JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

Parametrization of longitudinal development of cascade events in NTSim simulation framework

Supervisor:
Prof. Dmitry Naumov

Student:
Ilya Chernousov, Russia
Irkutsk State University

Participation period:
July 20 – August 30,
Summer Session 2023

Dubna, 2023

Contents

Abstract

NTSim is a framework developed by a team based at JINR with a purpose of carrying out simulations of neutrino telescopes. One of the main components of NTSim framework is a python interface for GEANT4, which allows us to use GEANT4 instrumentation to provide accurate results. Usage of GEANT4, however, comes at a significant performance cost.

The main goal of the conducted work was to find parametrization of longitudinal development of cascade events in order to speed up simulation process, while not compromising the accuracy of the result.

Introduction

NTSim is a framework designed to carry out simulations of neutrino telescopes. It consists of various modules some of which are based on existing methods of simulation, such as GEANT4. While fairly accurate, usage of GEANT4 comes at a significant performance cost, especially when it comes to simulating secondary particles (mainly $e^{\pm}$ and γ) in electromagnetic cascades. Therefore, it is advisable to use analytical approximations of the longitudinal distribution of charged particles in a cascade.

This report focuses on longitudinal parametrization of total track length of charged secondary particles in cascade events.

Chapter 1

Longitudinal distribution

The main source of information in neutrino telescope experiments and, as a consequence, in simulations of such experiments is Cherenkov radiation. Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. In case of cascade events in neutrino telescopes, the main source of Cherenkov light are secondary electrons and positrons. Cherenkov radiation can be characterized by its longitudinal (amount of Cherenkov photons emitted per unit length of shower axis) and angular distributions. The easiest way to obtain the longitudinal distribution of Cherenkov photons is to conduct Monte-Carlo (MC) based simulation. To do that, one can divide the shower axis into intervals or bins of equal size, and then count the number of Cherenkov photons produced from each interval, resulting in a histogram. Alternatively, one can take into account that the total amount of emitted Cherenkov photons is proportional to total length of tracks of charged particles:

$$N_{ch}^{tot} = n_{ch} L_{e^{\pm}},$$

Where n_{ch}– linear density of Cherenkov radiation for relativistic particles (typically, for water n_{ch} = 230 ÷ 240 photons/cm),
$L_{e^{\pm}}$ - total length of charged particles tracks. Hence, the longitudinal distribution of Cherenkov photons can be expressed in terms of distribution of charged particles track lengths, multiplied by linear density. However, obtaining such a distribution isn’t a straightforward process.

