STUDY OF PHOTONUCLEAR INTERACTION OF MUONS IN ROCK WITH THE MACRO EXPERIMENT

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Abstract

We present first results about the measurement of the characteristics of charged hadrons production by atmospheric muons in the rock above MACRO. Selection criteria which allow to discriminate hadron cascades from e.m. showers generated by muons are described. A comparison between the measured rate, with that expected from a Monte Carlo simulation which treats the process as dominated by photo-nuclear interaction is presented. These data can be used to validate such models aiming to the evaluation of hadron background from cosmic muons in different experimental environments.

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1 Introduction

The inelastic muon-nucleus interaction was discovered in by George and Evans (1955), who observed "stars" of charged hadrons produced by high energy muons. Since then the process is generally referred to as nuclear interaction of muons. At accelerators, this process is mainly studied in the range of large squared four-momentum transfer ($Q^2 \geq 1GeV^2$) with the principal aim of measuring nucleon structure functions (deep inelastic scattering experiments). However, the bulk of interactions are characterized by low Q^2 ($Q^2 \leq 0.1GeV^2$): hence they can be described with the exchange of a quasi-real photon between the muon and the nucleon and they are often referred to as photo-nuclear interaction of muons. Recently, it has been stressed that nuclear interactions of muons are an important source of background for many underground experiments (Khalchukov et al, 1995). Low energy protons coming either from the primary interaction of muons or from reinteraction of produced hadrons can be a relevant background in the detection of solar ν_e's by radio-chemical means (Cribier et al., 1997), while neutral hadrons may play a significant role in oscillation experiments at reactor or accelerators (see Kleinfeller et al., 1996). Furthermore, the question of hadron background generated by muons has been raised in the search of proton decay (Khalchukov et al, 1983) and in the study of atmospheric neutrinos, observed as contained events in Cherenkov detectors (Ryazhskaya, 1994; Becker-Szendy et al., 1992), or as upward going muons produced by CC interactions in the rock (MACRO Coll., 1997a).

A comparison between experimental measurements about the production of hadrons by muons and data obtained by Monte Carlo (MC) simulations is mandatory to test the reliability of theoretical models. In fact, uncertainties do exist on the cross section calculation for the process, mainly due to the extrapolation of photo-nuclear cross section at high energies, and in the simulation of the hadronic final state, because the smallness of the Q^2 does not allow the use of perturbative QCD, and models are required. These uncertainties also affect muon survival probability calculations in underground-underwater experiments (Kokoulin and Petrukhin, 1996).

The aim of the present work is to compare real data collected by the large area underground experiment MACRO (MACRO Coll., 1993), operating in the underground Gran Sasso laboratory, with a MC simulation based on the cross section calculated by Bezrukov and Bugaev (1981) and on DPM model (see for instance Capella et al, 1987) for the sampling of the final state. We shall look for comparison also to a complete different modelization available in the high energy physics library.

In next sections we briefly review the detector features and the model employed to calculate the cross section used in our simulation. Then we discuss the analysis and the preliminary results.

2 The Detector

A description of MACRO and in particular of his tracking system is given elsewhere (MACRO Coll., 1993, and references therein). We limit to remind here that MACRO operates at an average depth of 3800 hg/cm^2, where the average residual energy of muons is about 300 GeV. The horizontal area of MACRO is about 1000 m^2 and it

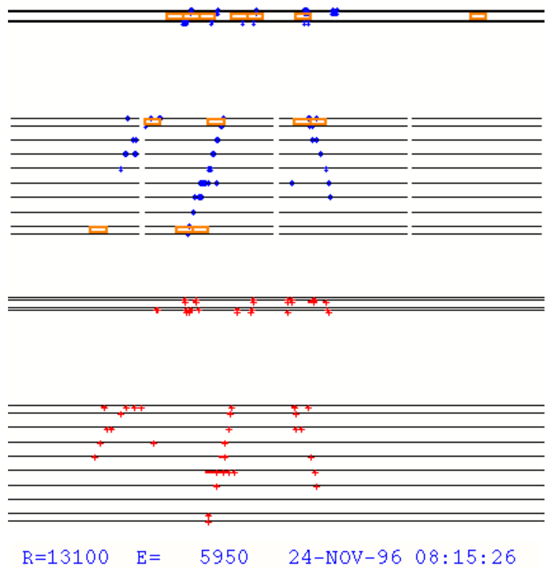

Figure 1: A typical candidate event as detected in MACRO. The two different projective views are shown one above the other.

