Inclusive particle production in the geometrical two-chain model of soft hadronic interactions

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The geometrical two-chain model was established to describe the soft, low-energy hadronic interaction. The main aim of the model was the applicability of creating a fast and accurate Monte Carlo interaction generator of such processes in complex and time-consuming simulation calculations as, e.g., that of the simulations of the hadron passage through the thick media. In this paper we present the model predictions concerning the inclusive particle production characteristics. A comparison with the FRITIOF model frequently used for high-energy event generation and experimental results is given.

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I. INTRODUCTION

Multiparticle production processes at low energies (below $\sqrt{s} \sim 100$ GeV) are dominated by soft hadronic interactions. They can be described only in a phenomenological way based partially on some theoretical model predictions. The basic description of the geometrical two-chain (G2C) model is given in Ref. [1]. In that paper the main results concerning multiplicity characteristics are discussed and it was concluded that the mean multiplicities and the multiplicity distributions at low energies are reproduced satisfactory. In the present paper we discuss some energetic characteristics of the inclusive production of stable (under strong interactions) charged and neutral particles, and also for meson and baryon resonances.

The importance of resonance production especially in the forward region, for calculations in the case of extensive air shower development was shown in Ref. [2] for very high particle energies. Our model is aimed at calculations of the cascading of much lower energy particles but the arguments given in that paper are still valid. Resonance production processes have not been studied experimentally with the same intensity as central region particle production, which is partially due to experimental difficulties; however, some data exist and can be used for our model examination. The standard FRITIOF model is also not very accurate for such specific uses [3] and should be modified for better data description (as was done, e.g., in Ref. [3]).

The geometrical two-chain model of particle production in soft hadronic collisions is constructed with minimum assumptions concerning the dynamics of the hadronization process. We try to reach a satisfactory data description using a general picture based on the "statistical" character of particle creation. The particle flavors and their transverse momenta are defined by the somehow random breakup of some intermediate object created during parton scattering. Then the longitudinal momenta are attached to the formed particles again randomly filling the available phase space. That treatment allows us to treat our model as a kind of "minimum" model which can be modified if needed for particular purposes. However, the accuracy achieved in the low energy data description, comparable with that given by the FRITIOF model and in some cases even better, is remarkable. This can lead to the conclusion that in soft processes the "statistics" is more important than is commonly presumed.

II. G2C INTERACTION MODEL DESCRIPTION

The model was described in Ref. [1]. In this model, the interaction can be treated as a compound of two distinct processes which can be parametrized, in general, as dependent on a so-called scaled impact parameter of colliding hadrons [4]. The first is "soft scattering" in which the interacting particles form an intermediate state which consists of two objects called hereafter chains (backward and forward). Each of the chains has a mass which is determined by the available energy and the impact parameter. A simple formula was found in Ref. [1]:

$$M = \frac{\sqrt{s}}{2}\left(\frac{\Omega(b)}{\Omega(0)}\right)^{\lambda}, \qquad (1)$$

where M is the chain mass, $\sqrt{s}$ is the interaction energy in the center of mass system, and Ω is the geometrical opacity of colliding hadrons and does not depend on the particle energies, if it is given as a function of the scaled impact parameter $b \sim r/\sqrt{\sigma_{\rm inel.}}$. The parameter λ is one of the two main model parameters.

The second "hadronization" step consists in the formation of hadrons from each chain leaving the interaction zone, its flavors, and momenta creation. The number of chain breakups in the G2C model is in principle given by the chain mass M and again depends on the impact parameter via some function $h(b)$:

$$n_{q\bar{q}} = h(b)(\alpha + \beta \ln M), \qquad (2)$$

where

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$$h(b) = h_0 \left(\frac{\Omega(b)}{\Omega(0)}\right)^{\chi} . \tag{3}$$

The parameters in the second, energetic, factor in Eq. (2) were found using the e^+e^- annihilation into hadrons data (the impact parameter was assumed to be 0). The parameter χ in Eq. (3) is the second main G2C model parameter and its value is obtained using the low energy hadron-hadron multiplicity distribution data.

