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**PREDICTIONS FOR SECONDARY PARTICLE PRODUCTION AT
EXISTING AND FUTURE HADRON-HADRON COLLIDERS**

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Abstract

We consider the predictions of the Quark-Gluon String Model (QGSM) and of the Lund Model algorithm (PYTHIA) for the inclusive spectra and multiplicity distributions of different secondary hadrons produced in pp (or $\bar{p}p$) collisions in the energy interval $\sqrt{s} = 62 \text{ GeV}-200 \text{ TeV}$. Both models describe reasonably well the existing experimental data, however their predictions for the case of very high energies are different. We discuss the possible reasons for these differences.

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1. INTRODUCTION

Soft processes in hadron-hadron collisions at high and superhigh energies are interesting from many points of view. They give information about the dynamics of strong interactions in the non-perturbative region and provide at the same time a realistic background for the search of new physics phenomena. Effective theoretical methods are needed to describe in detail their various characteristics, the goal being the most likely prediction for the bulk of soft inelastic interactions at future supercolliders.

In the present work we consider two theoretical approaches for the description of multihadron production in pp (or $\bar{p}p$) collisions at high energies. One of them is non-perturbative: the Dual Topological Unitarization (DTU) approach which allows to calculate analytically many features of high-energy production processes in terms of longitudinal variables, namely the inclusive spectra of different secondary hadrons, their multiplicities, KNO-distributions, etc., both for hadron-nucleon and hadron-nucleus collisions [1-7], in reasonable agreement with the experimental data. We use here the Quark-Gluon String Model (QGSM) [4-7] which is a particular version of the DTU approach. The high-energy interactions are considered in this model as proceeding via one or several-pomeron exchanges. All elastic and inelastic processes are the results of cuts between different numbers of pomerons and of different numbers of cut pomerons [8]. The inclusive spectra of secondaries are determined by the convolutions of diquark, valence and sea quark momentum distributions inside the incident particles and by the fragmentation functions of quarks and diquarks into secondary hadrons.

Another group of theoretical approaches is based on the Monte Carlo simulation of multiparticle production processes. Here we use the PYTHIA algorithm [9-12] as a typical version of the QCD Lund Model [13] which is very popular nowadays. It allows to calculate all the (in principle) experimentally measurable variables, which is of course the relevant feature of such an approach. Quark-antiquark pair production occurs via colour-string breaking. Single and multipomeron exchanges are accounted for as different numbers of possible semihard interactions (Multiple-Interaction Model) [14], tuned by comparison with the experimental data. However the increase of the effective number of cut pomerons with initial energy, as predicted in QGSM, seems to be absent (or very small) in PYTHIA. This results in some difference in the predictions of these two theoretical approaches at very high energies.

The formalism and input parameters used in both approaches exist in the literature, as well as various comparisons with existing experimental data [4-14]. In the present work we focus on a detailed comparison of the two models, from low (62 GeV) up to superhigh (200 TeV) energies. Let us note that the particle-production processes in pp and $\bar{p}p$ collisions are very similar at high energies in the central region. In the fragmentation region of course a difference arises in the fragmentation of protons with respect to antiprotons. Our results concern pp interactions: these can be used for $\bar{p}p$ collisions in the central region and in the proton fragmentation region. The predictions for the antiproton fragmentation region can be obtained by changing any secondary particle into its antiparticle.

2. INCLUSIVE SPECTRA AND MULTIPLICITY DISTRIBUTIONS AT ENERGIES $\sqrt{s} = 62\text{-}1800$ GeV

Let us first consider the energy region $\sqrt{s} = 62\text{-}1800$ GeV where some experimental data are available.

The comparison of the Feynman- x distributions for π^+ , K^- , and $\bar{p}$ secondaries produced in pp collisions at $\sqrt{s} = 62$ GeV (i.e. at the CERN ISR), as calculated with the QGSM and PYTHIA approaches, is shown in figs. 1a-c. We use the variable x_E/σ_{in} . $d\sigma/dx_F$ (where $x_F = 2p_L/\sqrt{s}$, $x_E = 2E/\sqrt{s}$, E is the energy of the secondary hadron and σ_{in} is the total inelastic pp cross-section, with single and double-diffraction dissociation processes included), since this variable is not affected by any kinematical singularity or zero for $E \simeq x_F \simeq 0$. The packages PYTHIA 5.5 and JETSET 7.3 [9-12] were used in the Monte Carlo simulation, with EHLQ-set1 structure functions [15]. The two models are in good agreement in the small x_F region, showing some small difference only at large x_F values. In figs. 2a-b, the predicted π^- and p x_F -distributions are compared with the experimental data [16, 17], showing indeed a very good overall agreement ¹⁾. In particular the "leading" hadron effect [18, 19], which corresponds to the quantum-number flow from the initial to the final state and is maximum for outgoing protons in pp collisions, is very well reproduced in both QGSM and PYTHIA models.