can reconstruct charged tracks, by means of a streamer tube system, in two projective views, with a space point accuracy of $\sim$1 cm and an angular accuracy better than 1 degree. The total thickness of the detector is such that the probability of detecting and containing a photonuclear interaction is small, and it is more convenient to study the interactions in the surrounding rock. The upper part of MACRO, in particular, is in practice a thin detector, imposing a low threshold on secondary particles. The lower part, thanks to the rock absorbers, allows to stop particles and measure their range up to few hundreds of MeV.

We consider events in which the muon interacts in the rock above the apparatus and both the muon and at least one charged hadron are observed in the horizontal planes of the tracking detector. An example is shown in Fig. 1, in which a muon enters the apparatus from above, along with at least one charged hadron. We have not the possibility of an efficient detection of the neutrons produced in the interaction: yet, hadronic cascades generated by inelastic collisions of multi GeV neutrons inside the rock absorber layers of our apparatus are observed.

With the aim of recognizing the muon, the standard MACRO muon tracking is used, selecting tracks entering from the uppermost plane, and with at least 7 hit horizontal planes and $cos(Zenith) \geq 0.4$. The additional tracks have been recognized by means of a specialized algorithm, looking for shorter tracks pointing towards the main track around a common vertex region contained in the rock above the detector. In practice we select charged hadrons with a minimum kinetic energy around 150 MeV.

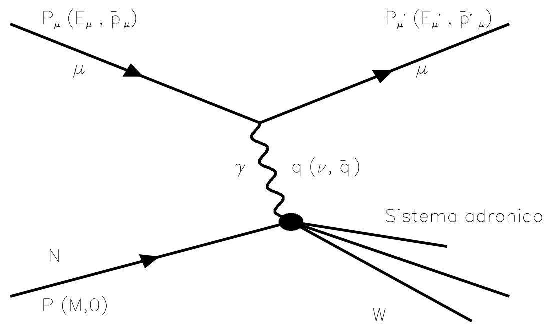

Figure 2: Lowest order diagram of the photonuclear process.

3 The physical process and its simulation

The process can be represented by the Feynman diagram shown in Fig. 2, in which P_μ and P'_μ are the four-momenta of the muon before and after the interaction respectively (their components in laboratory reference system are indicated); $q = P_\mu - P'_\mu$ is the four-momentum transferred to the nucleon by the photon; P and W are the four-momenta of the nucleon before interaction (supposed at rest, we shall neglect Fermi motion in the nucleus), and of the final state hadronic system. From the calculation point of view, the emission of the photon can be treated in the Williams-Weizsacker approximation, in which the passage of a charged lepton in a slab of material produces the same effects of a beam of quasi-real photons. As far as interaction of a muon with a nucleon at low Q^2 is concerned, the most used form for the differential cross section is the following:

$$\frac{\mathrm{d}^2\sigma_{\mu-\mathrm{N}}}{\mathrm{dv}\,\mathrm{dQ}^2} = \frac{\alpha}{\pi}\left(\Gamma_t\,\sigma_t + \Gamma_l\,\sigma_l\right) = \frac{\alpha}{\pi}\,\Gamma_t\left(\sigma_t + \epsilon\,\sigma_l\right) = \frac{\alpha}{\pi}\,\Gamma_t\,\sigma_{virt}(Q^2,\nu) \tag{1}$$

