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Production of Strange Particles in Hadronic Interactions

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Abstract. The NA61/SHINE collaboration has recently published high precision data on production of $\pi^{\pm}$ and $K^{\pm}$ mesons, protons, antiprotons and Λ hyperons in pp interactions at 20, 31, 40, 80 and 158 GeV/c, and in pC interactions at 31 GeV/c. The collaboration also presented experimental data on production of particles - $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, ρ^0, ω and K^{*0} in π^-C collisions at 158 and 350 GeV/c. The collaboration has compared these data with various Monte Carlo model calculations: UrQMD, EPOS, GiBUU, and others. All of the models have various problems. The latest version of the FTF (Fritiof) model of Geant4 solves most of these problems. In the FTF model, we have improved the fragmentation of quark-gluon strings with small masses and introduced dependencies of probabilities of strange mesons and baryon-antibaryon pair's creation on string masses. Due to these changes, we describe the data of the NA61/SHINE collaboration on particle production in pp, pC, and π^-C interactions.

The improved Geant4 FTF model also well reproduces experimental data on inclusive cross sections of Λ, $\bar{\Lambda}$ and K^0 production in antiproton-proton interactions at various energies. The modified FTF model allows one to simulate realistic processes with two particle productions - $\bar{p}p \to \Lambda\bar{\Lambda}$, $\bar{p}p \to K^+K^-$, $\bar{p}p \to \Lambda\bar{\Sigma}$, and $\bar{p}p \to \Sigma\bar{\Sigma}$, which will be studied in the future by the PANDA experiment at FAIR (GSI, Germany).

1 Introduction

Recently, very interesting and useful experimental data were published by the NA61/SHINE collaboration [1]. In 2017, the NA61/SHINE collaboration presented detailed experimental data on $\pi^{\pm}$, $K^{\pm}$, protons and antiprotons production in proton-proton interactions in a wide energy range from 20 GeV/c to 158 GeV/c [2]. In 2016, experimental data on Λ hyperon production in p-p interactions at 158 GeV/c [3] were published by the collaboration. At the beginning of 2016, the spectra of $\pi^{\pm}$, $K^{\pm}$, K^0_s, Λ and protons in proton-carbon interactions at initial momentum 31 GeV/c [4] appeared. Recently, the NA61/SHINE collaboration published a paper about the production of various hadrons in pion-carbon interactions at two initial momenta 158 GeV/c and 350 GeV/c [5].

Authors of the papers performed a comparison of the measured experimental data with predictions of various Monte Carlo models – EPOS 1.99 [6], UrQMD 3.4 [7, 8], GiBUU 1.6 [9, 10] and Geant4 [11] hadronic models: FTFB and QGSM. Main problems were observed in model descriptions of strange particles production.

The aim of our work was to improve the Geant4 FTF model to reproduce inclusive spectra of strange particles. The Geant4 FTF model is based on the Fritiof model [12,13] of the LUND university. We have modified the FTF model using the experimental data on strange particle and antiproton productions in proton-proton interactions at initial momenta larger than 20 GeV/c [2]. Then, we used the improved FTF model for describing the experimental data on pC and π^-C interactions given in the papers [3–5]. We also used the new FTF model to reproduce differential cross sections of Λ-$\bar{\Lambda}$ and K^+-K^- productions in antiproton-proton interactions [14–16], and kinematical properties of Λ, $\bar{\Lambda}$, K^0_S produced in antiptoton-proton interactions in a wide initial energy range – from 360 MeV/c up to 100 GeV/c [17–21].

2 Inclusive Spectra of Particles Produced in Proton-Proton Interactions at Momenta of 20, 31, 40, 80 and 158 GeV/c

It is assumed in the FTF model that hadrons turn into excited states in hadron-hadron inelastic interactions. If only one hadron is excited, the process is called diffraction dissociation. The excited states of hadrons are considered as quark-gluon strings. The Lund fragmentation model is used for quark-gluon string fragmentation. Strange particles are produced by the fragmentation of quark-gluon strings containing a strange quark or antiquark coming from the creation of $s\bar{s}$ pairs from the vacuum.

We have introduced some improvements in the FTF model for a better description of the experimental data [2] on $\pi^\pm$, proton, antiproton, and $K^\pm$ productions in pp-interactions at $P_{lab} \geq 20$ GeV/c.

