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**Forschungszentrum Karlsruhe**  
in der Helmholtz-Gemeinschaft

**Wissenschaftliche Berichte**

FZKA 7495

# **The EHISTORY Option of the Air-Shower Simulation Program CORSIKA**

**D. Heck, R. Engel**  
Institut für Kernphysik

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D. Heck, R. Engel

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# Abstract

## **The EHISTORY Option of the Air-Shower Simulation Program CORSIKA**

This report describes the EHISTORY option, which gives additional information for all muons arriving at the detector level on their precursors, the grandmother and mother particles. These may help to improve the understanding of the production and propagation of muons in air showers.

# Zusammenfassung

## **Die EHISTORY-Option des Luftschauer-Simulationsprogramms CORSIKA**

Dieser Bericht beschreibt die EHISTORY-Option, die für alle Myonen, die das Beobachtungsniveau erreichen, zusätzliche Informationen über ihre Vorläufer, die Großmutter- und Mutter-Teilchen gibt. Diese Informationen sind hilfreich für ein tieferes Verständnis der Erzeugung und Ausbreitung der Myonen in Luftschauern.



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# 1 Introduction

There are indications, that in Extensive Air Showers (EAS) simulated with the cosmic ray shower simulation program CORSIKA [1], most high-energy interaction models produce a significantly too low number of muons compared with experimental findings [2, 3, 4, 5, 6, 7, 8]. To improve the models one must know how the number and density of muons depend on the model parameters. This knowledge may be acquired by back-tracking the history of the muons. Therefore in simulations it is desirable to store parameters like energy and the components of momenta and positions of the mother and grandmother particles at the last hadronic interaction for further analysis before the mother particle decays to a muon. This capability is provided by the new option EHISTORY.

Usually the muons originate from the decay of charged pions or charged kaons, but also the  $K_L^0$  mesons contribute to some extent to the muon number by a 27 % branch of their decays. Additionally from the electro-magnetic component of an EAS the  $\gamma$ -rays with energies above  $\approx 1$  TeV produce (with a small production cross section)  $\mu^+\mu^-$ -pairs. At even higher energies the production of charmed hadrons increases the muon number and especially the decay of the D-mesons contributes to the high energy portion ( $E_\mu > 50$  TeV) of the muon energy spectrum [9, 10, 11]. By systematic studies of those interactions, which precede the mesonic decay to muons, the importance of low energy hadronic interactions of pionic, kaonic or nucleonic projectiles (referred to as grandmother particles) with air became obvious and triggered a more systematic study of such interactions in fixed target accelerator experiments [12, 13].

The implementation of the new EHISTORY option is done in a manner that it is compatible with nearly all other options available for CORSIKA. Especially the EHISTORY option can be combined with all high-energy and low-energy hadronic interaction models without any restrictions. The EHISTORY option may be combined also with the STACKIN option (see Sect. 5.3) which reads in the secondary particles of a primary interaction not foreseen in the usual high-energy interaction codes coupled with CORSIKA. If the NUPRIM option is used, which handles the development of EAS induced by primary neutrinos of all three kinds ( $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ ) by a call to HERWIG routines [14], special precautions have to be respected in the EHISTORY option for primary  $\nu_\mu$ -neutrinos (see Sect. 5.1).

The EHISTORY option cannot be combined with the INTTEST option, in which only the first interaction is treated. Therefore it does not make any sense to define mother and grandmother particles of muons written to the output particle file of the INTTEST option. Using the *./coconut* script for installation of CORSIKA (see Appendix A) this conflicting option is automatically indicated and *./coconut* blocks the simultaneous selection of EHISTORY and INTTEST.

## 2 Extended Additional Muon Information

If in the EISTORY option the key word MUADDI is used in the steering file with the FMUADD parameter set to .true., for each muon arriving at the detector level 4 consecutive entries of particle parameters are written to the particle data output file.

1. The first entry contains the additional muon information as in the standard CORSIKA version. This entry describes the muon at its production point. The structure is given in Table 1.
2. The second entry comprises the parameters of the mother particle at the place of its birth and is described in the following subsection 2.1.
3. The third entry contains the parameters of the grandmother particle at the point of interaction where the mother particle is created. Details are listed in the subsection 2.2.
4. The fourth entry gives the parameters of the muon arriving at the observation level. Details on this particle entry may be found in the CORSIKA User's Guide [15] (see there subsection *Normal Particle Output*).

