Study of the knee structure in the EAS electron and muon components

The EAS-TOP Collaboration

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Abstract

The region of the "knee" of the cosmic ray primary spectrum ($10^{15} < E_0 < 10^{16} eV$) is studied in the electromagnetic and muon components of Extensive Air Showers by means of the EAS-TOP array. Independent and correlated analysis of the two measurements are presented as a function of zenith angle (i.e. atmospheric depth).

1 Introduction

A study of the knee [1] structure is performed by means of the electromagnetic and muon detectors of EAS-TOP. The aims are of: a) checking the compatibility of the observations from the point of view of high energy hadron interactions; b) individuating the knee position and its structure in the Ne-$N\mu$ variables; c) comparing data obtained at different zenith angles.

The aim is to extract experimental informations as much as possible independent from the interpretation through interaction models. An interpretation of the wide range relation $N\mu - Ne$ is also discussed.

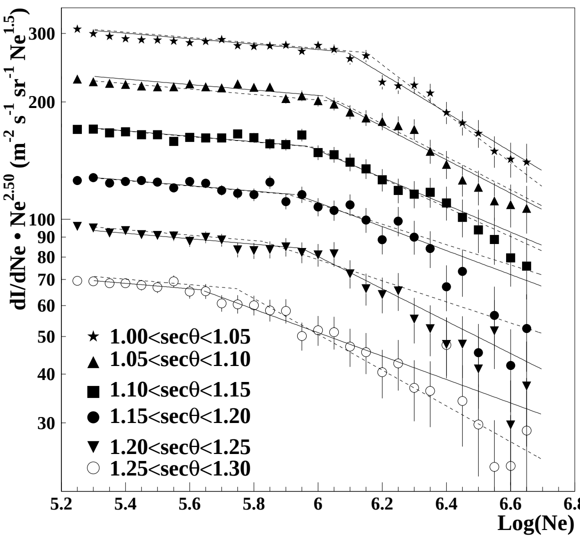
2 The experiment

The EAS-TOP array is located at Campo Imperatore, 2005 m a.s.l. (above the underground Gran Sasso laboratories), at $820\ g\ cm^{-2}$ atmospheric depth. Its electromagnetic detector [2] is made of 35 scintillator modules, $10\ m^2$ each. The distance between detectors ranges from $\sim\ 20\ m$ to $\sim\ 80\ m$. Event selection for the present analysis requires at least 6 (or 7) modules fired and the highest particle density recorded by an inner detector. The core location, the slope (s) of the lateral distribution (*ldf*) function and the shower size (Ne) are measured by means of a minimum χ^2 fit to the theoretical NKG *ldf*. The accuracy in the measurement, for $Log(Ne) > 5.2$, are: $\Delta r \leq 10m$ for the core location and $\Delta Ne/Ne \sim 10\%$ for the shower size [2].

The muon detector [3] covers a surface of $144\ m^2$ and consists of 9 identical planes. Each plane is made of two layers of streamer tubes (for muon tracking) and one layer of quasi proportional ones (for hadron calorimetry). Planes are separated by $13\ cm$ thick iron absorbers. On each plane the x coordinate of muon track is obtained from the signals of the anode wires (368 in a layer), the y one is measured from the induced signals on strips orthogonal to the wires. The distance among the wires and the width of the strips is $3\ cm$. A muon track is defined from the alignement of at least 6 hits (wires on) in different layers of tubes. The muon energy threshold for vertical events is $1\ GeV$.

