

# Hadron production simulation by FLUKA

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**Abstract.** For the purposes of accelerator based neutrino experiments, the simulation of parent hadron production plays a key role. In this paper a quick overview of the main ingredients of the PEANUT event generator implemented in the FLUKA Monte Carlo code is given, together with some benchmarking examples.

## 1. Introduction

FLUKA [1, 2] is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, and radiotherapy. 60 different particles plus heavy ions can be transported by the code. The energy range covered for hadron-hadron and hadron-nucleus interaction is from threshold up to 10000 TeV, while electromagnetic and  $\mu$  interactions can be dealt with from 1 keV (100 eV for photons) up to 10000 TeV. Nucleus-nucleus interactions are also supported up to 10000 TeV/n, thanks to the interfaces with a modified version of rQMD-2.4 [3, 4] (covering the intermediate energy range above  $\sim 100$  MeV/n) and with DPMJET-III [5] (invoked at high energies, that is above 5 GeV/n). At low energies, the BME event generator [6], which is part of the FLUKA code, applies. Neutron transport and interactions below 20 MeV and down to thermal energies are treated in the framework of a multi-group approach, with cross section data sets developed for FLUKA starting from standard evaluated databases (mostly ENDF/B, JENDL and JEFF).

Transport in arbitrarily complex geometries, including magnetic fields, can be accomplished using the FLUKA combinatorial geometry, supporting object repetition (lattice capability). A suitable voxel geometry module allows to model properly CT scans or other detailed 3D representations, e.g. of human beings, typically for dosimetry or therapy planning purposes.

The code has the ability to run either in fully analogue mode or in biased mode exploiting a rich variety of variance reduction techniques.

FLUKA is jointly developed by the European Organization for Nuclear Research (CERN) and the Italian National Institute for Nuclear Physics (INFN).

The approach to hadronic interaction modelling adopted in FLUKA has been detailed in several papers [7, 8, 9, 10, 11]. Hadron-nucleon inelastic collisions are described in terms of resonance production and decay up to a few GeV. At higher energies, a model [9] based on the Dual Parton Model (DPM) [12], that is a particular quark/parton string model providing

reliable results up to several tens of TeV, takes over. In DPM, hadron-hadron interactions result in the creation of two or more QCD color strings, from which hadrons have to be generated.

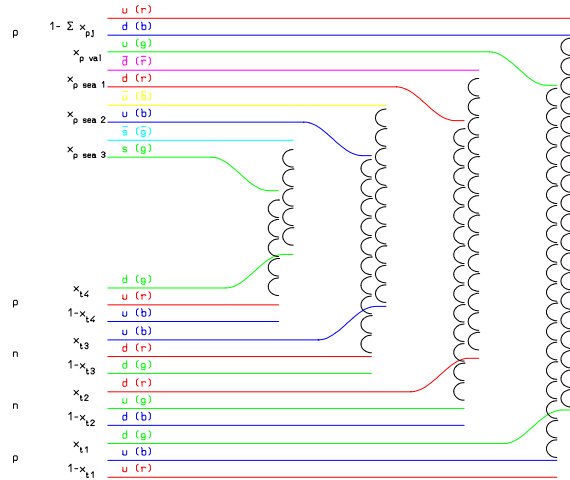
Hadron-nucleus (h-A) interactions as modelled in the PEANUT (PreEquilibrium-Approach-to-NUclear-Thermalization) event generator of FLUKA, can be schematically described as a sequence of three main steps: i) Glauber-Gribov cascade and high energy collisions, ii) Generalized IntraNuclear cascade and iii) Preequilibrium stage, which are eventually followed by the Evaporation/Fragmentation/Fission phase ending through  $\gamma$  deexcitation.

The next section will briefly recall the interpretation of the Glauber approach in terms of quark chain and particle production diagrams, as well as the essential features of the PEANUT “nuclear environment”, in particular the crucial formation zone concept. Its effect is manifestly displayed in the comparison with experimental data, together with the role of the Glauber multiple collision model.