From the above results in terms of x_F , we expect that the corresponding mean multiplicities and multiplicity distributions should also be similar in QGSM and PYTHIA. In fact we can see from table 1 and fig. 3a that it is really so and both calculated N_{ch} distributions (where N_{ch} is the total number of outgoing charged particles) agree well with respect to each other and to the experimental data [20]. This is also true for the average $\langle N_{ch} \rangle$ values reported in table 1. The K^- and p multiplicity distributions are shown figs. 3b and 3c, respectively. The agreement between QGSM and PYTHIA is better in the K^- case than in the p one, namely PYTHIA predicts a smaller proton multiplicity. The $\pi^\pm$ multiplicity distributions are not shown since these essentially coincide with the N_{ch} distributions given in fig. 3a where the agreement is good, as already pointed out.

The same kind of study has been repeated at higher energies. At $\sqrt{s} = 630$ GeV, corresponding to the energy range of the CERN $Spp\bar{p}S$, the pseudorapidity distributions of charged secondaries produced in pp collisions according to QGSM and PYTHIA are shown in fig. 4a, together with the corresponding experimental results [21]. The agreement is still fairly good, at the level of 20% accuracy. However the N_{ch} distributions of QGSM and PYTHIA in fig. 4b show some significant differences. At small N_{ch} (i.e. $N_{ch} \leq 20$), PYTHIA predicts a bump which is likely related to a more noteworthy contribution of single and double-diffraction dissociation processes. On the other hand, QGSM predicts higher probabilities for processes with $N_{ch} \gg \langle N_{ch} \rangle$, which can be attributed to the enhancement of multipomeron contributions in this model. These different behaviours correspond in fact to different $\langle N_{ch} \rangle$ values, as reported in table

1) The experimental data shown in figs. 2a-b are fits to the original distributions measured at the ISR [17], as derived in [16].

1. The PYTHIA prediction for $\langle N_{ch} \rangle$ at $\sqrt{s} = 630$ GeV is 30% smaller than the QGSM one. The comparison with the experimental N_{ch} distribution [22] is shown in fig. 4c. Here the energy has been slightly lowered ($\sqrt{s} = 540$ GeV) in order to fulfil the experimental conditions. The x_F -distributions for secondary π^- , K^- and proton production, as obtained with QGSM and PYTHIA at $\sqrt{s} = 630$ GeV, are shown in figs. 5a-c.

Moving now to Tevatron energies, i.e. $\sqrt{s} = 1800$ GeV, in fig. 6 we again compare the predictions of the two models with the experimental data [18] in terms of pseudorapidity. Here too the overall discrepancy does not exceed 20%. The predicted x_F -distributions for pions, kaons and protons, corresponding to the two models, are superimposed in figs. 7a-c. The QGSM approach shows a faster decrease of the π^- spectrum as x_F increases, which is again due to the effect of multipomeron processes where softer secondaries are produced. As far as the central region is concerned, figs. 8a-c show a blow-up of the same distributions for $|x_F| \leq 0.05$. At $x_F \simeq 0$, the difference between PYTHIA and QGSM spectra exceeds the 20% level for K^- and p only. The reason for this effect is not related to different particle production mechanisms, but to different input parameters in the two models: the probabilities of $s\bar{s}$ and diquark-antidiquark pair production in QGSM are higher than in PYTHIA. These translate into higher multiplicities of kaons and nucleons. The same differences appear in the π^- , K^- and p rapidity-distributions shown in figs. 9a-c. For the sake of completeness, the corresponding p_T distributions, which can only be derived using the PYTHIA Monte Carlo, are given in figs. 10a-c: the average p_T values are 0.38, 0.48 and 0.49 GeV/c for π^- , K^- and p , respectively.

3. INCLUSIVE SPECTRA AND MULTIPLICITY DISTRIBUTIONS AT ENERGIES $\sqrt{s} = 16$ -200 TeV

Next we consider the predictions in the superhigh energy region, where in principle only some information from cosmic-ray physics is available. We restrict ourselves to three energies ($\sqrt{s} = 16, 40$ and 200 TeV) which correspond to the existing projects of new colliders (LHC, SSC and ELOISATRON).

