STUDY OF HORIZONTHAL AIR SHOWERS AT EAS-TOP

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Abstract

Very inclined Extensive Air Showers (Horizonthal Air Showers) are studied in the electromagnetic and muon components at EAS-TOP. Their rate, angular distribution, absorption characteristics, and phenomenological properties are presented. Evidence for the dominance of muon showers originated by HE primaries at large distances in the atmosphere is presented.

1 Introduction:

A program to exploit the detection of Extensive Air Showers recorded at very large zenith angles (HAS) for the study of high energy penetrating particles, either produced in the atmosphere (μ) and of cosmic origin (ν), has been developed at the *EAS-TOP* array [Aglietta et al. 1986] (Campo Imperatore 2000 m a.s.l.) above the underground Gran Sasso Laboratories. In order to understand the nature of such events we studied their phenomenological properties, i.e. electron and muon contents, by following two different approaches. The first one by triggering on very large zenith angles Extensive Air Showers (HAS) by the e.m. array, the second one by triggering on very large zenith angle muon bundles (HMB) by the tracking muon detector.

The electromagnetic detector is made of 35 modules of plastic scintillators (10 m^2 each) distributed over an area $A \sim 10^5\ m^2$ [Aglietta et al. 1989] on the slope of *Mount Aquila* (average slope $\simeq 15°$). The triggering condition for the events under discussion is provided by the firing of a subarray made of 6 (or 7) contiguous modules, the central one recording the largest number of particles. The energy threshold is set at 30 % of the energy loss of a vertical minimum ionizing particle ($\Delta E_{m.i.p.}$). Arrival directions are measured from the time of flight technique with accuracy $0.8°$ for vertical incidence.

The μ-detector is a tracking module (140 m^2 area) made of 18 layers of streamer tubes and 9 layers of iron absorbers (13 cm thick). The read-out is performed on orthogonal x and y views . The energy threshold for vertical incidence is $E_{th} \approx 1GeV$ and the angular resolution $0.6°$ [EAS-TOP Coll. 1991,1999]. The effective area for muon counting at $\theta = 75°$ is $A_\mu = 70\ m^2$. The triggering condition is provided by the e.m. detector in the HAS experiment and by the coincidence among a subset of vertical and horizonthal streamer tubes layers in the HMB experiment (see in the following).

2 Angular distribution of EAS and evidence for HAS:

At zenith angles $\theta > 65°$ an excess of events (HAS) has been observed above the rate of EAS as expected from their attenuation length in the atmosphere [Böhm et al. 1973, EAS-TOP Coll. 1993,1994] (Fig.1).

The physical nature of the anomalous arrival directions of HAS is confirmed by the absence of events from the direction of the sky shaded by the top of the mountain on which the array is located (Fig.2).

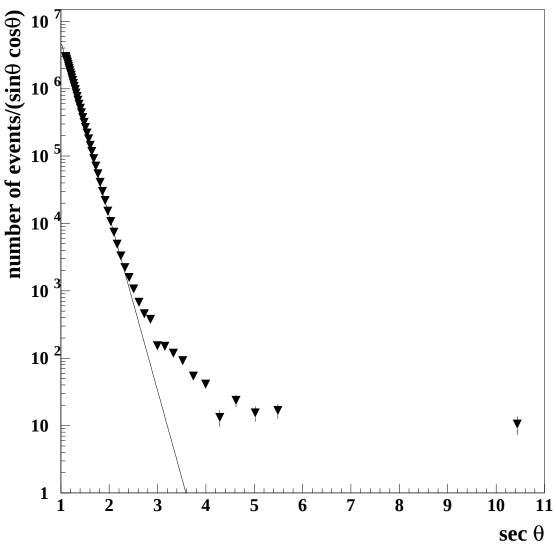

Figure 1: The zenith angle distribution of EAS as measured by the EAS-TOP e.m. array.

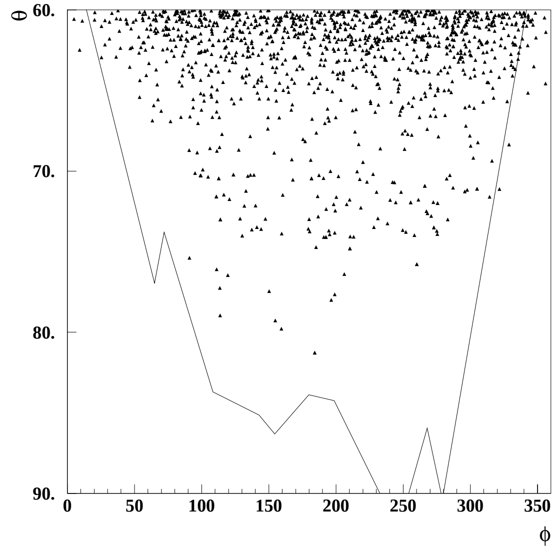

Figure 2: Arrival directions of EAS and the mountain profile seen by EAS-TOP.