The mechanism of particle flavor determination is, in general, based on the LUND fragmentation scheme. Most of the parameters describing the chain break-point flavors are taken from the JETSET release 7.3 [5] used in the FRITIOF 7.02 program. The recent version of JETSET (7.4) [6] (and its parameters which are slightly different) is not introduced either to the FRITIOF or to the G2C calculations presented in that paper. The parameters which have been tuned for our G2C program are the diquark-antidiquark pair production suppression factor (0.1, 0.05), the suppression of spin 1 diquarks compared to spin 0 ones (0.05, 0.03), and the probability that the formed light mesons have spin 1 (0.5, 0.55). (The default values used in JETSET 7.3 and those adopted in our program are given in the first and second set of parentheses, respectively.) The mixing of π^0, η, η', and ρ^0, ω, and ϕ proceeds in the standard way. For barions the SU(6) parameters used are also taken from the JETSET 7.3 code.

In the G2C model in the case of a proton-proton interaction the two quarks of each proton are always confined in a diquark at the faster end of each chain, while in the LUND fragmentation scheme the quarks J and L can be, in principle, separated. To preserve such a behavior we introduced in the G2C model the possibility that the leading diquark can be split. Thus the "leading" baryon does not have to be the most energetic one. The meson created from the L quark of the interacting proton can join the antiquark from the closest chain breakup and liberate the J quark which together with the remaining quark from the chain breakup can form another diquark and then a baryon of the lower rank. The LUND parameters of such a diquark splitting were used in the present calculations. However, one parameter has to be introduced into the G2C model at that point. This is the probability that the fast diquark from the incoming proton is going to be proceeded by the mechanism described above. The value used is 0.5, which is similar to the value of 0.6 proposed for a similar mechanism in Ref. [7].

The most important difference between the standard LUND hadronization model and ours is the suppression of massive particle production. In principle the energy and momentum conservation procedure used in our model is less restrictive than that in the JETSET realization of the LUND scheme, and so some corrections to heavier particle creation mechanisms have to be introduced. This could be done by the changing the hadronization parameters or by the addition of a mechanism to correct the model prediction. After examining both, we choose the second possibility. Modifying somehow the idea of the particle production via tunneling processes we use an additional particle production suppression factor proportional to

$$\exp[-\pi(m - m_l)^2/\kappa]. \tag{4}$$

The mass of the particle which is going to be created by joining the existing quark (or diquark) to a just generated antiquark, or diquark (or quark) is denoted by m, and by m_l we denote the mass of the lightest particle which can be formed using the existing quark (or diquark) as its constituent. The value of m_l is equal to π^0 mass (for u or d fixed quark), K^0 (for s), proton or neutron (for light diquark), Λ (for strange diquark), or Σ (for ss combination). The parameter κ in the denominator of Eq. (4) is the same as that used for transverse momenta creation.

The particle transverse momenta are generated during the chain breakup. At each breakup point the pair q-$\bar{q}$ (qq-$\overline{qq}$) appears and the transverse mass is attached to each released chain end by a mechanism similar to the tunneling used in the LUND fragmentation scheme. The arguments presented in Ref. [7] lead to the transverse momentum distribution determined by the suppression factor:

$$\exp\left(-\pi p_t^2/\kappa\right) \tag{5}$$

where κ is a model-free parameter of the order of the hadron mass describing the "mass density" along the string. In our model the value of κ is different for different flavors generated at the chain ends. This somehow contrads the simple "tunneling" picture, but the changes are not very large and can be treated as a phenomenological improvement of the "pure tunneling" caused by more sophisticated physical reasons. The value of $\sqrt{\pi/\kappa}$ used in the present calculations is equal to 0.28 GeV/c for the light quark created, 0.36 GeV/c for the strange one, and 0.5 GeV/c for the diquark. That change is not very critical for using Eq. (4); the main reason for its introduction was to reproduce with high accuracy the values of the mean transverse momenta of different particle species, which is very important for energy and momentum balance. For the same general reason another slight change in the "pure tunneling" picture was made. The situation observed in a real hadronic interaction is a bit more complicated when we try to describe the high p_t distribution tail. In the LUND model there are some additional processes such as, e.g., gluon bremsstrahlung and hard scattering, which, by definition, are not introduced in the G2C, soft, interaction picture. The distribution of transverse momenta given by Eq. (5) can (with some reasonable value of the κ parameter) reproduce the data below ~ 1 GeV/c, but for larger values it underestimates transverse momenta production. Because the detail of high p_t distributions strongly interfere with particle longitudinal momentum distributions, it is required to modify the p_t distribution to be closer to reality. This can be done simply by a kind of randomization of the transverse momentum generation process. The assumption that the value of κ has a non-Δ distribution makes the transverse momentum distribution wider. We found that if we use for each tenth time a value of κ twice as large as the p_t distribution tail measured by NA27 the experiment will be reproduced satisfactory up to ~ 3 GeV/c.

