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PROCEEDINGS
SUPPLEMENTS

Relevance of the hadronic interaction model in the interpretation of multiple muon data as detected with the MACRO experiment

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With the aim of discussing the effect of the possible sources of systematic uncertainties in simulation models, the analysis of multiple muon events from the MACRO experiment at Gran Sasso is reviewed. In particular, the predictions from different currently available hadronic interaction models are compared.

1. Introduction

As described in [1], a minimization procedure has been used to estimate the primary cosmic ray composition from the best fit of the MACRO experimental rates of multimuon events. The goal of this minimization procedure is to obtain a model of the chemical composition and elemental spectra of primary cosmic rays. The primary spectra are obtained from the estimate of the pa-

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rameters at the minimum of the minimized function.

Our results [1], obtained with the HEMAS interaction model [2] being chosen *a-priori*, exhibit some disagreement with the existing direct measurements in the primary energy region 10 ÷ 100 TeV. The spectra of the fit are consistent within errors with direct measurements for the three heaviest groups. For lighter elements the agreement with direct data is achieved only at lower energies (below 10 TeV), whereas the fitted spectra exceed direct data, especially for proton spectrum, at increasing energies. Possible inadequacies of the modelling of muon rates adopted in our simulation could be a source for this disagreement.

In fact, the interpretation of deep underground muon data requires a simulation which includes a hadronic interaction model, the air shower development, the propagation of muons through the rock and a detailed description of the detector. There are some systematic uncertainties in the Monte Carlo predictions that have been investigated in detail in [1]. These include: uncertainties in the hadronic interaction model, in the knowledge of the map of the rock around MACRO and in the muon propagation through the rock. As described in [1], the uncertainties from the knowledge of the rock around MACRO and the muon propagation through the rock can be cancelled by applying the best fit procedure to the muon rate ratios. Therefore the main contribution to systematic uncertainties in our Monte Carlo simulation is due to the hadronic interaction model, that could act differently in the various energy regions. A comparison of the features of the hadronic interactions that mostly effect the production of high energy muons has been presented at this conference[3]. In this paper the primary spectra estimated from the best fit of MACRO multimuon rates using different currently available models are compared.

2. Models of hadronic interactions

The simulation of the hadronic interactions of primary cosmic rays with air nuclei plays an essential role in the interpretation of indirect cosmic ray data. Important sources of uncertainties in the hadronic interaction model come from our limited knowledge of proton-air and nucleus-air inclusive meson production at very high energies. A model for hadronic and nuclear interactions to be used in cosmic ray physics should work from the pion production threshold up to the highest possible primary energies. Experimental results from collider and fixed target experiments at accelerators provide important inputs up to a proton energy $E_p \sim 1000$ TeV. However, in the highest energy part of the energy region investigated in this search, which corresponds to centre of mass energies $\sqrt{s} \approx 10$ TeV, no direct collider measurements are yet available, and lower energy data must be extrapolated. Nucleus-nucleus data from accelerator experiments need a much stronger extrapolation. This situation could lead to the hypothesis that possible inadequacies of interaction models, that are tailored to experimental data, are increasing with energy, but are virtually absent in the energy region below the knee.

Indeed a more careful study about hadronic interaction mechanisms shows that possible uncertainties are also present at lower energies. For the relevant kinematical region accessed (e.g., the Feynman-x interval), there are important differences between cosmic ray cascades and particle production at accelerators. At colliders, the central region in hadron-hadron collisions is usually best measured. At lower energies, in fixed target experiments, the forward fragmentation region is more easily accessible, yet very little data are available at x_F exceeding 0.1. Multiple muons observed in underground detectors come from different kinematical regions determined by the energy of primaries that produce the muons. In particular one can see [1] that multimuon events originating from less energetic primaries are preferentially produced from parents in the very forward fragmentation region, whereas at higher primary energies the corresponding production kinematical region is at lower x_F. It can be recognised that the highest x_F parents are the main contributors of the low multiplicity muon events and then largely determine the inclusive muon rates.

Therefore possible inadequacies of the hadronic interaction models in the far fragmentation region could, at least partly, explain the discrepancies between multimuon results and direct measurements.

