HEMAS: a Monte Carlo code for hadronic, electromagnetic and TeV muon components in air shower

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Abstract

The features of the HEMAS code are presented. The results of the comparison between the Monte Carlo expectation and the experimental data are shown.

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1 Introduction

Cosmic ray physics at energy $E \geq 10-100$ TeV, due to the steepening of the spectrum, can be performed only by using indirect measurements. An impressive amount of data has been collected by extensive air shower arrays, Cherenkov detectors and underground muon experiments. The challenge is the interpretation of these results. The bulk of the analysis are performed by assuming a given Cosmic Ray spectrum and chemical composition (trial model), simulating the particle interaction and the shower development in atmosphere and finally comparing the simulated results with the real data. The reliability of the Monte Carlo simulation used is therefore a primary task for the correct interpretation of these data: such difficulty stimulated a lot of experimental work to validate the existing model and many theoretical ideas to improve the simulation tools. Modelling a Monte Carlo to describe the high energy cosmic ray interactions in atmosphere is a hard task, since Cosmic Rays studied with indirect measurements extend to energy and kinematical regions non covered by the accelerator experiments yet. Moreover nucleus-nucleus collision have been investigated just up to few hundreds of GeV/nucleons. This poorness of experimental data is reinforced by the lack of a completely computable theory for the bulk of hadronic interactions, since QCD can be used only for high $p_t$ phenomena.

Many models have been developed in the last years, with different emphasis on the various components of the C.R. induced shower. Basically they can be splitted in two categories: the models using parametrization of collider results (NIM85,HEMAS) and the phenomenological models inspired for instance to the Dual Parton Model or similar approaches (DPMJET,SYBILL,QGSJET). I will concentrate in this talk on the HEMAS code[1], stressing the results of the comparison with the experimental data.

2 HEMAS: description of the code

The HEMAS code was developed in the early ’90, when a new generation of experiments (LVD, MACRO, EAS-TOP) were starting the data taking at Gran Sasso. This code is suited to simulate high energy muons ($E_{\mu} \geq 500$GeV) and the electromagnetic size of the shower. It is a phenomenological model, based on the parametrization of the collider data. The code describes multiple hadron production by means of the multicluster model, suggested by UA5 experiment.

The total p-Air cross section is one of the most important ingredients of the codes. Since the cross section of hadrons on nuclei is not measured directly at energies greater than several hundred of GeV, an extrapolation to higher energies is required and is performed in the context of ”log(s)” physics.

Figure 1 shows the HEMAS cross section p-Air as a function of the centre of mass energy $\sqrt{s}$ compared with the cross section used in other Monte Carlo codes.

Given the $\sqrt{s}$ of the interaction, the average number of charged hadrons $<n_{ch}>$ is choosen according with the equation:

$$<n_{ch}> = -7.0 + 7.2s^{0.127}.$$ (1)

The actual number of charged hadrons $n_{ch}$ is sampled from a a negative binomial distribution with

$$k_1 = -0.104 + 0.058ln(\sqrt{s})$$ (2)

Respect to the previous codes, where $n_{ch}$ was sampled according to a poissonian, this choice reflects in a larger fluctuation of underground muon multiplicity. Particles are then grouped in clusters, eventually decaying in mesons.
A relevant feature of HEMAS is the parametrization of muon parent mesons \( p_t \) distribution. While for single pion cluster \( p_t \) is always sampled from an exponential, for kaon clusters, for the leading particle and for pion clusters with at least two particles, \( p_t \) has a given probability to be extracted from a power low:

\[
\frac{dN}{dP_t^2} = \frac{\text{const}}{(p^0_t + p_t)^\alpha}
\]

where \( p^0_t = 3 \text{ GeV/c} \) while \( \alpha \) decreases logarithmically with energy

\[
\alpha = 3 + \frac{1}{(0.01 + 0.011 \ln(s))}
\]

Nuclear target effects are included too. The transverse momentum distribution is increased in p-N collision respect to the p-p case, according to the so called 'Cronin effect'\(^2\). The ratio \( R(p_t) \) of the inclusive cross section on a target of mass A to that on a proton target depends in principle from the particle produced. In HEMAS, \( R(p_t) \) has been approximated with a single function:

\[
R(p_t) = (0.0363p_t + 0.0570)K \quad \text{for} \quad p_t \leq 4.52 \text{GeV/c} \\
R(p_t) = 0.2211K \quad \text{for} \quad p_t > 4.52 \text{GeV/c}
\]

where \( K \) is a normalization constant.