Transverse momentum conservation is achieved in our model by its conservation at each breakup point. Both ends of the just broken chain obtain the same value of the transverse momentum in opposite directions. The final hadron p_t is a sum of p_t's of its constituents.

Additionally we add to the forward-going fragment of the interacting hadron an extra p_t according to the Gaussian distribution with a width 0.4 GeV/c, just as in the LUND scheme.

Longitudinal momenta creation in the G2C model is performed, as has been said, with minimum additional dynamic assumptions being made; i.e., they are determined only by the available phase space and conservation laws. The particles are first uniformly placed in the rapidity range given by the chain center of mass energy. Then their pregenerated rapidity values are moved to the final ones by the linear transformation $y' \to ay + b$ with the two parameters a and b determined by the energy and longitudinal momentum conservation requirements [8]. The difference in the leading particle treatment is achieved by a consecutive placement of the particles during the prerapidity generation; thus, the "leading" particle always has the highest rapidity value.

The interaction picture for a meson-induced reaction is essentially the same as described above for the case of proton-proton collisions. The only change is in the number of breakups of the meson-formed chain. The π-p opacity function in Eq. (3) is weighted by the fraction of valence quarks participating in the scattering phase of the interaction. Thus the mean number of breakups of the meson chain is $(3/2)^{\lambda}$ times higher than that of the baryon-formed chain.

III. G2C MODEL CALCULATION RESULTS

A. Total inclusive cross sections

The reproduction of π, K, proton, and antiproton mean multiplicities is the first test for each interaction model. In the G2C model they are determined at first by the suppression factors used to obtain the relative probabilities for creating a given flavor during the chain breakups and second by the energy available for particle creation. In the model there is always the possibility that the chain mass will be too small to generate a large number of heavy particles. This way the ratio of, say, K to π is decreased. That mechanism is amplified when we note that the transverse mass difference is even larger. For the interaction energies increasing that effect becomes smaller. It is responsible for the low energy behavior of K's and other heavy particle multiplicities. Figure 1 shows that it is enough to predict correctly the experimental data.

In the case of a proton-proton interaction the observed protons come mainly from the energetic chain ends, and their creation is determined by simple quark counting. The accuracy of the so-called "charge exchange" process description can be seen in Table I. Half of the difference of the number of incoming protons and the outgoing

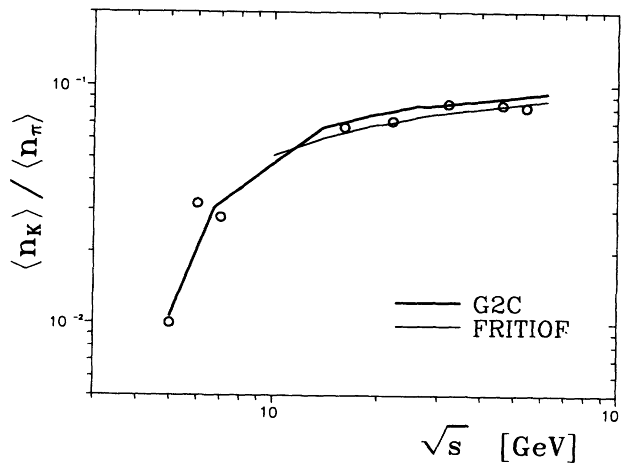

FIG. 1. The K^- to π^- mean multiplicity ratio as a function of the interaction energy.

ones (decreased by the number of protons created inside the chain which should be equal to the number of produced antiprotons) gives the probability that the interacting protons lose their charge leaving the interaction as a neutron. The value calculated from the numbers given in the Table I at the incoming proton laboratory momentum of 400 GeV/c is 0.38 for the G2C model (0.36 for the FRITIOF model) while the experimental valve measured is about 0.43. Processes such as that in the case of recharging energetic pions can play an important role in the development of the electromagnetic cascades associated with the energetic hadrons in thick media.

