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PROCEEDINGS SUPPLEMENTS

Experimental Study of Hadronic Interaction Models Using Coincident Data from EAS-TOP and MACRO

G. Battistoni[a] for the EAS-TOP and MACRO Collaborations

[a]INFN, via Celoria 16, Milano, 20133, Italy

The contemporaneous measurement of TeV muons in deep underground laboratories and of the e.m. component at the surface allows checking the hadron interaction models and the propagation codes used in EAS experiments in a primary energy range 10-50 TeV in which the primary spectra are measured by direct experiments. First results of such measurements between MACRO and EAS-TOP at the Gran Sasso laboratory, in this energy range, are here reported.

1. Introduction

Combined measurements of the e.m. component of EAS at the surface and of the high energy muons detected deep underground are performed by the EAS-TOP and MACRO detectors at the Gran Sasso Laboratories. EAS-TOP is the EAS array measuring the e.m. shower size at 2000 m a.s.l. (810 g cm^{-2}), while MACRO samples the number of muons ($N_{\mu}(E > 1.3\ TeV)$) at a minimum depth of 3100 m w.e. The two detectors are separated by 1100-1300 m of rock and are located at a relative zenith angle of $\sim 30°$. Details on the detectors and on their performances and the analysis of a first sample of coincident data have been presented elsewhere[1–4]. Two classes of events are selected: high energy coincidence events and low energy triggers. For the first class ($E_0 >$ 100÷200 TeV) full reconstructions are available from both experiments. They are analysed in terms of primary composition [5]. In the second class, the trigger is provided by at least a muon track in MACRO pointing to a fiducial area ($6.7 \cdot 10^3$ m^2) well internal to the EAS–TOP edges. The analysis is performed in terms of the rates of the number N of detectors fired in EAS–TOP. If N<4, EAS-TOP does not provide trigger, and we define the event as an "anti–coincidence". These particular events cover a primary energy range from approximately 2 TeV to a few tens of TeV. No shower reconstruction is performed by EAS-TOP for N< 7. In the energy intervals covered by the anti–coincidences it is possible to use, as input primary spectra, the sets of data obtained by experiments at the top of the atmosphere or in the outer space. This allows to test the predictions of different models for the EAS development. In this paper we report the results of a first comparison, where two different interaction models have been tested: 1) In HEMAS [6] the basic interaction model is obtained by a proper parameterization of experimental results as obtained at accelerators. 2) In HEMAS-DPMJET[7] the shower code of HEMAS is now interfaced to the DPMJET[8] interaction model. In contrast to the philosophy of the original HEMAS, this is a theoretically inspired model. It is based on the two component Dual Parton Model, including also the mini–jet production as predicted by the lowest order perturbative QCD.

2. The Set of Experimental Data

For this first analysis of anti–coincidences and low energy triggers, we have used a sample of data collected in the period ranging from May 3rd 1993 to September 6th 1994. We define in the muon event as seen by MACRO a center of gravity of the muon tracks at the level of the floor of the underground laboratory. The event is accepted if the back-extrapolation of the centroid coordinates up to the EAS-TOP height fall inside the above defined fiducial area in the central and denser part of the EAS-TOP array. Then, if EAS-TOP had a trigger within the time coincidence window, the event is classified according to

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the number of fired modules. The number of coincidence events thus defined in the considered time period is 1404 in 140.44 days of operation, taking into account also the dead time of both acquisition systems. Instead, if no trigger is detected by EAS-TOP, the event is considered as an "anti–coincidence". After a statistical correction for the dead–time we obtain 6515 anti–coincidences in 153.68 days (here correction for dead time is different from the case of coincidences).

3. Monte Carlo Simulation

For each Monte Carlo we have generated 5 different mass groups (H, He, CNO, Mg and Fe) with a continuous spectrum, for a corresponding live time of 100 (1000) days below (above) 200 TeV. The muon transport code in the rock is that of ref.[9]. The generated events have been folded with both detector simulation. The EAS-TOP trigger simulation takes into account the fluctuations of the number of particles hitting the detector modules and the electronics dispersions, as obtained from experimental data.