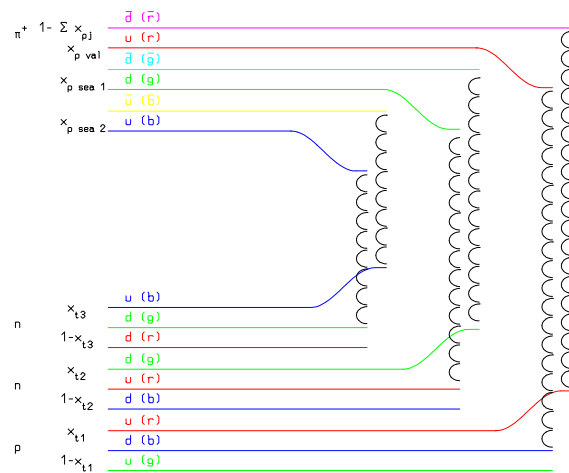
## 2. Hadron-nucleus reaction modelling

The Glauber formalism [13, 14] allows to compute the scattering amplitude as well as all relevant cross sections for hadron–nucleus interactions, using the knowledge of elementary hadron–nucleon scattering and of the nuclear ground state only.

The Glauber multiple collision model can be formulated as a field theory (the so called Glauber-Gribov model [15, 16, 17]) based on general principles such as unitarity and analyticity [18]. The various multiple collision terms can be shown to be in a one-to-one correspondence with the various Feynman graphs describing the interaction.



**Figure 1.** Leading two-chain diagrams in DPM for  $p - A$  Glauber scattering with 4 collisions. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities.



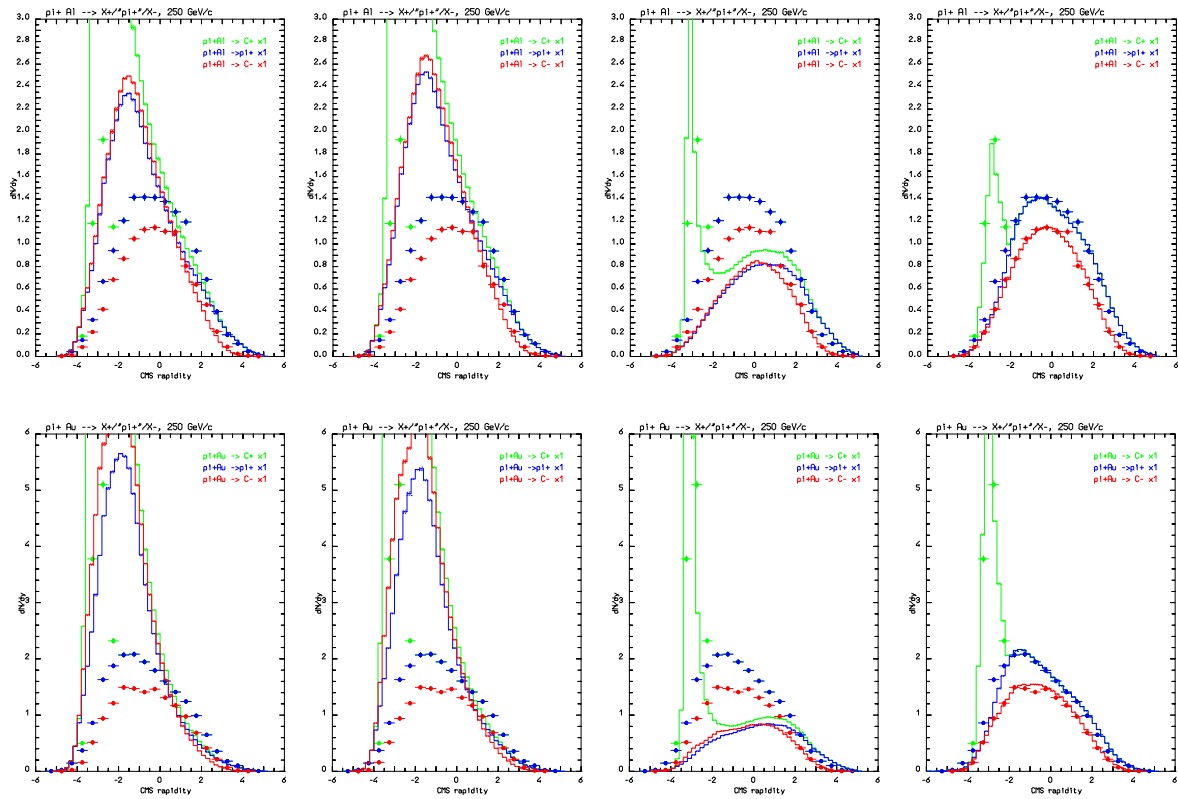
**Figure 2.** Leading two-chain diagrams in DPM for  $\pi^+ - A$  Glauber scattering with 3 collisions. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities.