The mean multiplicity of the π^0's is hard to measure, mainly due to the absence of low x_F data and the extrapolations made there. On the other hand the importance of its accurate reproduction is clear, e.g., for the reasons

TABLE I. Mean multiplicities of "stable" particles produced in p-p interactions at laboratory momentum of about 400 GeV/c. Comparison of the predications of the G2C and FRITIOF 7.02 models and the NA27 measurement data from Ref. [3].

Particle	G2C	FRITIOF	Experiment
π^0	4.19	4.35	3.87±0.12
			4.43±0.10[a]
			4.0±0.4[b]
π^+	3.92	4.17	4.11±0.11
π^-	3.23	3.54	3.34±0.08
K_s^0	0.28	0.30	0.20±0.02[b]
			0.23±0.01[c]
			0.26±0.01[d]
K^+	0.34	0.37	0.33±0.02
K^-	0.27	0.27	0.22±0.01
p	1.29	1.42	1.20±0.10
$\bar{p}$	0.047	0.147	0.060±0.002

[a] p_{lab} = 400 Gev/c [11].
[b] 360 GeV/c [12].
[c] 405 GeV/c [13].
[d] 360 GeV/c [14].

just mentioned. Because of the π^0 mixing with other neutral mesons, its multiplicity depends on the mass suppression introduced into the G2C model by Eq. (4). The production of η's in the G2C model is still overestimated, but that overproduction is significantly smaller than that predicted by the FRITIOF model. For η' production the NA27 experiment gives only the upper limit, but we can see that the G2C prediction does not contradict it.

Resonance creation is strongly effected by the G2C heavy particle suppression given by Eq. (4). The calculated multiplicities are given in Table II in comparison with the FRITIOF model prediction and the experimental data.

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Concerning the baryonic resonances we see there that the most abundant Δ cross sections are in agreement with the data for both models. For the strange particles and other resonances a general tendency is seen: The G2C model slightly underestimates while the FRITIOF model overestimates the production cross sections. Probably a better agreement may be obtained by tuning a JETSET parameter if needed.

The ρ meson production in G2C is controlled again by Eq. (4). This allows us to suppress the FRITIOF model ρ production to an acceptable level. This suppression could be a little too strong, which is seen for the charged ρ's, but we want to obtain a correct value of neutral ρ's which corresponds straightforwardly to the final neutral π production. The discrepancy seen for the relative ratios of the neutrals ρ^0, ω, and ϕ seen in G2C and FRITIOF predictions probably cannot be removed easily.

TABLE II. Mean multiplicities of some resonances produced in p-p interactions at laboratory momentum of about 400 GeV/c. Comparison of the predications of the G2C and FRITIOF 7.02 models and the NA27 measurement data from Ref. [3].

Particle	G2C	FRITIOF	Experiment
η	0.48	0.56	0.30±0.02
η'	0.11	0.29	<0.24
ρ^0	0.47	0.72	0.48±0.02
ρ^+	0.47	0.72	0.69±0.10
ρ^-	0.34	0.53	0.44±0.07
ω	0.37	0.62	0.49±0.03
ϕ	0.008	0.036	0.020±0.003
K^{*+}	0.10	0.20	0.17±0.02
			0.13±0.03[a]
K^{*-}	0.07	0.13	0.11±0.02
			0.11±0.06[a]
K^{*0}	0.07	0.16	0.15±0.03
$\overline{K}^{*0}$	0.06	0.13	0.11±0.02
Δ^{++}	0.29	0.28	0.27±0.04
Δ^0	0.14	0.15	0.18±0.01
Λ	0.094	0.18	0.12±0.01[b]
			0.125 ± 0.008[a]
			0.12 ± 0.02[c]
$\overline{\Lambda}$	0.007	0.039	0.013±0.003[b]
			0.020±0.004[a]
			0.013±0.004[c]

[a]405 GeV/c [13].
[b]p_{lab} = 400 Gev/c [11].
[c]360 GeV/c [14].