Further, by comparing the arrival directions as reconstructed by the e.m. and muon detectors, the angular resolution of the shower array has been studied for very inclined events [EAS-TOP Coll. 1998]. From the distribution of the differences between the two reconstructed directions, in a subset of events with $\theta \geq 65°$ and $N_\mu > 1$, a cut in the e.m. reconstruction ($\chi^2 \leq 1/$d.f. with efficiency $\epsilon > 85\%$) has been choosen, and the systematic deviations have been obtained. Applying such correction, the fraction of events due to contaminations from reconstruction uncertainties in the e.m. detector, for θ above $70°$, is less than 30%. The comparison of the zenith angle measurements of the two detectors is shown in Fig. 3. The existence of events with $\theta \geq 75°$, which cannot be explained by errors in the angular reconstruction is confirmed.

Moreover the dependence of the barometric effect on the zenith angle, shown in Fig.4, clearly shows a deviation from the $sec\theta$ behaviour for $sec\theta > 2$. This can be explained by a non-attenuated EAS component that amounts to $\approx 30\%$ at $70°$, and dominates at larger zenith angles.

3 Muon content and particle densities:

We concentrate our attention on events with $\theta \geq 75°$, for which the contamination from cosmic ray ”conventional” showers is ≈ 1%. In 986 observation days 37 events have been recorded. Very few of such showers have a negligible content of muons (2 over 37 have zero muons in the μ-detector) i.e. are μ-poor as expected for μ or ν induced showers in the atmosphere [Böhm et al. 1973]. On the contrary the muon density ($\rho_\mu = \bar{n}_\mu / A_\mu = 0.3\ muons \cdot m^{-2}$) is comparable with the total density of charged particles measured by the scintillator modules. The charged particle density as measured by the scintillator detector ($\Delta E / \Delta E_{m.i.p.}$) and the muon density measured by the tracking detector at the same distances from the shower axis are compared in Fig.5: all experimental points lay inside a $\pm 2 s.d.$ interval around the 1 to 1 correlation line. This is expected from ”pure” muon showers, indicating a marginal content of electrons in such showers.

4 Horizonthal Muon Bundles:

Since 1996 a new measurement is operating to study Horizonthal Muon Bundles (HMB). Two vertical ($3.0 \times 12.0 m^2$) streamer tubes layers have been added to the tracking calorimeter, providing a single muon ($\theta \geq 70°$) trigger. HMB ($N_\mu \geq 3$ and $\theta \geq 75°$) have been detected during 474 observation days with a rate

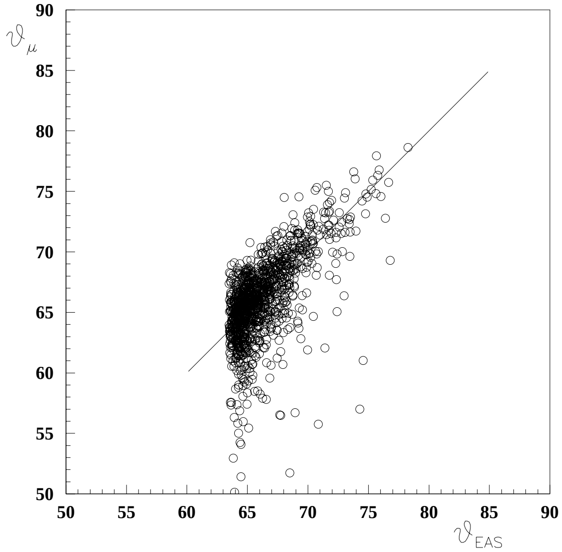

Figure 3: Scatter plot of the event directions obtained by the e.m. and muon detectors.

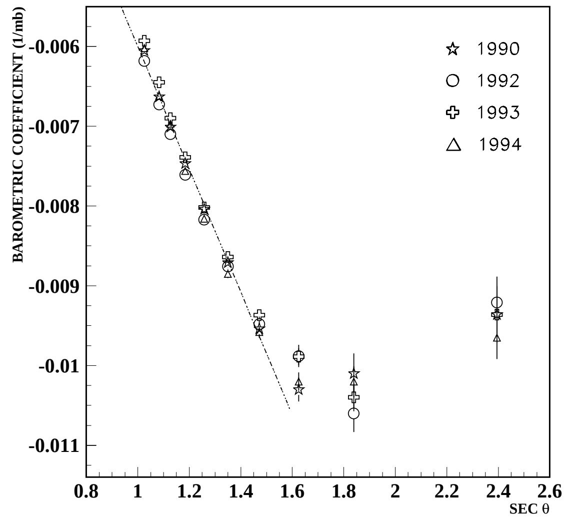

Figure 4: Barometric coefficient for different zenith angles measured by *EAS-TOP*.

of $8.4\ events \cdot day^{-1}$ (the geometrical acceptance of the triggering apparatus being $\Gamma = 35\ m^2 \cdot sr$). Their frequency distribution for different muon multiplicities is shown in Fig.6.