$\Delta \sec\theta$	γ_1	γ_2	$I(> Ne_k) \times 10^7$ $m^{-2}s^{-1}sr^{-1}$	$Log(Ne_k)$
$1.00 - 1.05$	2.56 ± 0.02	2.99 ± 0.09	0.99 ± 0.2	6.09 ± 0.05
$1.05 - 1.10$	2.55 ± 0.02	2.93 ± 0.11	1.01 ± 0.3	6.02 ± 0.07
$1.10 - 1.15$	2.55 ± 0.03	2.85 ± 0.12	0.93 ± 0.4	5.97 ± 0.08
$1.15 - 1.20$	2.56 ± 0.03	2.81 ± 0.16	0.80 ± 0.4	5.93 ± 0.14
$1.20 - 1.25$	2.59 ± 0.03	2.91 ± 0.26	0.52 ± 0.3	5.95 ± 0.11
$1.25 - 1.30$	2.55 ± 0.07	2.80 ± 0.11	1.30 ± 0.6	5.63 ± 0.12

Table 1: Results obtained on the Ne spectra measured in different bins of zenith angles.



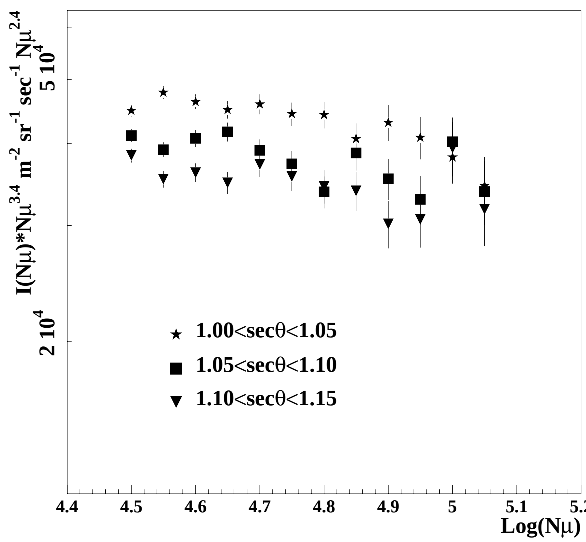


Figure 1: Differential shower size spectra measured at different atmospheric depths.

Figure 2: N_μ spectra measured at different atmospheric depths.

The muon size ($N\mu$) is obtained from the average measured muon *ldf*:

$$N\mu = \rho(\mu)\frac{r_0^{1.25} r^{0.75}}{0.269}\left(1 + \frac{r}{r_0}\right)^{2.5} \tag{1}$$

where $\rho(\mu)$ is the detected muon density and $r_0 = 300\ m$.

3 The data

3.1 Ne spectra The results are obtained from the analysis of 256 days of data taking ($\approx 1.4 \times 10^7$ events) using events with core location inside a fiducial area $A_f = 2.5 \times 10^4 m^2$. The differential size spectra are measured in different bins of zenith angles, with width $\Delta \sec\theta = 0.05$ (i.e. $\Delta x \approx 40 g cm^{-2}$). The results [4] are shown in figure 1 and table 1. In table 1 we report the obtained values of: the index of the power law spectra below (γ_1) and above (γ_2) the knee; the size at the knee (Ne_k, decreasing with increasing atmospheric depth); the integral intensity above Ne_k ($I(> Ne_k)$, costant inside the experimental uncertainties).

3.2 $N\mu$ spectra Muon number spectra are measured in the first three intervals of zenith angles. In order to avoid detector fluctuations and inaccuracies due to the used *ldf*, events are selected inside a narrow range of distances from the μ detector: $130 < r < 150 m$ ($A_f \sim 6 \times 10^3 m^2$). The obtained spectra with a data set of

$\Delta \sec\theta$	γ_{μ_1}	γ_{μ_2}	$I(> N\mu_k) \times 10^7$ $m^{-2}s^{-1}sr^{-1}$	$Log(N\mu_k)$
$1.00 - 1.05$	3.00 ± 0.1	3.60 ± 0.1	1.2 ± 0.2	4.65 ± 0.1
$1.05 - 1.10$	3.00 ± 0.1	3.55 ± 0.1	1.0 ± 0.2	4.60 ± 0.1
$1.10 - 1.15$	3.00 ± 0.1	3.55 ± 0.1	0.9 ± 0.2	4.65 ± 0.1

Table 2: Results obtained on the $N\mu$ spectra measured in different bins of zenith angles.