In Figure 1, the rapidity distributions of K^+ and K^- mesons produced in pp-interactions at momenta 20, 30, 40, 80 and 158 GeV/c are given. The experimental data are presented by points, the red lines are calculations with the FTF model in the Geant4 10.03.09 development release. As one can see, the calculations overestimate the K meson production at low energy, and describe the data at high energies.

The overestimation at low energies is connected with too large probability of strange quark production at string decays. We suppressed the probability of string $q\bar{q}$ pair production according to the formula:

$$P_{\bar{s}s} = 0.108 \cdot (1 - (m_{th}/M_{str})^4)\,, \tag{1}$$

where 0.108 is an asymptotical value of the probability, m_{th} is a threshold mass equals to the sum of two strange meson masses, M_{str} is a string mass. At this probability, the improved FTF model of Geant4 describes well the experimental

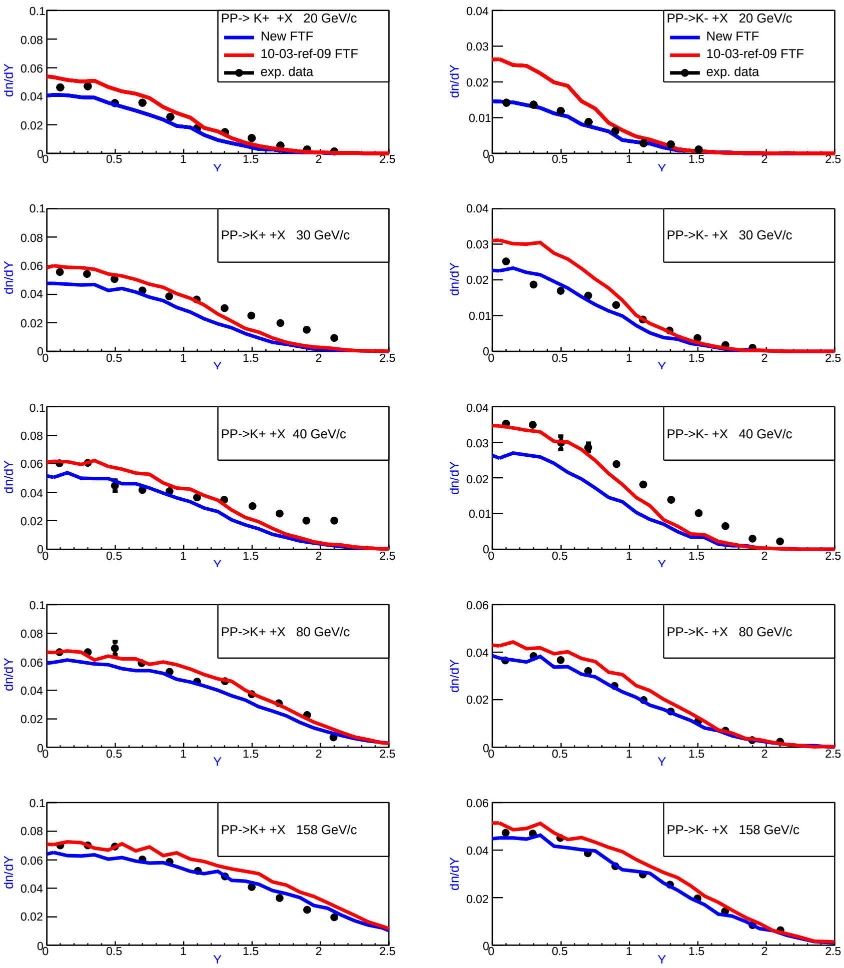

Figure 1. Rapidity distributions of K^+ (left side) and K^- (right side) mesons in pp interactions at various momenta.

data at all energies. Only at 40 GeV/c the new FTF model cannot describe K meson spectra. We note that these experimental data do not seem to follow the common trend of all the rest of the data.