B. Inclusive momenta distributions

The mean transverse momenta of created particles calculated in the G2C model depends on the interaction energy due to the energy conservation procedure. The mechanism of such a dependence is the same as that discussed above for the suppression of heavy particle production at low energies. Figure 2 shows that there is no need to introduce any extra mechanism available for the transverse momenta reduction as the interaction energy decreases. The set of constant parameters κ with the energy conservation requirement leads to a very good data description by the G2C model. In the energy range of applicability of the FRITIOF model ($\sqrt{s} \geq 10$ GeV) both models give similar results. The shapes of the transverse momentum distributions for charged π's, protons, and antiprotons are given in Figs. 3(a) and 3(b). The same for neutral pions and η's is given in the Fig. 3(c). The data points are from the NA27 experiment [3]. The accuracy of the G2C model predictions is satisfactory and comparable with that obtained by much more sophisticated, especially at that point, FRITIOF program.

The generation of particle longitudinal momenta is performed via particle rapidity generation, as was described above. How the "kinematical" procedure of the rapidity generation works is presented in Figs. 4 and 5 where the distributions for different particle species are presented in comparison with the NA27 data and with the FRITIOF model predictions. The shape of the tail of the rapidity distribution is the result of the conservation procedure

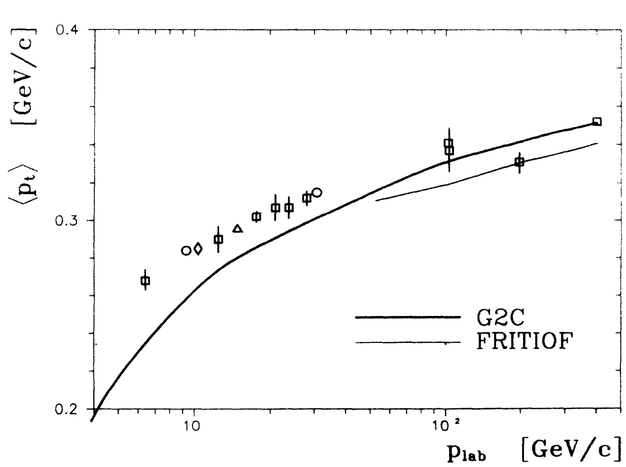

FIG. 2. The mean transverse momentum of π^- as a function of the interaction energy.

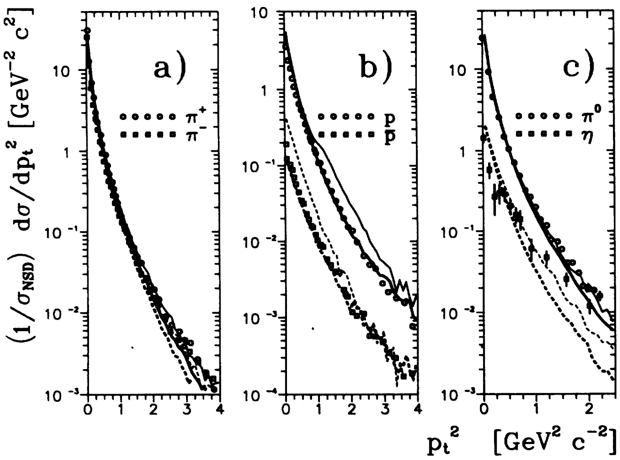

FIG. 3. The transverse momentum distribution of (a) charged π's, (b) protons, and antiprotons and (c) π^0's and η's produced in p-p interactions at the laboratory momentum of 400 GeV/c calculated for the G2C (thick) and FRITIOF (thin line) models in comparison with the NA27 data.