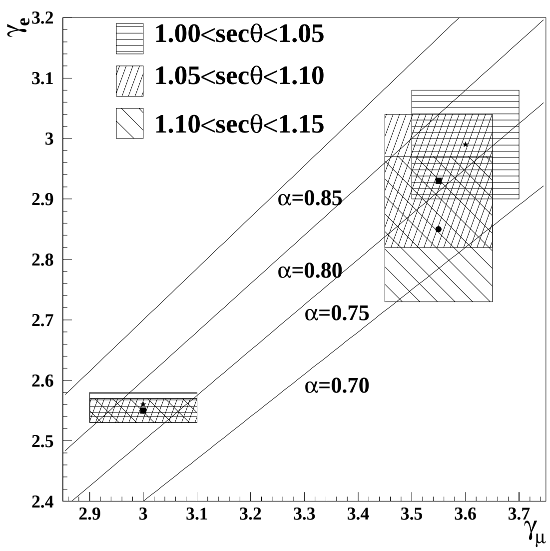


Figure 3: Comparison of the slopes of the Ne and $N\mu$ spectra measured below and above the knee.

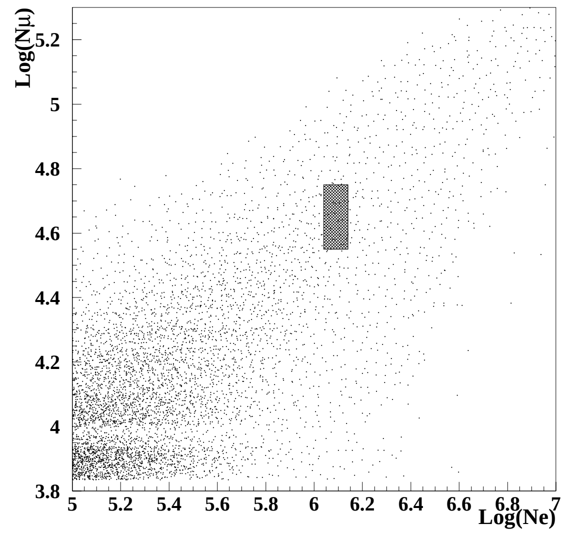


Figure 4: Scatter plot of experimental $Ne - N\mu$ data for vertical direction. The knee location error box is shown.

≈ 230 days of data taking, are shown in figure 2; the change of slope, at $Log(N\mu) \sim 4.7$, is visible in all of them in spite of the large statistical fluctations.

$\gamma_{\mu_{1,2}}$ and $N\mu_k$ are obtained by a minimum χ^2 procedure comparing the experimental data to a trial spectrum taking into account the poissonian fluctuations of the number of detected muons. $I(> N\mu_k)$ is obtained from the total number of events with $N\mu > N\mu_k$. The results are shown in table 2.

4 Electromagnetic and Muon data

From the comparison of the electromagnetic and muon data we obtain:

a) the integral fluxes above the knee $I(> Ne_k)$ and $I(> N\mu_k)$ are compatible at all atmospheric depths, as expected for a feature occurring at fixed primary energy (see tables 1 and 2).

b) The slopes of muon and electron number spectra below and above the knee, reported in figure 3, show that a value of $\alpha \sim 0.75$ (concerning the relation $Ne \propto N\mu^{\alpha}$) holds in all angular bins, thus indicating that no sudden changes in secondary production rates occurs at primary energies around the knee.

c) The location of the knee (Ne_k, $N\mu_k$) on the scatter plot of the $N\mu$-Ne data, at all zenith angles (see for example figure 4), is far from both the lower and upper (corresponding to proton and iron primaries respectively) edges of the distribution, indicating the preference for the identification of an ”intermediate” primary mass.