The Glauber-Gribov calculus allows to determine the probability distribution for the number  $n$  of target nucleons the projectile is going to interact with. In the DPM language these collisions are described by  $2n$  chains, neglecting the contributions from higher order diagrams (referred to as multiple soft collisions), that is considering at most one pomeron exchange with each target nucleon. Two of these chains originate from the projectile valence quarks together with the valence quarks of one target nucleon (resulting in 2 valence-valence chains), whereas the other  $2(n - 1)$  chains stem from  $(n - 1) q\bar{q}$  sea quarks of the projectile combined with the valence

quarks of the other target nucleons ( $2(n-1)$  sea-valence chains). Examples of this chain building process are reported in figures 1 and 2.

At energies high enough to consider coherent effects as corrections, h-A reactions are described as a cascade of two-body interactions, concerning the projectile and the reaction products. This mechanism is called IntraNuclearCascade (INC).

In PEANUT, particle trajectories in the nuclear medium are treated classically (curved in the mean nuclear+Coulomb field), with the nucleus divided into 16 radial zones of different density, plus 6 outside the nucleus to account for nuclear potential, plus 10 for charged particles. Respective nuclear densities and Fermi energies are adopted for neutrons and protons (the shell model ones for  $A < 16$ ). The interaction probability is calculated from  $\sigma_{free}$  taking into account the (density dependent) Fermi motion. Nonetheless, many significant quantum effects (Pauli blocking, formation zone, correlations...) are incorporated. Exact conservation of energy, momenta and all additive quantum numbers is assured on an event-by-event basis, including nuclear recoil.



**Figure 3.** Computed (histograms) rapidity distributions of positive, negative and  $\pi^+$  particles for 250 GeV/c  $\pi^+$  on Aluminium (top) and Gold (bottom), compared with experimental data [19]. No formation zone and no Glauber multiple collisions are taken into account in the first column. In the second column formation zone is not taken into account, while Glauber multiple collisions are. In the third column formation zone is taken into account, while Glauber multiple collisions are not. Eventually, in the last column both formation zone and Glauber multiple collisions are taken into account.

The INC goes on in PEANUT until all nucleons are below a smooth threshold around 50 MeV, and all particles but nucleons (typically pions) have been emitted or absorbed. The nuclear

configuration at this point is used as the starting condition for the preequilibrium stage, that follows the exciton formalism of M. Blann and coworkers [20], with some modifications [9].

The formation zone (or formation time) concept [21, 22] has been proposed since several years as a key factor in modelling high energy nuclear interactions. Formation zone is indeed essential in order to understand the observed reduction of the re-interaction probability with respect to the naive free cross section assumption. It can be understood as a “materialization” time. At high energies, the “fast” (from the emulsion language) particles produced in the Glauber cascade have a high probability to materialize already outside the nucleus without triggering a secondary cascade. Only a small fraction of the projectile energy is thus left available for the INC and the further stages.

Comparisons of calculated and experimental charged particle rapidity distributions, for  $\pi^+Al$  and  $\pi^+Au$  collisions at 250 GeV/c, are shown in figure 3, with Glauber multiple collisions and formation zone either activated or not.

### 3. Conclusion

We presented the FLUKA modeling of hadron-nucleus reactions relevant for the yield characterization of neutrino parents. The role of multiple Glauber collisions and formation zone was highlighted in comparison with experimental data.

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