# The FLUKA cosmic ray generator for the high energy region. Results and data comparison for the charge ratio of TeV muons detected underground.

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***Abstract*. In the framework of the underground experiments at the Gran Sasso laboratory, a high energy cosmic ray generator has been developed. This is based on the FLUKA Monte Carlo code and it is primarily dedicated to the analysis of high energy muons detected underground. For this purpose the code simulates both the air shower development and the muon transport in the rock.**
**We analyze the prediction for the charge ratio of underground muons, with the aim of investigating some features of the high energy particle production model. This measurement is particularly sensitive to the $\pi/K$ ratio of secondary mesons produced in the proton-Air and Nucleus-Air collisions.**
**We analyze the possible dependence of charge ratio on the event multiplicity and primary composition model. We also compare our predictions with published experimental results.**

***Keywords*: FLUKA, muons, underground**

## I. Introduction

In the framework of the application of the FLUKA Monte Carlo code to cosmic rays physics, a new generator for high energy cosmic rays has been developed, with the aim of extend the existing FLUKA cosmic rays library to include the TeV region.
The FLUKA-based generator for TeV muons provides a tool which has been validated and benchmarked along the years with the latest experimental results, outside the cosmic ray community and independently from the existing generators. Moreover, it is a self-consistent generator all in one, namely a generator able to handle all the simulation steps in a unique framework, from the primary interaction in atmosphere, to the shower development, particle transport in the overburden, sampling at the detector level and, in principle, the detector itself.
The application of FLUKA in cosmic ray physics arises from the interest in applied physics topics, such as radioprotection in space or in atmosphere [1], [2], and in basic research (e.g. the calculation of atmospheric neutrino fluxes [3], [4]).
In both cases it is important to check the reliability of calculations produced with a model which is benchmarked using only data coming from well controlled accelerator experiments. In this context, an important issue in the evaluation of a Monte Carlo calculation concerns the quality of the hadronic interaction models, i.e. their capability of reproducing the existing data.

## II. The FLUKA hadronic models

The FLUKA code [5] is a general purpose Monte Carlo code for the interaction and transport of particles. It is built and maintained with the aim of including the best possible physical models in terms of completeness and precision.
The FLUKA hadronic models are based as far as possible on a theoretical microscopic approach, having care to preserve correlations and fulfilling the necessary conservation laws in every single interaction. Free parameters are set by comparing predictions to data from thin target experiments at accelerators and are in general kept fixed for all projectile-target combinations and energies. This approach ensures predictivity also in regions where experimental data are not available. A basic description of hadronic interactions in FLUKA can be found in [6].
Hadron-nucleon interactions at energies below a few GeV are simulated in FLUKA by the isobar model, through resonance production and decay, and by taking into account elastic, charge and strangeness exchange. Elementary hadron-hadron collisions at energies above a few GeV are described thanks to an implementation of the Dual Parton Model (DPM) [7], coupled to a hadronization scheme. This model allows a successful description of soft collision processes since these cannot be addressed by pQCD.
Hadron-hadron collisions are the main building blocks of hadron-nucleus collisions. Multiple collisions of each hadron with the nuclear constituents are taken into account by means of the Glauber-Gribov mechanism [8]. Particular efforts are devoted to the study of nuclear effects on hadron propagation. These are treated by the FLUKA module called PEANUT. More details about PEANUT and the issues concerning its extension can be found in [6], [9]. PEANUT is used also to simulate $\gamma, \nu$ and stopping $\mu$ interactions, and nucleon decay. Nucleus-nucleus interactions above a few GeV/nucleon can be explicitly simulated in FLUKA by means of an interface to DPMJET [10], [11], again based on DPM but also

including leading order pQCD. At lower energies, an improved version of the Quantum Molecular Dynamics approach of ref. [12] is used.

## III. Generation of high energy muons

The generator is primarily dedicated to the physics of high energy muons detected underground, exploiting the full integration in the calculation of both air shower development and muons transport in the rock.
The aim is to predict multiple muon rates for different primary masses and energy within the framework of a unique simulation model. This work is under way, for instance within both the ICARUS [12] and OPERA [13] collaborations at Gran Sasso. Starting from an atmospheric shower generation, particles are transported in the Gran Sasso rock. A dynamic threshold is applied to select only muons with energy enough to cross the rock depth of their own trajectory, as read from the Gran Sasso map.
One of the feature of this package is that it is fully optimized for TeV cosmic ray muons, i.e. we adopted many biasing solutions in different phases of the simulation in order to speed up the production chain.
Moreover, we stress that the package is flexible enough to include different underground and/or underwater sites, provided that a detailed map of the overburden is fed to the generator (in the underground case). In the present version the LNGS underground site has been implemented, while the ANTARES underwater site [14] is in preparation.