Table 1: Structure of muon particle data at production.

Additional muon information : (7 resp. 8 words each)	
No. of word	Contents of word (as real numbers R*4)
$7 \times (n - 1) + 1$	particle description encoded as: part. id $\times$ 1000 + hadr. generation $\times$ 10 + no. of obs. level
$7 \times (n - 1) + 2$	px, momentum in x direction in GeV/c
$7 \times (n - 1) + 3$	py, momentum in y direction in GeV/c
$7 \times (n - 1) + 4$	pz, momentum in -z direction in GeV/c
$7 \times (n - 1) + 5$	x position coordinate (North) in cm
$7 \times (n - 1) + 6$	y position coordinate (West) in cm
$7 \times (n - 1) + 7$	z position coordinate (vertical) in cm
$7 \times (n - 1) + 8$	(weight in case of thinning)
	for $n = 1 \dots 39$

### 2.1 Mother Particle

The second entry of the extended additional muon information describes the momenta and positions of the mother particle at the interaction point at which this particle has been produced. The x and y-coordinates refer to the distance from the particle position to the intersection point of the shower axis with the observation level. The z-coordinate

Table 2: Structure of mother particle data.

Mother Particle Data : (7 rsp. 8 words each)	
No. of word	Contents of word (as real numbers $R^*4$ )
$7 \times (n - 1) + 1$	particle description encoded as: - part. id $\times$ 1000 + hadr. generation $\times$ 10 + no. of obs. level
$7 \times (n - 1) + 2$	px, momentum in x direction in GeV/c
$7 \times (n - 1) + 3$	py, momentum in y direction in GeV/c
$7 \times (n - 1) + 4$	pz, momentum in -z direction in GeV/c
$7 \times (n - 1) + 5$	x position coordinate (North) in cm
$7 \times (n - 1) + 6$	y position coordinate (West) in cm
$7 \times (n - 1) + 7$	z position coordinate (vertical) in cm
$7 \times (n - 1) + 8$	(weight = 0 in case of thinning)
	for $n = 1 \dots 39$

gives the altitude above sea level. For a clear discrimination against normal particles the identification of the mother particle is written with **negative** sign. The arrangement of these parameters and their meaning is given in Table 2.

## 2.2 Grandmother Particle

In the third entry of the extended additional muon information the momenta of the grandmother particle at its interaction point (end of range) are described as well as the generation counter of the **mother particle** and the penetrated matter thickness  $\chi$

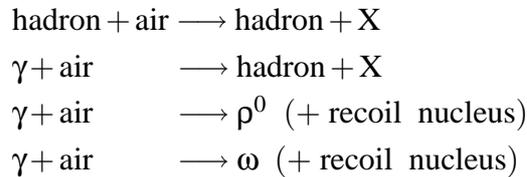
Table 3: Structure of grandmother particle data.

Grandmother Particle Data : (7 rsp. 8 words each)	
No. of word	Contents of word (as real numbers $R^*4$ )
$7 \times (n - 1) + 1$	particle description encoded as: - part. id $\times$ 1000 + hadr. generation $\times$ 10 + no. of obs. level
$7 \times (n - 1) + 2$	px, momentum in x direction in GeV/c
$7 \times (n - 1) + 3$	py, momentum in y direction in GeV/c
$7 \times (n - 1) + 4$	pz, momentum in -z direction in GeV/c
$7 \times (n - 1) + 5$	generation counter of <b>mother particle</b>
$7 \times (n - 1) + 6$	$\chi$ , penetrated matter thickness ( $g/cm^2$ ) between production and interaction point of grandmother particle
$7 \times (n - 1) + 7$	z position coordinate (vertical) in cm
$7 \times (n - 1) + 8$	(weight = 0 in case of thinning)
	for $n = 1 \dots 39$

between the birth and the end of range of the grandmother particle. In the case of an electro-magnetic particle as grandmother particle the value of  $\chi$  is set to 0. The z-coordinate gives the altitude above sea level of the interaction point and is - by construction - identical with the altitude of the production point of the mother particle. For a clear discrimination against normal particles the identification of the grandmother particle is written with negative sign. The arrangement and meaning of the parameters is given in Table 3.