3. Primary spectra and composition

The previous MACRO analyses [4–7,1], have been mainly based upon the HEMAS [2] shower code. In order to estimate the dependence of our results on the adopted event generator, we have also used the SIBYLL interaction model [8]. As reported in [1], SIBYLL more effectively produces detectable muons near the underground muon production threshold, whereas at higher energies it approaches HEMAS. The all-particle spectrum arising from the fitting procedure assuming the SIBYLL model is at most of the order of 10 % lower than the one obtained with HEMAS.

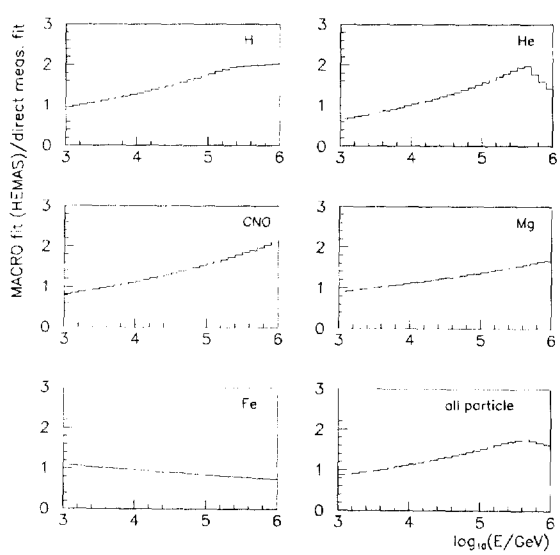

Figure 1. Ratio of the elemental and all-particle spectra arising from the fit of MACRO multimuon rates (using the HEMAS model) to direct measurement fit.

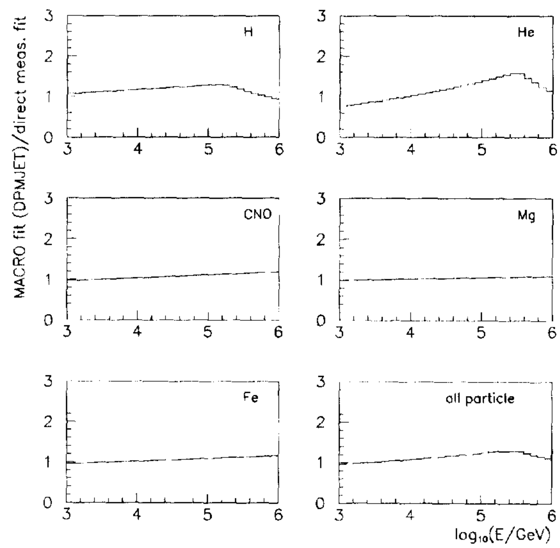

Figure 2. Ratio of the elemental and all-particle spectra arising from the fit of MACRO multimuon rates (using the DPMJET model) to direct measurement fit.

In the present analysis we extend the comparison using the DPMJET model [9]. DPMJET event generator has been inserted in the same shower code already used for HEMAS. For technical reason, the analysis is restricted to MACRO multimuon events coming from a limited solid angle ($20° < \theta < 40°$, $150° < \phi < 220°$). Only events with multiplicity $N_\mu < 15$ have been used, and therefore the estimated primary spectra are limited to the energy region below the knee. This is the region where the strongest discrepancy with existing cosmic ray data have been found in our previous analysis [1]. We applied the multi-parametric fit procedure, following the method described in [1], using the DPMJET code as hadronic interaction model. In order to compare with previous results, we show in Fig. 1 and 2 the ratio between the central value of the spectra obtained from the fits of MACRO multimuon rates (using the HEMAS and DPMJET models respectively) and the fit of direct measurements, for the elemental and the all-particle spectra. It can be seen that both the elemental spectra and the all-particle spectrum of the model obtained using DPMJET are in much better agreement with direct data with respect to the ones obtained using the HEMAS model. In fact, the all-particle spectrum obtained with HEMAS exceeds direct measurements by an amount ranging from 15% at 10 TeV to 50% at 100 TeV, while the one obtained with DPMJET by 7% at E=10 TeV and 23% at E=100 TeV. It is worth nothing that in terms of the dependence on energy of the average primary mass and relative abundances of mass groups the results obtained from the fit using the DPMJET model are very similar to the corresponding ones obtained with HEMAS.

4. Conclusions

In order to study the dependence of our best fit procedure on the adopted hadronic interaction model, we have compared different models. We have shown that the analysis based on the DPMJET model, which provides a larger muon yield underground, significantly reduces the disagreement between MACRO multimuon data and direct measurements data, with respect to previous analyses based on HEMAS.

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