In Figure 2, rapidity distributions of protons and antiprotons produced in pp-interaction at momenta 20, 30, 40, 80 and 158 GeV/c [2] are shown in a comparison with FTF model calculations. Looking at the antiproton spectra calculated by the FTF model in Geant4 10.03.09 release, it is seen that the calculations overestimate antiproton production at low energies. To suppress this overproduction, we introduced a probability of diquark-antidiquark pair creation

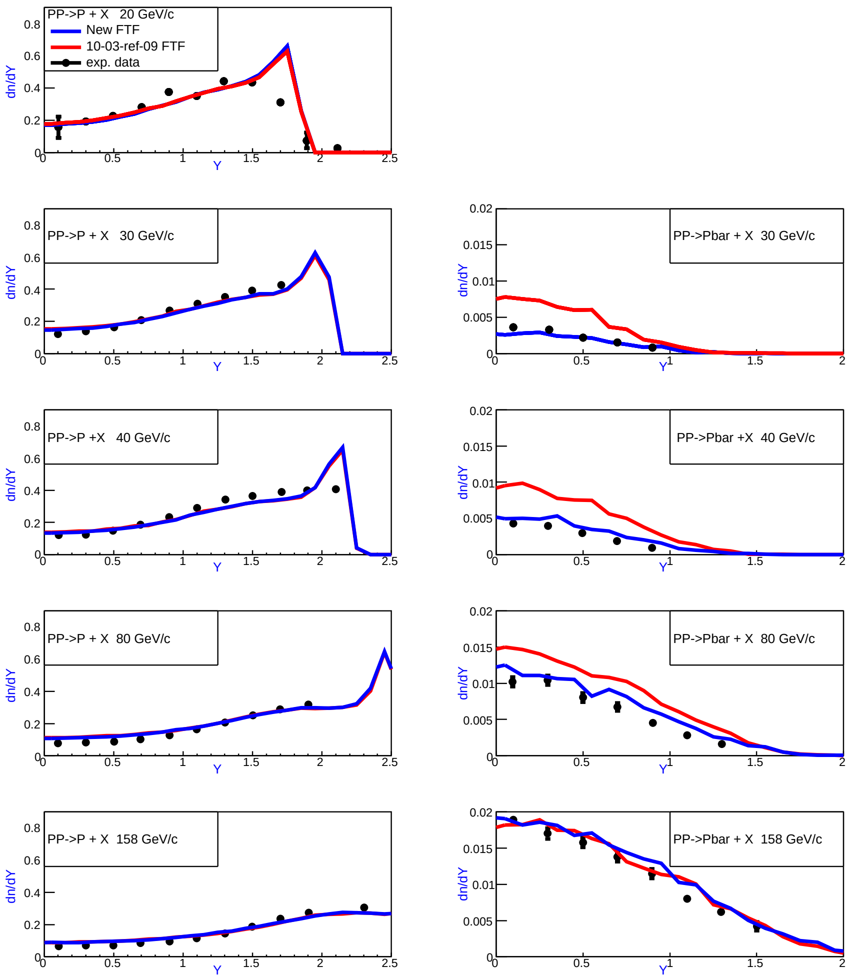

Figure 2. Rapidity distributions of protons (left side) and antiprotons (right side) in pp interactions at various momenta.

at a string decay given by the formula:

$$P_{qq-\bar{q}\bar{q}} = 0.15 \cdot (1 - (1400 \cdot N_b/M_{str})^2)\,, \qquad (2)$$

where 0.15 is the asymptotical value of the probability, M_{str} is the string mass, and N_b is a maximum number of baryons and antibaryons what can be produced. The FTF model calculations with this improvement are shown in the figure by the blue lines. As seen, the calculations reproduce well the antiproton distributions. It is very important that these changes of the FTF model don't affect the

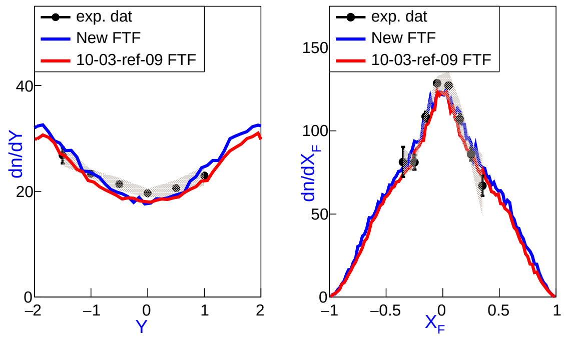

Figure 3. Rapidity (left side) and Feyman X (right side) distributions of Λ-hyperons in pp interactions at 158 GeV/c.

proton inclusive spectra. The FTF model describes the proton rapidity distributions quite well. The same situation is observed for π meson spectra.

