD is the muon hadron detector; black squares as in fig. 2a); (b) surface muon and (c) TeV muon components.

recorded by EAS-TOP (fig. 25); the reconstructed shower size at the surface is $N_e = 3.4 \times 10^5$ particles. The analysis of such class of events is of basic importance to study the c.r. primary composition[1, 4], and protons and nuclei interactions[11] at UHE.
ii) The e.m., GeV, and TeV muon components.

A threefold coincidence of the e.m. and GeV muon detectors of EAS-TOP at the surface and of the TeV muon LVD detector is shown in fig. 3. At present, the uncorrelated experimental data on $N_e$, $N_\gamma$(GeV) and $N_\mu$(TeV) lead to rather contradictory results on the c.r. primary composition[12]. Their simultaneous measurement is therefore essential to clarify the problem.

iii) The deep underground events and atmospheric Cherenkov light flashes.

An example of a deep underground event in LVD, correlated with an atmospheric Cherenkov light flash observed by EAS-TOP, is shown in fig. 4. In this particular event no e.m. trigger (as defined above) is observed at the surface, thus showing the power of the technique, i.e. of reducing the detection energy threshold of the shower in the coincidence experiment.

As a first indication, the detection efficiency for atmospheric cascades correlated with TeV muons deep underground, is thus improved by a factor $\approx 2$ compared to the e.m. array. The corresponding reduction of the energy threshold is a factor $\approx 3$. A discussion of such events is also reported in ref.[13].

iv) The EAS at surface and deep underground cascades.

Figure 5 shows a cascade with a total energy released in the LVD scintillator of $\approx 3.8$ GeV, produced by a high-energy muon. A large statistics of these events can extend the information on the energy spectrum of muons at given primary energy (again related to the composition and to the production processes).
Fig. 5. – High-energy cascade recorded by LVD, associated to an EAS event at the surface. The hits in the tracking system and the energy losses (MeV) in the scintillators are shown.

v) The search for the penetrating neutral component.

The thickness and modular structure of LVD allows the study of the penetrating neutral component produced by the high-energy cosmic rays interacting in the atmosphere.

For this analysis the three horizontal upper layers, and the two double vertical ones of scintillators of LVD in the direction of EAS-TOP are used as an anticoincidence. The efficiency of such configuration of the scintillator detector combined with the information of the streamer tubes has been studied. No muon-like track originated inside the detector has been observed in this first analysis.

4. – Conclusions.

The EAS-TOP and LVD combined detectors operating as a multicomponent array at Gran Sasso are in operation with good efficiency.

The experimental techniques and the methods of analysis provide a new methodology for studying a large variety of open problems in cosmic-ray and high-energy physics.

Examples of different classes of events detected so far have been reported.

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