### 3 Hadronic Generation Counter

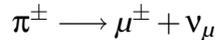
The hadronic generation counter is incremented at each hadronic interaction or decay by 1. These are interactions of the type:



But also in the  $\mu^+\mu^-$  pair creation

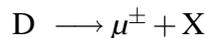


the counter is incremented by one. In addition the generation counter is incremented by one in all decays of hadrons. These are decays of  $\pi^0$ ,  $K^\pm$ ,  $K_S^0$ ,  $K_L^0$ ,  $\eta$ , all strange baryons, and all charmed hadrons. Deviations from this general rule exist in the decay of charged pions



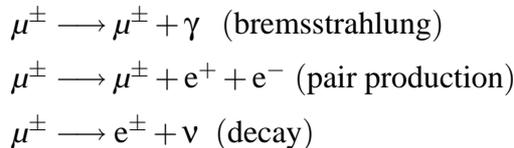
in which the counter is incremented by 51, but only if the counter of the decaying  $\pi^\pm$  is below 49. Otherwise it is incremented by 1.

In the decay of charmed mesons



the counter is incremented by 31. If after the incrementation the counter will exceed 99, it is clipped at 99. It is guaranteed that the generation counter never exceeds the value of 99.

For electrons/positrons resp. gammas coming from muon interactions or decays



the generation counter is incremented by 50 (**but not for the  $\mu^\pm$ !**), but only if the counter of the incoming muon is below 50.

But in the decay of shortlived resonances

$$\Delta \longrightarrow p + \pi$$

$$\Delta \longrightarrow n + \pi$$

$$K^* \longrightarrow K + \pi$$

$$\rho^0 \longrightarrow \pi^+ + \pi^-$$

$$\rho^\pm \longrightarrow \pi^\pm + \pi^0$$

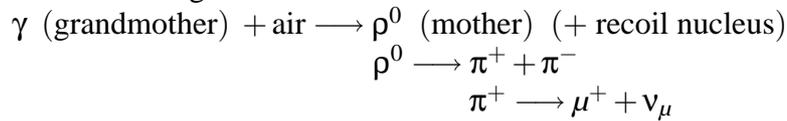
$$\omega \longrightarrow \pi^+ + \pi^- (+ \pi^0)$$

$$\omega \longrightarrow \pi^0 + \gamma$$

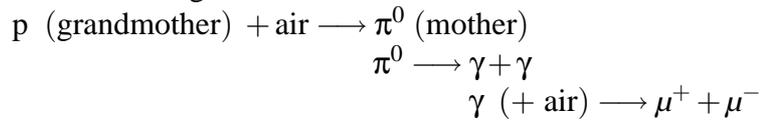
the generation counter is **not** incremented. This non-incrementation of the generation counter is adapted to the behavior of different interaction models: Some models are producing these shortlived resonances explicitly (e.g. HDPM), while most others subsume these decays into the interactions because of their short lifetimes without extra incrementation of the generation counter.

In ‘standard’ history chains with production of a charged pion or kaon as mother particle, the generation counter given for the final muon should be larger than that of the mother particle (which is given as the 5<sup>th</sup> element of the grandmother particle) by one (rsp. 51). But there exist various cases, in which the incrementation is not obvious or deviates from 1 (rsp. 51):

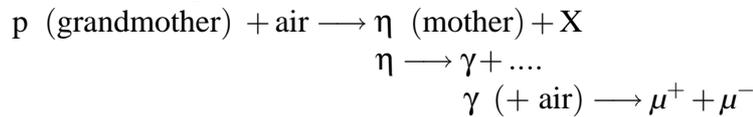
1. Difference in generation counter = 51 :



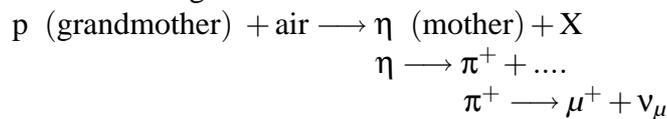
2. Difference in generation counter = 2 :



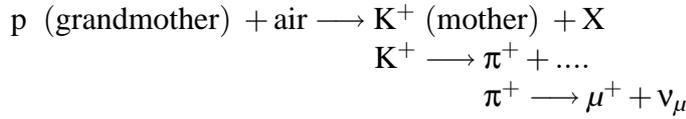
3. Difference in generation counter = 2 :