4. Analysis and Results

As input spectra, we use single power law fits to the fluxes of H and He as reported by JACEE in 1993[10] and 1995[11]. The data of higher mass components are taken from other experiments[12,13]. Our best fits for p and He fluxes provide the following spectra in units of ($m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}$):

$$p: \quad 5.57 \cdot 10^4\ (E/GeV)^{-2.86} \qquad (1)$$
$$He: \quad 9.15 \cdot 10^3\ (E/GeV)^{-2.68}$$

The errors on the fit parameters allow an uncertainty of about 15% of these fluxes in the energy range of interest. The results are shown in Table 1, after the normalization of experimental and simulated data to 100 days of live time. The interaction model in the present configuration is tested in the energy range 2 to 100 TeV. Anti–coincidences are found to be dominated by H and He primaries. As far as the number of simulated events is concerned, the previously quoted uncertainty on the primary flux should be allowed, together with the systematics of the trigger threshold simulation (ranging from 7 to 15%, according the nature of primary). With such attention, the higher energy rates ($N > 4$) can be described by both models. Even with such care, at the lower energies ($N < 4$) the HEMAS codes underestimates the rate of events much more significantly than DPMJET. In Fig. 1 we show the relative contribution to simulated anti–coincidence events as a function of total primary energy for protons and He nuclei, as calculated by HEMAS and HEMAS-DPMJET. This plot shows how most of the differences in the codes manifest themselves for values of energy/nucleon near the threshold for the production of TeV muons. The contribution of protons to anti–coincidences increases by 18% from HEMAS to HEMAS-DPMJET, while, for He nuclei, the increase is ~64%. Also the average detected muon multiplicity changes, as

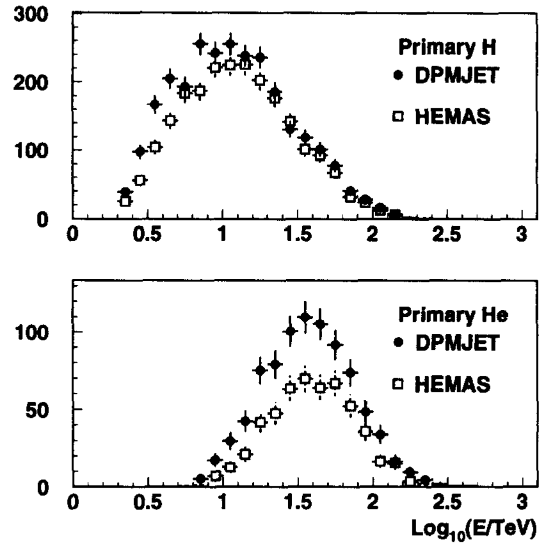

Figure 1. *Relative contribution to simulated anti-coincidence events as a function of total primary energy for protons and He nuclei, as calculated by HEMAS and HEMAS-DPMJET*

Table 1
Comparison among the measured number of events with N modules fired in EAS–TOP (triggered by a muon in MACRO) and the expectations from two interaction models. Statistical and systematic errors have been added quadratically.

No. of EAS–TOP modules fired	$N < 4$ Antic.	$4 \leq N \leq 6$ Low En. Coinc.	$N > 6$ High En. Coinc.	$N \geq 0$ Total
Exp. Data	4239 ± 639	376 ± 60	624 ± 97	5239 ± 789
DPMJET Int. Mod.	3502 ± 529	314 ± 50	560 ± 87	4378 ± 660
HEMAS Int. Mod.	2729 ± 413	324 ± 52	600 ± 93	3653 ± 551

Table 2
Comparison between the measured average detected muon multiplicity for the anti–coincidence events and the expectations from the two interaction models.

	$< N_\mu >$	$< N_\mu >$(H)	$< N_\mu >$(He)
Exp. Data	1.321 ± 0.003	–	–
DPMJET Int. Mod.	1.310 ± 0.003	1.284	1.424
HEMAS Int. Mod.	1.282 ± 0.003	1.269	1.386

shown in Table 2 (where the contribution from H and He is again separated), favoring again the DPMJET interaction model. At this first stage we can conclude that for a fixed minimum muon energy, in the total energy region below <50÷100 TeV, high x_F values become relevant for the TeV muon yield, and this is even more important for primaries heavier than protons. There, the DPMJET model seems more adequate. Considering the basic nucleon-Nucleus interaction, we can quantify the conclusion in terms of of the "spectrum weighted moments" for charged pions: $Z_\pi = \int_0^1 \frac{dN(p+Air\rightarrow\pi+X)}{dx} x^{1.7} dx$. As shown in [7], DPMJET (and other codes based on similar hypotheses) provide larger values with respect to HEMAS: 0.068 in the range 1÷ 100 TeV against 0.061÷0.057 for HEMAS in the same energy range. We can therefore conclude that the coincident data collected by EAS-TOP and MACRO in the region below 50÷100 TeV, where direct measurements on primary fluxes are available, can be used to discriminate the prediction of different hadronic interaction models. A minimum value of $Z_\pi(E < 100\ TeV)$ ~0.068 is required to obtain an agreement with the present primary fluxes at 68% c.l.

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