where σ_t and σ_l are the cross sections for the interaction of transverse and longitudinal photons with a nucleon, $\epsilon = \frac{\Gamma_l}{\Gamma_t}$ is the polarization factor an depends upon E, ν, Q^2. In the Williams-Weizsacker approximation, Γ_t is related to the energy spectrum of equivalent photon beam. Both σ_l and σ_t, and hence σ_{virt} in Eq. 1 are closely related to $\sigma_{\gamma-N}(\nu)$, the cross section for the interaction between a real photon with energy ν and a nucleon. In the low Q^2 region, σ_{virt} can be expressed in the form $\sigma_{virt} = \sigma_{\gamma-N}(\nu)\,F(Q^2)$, where $F(Q^2)$ is the nucleon structure form factor. When the interaction with a *nucleus* with mass A is considered, the "shadowing" effect has to be taken into account: this effect is expressed by the fact that $\sigma_{\mu-A}$ is somewhat less than the mere $A\,\sigma_{\mu-N}$. In the framework of the "Vector Meson Dominance" (VMD) the photon radiated by the muon interacts with nucleons in a nucleus by virtually converting in a vector mesons (mostly ρ). Thus, by using the optical model for hadron-hadron interaction, shadowing is explained as due to destructive interference of scattering amplitudes. By using the generalized version of this model (GVD), Bezrukov and Bugaev (1981) calculated the differential cross section for photon-Nucleus and hence for muon-Nucleus interactions. In the FLUKA Monte carlo code (Fassó et al, 1997) , this process has been implemented, following the quoted Bezrukov-Bugaev model. The algorithm in FLUKA for the photonuclear interaction is realized according to the following steps. Photon energy $E_\gamma = E_\mu \, v$ is sampled according to $\frac{\mathrm{d}\sigma}{\mathrm{dv}}$ given by Bezrukov and Bugaev (1981). Then, following VMD, the photon is coupled to a vector meson (ρ, ω, and ϕ) with the known branching ratios. Whenever photon energy is too small, it is treated like a pion. An on shell mass is given to V according to its observed width. The interaction is treated in the γ-nucleon centre of momenta system, and the final state is sampled according to the Dual Parton Model at high energies, or to a cascade pre-equilibrium model at low energy. Deep inelastic scattering of muons on nucleons is not yet included in FLUKA. As already mentioned, this should not be a great problem because the region of low Q^2 gives the main contribution to the cross section.

We have chosen this code as a main reference to generate the underground muon events, taking into account the following steps. The direction of incident muons is sampled according to the local angular distribution measured by MACRO and properly unfolded to take into account the anisotropic acceptance of the apparatus. As far as muon residual energy at a depth h (in km w.e.) is concerned, we chose to sample it according to the approximate distribution (Gaisser, 1990) following from a simple power muon spectrum at surface $\left(\frac{\mathrm{dN(E_\mu,0)}}{\mathrm{d(E_\mu)}} = K\, E_\mu^{-\gamma}\right)$ and a mean energy loss given by: $-\frac{\mathrm{dE_\mu}}{\mathrm{dx}} = a + b\,E = a\,(1+\epsilon\,E)$:

$$\frac{\mathrm{dN(E_\mu, h)}}{\mathrm{d(E_\mu)}} = K\, e^{-b\,h(\gamma-1)}\,(E_\mu + \epsilon\,(1-e^{-b\,h}))^{-\gamma} \qquad (2)$$

where $\gamma = 3.5$, $b = 4\cdot 10^{-6} cm^2/g = 0.4 (km\, w.e.)^{-1}$ and $\epsilon = a/b \approx 540$ GeV.

Given the direction, the slant depth of rock h crossed by the muon can be obtained from the map of the mountain overburden. In the simulation, muons are allowed to interact in a 13 m thick layer of rock positioned all around the experimental hall. This thickness corresponds to about 35 interaction lengths for hadrons, and this is enough to fully contain hadronic showers: interactions outside this region are practically invisible because of the ranging out of all the particles possibly produced. The actual compound mixture measured at the level of the underground laboratories has been considered in the simulation. If a photo-nuclear interaction occurs in the region of rock described above, the muon and secondary particles are transported through the rock, along with e.m. and hadronic showers possibly produced. If both the muon and at least one additional particle reach the tunnel, the event is stored. Furthermore, if the direction of muon happens to cross at least four planes of MACRO tracking detector, a full simulation of the apparatus response is performed by a GEANT 3.21 based package (Brun et al., 1992), where, as far as hadron interactions are concerned, GEANT-FLUKA interface has been used. GEANT cuts for $e^\pm, \gamma$ were set to $E^\gamma_{cut} = 100 KeV$, while 1 MeV was used for charged hadrons and 10 MeV for neutrons. The simulated data are treated with the the same analysis instruments of real data.