### A. Main features of the underground muons generator

- The geometry setup includes the whole Earth, its surrounding atmosphere and the overburden. The Earth is assumed to be a sphere of radius R = 6378.14 km, while the atmospheric profile is modeled with a set of 100 concentric spherical shells whose density and composition is varied according to the model described in [4]. As far as the overburden is concerned, its modeling depends on the case considered. Here, instead of simulating the whole mountain profile, a fastest and more flexible solution has been adopted. For each event, the primary direction is sampled and then the amount of rock d in that direction is readout from the map of the overburden. A rock sphere, centered in the underground experimental hall, is defined with a radius R which is dynamically changed event by event (Fig. 1). This procedure, other than speeding up the computation time, allows to easily adapt the code to other sites provided that the corresponding rock map is supplied.
- The source beam (sampled from a primary mass composition model at present derived from [15], i.e. a description of the relative abundances of cosmic rays and their energy spectra) is defined by the type of primary particles to be propagated throughout the geometry setup, their kinetic energy, injection point and direction. For each primary nucleus and for each direction (i.e. for each amount of overburden to be crossed), we compute the minimum energy required to produce at least one muon underground with a predefined small probability value. This value is then used both for primary energy sampling and for the tracking of particles in atmosphere: once a given particle falls below this lower bound, its tracking is stopped. Similar solutions are envisaged for tracking inside the overburden. Only nearby the experimental sites these energy cuts are lowered to 100 MeV in order to take into account all the muon-induced secondaries.
- The FLUKA hadronic interaction model.

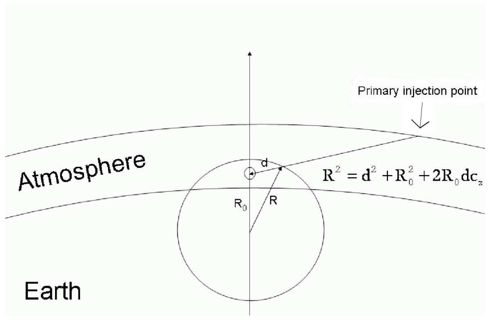


Fig. 1. Sketch of the sampling procedure for underground sites. Once the primary direction is sampled, a rock sphere is created around the experimental hall with a radius R equal to the corresponding amount of rock that has to be crossed to reach the underground site. Ths value is read from the map location. The primary direction is then traced back to the upper atmosphere, thus locating the primary injection point.

Once this set of information are supplied, a FLUKA run can start producing a user-defined number of stories which can be translated a-posteriori in the corresponding lifetime.

## IV. The muon charge ratio $R_{\mu^+/\mu^-}$

In order to improve the models of the interactions of cosmic rays in the atmosphere, we present a comparison with the muon charge ratio measured by the MINOS experiment [16].
The muon charge ratio reflects the excess of $\pi^+$ over $\pi^-$ and $K^+$ over $K^-$ in the forward fragmentation region of proton initiated interaction together with the fact that there are more protons than neutrons in the primary spectrum.
Because of their strangeness (S = +1), $K^+$ and $K^0$ can be yielded in association with a leading barion $\Lambda$ o $\Sigma$. On the other hand, the production of $K^-$,$\bar{K^0}$ (S = -1 doublet) requires the creation of a sea-quark pair $s - \bar{s}$ together with the leading nucleon and this is a superior order process [17]. For this region $K^+$ yield is greater than $K^-$ yield, differently from $\pi^+$ and $\pi^-$ yields because of their isospin symmetry. So the $K^+/K^-$ ratio is larger than the $\pi^+/\pi^-$ ratio.
The muons result from pions and kaons decaying in the atmosphere, so muon charge ratio reflects kaon and pion charge ratio.

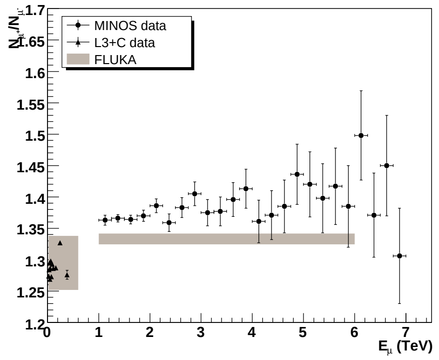


Fig. 2. FLUKA comparison with L3+C and MINOS $N_{\mu^+}/N_{\mu^-}$ experimental data.