The NA61/SHINE collaboration also published various specrtra of Λ hyperons, especially, rapidity and Feyman X distributions [3] in proton-proton interactions at P_{lab}=158 GeV/c. The authors of the paper compared these data with various model calculations – UrQMD, Fritiof 7.0 and EPOS 1.99. Only EPOS model described the experimental data. Now, the FTF model also describes well these data, as seen in Figure 3.

We conclude that the improved FTF model works as well as the EPOS 1.99 model.

3 Production of Strange Particles in Hadron-Nucleus Interactions

The FTF model uses the Glauber approach for estimating the number of participating nucleons in hadron-nucleus collisions. In the model, the participating hadrons transform into quark-gluon strings which fragment into secondary particles, including the strange particles.

The NA61/SHINE collaboration presented measurements of spectra of charged pions, kaons, and protons as well as K_s^0 and Λ hyperons in pC interactions at 31 GeV/c in the paper [4]. In that paper, data are compared with calculations of FTF + Binary Cascade model, Venus, EPOS1.99, and GiBUU models. The conclusion of the paper was that none of the models provided a satisfactory description of all the spectra.

In Figure 4, we present the differential cross sections of K^+ mesons produced in pC interactions as functions of laboratory momentum of the mesons. The experimental data are given at various emission angles of K^+ – 0-20 mrad, 20-40 mrad, 40-60 mrad and so on up to 240-300 mrad. Before the improvement, the FTF model calculations (red lines) overestimated the maxima of the distributions by about 50%. After the improvement, the FTF model reproduces

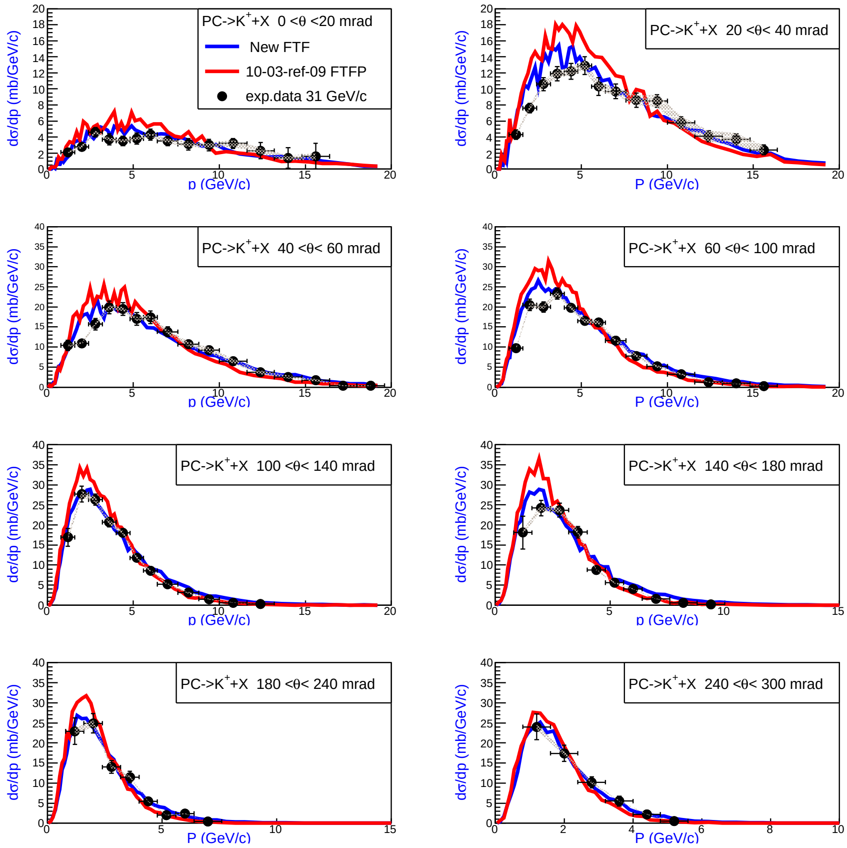

Figure 4. Momentum distributions of K^+ mesons in pC interactions at 31 GeV/c at various angles.

the inclusive spectra of K^+ mesons quite well. The same situation takes place for the momentum distributions of K^- and K^0_S mesons produced in pC interactions at 31 GeV/c. Now, we have reached a good agreement between the FTF calculations and the experimental inclusive spectra of mesons and Λ hyperons.