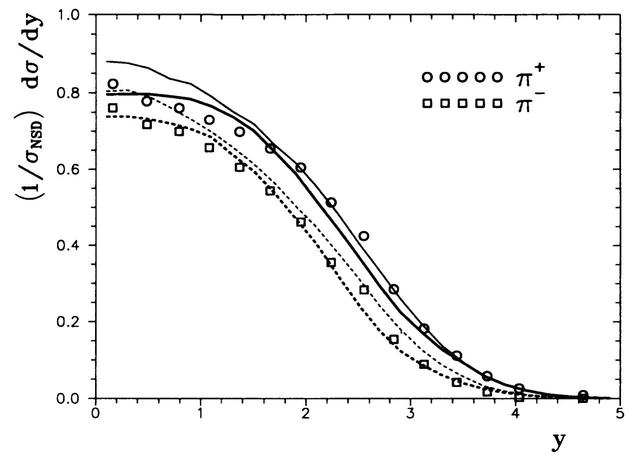

FIG. 5. The same rapidity distribution of charged π's as given in Fig. 4(a) in a linear scale to see better the central plateau region.

used, while the widths and the plateau heights can be controlled by the G2C model parameters in Eqs. (1)–(3). For the particle produced inside the chains the agreement achieved is very good. Some discrepancies are seen for the protons which are mainly produced at the faster ends of the chains. These processes are certainly strongly affected by energy conservation and thus they depend very much on the transverse momentum given to the leading particle. The problem is unclear and needs more careful treatment in further model investigations.

A correct description of the particle longitudinal momenta distributions needs the right transverse momenta and rapidity distributions but also the proper correlation between p_t and y. In our model the only correlation is that introduced by the used energy and momentum conservation procedure, and so the obtained p_l (or $x_F = p_l/p_{\max}$) has a "kinematical" progenitor. The x_F distribution of charged π's and protons is presented in Fig. 6. The small discrepancy seen for the G2C model in a very forward region is connected again with the leading particle treatment discussed above.

The test of the model reproduction of the correlation between the transverse and longitudinal momenta of created particles is presented in Fig. 7. The data are taken from Ref. [9] at the laboratory momentum of 360 GeV/c pp interaction. The agreement for the charged π's is very good.

We have shown in Ref. [1] that the multiplicity characteristics of the meson-induced interactions can be described by the weighing the opacity function. In Fig. 8

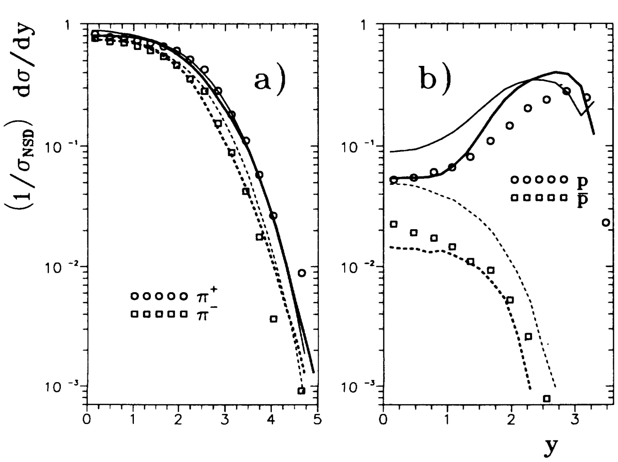

FIG. 4. The rapidity distribution of (a) charged π's, (b) protons and antiprotons produced in p-p interactions at the laboratory momentum of 400 GeV/c calculated for the G2C (thick) and FRITIOF (thin line) models in comparison with the NA27 data.

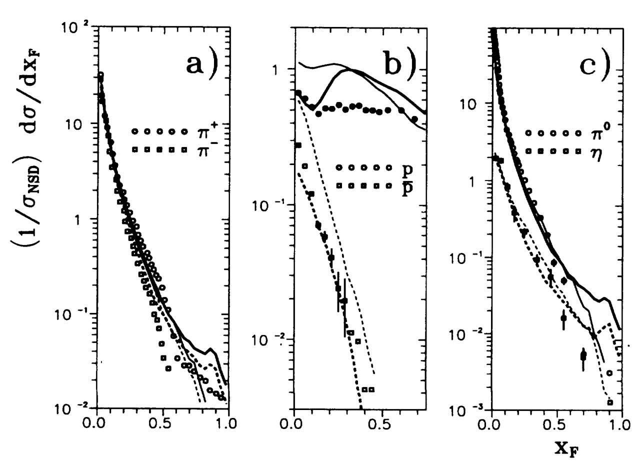

FIG. 6. The x_F distribution of (a) charged π's, (b) protons and antiprotons, and (c) π^0's and η's produced in p-p interactions at the laboratory momentum of 400 GeV/c calculated for the G2C (thick) and FRITIOF (thin line) models in comparison with NA27 data.