The distributions of $N\mu$ for $Ne_k - 1\sigma_{Ne_k} < Ne < Ne_k + 1\sigma_{Ne_k}$ obtained with different hadron interaction models (from CORSIKA code [5]) for primary protons at vertical incidence are shown in figure 5. For all interaction models the knee location is at the upper edge of the distribution, thus showing that a break in the

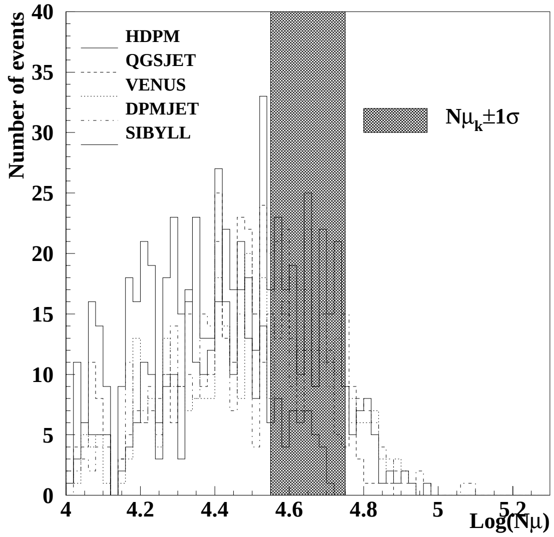


Figure 5: $N\mu$ distribution for events with $Ne_k - 1\sigma < Ne < Ne_k + 1\sigma$ obtained for primary protons with the CORSIKA code for different interaction models.

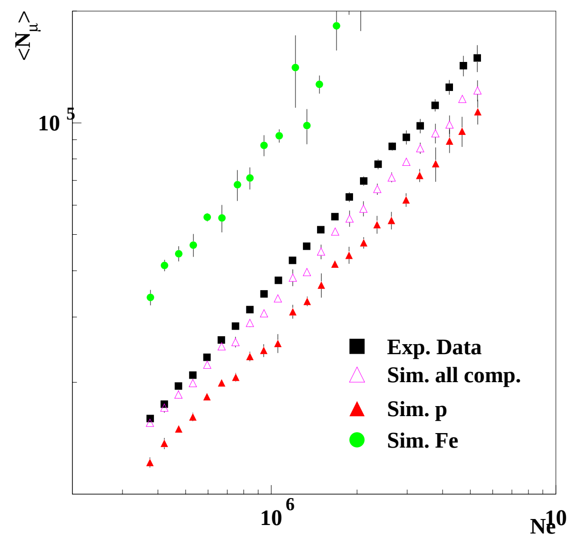


Figure 6: $N\mu$ vs Ne relation for experimental data and a composition with the same slope ($\gamma = 2.75$) for all components. Pure proton and pure iron are also plotted for comparison.

proton component is unlikely. A break in the Helium or CNO spectrum provides a better representation of the data [6]. For He or CNO primaries the knee energy corresponding to the Ne_k is respectively 3.4 and $4.1 \times 10^{15} eV$ ($2.7 \times 10^{15} eV$ for primary protons), in agreement with the cerenkov light data of reference [7]
d) Figure 6 shows the behaviour of the mean value $\overline{N}\mu$ observed, in vertical direction, in narrow bins of Ne ($\Delta Log(Ne) = 0.05$). The experimental result (160 days of data taking) are compared with the results of a complete shower simulation including detectors' responses. In the simulation the $1TeV$ composition is used with equal slopes ($\gamma = 2.75$) for all components. It appears that the experimental measurements of $\overline{N}\mu$ shift systematically towards higher values with respect to the simulated ones for increasing Ne. The difference between the measured and simulated values of $N\mu$ ($\Delta\overline{N}\mu$) is, for $\Delta Log(Ne) = 1$: $\Delta\overline{N}\mu/\overline{N}\mu \approx 0.17$. The corrispondent change in $\overline{A}$ is $\Delta\overline{A}/\overline{A} \approx 0.7$ over the Ne decade around the knee. The simulation is performed using the HDPM code that gives a good representation of the EASTOP-LVD data [8] and that seems to "minimize" the observed effect, due to the large μ yield when compared to other models.

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