The Fritiof (FTF) Model in Geant4

V.V. Uzhinsky[*†‡]
On behalf of the Geant4 Hadronics Working Group
E-mail: Vladimir.Uzhinskiy@cern.ch

The Fritiof model, or FTF for short, is used in Geant4 to simulate hadron-nucleus interactions with $P_{lab} > 3$–4 GeV/c, nucleus-nucleus interactions with $P_{lab} > 2$–3 GeV/c/nucleon, and antibaryon-nucleus interactions as well as antinucleus-nucleus interactions without low energy threshold. Because the model does not include multi-jet production in hadron-nucleon interactions, the upper limit of its validity is about 1000 GeV/c. The main ingredients of the model and its results are shortly described.

Calorimetry for High Energy Frontiers - CHEF 2013,
April 22-25, 2013
Paris, France

[*]Speaker.
[†]CERN, CH-1211, Geneva 23, Switzerland
[‡]LIT, JINR, 141980 Dubna, Russia

The Fritiof model[1, 2] assumes that all hadron-hadron interactions are binary reactions, $h_1 + h_2 \rightarrow h'_1 + h'_2$, where h'_1 and h'_2 are excited states of the hadrons with discrete or continuous mass spectra (see Fig. 1, left part). If one of the final hadrons is in its ground state ($h_1 + h_2 \rightarrow h_1 + h'_2$) the reaction is called "single diffraction dissociation", and if neither hadron is in its ground state it is called a "double-diffractive" interaction. The excited hadrons are considered as QCD-strings, and the corresponding LUND-string fragmentation model is applied in order to simulate their decays.

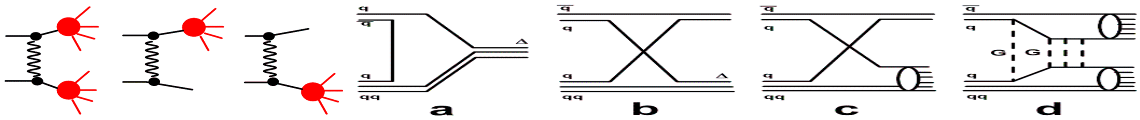

Figure 1: Processes considered in the FTF model.

In the constituent quark model of hadrons, the creation of s-channel Δ-isobars, in πp-interactions for example, is explained by quark–anti-quark annihilation (see Fig. 1a). The production of two mesons may result from quark exchange (see Fig. 1b). A quark–di-quark (q–qq) system created in the process 1c can be in a resonance state (1b), or in a state with a continuous mass spectrum. In the latter case, multi-meson production is possible. Amplitudes of these two channels are connected by crossing symmetry to annihilation in the t-channel, and with non-vacuum exchanges in the elastic scattering according to the reggeon phenomenology. According to that phenomenology, pomeron exchange must dominate in elastic scattering at high energies. In a simple approach, this corresponds to two-gluon exchange between colliding hadrons. It reflects also in one or many non-perturbative gluon exchanges in the inelastic reaction. Due to these exchanges, a state with subdivided colors is created (see Fig. 1d). The state can decay into two colorless objects. The quark content of the objects coincides with the quark content of the primary hadrons, according to the FTF model, or it is a mixture of the primary hadron's quarks, according to the Quark-Gluon-String model (QGSM).

The processes are very important at low energies ($<$ 5–15 GeV). In order to extend the Fritiof model to this energy domain, we include the processes 1b, 1c in the Geant4 FTF model. The process 1a with a quark annihilation is considered only in the case of anti-baryon-baryon interactions.

The key ingredient of the Fritiof model is a sampling of the string masses. In general, the set of final states of interactions can be represented by Fig. 2 (left), where samples of possible string masses are shown. There is a point corresponding to elastic scattering, a group of points which represents final states of binary hadron-hadron interactions, lines corresponding to the diffractive interactions, and various intermediate regions. The region populated with the red points is responsible for the double-diffractive interactions. In the model, the mass sampling threshold is set equal to the ground state hadron masses, but in principle the threshold can be lower than these masses. The string masses are sampled in the triangular region restricted by the diagonal line corresponding to the kinematical limit $M_1 + M_2 = E_{cms}$ where M_1 and M_2 are the masses of the h'_1 and h'_2 hadrons, and also of the threshold lines. If a point is below the string mass threshold, it is shifted to the nearest diffraction line.The original model had no points corresponding to elastic scattering or to the binary final states.

