## Geant4 FTF model description of the latest data by the NA61/SHINE collaboration on <sup>40</sup>Ar + <sup>45</sup>Sc interactions

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## Abstract

It is shown that the Geant4 FTF model, which does not include the simulation of the hard parton-parton scattering and the formation of the quark-gluon plasma (QGP), describes well the NA61/SHINE data on  $\pi^-$  meson distributions for the interactions at  $\sqrt{s_{NN}} = 5.2$ , 6.1, 7.6 and 8.8 GeV. At higher energies,  $\sqrt{s_{NN}} = 11.9$  and 16.8 GeV, the model underestimates the data. This is considered as an indication of the formation of QGP at higher energies in central collisions of light and intermediate nuclei than in collisions of heavy nuclei ( $\sqrt{s_{NN}} \sim 6$  GeV).

Recently, the NA61/SHINE collaboration has published [1] experimental data on  $\pi^-$  meson production in central  $^{40}\mathrm{Ar} + ^{45}\mathrm{Sc}$  interactions at beam momenta from 13A to 150A GeV/c. The collaboration has compared their results with EPOS [2], UrQMD [3, 4] and Hijing [5, 6] model calculations. It was shown that EPOS and UrQMD models give a satisfactory description of the data only at the momentum 150A GeV/c (see Fig. 1). At lower energies, EPOS model overestimates dn/dy for  $\pi^-$  mesons at  $y \sim 0$ , and UrQMD model underestimates the data. As it will be shown below, the Geant4 FTF model – using the version 10.7 with minimal changes that will be included in the next release – describes well the data except at momenta 75A and 150A GeV/c.

The Geant4 FTF model [7] is based on the well-known Fritiof model [8, 9] which was widely applied for simulations of hadron-nucleon, hadron-nucleus and nucleus-nucleus interactions. It is assumed in the model that all nucleon-nucleon interactions are binary reactions with creation of resonances and excited nucleons in final states. The spectrum of squared masses of the excited nucleons is a key ingredient of the model. We chose to parameterize the spectrum for non-diffractive interactions as  $a/M_x^2 + b$ . Excited nucleons are considered as quark-gluon strings whose fragmentation produces hadrons. The fragmentation of strings is simulated using a modified version of the LUND algorithm [10, 11] implemented in the Geant4 toolkit.

The Geant4 FTF model considers diffraction dissociation into high mass states, quark-exchange processes and non-diffractive interactions. Phenomenological parametrizations of the corresponding cross sections are implemented in Geant4 (see details in Geant4 Physics Reference Manual [12]). For the simulation of nucleus-nucleus interactions we apply a simplified Glauber approximation. Fermi motion of nuclear nucleons is accounted for according to the method of Refs. [13, 14]. A fine tuning of the FTF model parameters has been done using the NA61/SHINE data on pp interactions at various energies [15].

FTF model results for rapidity distributions of  $\pi^-$  mesons in  $^{40}$ Ar +  $^{45}$ Sc interactions are presented in Fig. 1 together with the experimental data for 0–5 % centralities. Having no geometrical description of the NA61/SHINE Projectile Spectator Detector (PSD) used for selection of central interactions, we have chosen the impact parameter range (0 – 3.1 fm) to reproduce the height of the rapidity distribution at 19A GeV/c. As seen in Fig. 1, we describe quite well the rapidity distributions of  $\pi^-$  mesons at beam momenta 13A, 30A and 40A GeV/c. At higher momenta we underestimate the data.

As seen also in Fig. 1, the Hijing model overestimates the data at all energies. However, a good description can be reached by scaling down the Hijing results by 10 - 15 %, though the widths of the distributions at 13A, 19A and 40A GeV/c are overestimated. A simplest way to decrease the Hijing results is by increasing of the probability of the one-vertex diffraction dissociation in nucleon-nucleon interactions, as it was suggested in Ref. [16]. With this, the NA61/SHINE data on pp interactions [15] are described [16]. There are also additional possibilities to improve the Hijing results [17].

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We did not find a simple recipe to improve the EPOS model results at low energies.

The FTF model does not consider hard interactions and quark-gluon plasma (QGP) formation. This could explain the deviation of the FTF model results from the data at 75A and 150A GeV/c. In heavy ion collisions the formation probably takes place at  $\sqrt{s_{NN}} \simeq 6-7$  GeV (see Refs. [18, 19]). Thus, we expected that the deviation of the FTF results from the  $^{40}{\rm Ar} + ^{45}{\rm Sc}$  interaction data would start also at  $\sqrt{s_{NN}} \sim 6-7$  GeV. This is not the case. Therefore, we interpret our results as an indication of the QGP formation at higher energies in central collisions of light and intermediate nuclei with respect the collisions of heavy nuclei. It would be interesting to check this hypothesis by using NA61/SHINE data on  $^7{\rm Be} + ^9{\rm Be}$  interactions.