As energy increases, the fraction of muons seen from kaon decays also increases because the longer-lived pions ($\pi^{\pm}$ : $c\tau_0 = 780$ cm, $\epsilon = 115$ GeV) have more probability to interact before decaying than the shorter-lived kaons ($K^{\pm}$ : $c\tau_0 = 371$ cm, $\epsilon = 850$ GeV) [1]. Consequently, kaon decays are increasingly more important contribution to the muon charge ratio at these energies. Since strong interaction production channels lead to a muon charge ratio from kaon decays that is greater than that from pion decays, the measured charge ratio is expected to increase.

Several competing processes, however, could counterbalance this increase at even higher energies. Decay of charmed hadrons is one of such processes.

There is also the possibility that heavier elements become a more important component of cosmic ray primaries as the energy increases. This increasingly heavy composition would decrease the ratio of primary protons to neutrons, thereby decreasing the muon charge ratio.

### A. *Muon bundle multiplicity dependence*

Coincident multiple muons, detected in a deep underground detector, must have high energy at production in the atmosphere, so only the highest energy part of the cascade is relevant. Therefore, the problem of the chemical composition of the primary cosmic rays above $10^{15}$ eV can be investigated by means of our depth selecting muons.

Interpretation of the results also depends on details of hadronic interactions at high energies, particularly the transverse momentum distribution, which determines the fraction of the muons above threshold that falls within the detector.

The multiplicity distribution underground involves a convolution of muon production with the primary energy spectrum as well as with the composition. A high muon bundle multiplicity is strictly related to a high primary energy and a high primary mass number.

[1] $critical\ energy$ $\epsilon$ = energy where interaction and decay processes have the same magnitude. Beyond this energy interaction process dominates on decay.

Since the muon charge ratio is expected to decrease with growing primary mass number because of the increasing number of neutrons in heavy elements with respect to protons, we expect that muon charge ratio decreases with growing multiplicity.

## V. RESULTS AND CONCLUSIONS

The FLUKA models have been benchmarked with experimental data from accelerator experiments and from atmospheric muons experiments. FLUKA has been bechmarked with the L3+C charge ratio experimental data [18] in the energy region $E_\mu < 1$ TeV. The agreement is within 0.8 % [19].

$$R^{FLUKA}_{\mu^+/\mu^-} = 1.29 \pm 0.05 \quad (1)$$

$$R^{L3+C}_{\mu^+/\mu^-} = 1.285 \pm 0.003(stat.) \pm 0.019(sys.) \quad (2)$$

The MINOS [16] experiment has recently published the muon charge ratio at the surface in the energy region 1 TeV $< E_\mu <$ 7 TeV:

$$R^{MINOS}_{\mu^+/\mu^-} = 1.374 \pm 0.004\,(\text{stat.})^{+0.012}_{-0.010}\,(\text{syst.}) \quad (3)$$

In this work, the muon charge ratio in the TeV energy region, as results from the underground muons simulation with the FLUKA Monte Carlo code is:

$$R^{FLUKA}_{\mu^+/\mu^-} = 1.333 \pm 0.007 \quad (4)$$

$$R^{FLUKA}_{\mu^+/\mu^-(from\ \pi\ decay)} = 1.237 \pm 0.007 \quad (5)$$

$$R^{FLUKA}_{\mu^+/\mu^-(from\ K\ decay)} = 1.897 \pm 0.024 \quad (6)$$

The agreement with MINOS data is within 3 % but we emphasize that the discrepancy is systematically remarkable and is indicative of something to be seen through. We also note that we observe no dependence on muon momentum in the atmosphere, in the range considered in the FLUKA simulation.

Fig. 2 shows the comparison between FLUKA and experimental data.

In Tab. I are given the primary mass groups distribution mean values for Gran Sasso site and large area acceptance. The primary average mass number grows with underground muon multiplicity.

TABLE I
PRIMARY MASS GROUPS DISTRIBUTION MEAN VALUE FOR DIFFERENT MUON MULTIPLICITY

| Multiplicity | Primary mass number mean value |
|---|---|
| 1 | 3.051 ± 0.011 |
| 2 | 6.751 ± 0.079 |
| 3-5 | 13.35 ± 0.22 |
| 6-15 | 31.77 ± 0.87 |
| 16-50 | 44.53 ± 2.1 |

In Fig. 3 we show the FLUKA code prediction about the charge ratio trend with respect to multiplicity of the underground muon events. Muon charge ratio decreses, as expected.