All of these allowed us to describe satisfactorily, according to our point of view, meson pro-

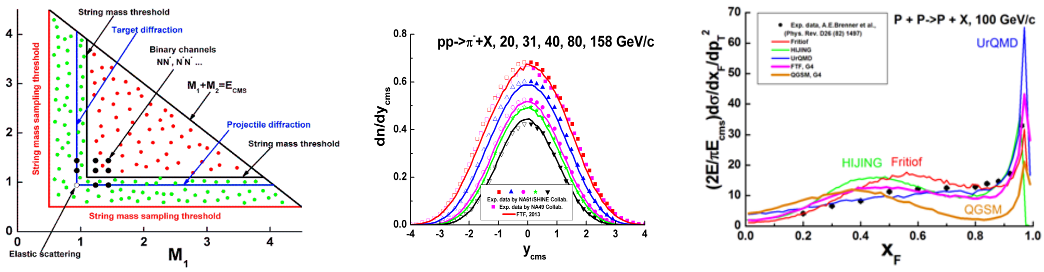

Figure 2: (*left*) Diagram of final states of the FTF model. (*center*) Description of π-meson production in pp-interactions. (*right*) Description of the proton spectrum. Points are experimental data [3],[4],[5].

duction in $\pi^{\pm}p$-, $K^{\pm}p$-, pp- and $\bar{p}p$-interactions. As an example, we show in Fig. 2 (center) our calculations in a comparison with data by the NA61/SHINE [3] and NA49 [4] Collaborations. Though, there are some problems with a description of baryon spectra (see Fig. 2 (right)).

In the case of hadron-nucleus or nucleus-nucleus interactions it was assumed that the excited hadrons created after a first intra-nuclear collision can interact further with other nuclear nucleons and excite other nuclear nucleons. The Glauber model is used for a sampling of the multiplicity of the intra-nuclear collisions. The Gribov inelastic screening is not considered. For medium and heavy nuclei a Saxon-Woods parameterization of the one-particle nuclear density is used, while for light nuclei a harmonic oscillator shape is used. Center-of-mass correlations and short range nucleon-nucleon correlations are taken into account.

The Glauber cross sections of multi-particle production processes in hadron-nucleus interactions are obtained in the reggeon phenomenology applying the asymptotical Abramovski-Gribov-Kancheli cutting rules [6, 7, 8] to the elastic scattering amplitude. Thus, the multiplicity of the intra-nuclear collisions in hadron-nucleus interactions is varied from one to the mass number of the target nucleus. But a large number of the collisions cannot be reached in interactions with heavy nuclei at low energy. To restrict the number, it is needed to introduce finite energy corrections to the cutting rules. Because there is no defined prescription for accounting of these corrections, let us undertake a phenomenological consideration, and start with the cascade model.

As known, a simple cascade model considers only pions and nucleons. Due to this it cannot work when resonance production is a dominating process in hadronic interactions. But if the energy is sufficiently low the resonances can decay before a next possible collision, and the model can be valid. Let p be the momentum of a produced resonance (Δ). The average life time of the resonance in its rest frame is $1/\Gamma$. In the laboratory frame the time is $E_\Delta/\Gamma\ m_\Delta$. During this time, the resonance will fly a distance $\bar{l} = v\ E_\Delta/\Gamma\ m_\Delta = p/\Gamma\ m_\Delta$. If the distance is less than an average distance between nucleons in nuclei ($\bar{d} \sim 2$ fm), the model can be applied. From the condition, we have: $p \leq \bar{d}\ \Gamma m_\Delta \sim 1.5$ (GeV/c).

Direct Δ-resonance production takes place in πN interactions at low energies. Thus the model cannot work well at a momentum of pions above 2 GeV/c. In nucleon-nucleon interactions, due to momentum transfer to a target nucleon, the boundary can be higher.