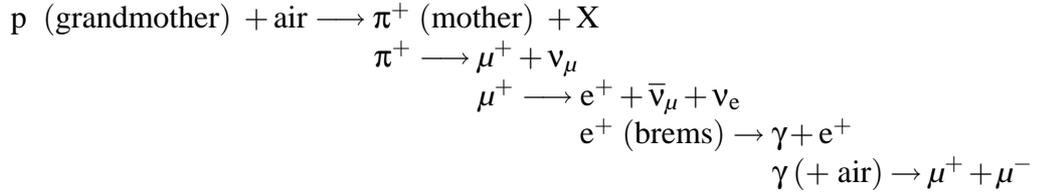
4. Difference in generation counter = 52 :



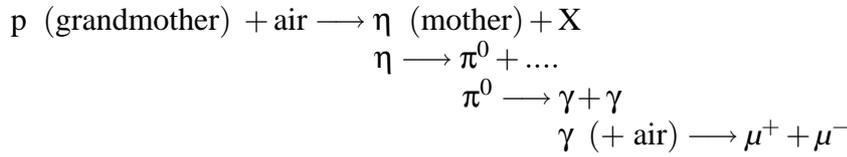
5. Difference in generation counter = 52 :



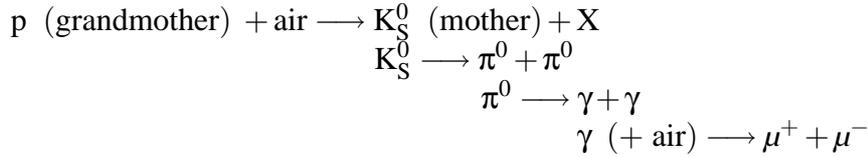
6. Difference in generation counter = 52 :



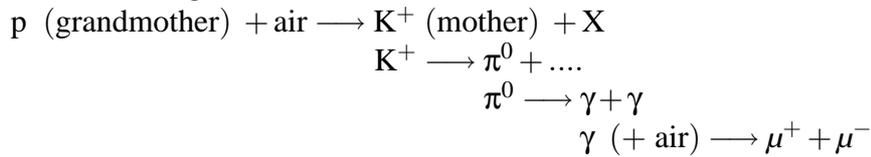
7. Difference in generation counter = 3 :



8. Difference in generation counter = 3 :



9. Difference in generation counter = 3 :



10. Difference in generation counter  $> 3$  (or  $> 53$ ) :

These are very rare processes and are not considered here.

This list of examples is by far not complete, but should show the principles which informations may be extracted out from the extra additional muon information and how they should be interpreted.

## 4 Example of Data Structure

The *Normal Particle Output* of an example is given here after converting it to the printable ASCII format, omitting the RUNH and EVTH sub-blocks and starting at the first

data sub-block :

```

7.55310E+04 1.82518E-01 4.69967E-02 2.95816E+01 5.68648E+02 2.07471E+02 1.31523E+06
-8.00000E+03 2.93559E-01 1.08935E-01 4.48802E+01 5.96484E-01 1.76690E+00 1.40207E+06
-1.40000E+04 2.94225E-02 8.65075E-02 1.06033E+03 2.00000E+00 4.78742E+00 1.40207E+06
5.53100E+03 1.30290E-01 8.06676E-03 2.75639E+01 6.34655E+03 8.63597E+02 4.26427E+04
3.54100E+03-4.52725E-02 3.71730E-03 2.63386E-01-7.44258E+04 4.76747E+03 4.28313E+04
7.55610E+04 1.35527E-01 3.70782E-02 1.26679E+00 9.37453E+02 1.55127E+02 6.90708E+05
-1.10000E+04 2.78868E-01 3.90948E-01 2.15358E+00 4.18276E+02-6.17455E+01 6.95700E+05
-1.40000E+04 2.94180E-01 6.45013E-03 4.45223E+01 4.00000E+00 6.56265E+01 6.95700E+05
5.56100E+03 7.64322E-02-6.92760E-03 3.86123E-01 8.03748E+04-1.21128E+03 4.30403E+04
.....
.....