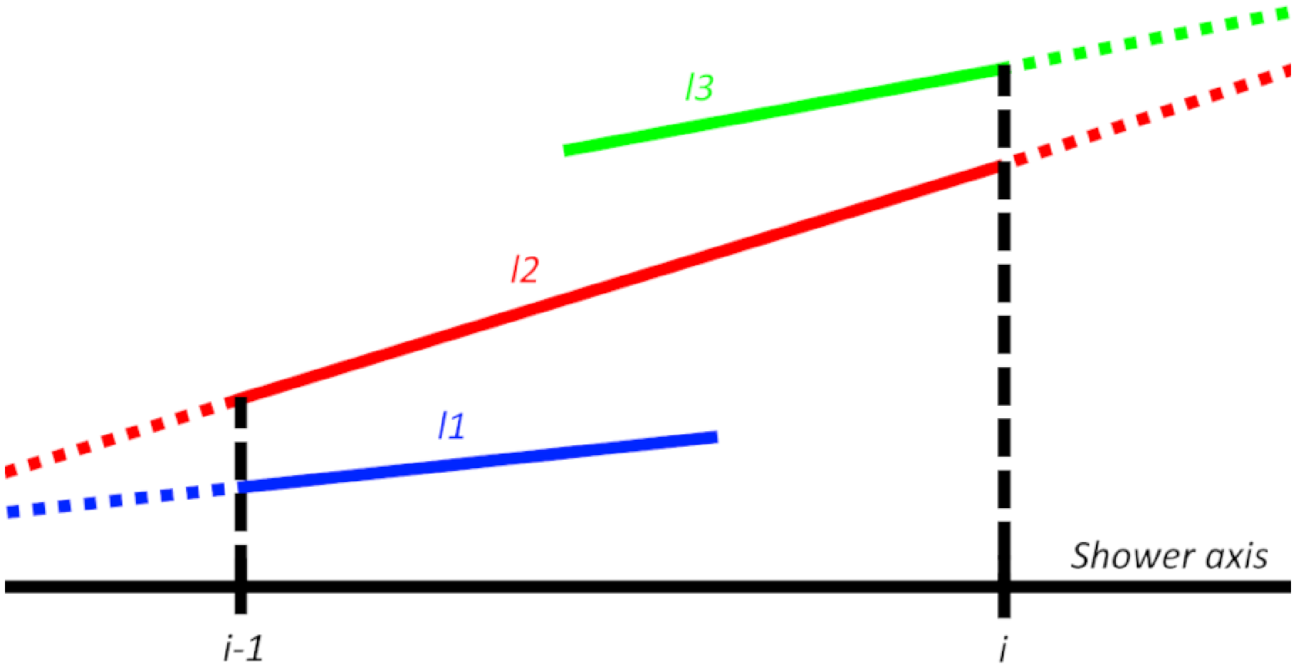

Figure 1: method used to count total tracks length in i-th bin.

Figure 1 schematically shows the method, which was used in this work to count total track lengths per bin. To count total tracks length in i-th bin we add together segments of individual tracks which correspond to said bin:

$$L_i = l_1 + l_2 + l_3,$$

Where L_i – i-th bin count. Longitudinal distributions of Cherenkov photons produced by electron obtained using both methods are shown in figure 2. Shower axis is aligned with z axis and $t = \frac{z}{x_0}$ – shower depth, where $x_0 \approx 0.36\ m$ – radiation length. Note that number of photons shown in figure 2 is 1000 times smaller than actual number of photons produced, since during the simulation process only every 1000-th photon was actually simulated. This was done in order to complete the simulation within a reasonable time frame.