The average \( <n_{ch}> \) in p-Air collisions is obtained using the relation between the rapidity density with a nuclear target and that with a target nucleon:

\[
\frac{dn/|dy|}{(p-A)} = A^{\beta(z)}
\]

where \( y \) is the laboratory rapidity and \( z = y/\ln(s) \).

The HEMAS p-Air model interaction assumes a scaling violation in the central region and a small violation in the forward region \( (x_f > 0.5) \). The original HEMAS code included a naive muon transport code. This code was later replaced with the more sophisticated PROPMU code\(^3\). Moreover in 1995, HEMAS was interfaced with DPMJET, a dual parton model inspired code\(^5\). The user has therefore the possibility of changing the original HEMAS hadronic interaction model with DPMJET. As far as the CPU time is concerned HEMAS is a fast code. Table 1 shows the CPU time required for protons of different energies, while Table 2 shows the comparison with other codes for a 200 TeV proton.

| \( E_p (TeV) \) | CPU (HP-UX 9000) |
|-----------------|------------------|
| 20              | 0.01 sec/event   |
| 200             | 0.17 sec/event   |
| 200             | 0.93 sec/event   |

Table 1: HEMAS CPU time for protons with different energies

An explanation of the faster performance of HEMAS, respect to other codes, is in the treatment of the electromagnetic part of the shower. Electromagnetic particles \( (e^+, e^-, \gamma) \), coming
from $\pi_0$ decay, are computed using the standard NKG formula. Hadrons falling below a given threshold are not transported in atmosphere and their contribution to the electromagnetic size $N_e$, is computed according with the parametrization of pre-computed Monte Carlo runs[4]. Of course the threshold is high enough ($E_{th}\simeq 500$ GeV) to follow the hadrons until they can decay into an high energy muon, with some probability to survive deep underground. Anyway, as far as the validity of this approximation is concerned, it must be stressed that for primary cosmic rays with energy greater than $\simeq 10$ TeV, the total contribution of low energy hadrons to the electromagnetic size is $\simeq 10\%$.

### 3 Comparison with experimental data

The HEMAS code has been widely used to simulate the underground muons detected at Gran Sasso. When dealing with underground muons, many experimental observables depend both on the cosmic ray chemical composition and on the features of the hadronic interaction model. To test the reliability of the Monte Carlo codes it’s therefore important to study observables allowing a disentangle. The shape of the decoherence, i.e. the distribution of the distance between muon pairs, is weakly dependent on C.R. composition. This distribution is therefore a nice test to check the reliability of a Monte Carlo code. The decoherence gets contribution from various sources in the shower development:

- The primary cosmic ray cross section;
- the $p_t$ distribution of the muon parent hadrons;
- the multiple scattering of muons through the rock.

Fig. 2 shows the average $p_t$ of the muon parent mesons as a function of the average muon separation deep underground. The correlation between $p_t$ and $<D>$ is evident.

The MACRO detector[6] is a powerful experiment to study such distribution, taking advantage of an acceptance $A\simeq 10,000$ $m^2sr$. Recent results have been presented in[7]: the decoherence function has been studied with a statistical sample of $\simeq 350,000$ real and $690,000$ simulated muon pairs. Fig.3 shows the comparison between HEMAS expectation(MACRO composition model[8]) and the MACRO data, properly corrected for the detector effects: the agreement is impressive. The selection of high muon multiplicity events allows to study very high energy primary cosmic rays. Muons with multiplicity $N_{\mu}\geq 8$, come from primary cosmic rays with energy $E\geq 1000$ TeV. The HEMAS expectation reproduces well the experimental data of this subsample of events too(Fig. 4). The two extreme composition models used are taken from[9]. The comparison between data and Monte Carlo has been performed also in different windows of rock depth and $\cos \theta$. Fig. 5 shows the average distance between muon pairs in these windows: again HEMAS reproduces quite well the experimental data.

Summarizing, the MACRO data showed that, as far as the lateral distribution of underground
muons is concerned, the HEMAS capability in reproducing the real data is impressive. Some doubts pointed out by the HEMAS authors of a possible $p_t$ excess in the code are not supported by the MACRO data [12].

Nevertheless, since the indirect measurements aim to study the primary cosmic ray spectrum and composition, a delicate sector of Monte Carlo simulation tools is the "absolute" muon flux. It is of course an hard task to test experimentally the performance of the Monte Carlo codes, since the muon flux deep underground is the convolution of the cosmic ray spectrum and composition with the hadronic interaction and the shower development features. Since the Cosmic Ray spectrum is unknown we cannot use the muon flux deep underground to test the Monte Carlo.

