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NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

High Energy Cosmic Ray Physics with the MACRO Experiment at Gran Sasso

The MACRO Collaboration

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The multimuon data collected by the MACRO detector at Gran Sasso have been analyzed using a new method. The resulting all-particle spectrum is consistent with EAS measurements but higher and flatter than the one obtained from direct experiments.

1. INTRODUCTION

One of the most important problems in high-energy cosmic-ray physics is the study of the primary flux with energies between 10^{14} and 10^{17} eV where a "knee" of the all-particle primary spectrum is observed.

In the present work we describe a new approach for measuring the primary spectrum and composition, using a multi-parametric fit of the

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MACRO multimuon events.

2. EXPERIMENTAL RESULTS

A minimization procedure is used to estimate the primary cosmic ray composition from the best fit of the MACRO experimental rates of multimuon events (see [1] for more details about the experimental method used). We minimize the function:

$$\chi^2_M = \sum_{N_\mu} \frac{[R^{meas}(N_\mu) - R^{calc}(N_\mu)]^2}{\sigma^2[R^{meas}(N_\mu)] + \sigma^2[R^{calc}(N_\mu)]} \quad (1)$$

where $R^{meas}(N_\mu)$ are the experimental points and $R^{calc}(N_\mu)$ are calculated according to:

$$R^{calc}(N_\mu) = \Omega S \sum_A \int dE \; \Phi_A(E) D_A(E, N_\mu) \quad (2)$$

where E and A, denote the energy and mass number of the primary whose spectrum is represented by $\Phi_A(E)$. The function $D_A(E, N_\mu)$ represents the probability (averaged over the solid angle Ω and the sampling area S) for a primary of mass A and energy E to be reconstructed as an event with N_μ muons in MACRO. This function depend on the hadronic interaction model, muon propagation through the rock and detector geometry.

We assume that the energy spectrum of each elemental group can be expressed by:

$$\Phi_A(E) = K_1(A)E^{-\gamma_1(A)} \quad \text{for } E < E_{cut}(A) \quad (3)$$

$$\Phi_A(E) = K_2(A)E^{-\gamma_2(A)} \quad \text{for } E > E_{cut}(A) \quad (4)$$

with $K_2 = K_1 E_{cut}^{\gamma_2 - \gamma_1}$. This correspond to 4 free parameters $(K_1, \gamma_1, \gamma_2, E_{cut})$ to be determined for each elemental primary spectrum that we want to estimate.

In order to get successful fits with five mass groups we are forced to reduce the number of free parameters and to restrict the parameter space.

We adopted therefore the physical hypothesis that the cutoff in the primary energy spectrum is attributed to particle leakage in the Galaxy at fixed magnetic rigidity. In practice, we assume that the energy cutoffs of elemental groups follow the relationship:

$$E_{cut}(Z) = E_{cut}(Fe) \cdot Z/26 \quad (5)$$

The parameter space has been bounded taking into account recent direct measurements of the five mass groups [2][3][4]. This has been achieved inserting direct measurements in the minimization function so that they can act as starting points and constrain the primary spectra below the knee (see [1] for details).

We will refer the composition model obtained as best fit of our data with the above conditions as our "standard fit". Fig. 1 shows the "standard fit" all-particle spectrum, superimposed to a collection of experimental data. The bold line gives the central value of the fit, the dashed lines represent the uncertainties on the spectra (1 σ errors) calculated using the covariance matrix of the parameters given by fitting procedure. It can be easily recognized that the spectrum of the fitted model is higher and flatter than the one obtained from direct measurements alone (shown in Fig. 1 as a dark area). The discrepancy is ~10%

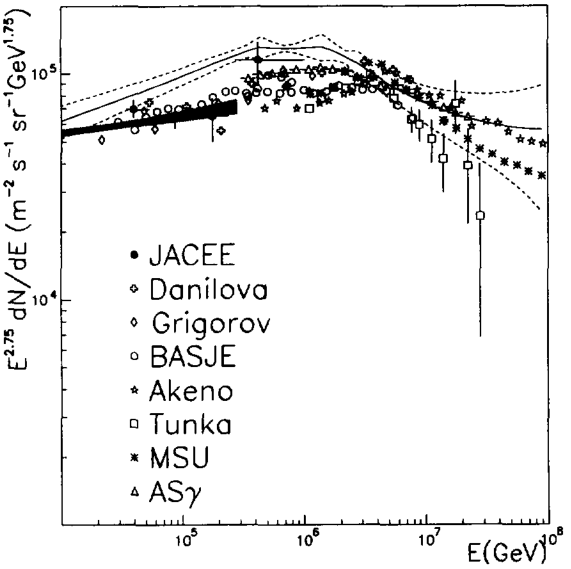

Figure 1. The "standard fit" all-particle spectrum (solid line: best value; dashed lines: ±1σ error) compared with a collection of experimental data (JACEE [2], different EAS arrays and -dark area- spectrum obtained from the fit of direct measurements at lower energy.)

at 10 TeV and ~50% at 100 TeV. On the other hand, it shows a good consistency with EAS array measurements above the "knee". The spectral indexes of the fitted energy spectrum are 2.56±0.05 for E<500 TeV and 2.9±0.3 for E>5000 TeV with a gradual change at intermediate energies.

A remarkable outcome of this analysis is that, for the first time, an underground experiment shows sensitivity to the knee.

To prove this, a different fit has been performed under the assumption of a single power law for each group (corresponding to 10 free parameters). As a result we obtained a χ^2 probability of 5.8 % to be compared with the value of 95 % in the case of the two spectral index hypothesis. It has to be emphasized that this result emerges directly from multimuon data, since single slope spectra give a good description of the direct measurements data. In Fig. 2, the average mass number obtained in our "standard fit" is compared with other measurements and predictions. $\langle A \rangle$ shows a weak dependence on the primary energy below 10^6 GeV with a value of 10.1±2.5 at 100 TeV. Even within larger uncertainties our data show that the composition changes at the knee and support a possible moderate increase of the average mass number at higher energies.