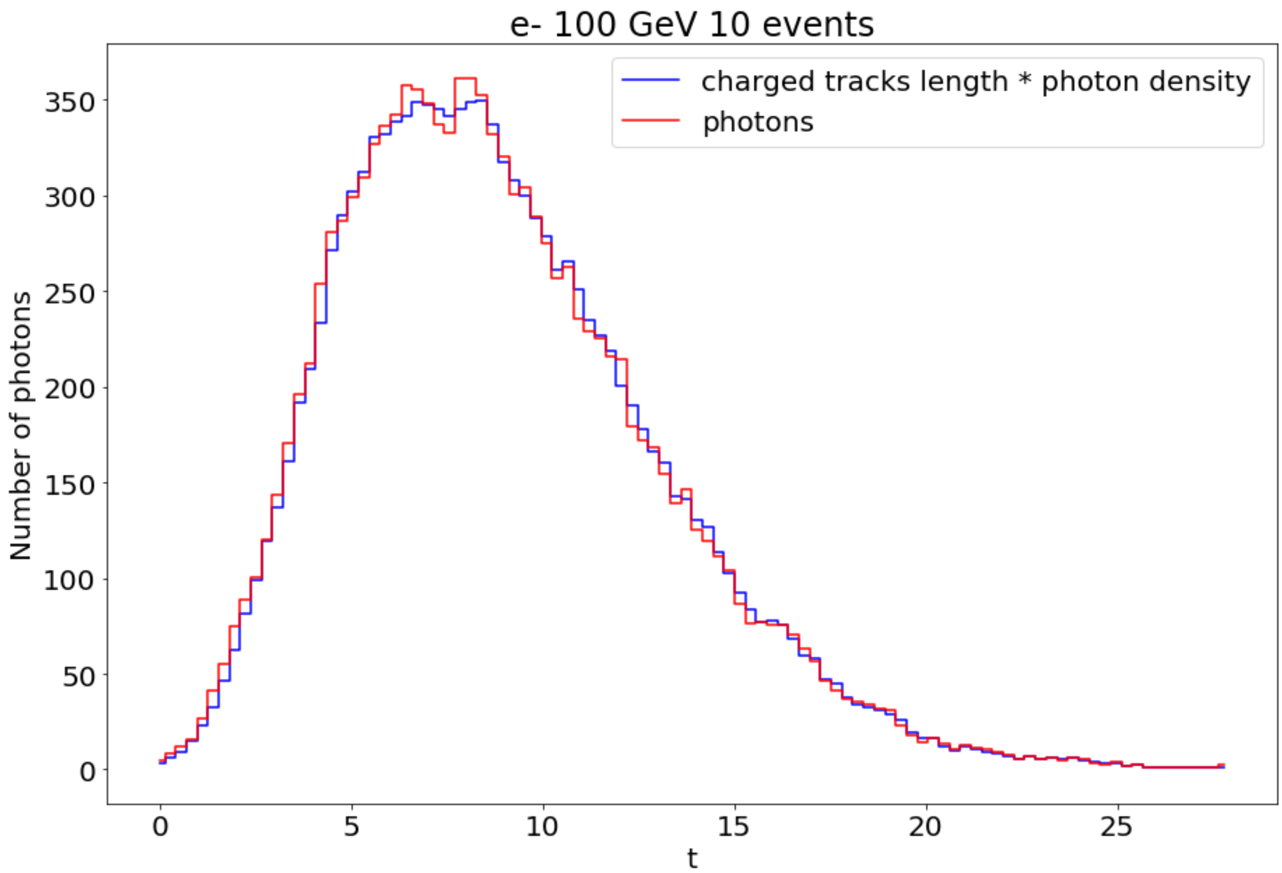

Figure 2: Longitudinal distribution of Cherenkov photons produced by electron with $E_0 = 100GeV$. Red and blue histograms represent first and second methods respectively. Shown are distributions averaged over 10 events.

The distributions for higher energies, as well as for various primary particles (in particular, positrons) retain generally the same shape, which allows us to believe that these distributions can be described using a universal analytical approximation. In this work we focused on finding analytical approximation of longitudinal distribution for track lengths.

Chapter 2

Parametrization

As mentioned earlier, longitudinal distributions of track lengths can be described with universal function. For that purpose, we chose slightly modified gamma distribution as our fitting function:

$$f(t, N, t_{max}, q) = \frac{N}{\Gamma(q) t_{max}} \left(\frac{qt}{t_{max}} \; e^{-\frac{t}{t_{max}}} \right)^{q},$$

Where N, t_{max}, q – parameters of fitting function. Parameters N and t_{max} have a physical interpretation: N - is the total track length of all particles in the shower, and t_{max} – is the depth at which the maximum shower development is achieved. Parameters were fitted to the distributions using curve_fit method from Python package called scipy. Fit results are shown in the figure 3.