In figs. 11a-c the Feynman- x distributions of π^+ , K^- and p secondaries are presented at $\sqrt{s} = 16$ TeV. The differences in the predictions of the two models in terms of absolute yields increase with respect to lower energies. For instance for K^- mesons (fig. 11b), this difference is about a factor of 2. However the shapes of the QGSM and PYTHIA x_F -distributions are rather close. The same holds true for the corresponding rapidity distributions of secondary π^+ , K^- and p , presented in figs. 12a-c. In fig. 13a we compare the predictions for the multiplicity distribution of all charged particles. We can observe a significant difference in shape. In the QGSM approach, there is a relatively small contribution from diffraction dissociation and then a wide maximum with a long tail which corresponds to the superposition of contributions from different numbers of pomerons. PYTHIA predicts in turn a large contribution of diffraction dissociation and a relatively narrow peak from nondiffractive multiple interaction processes. The K^- and $\bar{p}$ multiplicity distributions are shown in figs. 13b-c. Here again QGSM clearly predicts

higher probabilities for large multiplicities, as compared to PYTHIA predictions. The difference in the predicted $\langle N_{ch} \rangle$ values of mean multiplicity becomes about 40% (see table 1).

At $\sqrt{s} = 40$ TeV, the expected π^+ , K^- and p x_F -distributions (figs. 14a-c) and y -distributions (figs. 15a-c) show the same trend. QGSM predicts a softer pion spectrum in comparison to PYTHIA. The shapes of kaon and proton spectra in both models are similar but their absolute yields in PYTHIA are about 2 times smaller than in QGSM. The difference in the N_{ch} distributions at 40 TeV is qualitatively the same than at 16 TeV, although quantitatively larger (see fig. 16 and table 1).

Finally the predictions for the ELOISATRON energy ($\sqrt{s} = 200$ TeV) in terms of Feynman- x distributions of secondary π^- , K^- , p and $\bar{p}$ particles are presented in figs. 17a-d. In figs. 18a-d we show the rapidity distributions of these particles, and in figs. 19a-d their p_T distributions. As before, we can see that QGSM predicts a softer spectrum of secondary pions with respect to PYTHIA. The QGSM x_F -spectrum of antiprotons is also softer than the PYTHIA one, while only some small differences appear in the spectra of kaons and protons. The PYTHIA predictions for the average p_T -values of pions, kaons, protons and antiprotons are 0.49, 0.70, 0.76 and 0.86 GeV/c, respectively. The p_T distributions (figs. 19a-d) at $\sqrt{s} = 200$ TeV are significantly wider than at lower energies (see figs. 10a-c). The difference between QGSM and PYTHIA extrapolations for N_{ch} is further enhanced at this energy, as it appears in fig. 20 and table 1.

The increase of multipomeron contributions with initial energy in QGSM results in particular in a significant violation of KNO-scaling. In fig. 21 we present the calculated values of $F_{KNO} = \langle N_{ch} \rangle \cdot \sigma(N_{ch})/\sigma_{in}$ versus $z = N_{ch} / \langle N_{ch} \rangle$ in the energy interval $\sqrt{s} = 62$ GeV-200 TeV. PYTHIA also predicts KNO-scaling violation, as it appears from the comparison of the N_{ch} distributions of figs. 3a and 20.

4. CONCLUSION

Two theoretical approaches, based on different physical assumptions, predict similar inclusive spectra in terms of Feynman- x , rapidity distributions and multiplicity distributions of secondary hadrons (π , K , p), for energies up to the unprecedented limit of $\sqrt{s} = 200$ TeV. The overall differences between QGSM and PYTHIA are as a rule contained within a factor of 2 when a particular structure function parametrization (i.e. EHLQ-set1) is adopted in PYTHIA. This allows to be more confident about the possible extrapolations which can be performed using either one or the other approach. However the differences arising between the two models are very interesting for the understanding of the theory and phenomenology of high-energy hadron interactions. In particular, the choice of a different set of structure functions in PYTHIA, whose effect is indeed non-negligible at $\sqrt{s} = 200$ TeV [23], should be carefully investigated in the future via a detailed comparison with new experimental results.

Finally, as far as the "leading" hadron effect is concerned, the key point of the present study is that in pp (or $\bar{p}p$) interactions, the outgoing proton remains "leading" up to $\sqrt{s} = 200$ TeV, as shown in figs. 22a-b for QGSM and PYTHIA, respectively.

In particular, in the QGSM approach (fig. 22a), the $\bar{p}p$ pair yield in the central region increases with $\sqrt{s}$ but the relative cross-section level for protons in the forward region scales, no matter what the initial energy is.

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Table 1

The mean multiplicities $\langle N_{ch} \rangle$ and dispersions $D = \sqrt{\langle N_{ch}^2 \rangle - \langle N_{ch} \rangle^2}$ in PYTHIA and in QGSM.

	PYTHIA		QGSM	
$\sqrt{s}$ (TeV)	$\langle N_{ch} \rangle$	D	$\langle N_{ch} \rangle$	D
0.062	12.5	6.5	12.4	6.4
0.63	24.9	16.5	32.5	19.9
1.8	34.3	24.4	45.8	29.8
16	60.1	45.3	83.1	63.4
40	74.3	57.4	107.	87.
200	124.	70.5	159.	139.