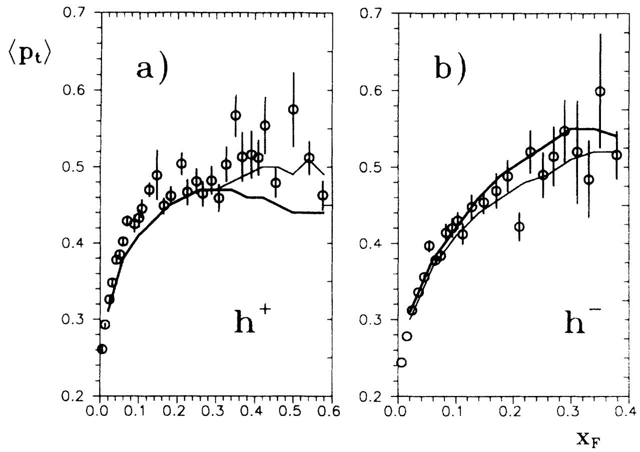

FIG. 7. The mean transverse momentum as a function of the x_F of (a) π^+ and (b) π^- produced in p-p interactions at the laboratory momentum of 360 GeV/c calculated for the G2C (thick) and FRITIOF (thin line) models in comparison with the data.

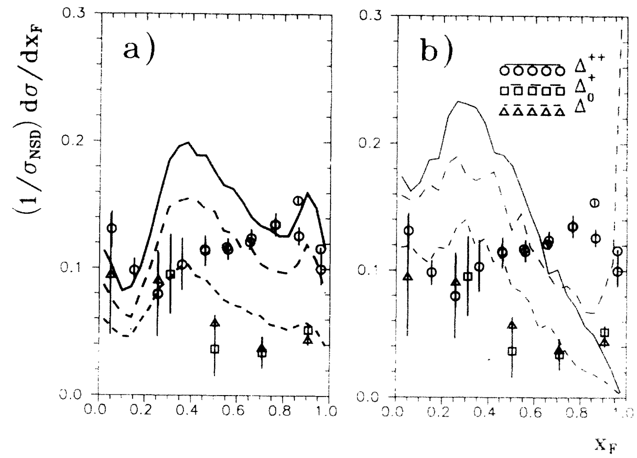

FIG. 9. The x_F distribution of Δ resonances measured in p-p interactions at laboratory momentum of 400 GeV/c compared with the predictions of (a) the G2C model and (b) the FRITIOF model.

the rapidity and x_F distributions for the π^+ interaction with protons at the laboratory momentum of 250 GeV/c are shown. The data are from the EHS-NA22 measurement [10]. The accuracy of the G2C model predictions is comparable with that discussed previously for a proton-proton interaction.

The creation of Δ resonances and especially their energetic characteristics is an important point in the study of energy transmission between the hadronic and electromagnetic components in the development of particle cascades in the thick media. It has been shown in Ref. [3] that the description of x_F (and other) Δ's distribution by the standard FRITIOF code (2.0 version with some improvements) is not quite correct. Our calculation with the FRITIOF 7.02 code confirmed such a conclusion. Although the total production cross sections are acceptable or even better, the inclusive characteristics are incorrect. The situation is presented in Fig. 9. The high peak seen in Fig. 9(b) for the Δ^+ near the x_F equal 1 is simply not seen in the experiment, but the worst is the tendency observed for the Δ^{++} in the high x_F region. The data show clearly a wide peak near 0.8 while the FRITIOF model predictions are just declining down starting from the value of 0.3.