Very interesting experimental data on π^-C interactions have been published by the NA61/SHINE collaboration in Ref. [5].

Figure 5 shows the experimental data on $\pi^\pm$, $K^\pm$, proton and antiproton momentum distributions in π^-C interactions at 158 GeV/c. The authors of the paper [5] showed also calculations of different models: QGSJet, Sybill, DpmJet and EPOS. The main difference between the models was observed in the calculations of K^+, K^- mesons and antiprotons. In Figure 5, we present the FTF model calculations. In general, the improved FTF model calculations (blue lines) describe better the experimental data than other models presented in Ref. [5].

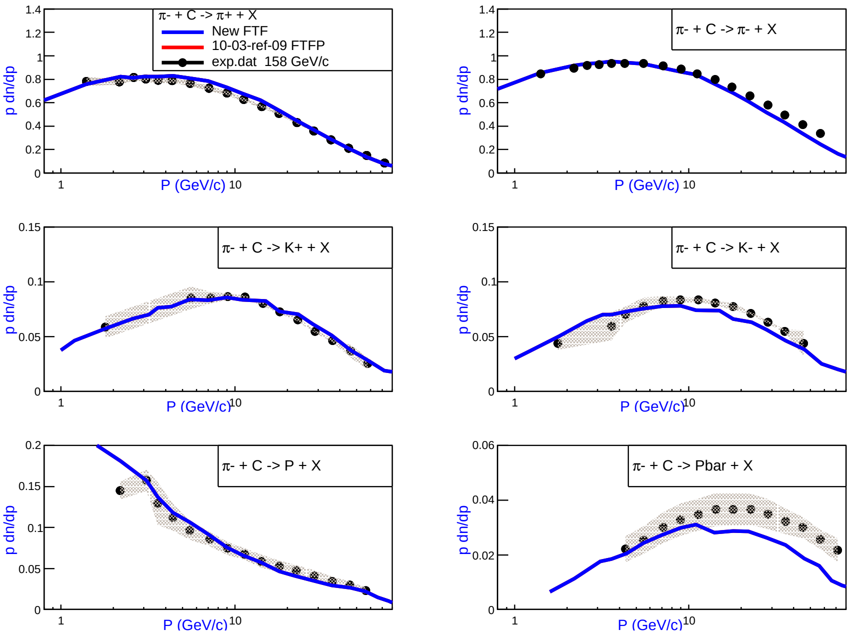

Figure 5. Momentum distributions of π^+, π^-, K^+, K^-, p, $\bar{p}$ in π^-C interactions at 158 GeV/c.

The FTF model results are in agreement with the data on $\pi^{\pm}$, protons, and $K^{\pm}$ mesons. At the same time, the FTF calculations are slightly lower than the data for antiprotons with momenta larger than 10 GeV/c.

We have a similar situation for the description of the experimental data on pion, kaon, proton and antiproton production in π^-C interactions at 350 GeV/c [5].

Summing up, we conclude that the FTF model with the new probabilities describes quite well the inclusive spectra of protons, antiprotons, $\pi^{\pm}$, $K^{\pm}$, K^0 mesons and Λ-hyperons produced in pp, pC, and π^-C interactions.

4 Production of Strange Particles in Antiproton-Proton Interactions

A detailed experimental study of antiproton-proton and antiproton-nucleus interactions is foreseen at the future FAIR facilities (GSI, Darmstadt, Germany) by the PANDA Collaboration [22]. Simulations of antiproton interactions with protons and nuclei are needed for cosmic space experiments like PAMELA, BESS, AMS, CAPRISE, which are going to search for anti-nuclei in cosmic rays. For the simulation of antiproton-proton interactions, the Geant4 FTF model uses the main assumptions of the Quark-Gluon-String Model [23]. The FTF model assumes production and fragmentation of quark-anti-quark and diquark-anti-