```

This example is now read by the `./corsikaread_history` program. Its output is displayed here:

Opening file DAT690009

CORSIKA data file header:

```

run number:          690009
date of start:       20090511
program version:     6.950

```

ANALYSIS: initialization of histograms 100

GET\_SHOWER\_HEADER: new shower: 690009

ID	ENERGY	P_x	P_y	P_z	x	y	z
					gen.counter	chi	z

muon production point entry found:

```
75 2.958E+01 1.825E-01 4.700E-02 2.958E+01 5.68648E+02 2.07471E+02 1.31523E+06
```

muon mother/grandmother entry found:

```
-8 4.488E+01 2.936E-01 1.089E-01 4.488E+01 5.96484E-01 1.76690E+00 1.40207E+06
```

muon mother/grandmother entry found:

```
-14 1.060E+03 2.942E-02 8.651E-02 1.060E+03 2.00000E+00 4.78742E+00 1.40207E+06
```

muon entry found:

```
5 2.756E+01 1.303E-01 8.067E-03 2.756E+01 6.34655E+03 8.63597E+02
```

muon production point entry found:

```
75 1.275E+00 1.355E-01 3.708E-02 1.267E+00 9.37453E+02 1.55127E+02 6.90708E+05
```

muon mother/grandmother entry found:

```
-11 2.261E+00 2.789E-01 3.909E-01 2.154E+00 4.18276E+02 -6.17455E+01 6.95700E+05
```

muon mother/grandmother entry found:

```
-14 4.453E+01 2.942E-01 6.450E-03 4.452E+01 4.00000E+00 6.56265E+01 6.95700E+05
```

muon entry found:

```
5 4.076E-01 7.643E-02-6.928E-03 3.861E-01 8.03748E+04 -1.21128E+03
```

```

.....
.....
ANALYSIS: one complete shower read      1
  ID | ENERGY | P_x | P_y | P_z |      x      |      y      |      z
                                           |gen.counter|      chi      |      z
ANALYSIS: total number of showers:      1
CORSIKA_READ: analysis of file completed.

```

After the first muon (entries 1 to 4) an electron (entry 5) with ID = 3 and generation counter 53 arrives at the observation level, but as it is no muon, it is skipped in the `/corsikaread_history` program. In each entry the first word with the particle ID is disentangled, but only the particle ID is printed in the first column (without the generation counter and the observation level number). Additionally to the three momenta components, printed in columns 3 to 5, the energies of the particles are calculated from these momenta and printed in the second column. Columns 6 to 8 contain the position coordinates, in case of the grandmother particle the columns 6 and 7 are filled with the generation counter of the **mother** particle and the penetrated matter thickness  $\chi$  of the grandmother particle.

In the above example the first muon with generation counter 53 comes from the decay of the  $\pi^+$  mother particle with generation counter 2; it is a normal particle history with a proton grand mother particle. The second muon with generation counter 56 has a proton grand mother particle and a  $K^+$  ‘mother’ particle with generation counter 4, the generation counter difference of 52 corresponds with the example 5 of the previous section 3.

## 5 Limitations

### 5.1 Neutrino Induced Showers

With the NUPRIM option in  $\nu_\mu$ -neutrino induced showers, a muon is produced in the first interaction due to lepton number conservation:

$$\nu_\mu (\text{grandmother}) + \text{air} \longrightarrow \mu^- (\text{mother}) + X$$

If such a muon penetrates down to the detector level the extended additional muon information gives the neutrino as grandmother and the muon as mother, even if the muon did not make any further interaction. The generation counter of the  $\mu^-$  (mother) is 1, as well as in the standard muon additional information (ID = 75011).

### 5.2 Thinning

If the THIN option is selected together with the EHISTORY option the data structure will contain 8 words per item (instead of 7 without the THIN option). Weights are

given for all particles, but for the mother and grandmother particles the weights are set to zero. Therefore it makes not very much sense to use the THIN option in combination with the EHISTORY option and it is recommended to set the threshold for the thinning at such a low level that the particles of interest have always the weight equal to unity.

### 5.3 Combination with STACKIN Option

A combination of the EHISTORY option with the STACKIN option is possible. The secondary particles of the first interaction treated outside CORSIKA in a separate program are read in and their generation counter is set to 1. If one of these particles decays directly to a muon which arrives at the detector level, the mother and grandmother particles are written in the extended additional muon information as usual. Despite the grandmother particle interaction being simulated in an external program, it appears as grandmother particle with its parameters before its interaction. Only the penetrated matter thickness between the birth of the grandmother particle and its interaction remains undefined.