These events can be easily interpreted as EAS originated at large distance in the atmosphere, in which the e.m. component has been completely absorbed and the remnant muons are observed (we remember that the μ component of EAS at large zenith angles is strongly enhanced by higher π decay probability).

By using the Corsika simulation code to propagate very inclined Extensive Air Showers in the atmosphere (including the geomagnetic field and using QGSJET hadron interaction model) the expected rate of muon bundles of different detectable multiplicities has been calculated and compared with the data. Such expectations are superimposed to the experimental data of Fig.6 showing very good agreement. The uncertainties on the primary spectrum and composition and hence on the event rate and total muon number in the shower at a given primary energy induce an error on the calculated frequency which can be estimated $\approx 50\%$. It appears that events with detected muon multiplicity $N_\mu \geq 10$ are due to primaries with typical energy $E_0 = 10^{17} \div 10^{18} eV$, detected at core distances $r = 500 \div 1000\ m$.

The dashed istogram of Fig.6 represents the frequency of events which fire the e.m. trigger too. It is interesting to notice that, as the muon multiplicity increases, the two experiments (HAS and HMB) coincide. For $N_\mu \geq 10$ about 50% of HMB could be as well intended HAS: the muon triggers include the scintillator triggers. This means that very large zenith angle muon bundles are mostly responsable for the excess of events in the EAS angular distribution (HAS). For smaller muon multiplicities the density threshold in the individual scintillator ($\rho_{th} \approx 0.2\ m^{-2}$) reduces the e.m. trigger rate.

5 Conclusions:

Very inclined EAS ($\theta \geq 75°$, HAS) due to a "penetrating" component (confirmed by the barometric coefficient) are observed. Two measurements, based respectively on all charged particles and muon number triggers provide similar particle densities in both detectors. It is shown that HAS are dominated by "muon" showers, the e.m. component being generally explained by the muon local interactions. The observed rate of multiplicities of Horizonthal Muon Bundles agrees with the expected one.

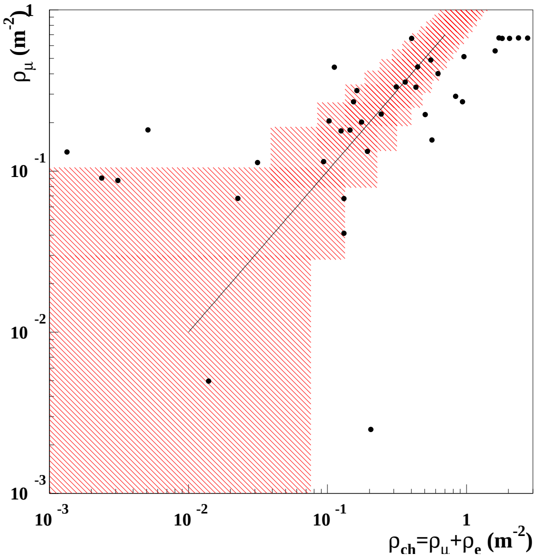

Figure 5: Particle density as measured by the scintillator and tracking detectors. 1 s.d. error boxes are shown. A few points at the upper $\rho_\mu - \rho_{ch}$ edge are out of the statistics, since lower limit to ρ_μ is given, due to saturation of the μ-detector at such large zenith angles.

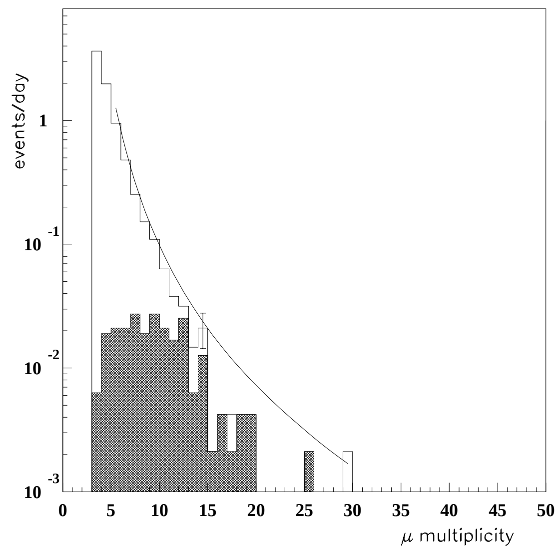

Figure 6: Frequency of HMB of different multiplicities. Shaded area corresponds to events in coincidence with the e.m. detector. Line represents the expected muon bundles rate (50% uncertainty in the calculation is expected).

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