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CHARM AND BEAUTY HADROPRODUCTION MODELS: QGSM vs. LUND

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Abstract

Predictions for charm and beauty production in hadron-hadron collisions are presented in the framework of the Quark-Gluon String Model (QGSM) and of the Lund Model (implemented via the PYTHIA algorithm) in terms of total cross-sections and inclusive spectra of charm and beauty mesons and baryons for different parton structure functions and K-factors. The structure of events with and without heavy flavour production is also discussed. The features of the two models are exhaustively investigated and compared with each other and with existing experimental data. Predictions are given at the energies of present and future colliders.

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1. INTRODUCTION

Heavy flavour production processes in hadron-hadron interactions at high energies are usually considered in the framework of QCD, see e.g. [1-4], which allow one to describe quantitatively the cross-sections for c , b and t quark production, their dependence on transverse momentum, rapidity, etc. at the parton level. However this approach does not allow one to calculate the spectra of the various hadrons (mesons and baryons) produced. In addition there are problems related to the parton structure function behaviour at very small x and to the absorptive corrections in the region where the gluon density is very high [3-7]. Moreover the different structure of events with and without heavy flavours cannot be configured.

One possibility to obtain more detailed predictions is to use some Monte Carlo technique. Well-known is the PYTHIA event generator which is based on the physical ideas of the Lund Model [8] and allows one to calculate all the details of soft as well as hard hadron collisions in reasonable agreement [9] with the experimental data. Heavy flavour production is calculated in PYTHIA via leading-order (LO) perturbative QCD formulae and then the process of soft quark-antiquark pair production occurs via colour-string breaking. In the present paper we consider the predictions of PYTHIA 5.6 (for event generation) and of JETSET 7.3 (for fragmentation and decay) applied to charm and beauty hadroproduction at high energies for different nucleon structure functions. Different forms of K-factors which effectively account for the non-leading-order (NLO) α_s contributions are also used.

Another possibility is the Quark-Gluon String Model (QGSM) which is a version of the Dual Topological Unitarization (DTU) approach and describes many features of high energy production processes such as the inclusive spectra of different secondary hadrons, their multiplicities, KNO-distributions, etc. both for hadron-nucleon and hadron-nucleus collisions [10-13]. The high energy interactions are considered in this case as proceeding via one or several pomeron exchanges and all elastic and inelastic processes are the results of different numbers of cut pomerons or of cuts between different numbers of pomerons [14]. The possibility of exchange of different numbers of pomerons results in absorptive corrections for the inclusive cross-sections which, for light quark production, are in agreement with experimental data. Inclusive spectra of heavy-flavoured hadrons in QGSM were considered earlier in [15, 16].

The results of both approaches are compared here with existing experimental data on heavy flavour production in hadron-hadron interactions, in terms of:

- total cross-sections;
- transverse and longitudinal production distributions of different heavy flavoured states;
- structure of events (i.e. average multiplicity and multiplicity distribution) with and without heavy flavours.

The differences in the results obtained with different structure functions (and K-factors) are carefully investigated. Finally detailed predictions for charm and beauty production at existing and future supercolliders are presented, starting from $S\bar{p}\bar{p}S$ ($\sqrt{s} = 630$ GeV) up to SSC ($\sqrt{s} = 40$ TeV) and ELOISATRON ($\sqrt{s} = 200$ TeV).

2. STRUCTURE FUNCTIONS AND K-FACTORS IN PYTHIA

We consider 10 different nucleon structure functions which are presented in table 1, namely 2 sets of EHLQ [17], 2 sets of DO [18], 4 sets of MT [19] and 2 sets of GRV [20] parametrizations. The most important difference between them is the different behaviour of the gluon distributions (giving the main contribution to heavy flavour production cross-sections at high energies [21]) at small x values. The first four relatively "old" sets assume $xG(x, Q^2) = \text{const.}$ at $x \rightarrow 0$ (with $Q^2 \approx Q_0^2$) and the last six "modern" sets assume a power increase of $xG(x, Q^2)$ with decreasing x , which is of course dumped at very small x by shadow corrections [5, 22].

It is well known (see e.g. [1, 2, 21]) that the LO contribution (leading-order $\sim \alpha_s^2$) is not enough to derive heavy quark production cross-sections in hadron-hadron collisions with sufficient accuracy. The NLO contribution (next-to-leading-order $\sim \alpha_s^3$) increases the cross-sections by $1.5 \div 3$ times depending on the structure functions, their normalization point, the masses of produced quarks and the initial energy. In PYTHIA only the LO contribution is calculated and then multiplied by a K-factor to approximately account for the NLO contribution. There are 3 variants of K-factor implementation in PYTHIA: using the same K-factor for all diagrams (K1), using different K-factors for diagrams with and without colour annihilation (K2) or introducing the K-factor as a shift of the Q^2 argument of α_s expression (K3), in accordance with [23].