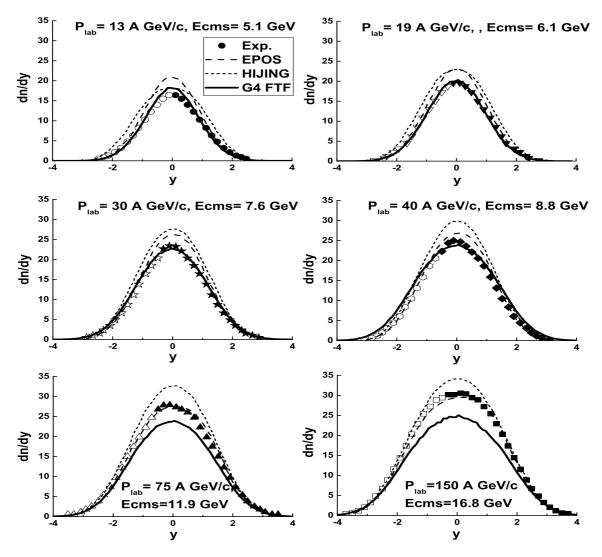


Figure 1: Rapidity distributions dn/dy of  $\pi^-$  mesons for all six beam momenta. Black points are data measured by the NA61/SHINE for 0–5 % centralities. Open points are values extrapolated by the collaboration into unmeasured region. All experimental uncertainties are smaller than the symbol size. Predictions of EPOS and Hijing models obtained by the collaboration [1] are shown by long and short dashed curves, respectively. The FTF model results are shown by solid lines.

In the following, we analyze the  $p_T$  distributions of the  $\pi^-$  mesons produced in the interactions. In Fig. 2 we show the NA61/SHINE experimental data compared with model predictions. One can see that the FTF model describes well the distributions at momenta 13A, 19A, 30A and 40A GeV/c. The model underestimates the tails of the distributions at 75A and 150A GeV/c, and underestimates the data at  $p_T < 200 \text{ MeV/c}$ . Again, this discrepancy could be caused by the absence of hard processes in the FTF model.

The Hijing model considers hard and semi-hard interactions. But it appears that these processes are

switched on too early in the model starting from  $19A~{\rm GeV/c}$ . Only at  $150A~{\rm GeV/c}$  the model predictions are in agreement with the experimental data. Thus, it would be good to improve the energy dependence of these processes in the model. In doing this, also the total multiplicity of produced mesons can be decreased.

For the EPOS model the situation is more complicated. The model describes well the data at 75A and 150A GeV/c. At lower momenta, the model describes the data only at  $p_T \ge 800$  MeV/c. Thus, we believe that the energy dependence of the hard and semi-hard processes is correctly reproduced in the model. Soft interactions play a role at small  $p_T$  ( $p_T < 800$  MeV/c) and lower projectile momenta. It is more complicated to improve the soft string fragmentation, as we have done in the Geant4 FTF model.

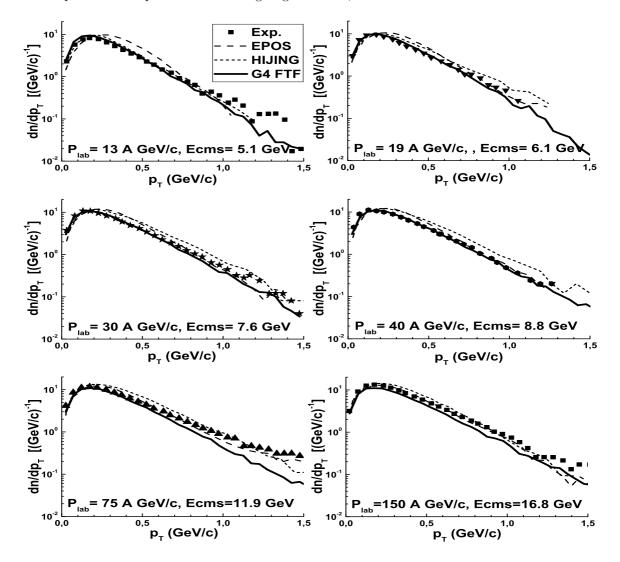


Figure 2: Transverse momentum distributions  $dn/dp_T$  at mid-rapidity (0 < y < 0.1) for all six beam momenta. Points are the NA61/SHINE experimental data for 0–5 % centralities. All experimental uncertainties are smaller than the symbol size. Predictions of EPOS and Hijing models taken from Ref. [1] are shown by long and short dashed curves, respectively. The FTF model results are shown by solid lines.

## Conclusion

1. The Geant4 FTF model calculations are in good agreement with experimental data of the NA61/SHINE collaboration on transverse momentum and rapidity distributions of  $\pi^-$  mesons produced in  $^{40}$ Ar +  $^{45}$ Sc interactions at  $\sqrt{s_{NN}} < 10$  GeV.

- 2. At higher energies the FTF model underestimates dn/dy and the tails of  $dn/dp_T$  distributions. These discrepancies could be compensated by including hard processes and creation of QGP.
- 3. It would be good to reproduce the energy distributions in the Projectile Spectator Detector of the NA61/SHINE collaboration used for centrality selection. These are presented in Ref. [1]. Their reproduction would allow to check the nuclear residual fragmentation model in FTF, and allow to use the same criteria for centrality determination as in the experiment. It is not possible to do this at the moment without the exact geometrical description of the detector and its response.
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