Returning back to the FTF model, let us assume that projectile originated strings have an average life time $1/\Gamma$, and an average mass m^*. The strings can interact on average with $\bar{l}/\bar{d} =$

$p/\Gamma\ m^*\bar{d} = p/p_0$ nucleons. Here p_0 is a new parameter. According to our estimates it is about 3–5 GeV/c. Thus, we can assume that at any energy there is a maximum number of intra-nuclear collisions in the FTF model – $\nu_{max} = p/p_0$. This restriction is implemented in the current version of the FTF model, and puts a low boundary of the model application region to 4–6 GeV/c. For the determination of the p_0 parameter we used the HARP-CDP data, as it is demonstrated in Fig. 3.

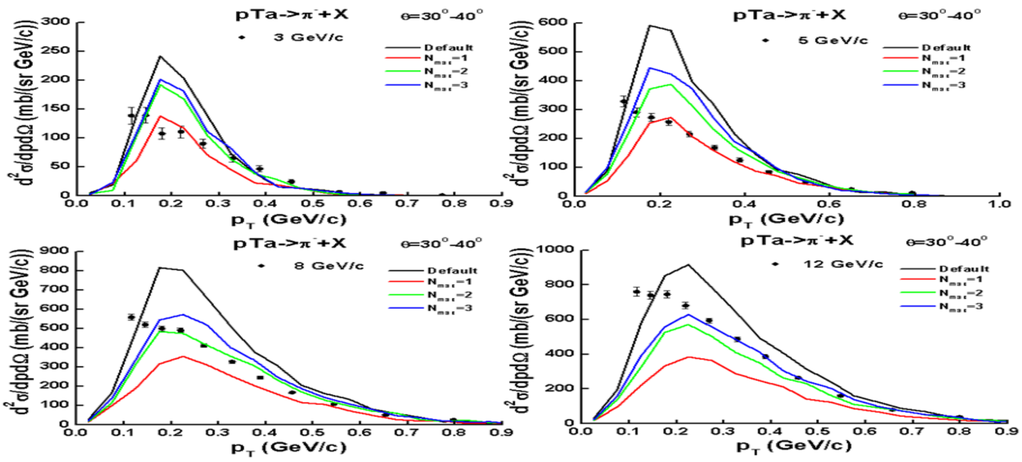

Figure 3: π^--meson P_T distributions in pTa-interactions. Points are experimental data [9]. Lines are FTF calculations with various values of ν_{max}.

The modeling of hadron-nucleon interactions in the FTF model includes simulations of elastic scattering, binary reactions such as $NN \to N\Delta$, $\pi N \to \pi\Delta$, single diffractive and non-diffractive events, and annihilation in anti-baryon-nucleon interactions. It is assumed that the unstable objects created in hadron-nucleus and nucleus-nucleus collisions can have analogous reactions.

As known, the Glauber approximation used in the Fritiof model and in the other string models does not provide enough intra-nuclear collisions for a correct description of a nuclear destruction. Additional cascading in nuclei is needed! Usage of a standard cascade for secondary particle interactions leads to a large multiplicity of produced particles. Usually, it is assumed that an inclusion of a secondary particle's formation time can help to solve this problem, but there is no unified solution. Thus, the reggeon-inspired model RTIM of nuclear destruction [10] is applied in the FTF model for a description of secondary particle intra-nuclear cascading. Excitation energies of residual nuclei are estimated in the "wounded nucleon" approximation [11]. This allows for a direct coupling of the FTF model to the Precompound model of Geant4 and hence with the GEM nuclear fragmentation model. All of these provide a smooth transition from the FTF model and low energy Bertini and Binary cascade models of Geant4 [12, 13, 14].

There are many comparisons of FTF model calculations with various experimental data at $P_{lab} = 3$–400 GeV/c. Most of them are presented at the Geant4 hadronic Validation pages ([15], test22). In general, the model reproduces reasonably well meson and baryon production in hadron-nucleus interactions at high energies.