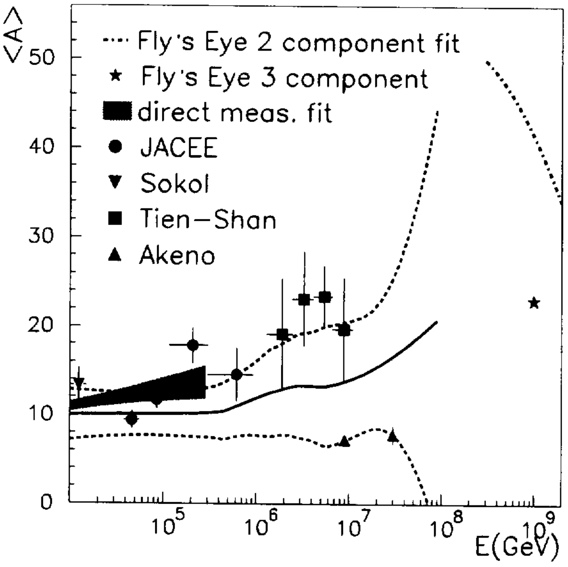

Figure 2. Comparison of the average primary mass arising from our "standard fit" (solid line: central value; dashed line: value at one sigma error) with other measurements.

3. FEW REMARKS ABOUT THE MONTE CARLO USED

In all indirect measurements in cosmic ray physics the final interpretation is unavoidably dependent on the model adopted to describe the secondary production and transport. The present analysis has been mainly based upon the HEMAS[5] shower code. The reliability of this code in term of underground multimuon characteristics has been proved by comparison with some other codes.

The two most important steps in the shower development simulation are the hadronic interaction and the muon propagation through the rock. We have therefore compared the rate of underground multimuon events obtained with HEMAS standard hadronic interaction code with the one obtained using SIBYLL[6] and DPMJET[7] code. Differences below 10% have been found.

Another important source of systematic uncertainties is the knowledge of the rock around MACRO and the simulation of the muon propagation through the rock. A study in term of the ratio between the rate at a certain multiplicity R(N_μ) and the rate of single muons R(1) permits to cancel these effects because they do not alter significantly the shape of the multiplicity distribution. We applied therefore the multiparametric fit procedure also to the muon rate ratios r(N_μ)=R(N_μ)/R(1), defining χ^2_M with r(N_μ) in place of R(N_μ). In this way only the shape of the multiplicity distribution is taken into account, while the absolute normalization of the primary fluxes is fixed by the data of the direct measurements. The all-particle spectrum arising from this fit is shown in Fig. 3. This spectrum has the same shape of the "standard fit" one and, as expected, is in better agreement with the direct measurements, for what concerns the absolute normalization. However, at higher energies, the spectrum shown in Fig. 3 is less consistent

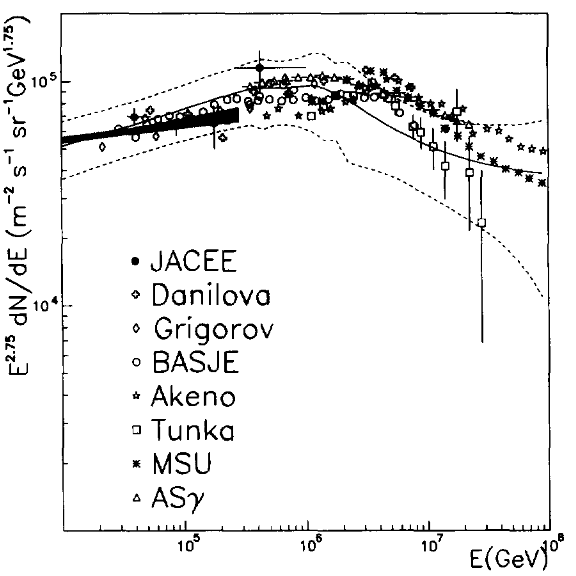

Figure 3. All-particle spectrum arising from the fit of of the rate ratios r(N_μ)=R(N_μ)/R(1), superimposed to previous experimental data. Dark area: spectrum obtained from the fit of direct measurements.

with the EAS measurements with respect to the one obtained from the fit of the absolute rates.

4. SUMMARY

The MACRO experiment is able to perform precise measurements on a high statistics sample of TeV muon component induced by primary cosmic rays, with a good control of detector systematics. Our "standard fit" all-particle spectrum shows a good consistency with EAS array measurements whereas, in the lower energy region, it is higher and flatter than the one obtained from direct measurements alone. The average mass number show a weak dependence on the primary energy below 10^6 GeV. Even within larger uncertainties, our data support an increase of the average mass number at higher energies.

REFERENCES

1. The MACRO Collaboration (M. Ambrosio et al.), *Submitted to Phys. Rev. D*
2. JACEE Collaboration (T.H. Burnett et al.): Ap.J., **349** (1990) L25; *Proc. of 23rd Int. Cosmic Ray Conf., Calgary,* 2 (1993) 5, 21, 25
3. I.P Ivanenko et al., *Proc. 22nd Int. Cosmic Ray Conf., Dublin,* **2** (1991) 17
4. CRN collaboration, D. Muller et al., *Ap.J.* **374** (1991) 356
5. C. Forti et al., *Phys. Rev. D* **42** (1990) 3668.
6. R. S. Fletcher et al., *Phys. Rev. D* **50** (1994) 5710.
7. G. Battistoni, C. Forti and J. Ranft, *Astroparticle Phys.*, **3** (1995) 157