In order to make a comparison with a different model, we have repeated the event generation in the rock with the photonuclear code of GHEISHA code (Fesefeldt, 1985) inside GEANT. No other simulation of this particular process is available in the present GEANT environment. One of the most important differences is in the total cross section, as shown in Fig. 3. For a more detailed discussion of the differences between FLUKA and GEANT-GHEISHA for this process, see Battistoni et al., (1997).

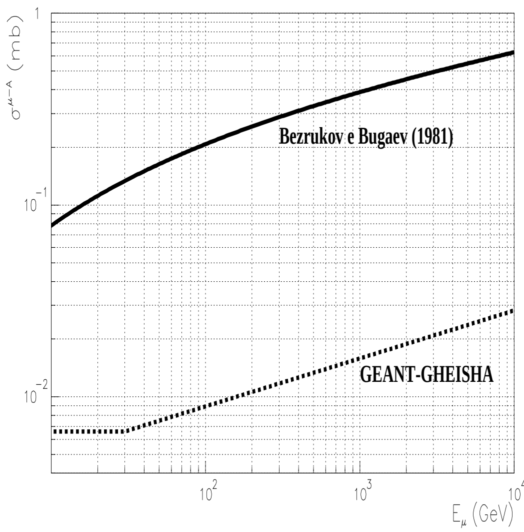

Figure 3: The total cross section for the photonuclear interaction of muon in rock as a function of muon energy in the two considered models.)

4 Data Analysis

The main difficulty in our analysis is to achieve the necessary rejection factor against the physical background. Such a background is largely dominated by two processes: 1) the e.m. interactions of muons in the rock (bremsstrahlung and pair production, which have a much larger cross section than the photonuclear reaction); 2) multiple muon events in which one of the muons stops inside the detector. Examples of background events are shown in Fig. 4 and 5

This background has been extensively studied with our simulation tools. In the case of the e.m. interactions, the mean angular separation between the muon and the additional tracks is less than the corresponding separation observed in photonuclear interactions. Besides that, e.m. events often show very large clusters of fired tubes near the muon track. These features are used to achieve a rejection factor against e.m. events at the level of $4.5 \cdot 10^{-6}$, maintaining the recognition efficiency for hadronic events at the level of 55%.

In order to reject the muon bundle backgrounds, additional cuts based on the parallelism of tracks have to be considered. We have studied the events generated with the HEMAS code (Forti et al., 1990) using for the primary cosmic ray spectrum and mass composition the results from the best fit reproducing the MACRO data themselves (MACRO Coll., 1997b). The rejection factor achieved for muon bundle background at the level of $1.5 \cdot 10^{-4}$, at the price of a slight reduction of the selection efficiency, which is now at 47%.

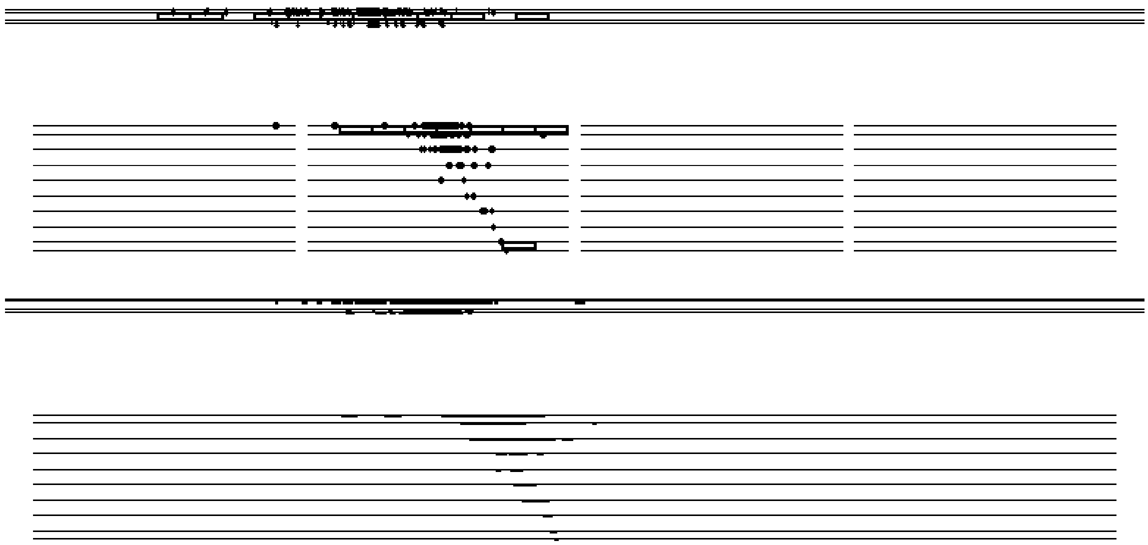

Figure 4: Example of background event: e.m. interaction of muon in the rock.