Recently a simulation of nucleus-nucleus interactions at RHIC and LHC energies was implemented in the FTF model. Some preliminary results are shown in Fig. 4.

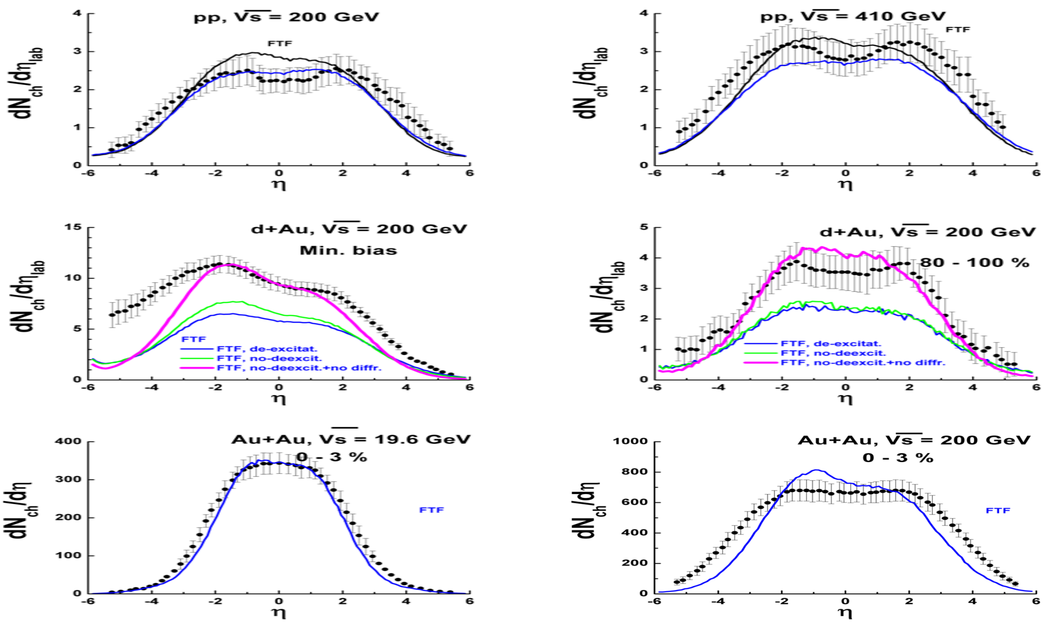

Figure 4: Preliminary results of the FTF model simulations of nucleus-nucleus interactions at RHIC energies. Lines are the model calculations. Points are experimental data.

The author is thankful to the Geant4 hadronic working group for many useful considerations of the results and critical remarks.

References

[1] B. Andersson et al. *Nucl. Phys.*, B281:289, 1987.

[2] B. Nilsson-Almquist and E. Stenlund. *Comp. Phys. Comm.*, 43:387, 1987.

[3] N. Abgrall et al. 2012.

[4] C. Alt et al. *Eur. Phys. J.*, C45:343, 2006.

[5] A.E.Brenner et al. *Phys. Rev.*, D26:1497, 1982.

[6] V.N. Gribov. *JETP*, 53:654, 1967.

[7] V.N. Gribov. *Sov. Phys. JETP*, 26:414, 1969.

[8] V.N. Gribov. *Sov. J. Nucl. Phys.*, 9:369, 1969.

[9] JINR) et al. A. Bolshakova (Dubna. *Eur. Phys. J.*, C63:549–609, 2009.

[10] Kh. Abdel-Waged and V.V. Uzhinsky. *Phys. Atom. Nucl.*, 60:828, 1997.

[11] J. Hufner A.Y. Abul-Magd, W.A. Friedman. *Phys. Rev.*, C34:113, 1986.

[12] S. Agostinelli et al. *Nucl. Instrum. Meth.*, A506:250, 2003.

[13] J. Allison et al. *IEEE Transactions on Nuclear Science*, 53:270, 2006.

[14] http://geant4.web.cern.ch/geant4/.

[15] http://g4validation.fnal.gov:8080/G4ValidationWebApp/G4ValHAD.jsp.