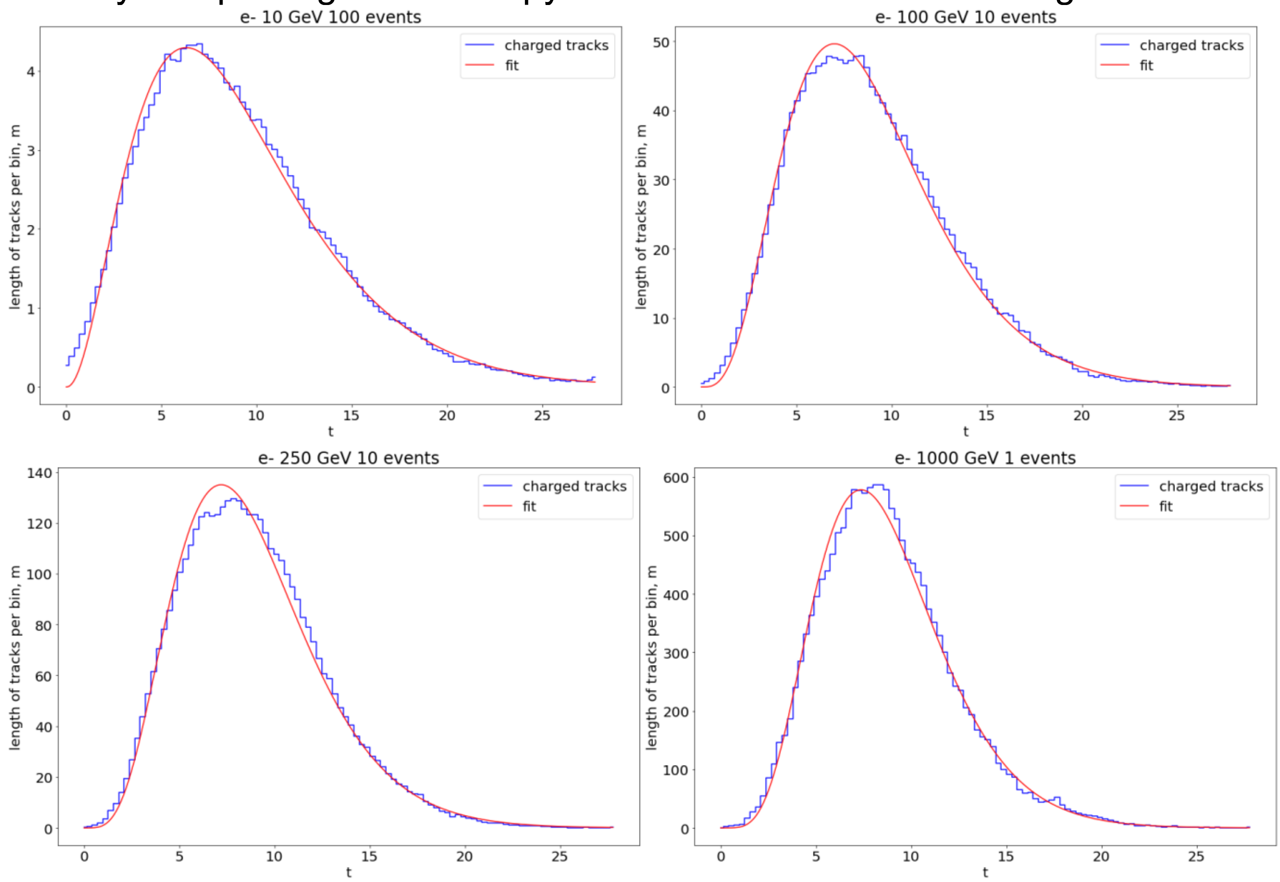

Figure 3: fit results for distributions produced by electron with energies 10 GeV, 100 GeV, 250 GeV, 1000 GeV.

Track length distributions were obtained using g4camp, a Python-based interface for GEANT4. Exact values of the parameters for electron with different initial energies E_0 are given in the table 1.

E_0, GeV	N, m	t_{max}	q
10	47.38	6.304	2.208
100	473.05	6.993	3.547
250	1182.8	7.203	4.409
1000	4727.34	7.375	5.271