5 Results

We have analysed a data sample corresponding to about 11000 hours of full running of the detector. With the above selection criteria, we have found 1938 candidate events over a total sample of 9544318 muon events. From our knowledge of the background, we expect that our candidates are contaminated by 11 events from the e.m. interactions in the rock, and by 107 events muon bundles surviving the cuts. We can express the results in terms of the ratio $R_{\mu+h}$ of the selected μ+hadrons events (background subtracted) to the number of muon events in the same time. We then compare the experimental results to the MC prediction having used the same selection criteria. After the subtraction of the background, we find for $R_{\mu+h}$ in real data and in the MC simulations the following results:

- $R_{\mu+h}(DATA) = (1.91 \pm 0.05_{stat} \pm 0.03_{syst}) \cdot 10^{-4}$,
- $R_{\mu+h}(MC - FLUKA) = (1.89 \pm 0.16_{stat} \pm 0.02_{syst}) \cdot 10^{-4}$.
- $R_{\mu+h}(MC - GEANT/GHEISHA) = (1.31 \pm 0.14_{stat} \pm 0.02_{syst}) \cdot 10^{-5}$.

The systematic error on the experimental data is due to the uncertainties on background subtraction, while the systematic error on the simulation is dominated by the uncertainties on the muon energy spectrum.

From this preliminary measurement, we can conclude that the MACRO experiment can perform the measurement of the charged hadron ($E_{kin} > 150$ MeV) production in the rock at the desired level of accuracy. The FLUKA predictions, based on the Bezrukov and Bugaev model of photonuclear interaction are in very good agreement with data, while the GEANT-GHEISHA model gives absolute predictions lower by an order of magnitude.

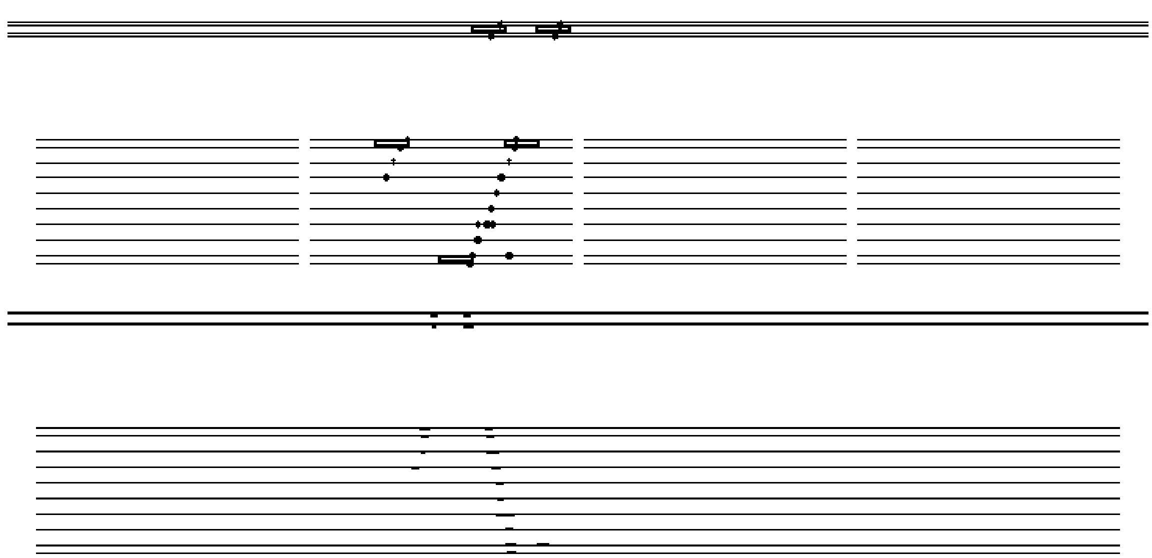

Figure 5: Example of background event: fake event from the muon bundle sample.

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