## 6 Application Example

In the following example 500 air showers induced by protons of  $10^{15}$  eV with vertical incidence are analyzed. In the simulations the QGSJET01 [16] has been used for the high-energy interactions, hadrons with energies below 80 GeV are treated by the FLUKA model [17]. For the electro-magnetic portion of the showers the analytical NKG-formulas [1, 18] have been used, so no muons e.g. coming from  $\mu^+ + \mu^-$  pair creation are to be expected.

In the Fig. 1 the kinetic energy spectra of various types of grandmother particles are plotted for the lateral distance range of the muons between 0 and 500 m at ground level. In Fig. 2 the kinetic energy of all hadronic grandmother particles is plotted for different lateral distance ranges of the muons arriving at ground. Similar energy spectra but simulated with different interaction models are given in Fig. 3.5 of Ref. [12], which have been produced with a preliminary version of the EHISTORY option.

A further example of an earlier version of the EHISTORY option is given in Ref. [19], where the pseudo-rapidities of muons arriving at the detector level are compared with those of their (mesonic) mother particles.

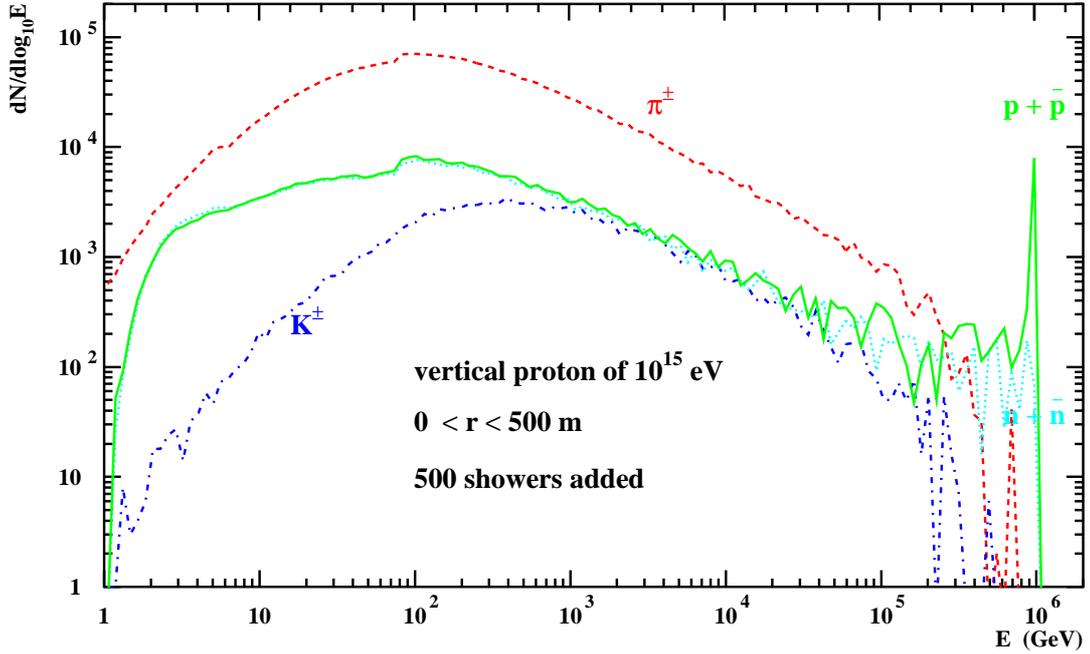


Figure 1: Distribution of kinetic energy of different grandmother particle types in vertical proton induced air showers for a muon lateral distance of 0 - 500 m at ground level.