Table 1: exact values of parameters for different energies

Energy dependencies of parameters are shown in figure 4

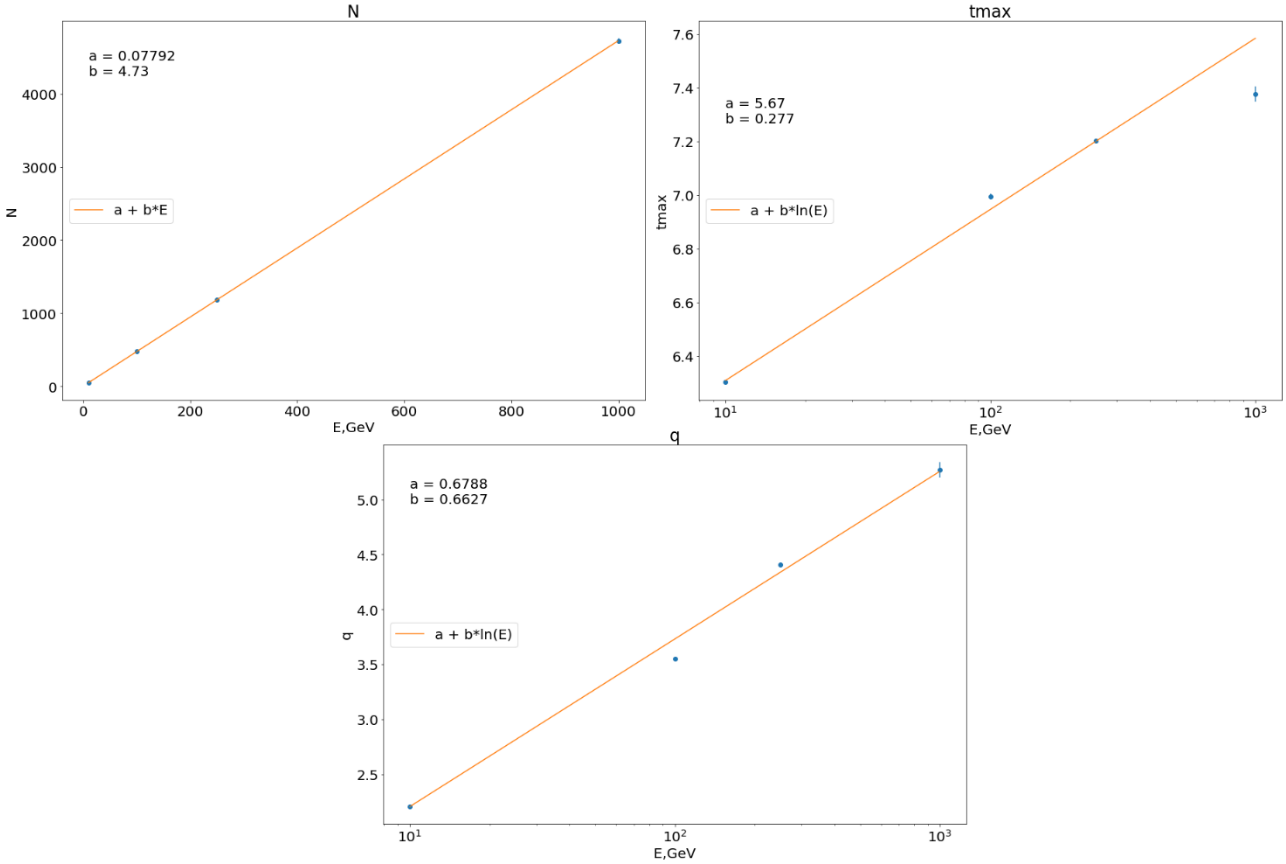

Figure 4: energy dependencies of parameters. Note that for t_{max} and q scale on the x-axis is logarithmic.

As shown in figure 4, parameters turned out to be energy dependent, with N following linear dependence, and both t_{max} and q following logarithmic dependence. However, it is important to note that value of t_{max} for $E_0 = 1000\ GeV$ doesn't follow the trend line and is likely a software bug, further investigation required.

Conclusion

As a result of the work carried out, an analytical approximation of the longitudinal distribution of track lengths of charged secondary particles was found, parametrization parameters were determined, as well as their dependence on energy. However, further research is needed regarding higher initial energies of primary particles, as well as the collection of additional statistics.

Acknowledgments

The author expresses gratitude to the NTSim development team for giving valuable feedback on conducted work and especially Sergey Zavyalov for extensive technical support. The author also expresses gratitude to START Program organizers for providing the opportunity to participate in this wonderful program.