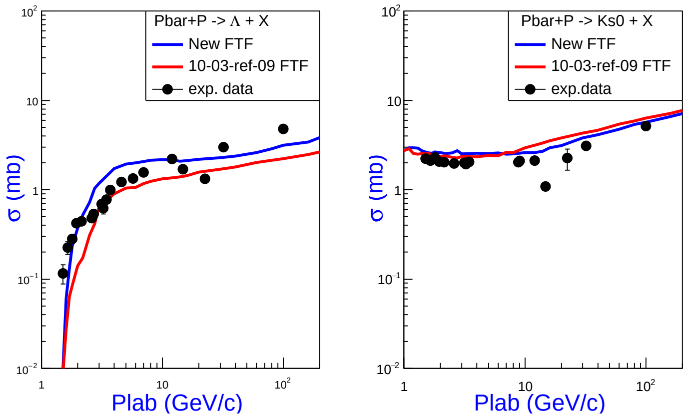

Figure 6. Inclusive cross sections of Λ-hyperon and K_s^0-meson production in antiproton-proton interactions as function of projectile momentum.

diquark strings in the mentioned interactions. Main ingredients of the FTF model are cross sections of string creation processes [24] and the use of the LUND string fragmentation algorithm. They allow to achieve a satisfactory description of a large set of experimental data, in particular, strange particle production, such as Λ hyperons and K mesons [25]. To develop the hypernucleus program of the Panda experiment, it is needed to estimate multiplicity of hyperons and correctly reproduce their kinematical characteristics. Thus, we calculate with the FTF model the average multiplicities of Λ hyperons and K_S^0 mesons in anti-proton-proton interactions presented in Figure 6.

The figure shows experimental data [17] on inclusive cross section of Λ hyperon and K_S^0 meson in antiproton-proton interactions as a function of projectile momentum. As seen, the FTF model describes well K_S^0 meson cross sections at low energies, and overestimates, a little bit, the yield of K_S^0 mesons at momenta more than 10 GeV/c. Calculations by the old version of FTF underestimated the production cross section of Λ hyperons at low momenta, less than 2 GeV/c, and were in agreement with the experimental cross section at higher energies up to 30 GeV/c. The developed FTF model calculations are in agreement with Λ production cross section at low energies up to 3 GeV.

Distributions of the strange particles on kinematical variables are very important for experiments. Distributions of Λ hyperons and K_S^0 mesons on rapidities, Feyman X, and squared transverse mometum in $\bar{p}p$ interactions at momenta of 12, 24 and 100 GeV/c calculated with the FTF model are presented in Figure 7.

As seen, there is a good agreement between the improved FTF model calculations (blue lines) and the experimental data on the inclusive spectra at 12 GeV/c [19] and 22.4 GeV/c [20].

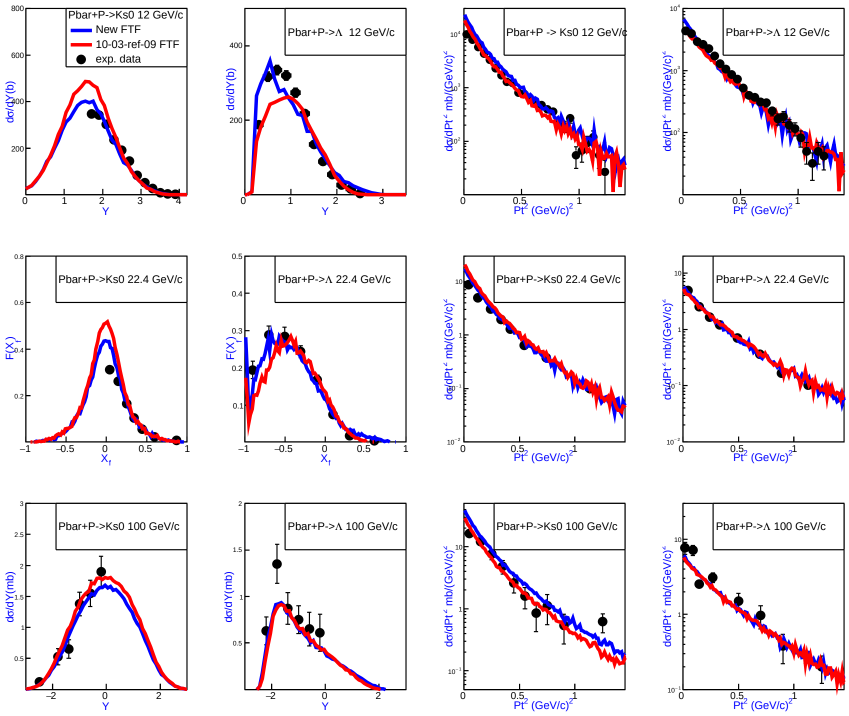

Figure 7. Rapidity, Feyman X, Pt^2 distributions of K_s^0-mesons and Λ-hyperon in $\bar{p}p$ interactions at 12, 22.4, 100 GeV/c.