This behaviour gives us the chance to investigate on the primary spectrum composition.

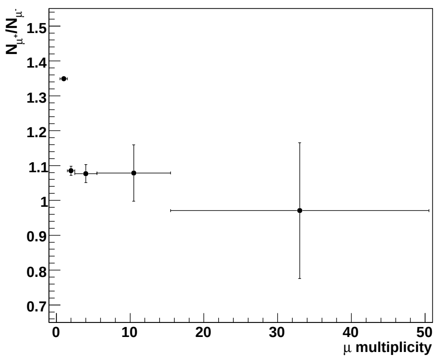


Fig. 3. Muon charge ratio VS muon bundle multiplicity.

The experiments [20] that has measured the muon charge ratio in this energy range give values slightly higher than the one of the FLUKA prediction.

The mismatch between MINOS data and FLUKA simulation suggests that the ratio

$$\frac{N_{K^+}/N_{K^-}}{N_{\pi^+}/N_{\pi^-}} \quad (7)$$

or $N_{K^+}/N_{K^-}$ should be greater or both.

FLUKA $K$ production [21] has been benchmarked up to $E_{lab} = 450$ GeV [22], [23], [24] for the CNGS beam construction in a limited phase space for cosmic rays physics. At present we have no available accelerator data at higher energies.

Air shower models, used for this reconstruction, are based on state of the art hadronic and nucleus scattering models. However it is mandatory a tuning of this models to data taken in an accelerator controlled way and new measurements in the forward region are strongly encouraged.

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## REFERENCES

[1] G. Battistoni, A. Ferrari, M. Pelliccioni and R. Villari, Rad. Prot. Dosim. 112 (2004) 331.
[2] F. Ballarini et al. Journal of Physics: Conference Series 41 (2006) 135.
[3] G. Battistoni et al., Astropart. Phys. 123152000.
[4] G. Battistoni et al., Astropart. Phys. 192692003 [Erratum-ibid. 19 291 (2003)].
[5] A. Fassò, A. Ferrari, J. Ranft and P.R. Sala, CERN Yellow Report 2005 - 10 (2005), INFN/TC 05/11; A. Fass'o et al., Proc. of CHEP2003, eConf C0303241, arXiv:hep-ph/0306267.
[6] A. Ferrari and P.R. Sala, Proceedings of Workshop on Nuclear Reaction Data and Nuclear Reactors Physics, Design and Safety, A. Gandini, G. Reffo eds., Trieste, Italy, April 1996, n. 2 (1998) 424.
[7] A. Capella, U. Sukhatme, C.I. Tan, J. Tran Thanh Van, Phys. Rep. 236 (1994) 225.
[8] L. Bertocchi, Nuovo Cimento 11A (1972) 45.
[9] G. Battistoni et al., Proc. 11th Int. Conf. on Nuclear Reaction Mechanisms, Varenna, 12 - 16 June 2006.
[10] S. Roesler, R. Engel, J. Ranft, Proc. MonteCarlo 2000 Conference, Lisboa, 23 - 26 October 2000, Springer Verlag eds. (2001) 1033.
[11] J. Ranft, Phys. Rev. D 51 (1995) 64.
[12] S. Amerio et al., Nuclear Instruments & Methods A 526 (2004) 329.
[13] R. Acquafredda *et al.* [OPERA Collaboration], 2009. JINST 4 P04018.
[14] ANTARES Collaboration, Proposal, astro-ph/9907432 (1999).
[15] J.R. Hörandel, Astroparticle Physics 19 (2003) 193-220
[16] P. Adamson *et al.* Phys. Rev. D **76**, 052003 (2007)
[17] "Cosmic Rays and Particle Physics". Gaisser, T.K., Cambridge University Press 1990.
[18] P. Achard *et al.* Phys. Lett. B **598**, 15 (2004)
[19] S. Muraro, "The calculation of atmospheric muon flux using the FLUKA Monte Carlo code", Ph.D. Thesis, Milano University, 2006.
[20] M. Sioli for the OPERA Collaboration, "Cosmic ray physics with the OPERA detector", in ICRC09 (these proceedings), 2009.
[21] H.W Atherton et al., CERN 80-07, 1980.
[22] G. Ambrosini et al., Phys. Lett. B 425 (1988) 208.
[23] G. Ambrosini et al., Measurement of charged particle production from 450 GeV/c protons on beryllium, Eur. Phys. J. C 10, 605-627 (1999).
[24] G. Collazuol, A. Ferrari, A. Guglielmi, P.R. Sala, Nucl. Instr. Meth. A449, 609 (2000)