The situation for the G2C model is not very much better. First we have to say that the descending of the Δ^{++} x_F distribution is not so fast, and, what is more important, the high x_F peak appears at about 0.9 and its height is as that of the measured distribution. The maximum near 0.4 is similar to that seen in Fig. 6(b) and can be understood as a result of the improper treatment of the fast chain end during generation of transverse momenta. All that can be a pure coincidence, however. The NA27 experiment showed that the bulk of the Δ^{++}'s comes from interactions with a relatively low multiplicity of charged particles created and a small four-momentum transfer. This suggests that all the discussed interpretation difficulties can be due to a non-negligible contamination of the diffractionlike interactions in the experimental results which is not taken into account in the calculations. Concerning Δ^+ and Δ^0 production the other surprising experimental result of the similarity of their x_F distributions is still not clear; either the G2C or the FRITIOF model predicts about a 50% difference.

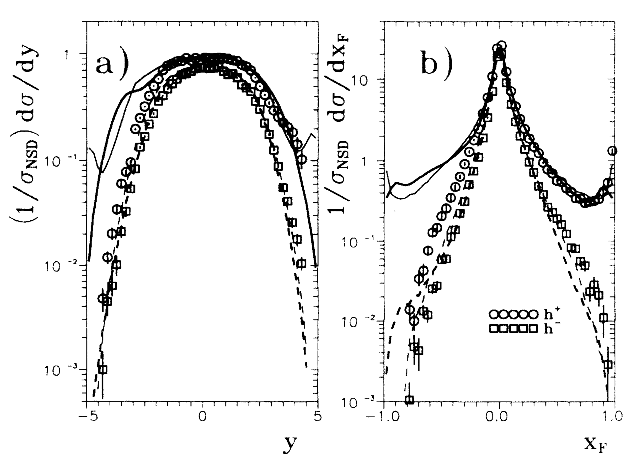

FIG. 8. The rapidity (a) and x_F (b) distributions of positively and negatively charged particles produced in π^+-p interactions at the laboratory momentum of 250 GeV/c compared with the predictions of the G2C and the FRITIOF model. The slow protons are removed from the data.

IV. CONCLUSIONS

The soft event generator based on the geometrical two-chain interaction picture has been created. In this paper we compare its prediction with inclusive particle production data and with the frequently used FRITIOF generator produced events. That comparison can be summarized in the following statements.

The obtained multiplicities of different kinds of particles are correct at a $\sqrt{s}$ of about 30 GeV for particles which are dominant in the hadronic interactions (which mean multiplicity is higher than ~ 0.1).

The suppression of heavy particles (such as, e.g., K's) and the mean p_t of the created particles for very low interaction energy are well reproduced using only the energy and momentum conservation requirement.

Transverse momenta distributions of different kinds of particles are determined with good accuracy by the "randomized tunneling" mechanism.

Rapidity distributions, except the leading particle case, are very accurately reproduced either at the central and at the fragmentation regions.

Longitudinal momenta distributions (again except the leading particles) are, in general, consistent with the data. The discrepancy seen at the very high x_F tail seems to be connected with the leading particles distributions.

The so-called "seagull" effect determined in the G2C model by the energy and momentum conservation mechanism reproduced the data very well.

The simple G2C model extension to the meson-induced interactions proposed in Ref. [1] is confirmed by the satisfactory produced particle momenta generation.

In all of the above statements the comparison with the FRITIOF 7.02 program shows that our model gives results not worse and even, for some purposes, slightly better.

An exact treatment of the transverse energy generation at the fast end of the chains is needed. The creation of Δ resonances is also somehow connected with that, as has been said above. It looks like the solution of the leading particle problem, however important it is, can remove most of the model difficulties. Certainly, to solve that problem accurate data are needed, and also a consistent way of introducing diffractive processes is foreseen.

The G2C model was developed to build a fast and accurate generator of soft hadronic interactions to be used in extensive simulation calculations, i.e., for the particle passage through the thick media. The accuracy of the proton-proton data reproduction achieved so far in Ref. [1] and in this paper is satisfactory. There is one more advantage to our generator in comparison with the discussed FRITIOF 7.02: Our generator is about 100 times faster than that of the FRITIOF program run with the default values of its parameters.

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