When we consider antiproton-proton interactions at very high momenta, 100 GeV/c, annihilation processes are absent. Here, only diffraction processes of FTF are working. At this energy, FTF gives a quite good description of K_S^0 and Λ rapidity and P_T^2 spectra.

Let us consider now binary reactions with strange particle production in antiproton-proton annihilations.

There are a lot of experimental data on differential cross sections of Λ-$\bar{\Lambda}$ production in antiproton-proton interactions. We have gathered most of them, performed corresponding simulations by the FTF model and compared with the experimental data. For example, in Figure 8 we present differential cross sections of Λ-$\bar{\Lambda}$ at various initial momenta: 1.56, 1.76, 1.88 and 2.06 GeV/c.

To describe the data [15], we introduced in the FTF model the spatial rotation of quark-gluon strings. The FTF model without rotating strings does not describe the experimental data [15]. The FTF model results with the rotating strings are in agreement with the experimental distributions.

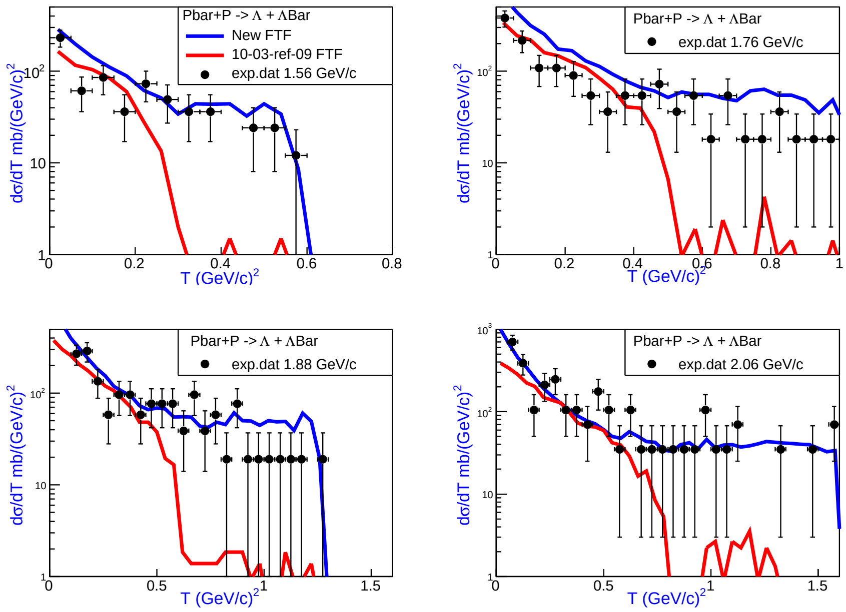

Figure 8. Differential cross section of Λ-hyperon production as function of transferred momentum in $\bar{p}p$ interactions at various energies.

5 Conclusion

A new formula for the probability of strange $q\bar{q}$ pair production at string decay is proposed and implemented in the FTF model of Geant4. The new probability improves considerably the description of the strange particle production in the FTF model.

A new formula for the probability of diquark-antidiquark pair production at string decay is proposed and implemented in the FTF model. The new probability helps to improve the description of antiproton and Λ hyperon production in the FTF model.

Good agreement between the improved FTF model calculations and the NA61/SHINE experimental data is reached on $K^{\pm}$, K^0_S, and Λ production in proton-proton, proton-Carbon and π^--meson-Carbon collisions in a wide energy range.

Kinematical properties of Λ hyperons and K^0_S mesons produced in $\bar{p}p$ reactions are calculated in the improved FTF model with the rotating strings, and compared with the experimental data at various initial momenta. Good description of the experimental data is obtained in the FTF model with the new probabilities.

The differential cross sections of the processes $\bar{p}p \to \Lambda\bar{\Lambda}$ are calculated in various versions of the FTF model. Reasonable description of the experimental data is reached in the FTF model with the rotating strings and the new probabilities.

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