Figure captions

- Fig. 1 : Feynman- x distributions of π^+ (a), K^- (b), and $\bar{p}$ (c) secondaries produced in pp collisions at $\sqrt{s} = 62$ GeV in PYTHIA (black points) and QGSM (open points).
- Fig. 2 : x_F distributions for pions (a) and protons (b) produced in pp collisions at $\sqrt{s} = 62$ GeV in QGSM (open points) and PYTHIA (black points), compared with the experimental data [16, 17] (stars).
- Fig. 3 : Multiplicity distributions of all charged secondaries (a), K^- mesons (b) and protons (c) produced in pp collisions at $\sqrt{s} = 62$ GeV in PYTHIA (black points) and QGSM (open points). The corresponding experimental data [20] (stars) are superimposed in (a).
- Fig. 4 : Pseudorapidity (a) and multiplicity (b, c) distributions of charged secondaries produced in pp collisions at $\sqrt{s} = 630$ GeV (a, b) and $\sqrt{s} = 540$ GeV (c), in PYTHIA (black points) and QGSM (open points). The corresponding experimental data obtained in $p\bar{p}$ collisions at the same energies [21, 22] (stars) are superimposed in (a) and (c).
- Fig. 5 : QGSM (open points) and PYTHIA (black points) predictions for the x_F distributions of π^- (a), K^- (b) and p (c) particles in pp interactions at $\sqrt{s} = 630$ GeV.
- Fig. 6 : Pseudorapidity distributions of charged secondaries produced in pp collisions at $\sqrt{s} = 1800$ GeV in PYTHIA (black points) and QGSM (open points), compared with the experimental data (stars) relative to $p\bar{p}$ collisions at the same energy [21].
- Fig. 7 : Feynman- x distributions of π^- (a), K^- (b) and p (c) particles produced in pp collisions at $\sqrt{s} = 1800$ GeV in PYTHIA (black points) and QGSM (open points).
- Fig. 8 : Same as fig. 7, with the $|x_F| < 0.05$ region magnified.
- Fig. 9 : Rapidity distributions of π^- (a), K^- (b) and p (c) secondaries produced in pp collisions at $\sqrt{s} = 1800$ GeV in PYTHIA (black points) and QGSM (open points).
- Fig. 10 : PYTHIA predictions for the p_T distributions of π^- (a), K^- (b) and p (c) secondaries produced in pp collisions at $\sqrt{s} = 1800$ GeV.
- Fig. 11 : Feynman- x distributions of π^+ (a), K^- (b) and p (c) hadrons produced in pp collisions at $\sqrt{s} = 16$ TeV in PYTHIA (black points) and QGSM (open points).

- Fig. 12 : Rapidity distributions of π^+ (a), K^- (b) and p (c) hadrons produced in pp collisions at $\sqrt{s} = 16$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 13 : Multiplicity distributions for all charged (a), K^- (b) and $\bar{p}$ (c) secondaries produced in pp collisions at $\sqrt{s} = 16$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 14 : Feynman- x distributions of π^+ (a), K^- (b) and p (c) hadrons produced in pp collisions at $\sqrt{s} = 40$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 15 : Rapidity distributions of π^+ (a), K^- (b) and p (c) hadrons produced in pp collisions at $\sqrt{s} = 40$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 16 : Multiplicity distributions of all charged secondaries produced in pp collisions at $\sqrt{s} = 40$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 17 : Feynman- x distributions of π^- (a), K^- (b), p (c) and $\bar{p}$ (d) hadrons produced in pp collisions at $\sqrt{s} = 200$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 18 : Rapidity distributions of π^- (a), K^- (b), p (c) and $\bar{p}$ (d) hadrons produced in pp collisions at $\sqrt{s} = 200$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 19 : PYTHIA predictions for the p_T distributions of π^- (a), K^- (b), p (c) and $\bar{p}$ (d) secondaries produced in pp collisions at $\sqrt{s} = 200$ TeV.
- Fig. 20 : Multiplicity distributions of all charged secondaries produced in pp collisions at $\sqrt{s} = 200$ TeV in PYTHIA (black points) and QGSM (open points).
- Fig. 21 : QGSM prediction for KNO-scaling violation. The curves numbered as 1, 2, 3, 4, 5 and 6 correspond to the energies $\sqrt{s} = 62$ GeV, 630 GeV, 1800 GeV, 16 TeV, 40 TeV and 200 TeV, respectively.
- Fig. 22 : x_F -distributions of outgoing protons in pp collisions at $\sqrt{s} = 62$ GeV, 1.8 TeV and 200 TeV, as indicated, derived with QGSM (a) and PYTHIA (b).

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