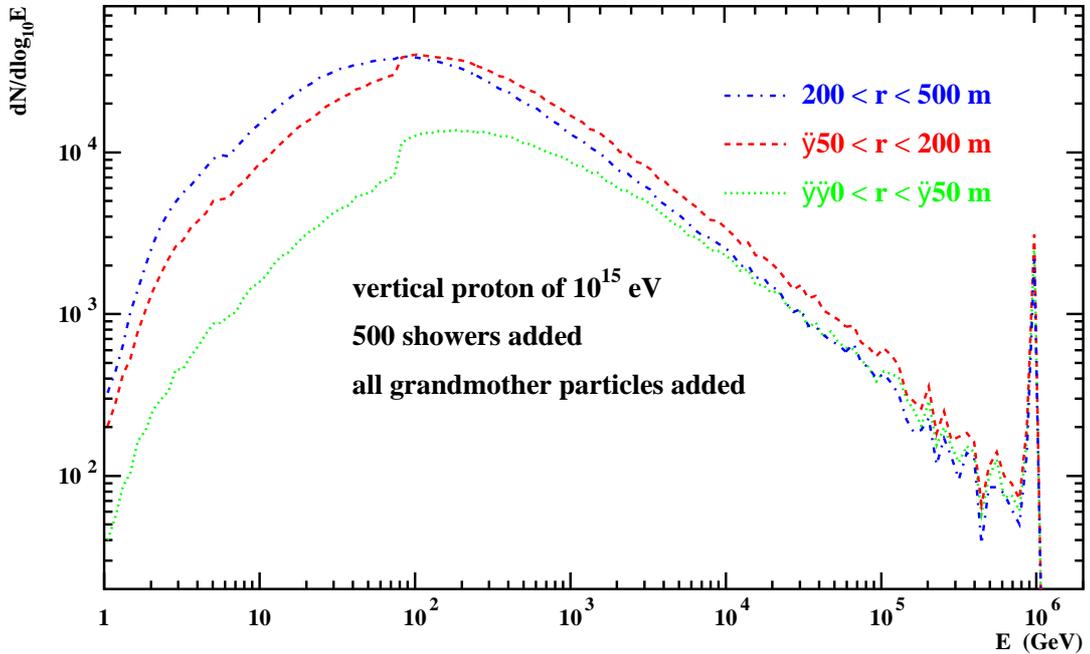


Figure 2: Kinetic energy spectra of all grandmother particle types summed in vertical proton induced air showers for different lateral distance ranges of the muons at ground level.

## 7 Final Remarks

The previous examples demonstrate the usefulness of the EHISTORY option for systematic studies on the production history of muons in air showers. All relevant parameters of the grandmother and mother particles and of the muons are stored in the four items of the extended additional muon information to derive their energy spectra, the distributions of their production positions (altitude resp. distance from the shower axis), and their generation sequence. Further parameters like the transverse momentum distribution obtained by the mother particles at their production may easily be calculated from the momenta components of grandmother and mother particles. All interesting features may easily be extracted by applying appropriate selections and cuts to one or several parameters of the extended additional muon information when filling histograms in a run with a suitably modified and extended version of the *corsikaread\_history* program.

## A Installation of the EHISTORY Option

It is recommended to use the *./coconut* (CORSIKA CONfiguration UTility) procedure for the installation of the CORSIKA executable file. This script provides a user interface through questions and answers for the various CORSIKA options. The question ‘Which additional CORSIKA program options do you need ?’ should be answered by typing ‘s’ which selects the EHISTORY option. The EHISTORY option should work in combination with nearly all other available options, especially with all high-energy and low-energy hadronic interaction models, with the options CERENKOV, CHARM, CURVED, NEUTRINO, NUPRIM (primary neutrino), SLANT, STACKIN, or UPWARD, but **not** with the INTTEST option, as in the INTTEST option only the first interaction is considered, so the generation sequence of grandmother and mother particles is not established. Further details on the CORSIKA installation you find in the CORSIKA User’s Guide [15].

For reading the output particle file, a program frame *corsikaread\_history.f* is supplied which might be modified to include the production of histograms for plotting. In its basic version it prints just the extended additional muon information (i.e. including that on mother and grandmother particles) for those muons which arrive at the observation level. After compilation and linking of the *corsikaread\_history.f* program the run is performed by calling:

```
./corsikaread_history > test.out
```

Then enter the file name (for example DAT690009).

The information for the arriving muons is written into the file *test.out* in the readable ASCII format. If the THIN option has been used in the CORSIKA run, the COMMON BLOCK sizes have to be adapted to use *./corsikaread\_history* with thinned/unthinned showers by setting the LENPAR parameter (LENPAR = 7 for un-thinned, LENPAR = 8 for thinned showers).

## References

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