A step forward in this direction has been carried out by the MACRO and EAS-TOP Collaborations, with the so called "anti-coincidences" analysis[11]. By selecting a muon events in MACRO pointing to a fiducial area well internal to the EAS-TOP edges, it’s possible to select two event samples:
a) if the number of fired detectors $N_f$ in EAS-TOP is <4, EAS-TOP does not provide any trigger and the event is flagged as 'anti-coincidence'. The correspondig C.R. energy ranges between 2 and few tens of TeV;
b) if 4<$N_f$<7, EAS-TOP provides a trigger and the events is flagged as 'low energy coincidences'.

In the energy range covered by 'anti-coincidences' and 'low energy coincidences' direct measurements of cosmic ray spectrum and composition are available. It is therefore possible to use these data as input to the Monte Carlo simulation to test the hadronic interaction model, by comparing the experimental data with the expectation. They used a single power low fits to the fluxes of H and He, as reported by JACEE[14].

\[
p : \quad 5.574 \cdot 10^4 (E/GeV)^{-2.86} (m^{-2}s^{-1}sr^{-1}GeV^{-1})
\]

\[
He : \quad 9.15 \cdot 10^3 (E/GeV)^{-2.86} (m^{-2}s^{-1}sr^{-1}GeV^{-1})
\]

I stress that this analysis cannot be performed with MACRO alone, since low muon multiplicity events get contribution also from higher energy cosmic ray($E\geq 100$ TeV), where the spectrum and the chemical composition have not been measured with direct techniques.

Table 3 shows the results of the analysis and the comparison between the real data and the Monte Carlo codes HEMAS and HEMAS-DPMJET. Taking into account a 15-20% uncertainty in the JACEE data fits, the low energy coincidences are reproduced by both the Monte Carlo codes. On the contrary HEMAS understimates the number of anti-coincidences respect to the real data, while, within a 20% accuracy, HEMAS-DPMJET reproduces the experimental data.

Sometime people is concerned by the fact that the HEMAS hadronic interaction model reproduces the experimental data at high energy($E\geq 100$ TeV) better than at lower energies,
TeV ≤ E ≤ 100 TeV) being the latter closer to the energy range already explored by accelerator experiments. It must be stressed that muons produced from the interaction of cosmic rays with energy E ≃ few TeV, come from the decay of pions with x_f ≃ E_π/E_o ≃ 1. This is the so called ‘forward region’, poorly studied in accelerator experiments, requiring therefore an extrapolation in the Monte Carlo. As it has been stressed in [3], the higher muon flux in DPMJET in this kinematical region, reflects an intrinsic feature of this code, originating from the LUND treatment of the fast valence ”diquark” fragmentation in the projectile. Fig.6 shows the average number of muons survived deep underground (h=3400 hg/cm^2) as a function of the proton energy for different Monte Carlo codes. The main difference between these codes is in fact found at low energy, where each code has to extrapolate the collider results with some algorithms. From this point of view, models based on the Dual Parton Model, can in principle take advantage of the limited number of free parameters, avoiding, at least in part, delicate extrapolations.

4 Conclusions

HEMAS is a fast Monte Carlo code for the simulation of high energy muons and electromagnetic components of the air shower. MACRO data confirm the HEMAS capability in reproducing the lateral distribution of muons detected deep underground.

The 'low-energy coincidences' analysis performed by the EAS-TOP and MACRO collaborations pointed out a satisfactory agreement with HEMAS and HEMAS-DPMJET codes, within the primary C.R. spectrum uncertainty; the 'anti-coincidences' analysis suggested a possible HEMAS muon deficit at threshold energies (E_o ≃ few TeV). An improvement of the agreement is found when using HEMAS interfaced with DPMJET.

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Figure 1: Comparison of the cross section p-Air used by different Monte Carlo codes.

Figure 2: Relation between the muon parent mesons average $P_t$ and the average muon pair distance deep underground.
Figure 3: The decoherence function: comparison of the MACRO data with the HEMAS expectation.

Figure 4: Comparison of the MACRO data and HEMAS expectation for events with muon multiplicity $N_\mu \geq 8$. 
Figure 5: Comparison of the average separation between muon pairs in different rock depth and $\cos\theta$ windows.

Figure 6: Average number of muons survived underground (3400 $hg/cm^2$) for different Monte Carlo codes as a function of proton energy. The same muon transport (PROPMU) has been applied in all runs.