Detailed low-energy data on charm production in pp collisions were obtained at $\sqrt{s} = 27$ GeV [24] in terms of total cross-section, x_F (Feynman- x) and p_T -distributions of D -mesons. So we will start from this energy. Let us first illustrate the difference between K1, K2 and K3. In fig. 1 we present their values vs. x_F and p_T^2 , as obtained in PYTHIA for D -mesons using EHLQ1 and MT2 structure functions. K1 and K2 are in the range $1.5 \div 2$ and practically independent of x_F and p_T^2 . Their values are in reasonable agreement with analytical calculations [1, 2, 21]. Other structure functions give the similar results. On the other hand the values of K3 are significantly higher and of course disagree with the analytical results.

The experimental x_F -distribution of D -mesons [24] produced in the $x_F > 0$ hemisphere and the corresponding p_T^2 -distribution (normalized to the whole x_F -range) are compared with PYTHIA results in figs. 2-6, for different sets of structure functions. We can see once more that the variant K3 is in strong disagreement with the data. The reason is that the value of K3 is actually obtained in PYTHIA by multiplying the argument Q^2 of α_s by the factor 0.075. The values of Q^2 are taken usually to be equal or close to the squared mass (or transverse mass) of the heavy quark. In the case of the c -quark with relatively small mass (about 1.5 GeV), the value $0.075 \cdot Q^2$ is close to the value of Λ_{QCD} and the value of α_s becomes significantly larger than unity. Therefore this K3 factor becomes unusable for charm production¹⁾.

1) In the case of beauty production, similar calculations with PYTHIA for B -mesons in pp interactions at $\sqrt{s} = 630$ GeV, show that there is no large difference between K1, K2 and K3, whose values are all contained in the interval $1.5 \div 2$, in agreement with analytical calculations [1, 2, 21].

As a rule, the variant K2 gives a little better agreement with the data in figs. 2-6 and this is the variant we will adopt in the following. We will use "old" and "modern" sets of parton distributions in order to study their influence on heavy flavour yields.

3. QGSM FORMALISM

As previously mentioned, the high energy hadron-nucleon as well as hadron-nucleus interactions are considered in QGSM as proceeding via the exchange of one or several pomerons. Each pomeron corresponds to a cylindrical diagram so in the case of a pomeron cut two showers of secondaries are produced (see fig. 7). The inclusive spectra of secondaries are determined by the convolutions of diquark, valence and sea quark distributions $u(x, n)$ in incident particles and fragmentation functions of quarks and diquarks to secondary hadrons $G(z)$. The diquark and quark distribution functions depend on the number n of cut pomerons in the considered diagrams. For nucleon targets, the inclusive spectrum of a secondary hadron h has the form [10]:

$$1/\sigma_{inel} \cdot d\sigma/dx = \sum_{n=1}^{\infty} w_n \phi_n^h(x) + V_D^{(1)} \phi_D^{(1)}(x) + V_D^{(2)} \phi_D^{(2)}(x) \quad (1)$$

where the functions $\phi_n^h(x)$ determine the contributions of diagrams with n cut pomerons and the factors w_n are the probabilities of these processes. The last two terms in eq. (1) account for the contributions of diffraction-dissociation processes and they are negligibly small for charmed and beautiful hadron production.

In the case of pp collisions:

$$\phi_n^h(x) = f_{qq}^h(x_+, n) f_q^h(x_-, n) + f_q^h(x_+, n) f_{qq}^h(x_-, n) + 2(n-1) f_s^h(x_+, n) f_s^h(x_-, n), \quad (2)$$

with

$$x_{\pm} = \frac{1}{2} [\sqrt{4m_T^2/s + x^2} \pm x]. \quad (3)$$

The functions f_{qq} , f_q and f_s correspond to the contributions of diquarks, valence and sea quarks, respectively. They are determined by the convolutions of diquark and quark distributions with fragmentation functions, e.g.:

$$f_q^h(x_+, n) = \int_{x_+}^1 u_q(x_1, n) G_q^h(x_+/x_1) dx_1. \quad (4)$$

In the case of πp collisions, the diquark contributions in eq. (2) should be changed into the contributions of valence antiquarks. The diquark and quark distributions as well as the fragmentation functions are assumed to be expressed via their asymptotic behaviour (at $x \sim 0$ and $x \sim 1$), with conservation laws duly taken into account [10, 12].

In the present calculations we use the quark and diquark distributions of the proton in the form [10]:

$$u_{uu}(x, n) = C_{uu} x^{2.5} (1-x)^{n-1.5}, \quad (5)$$

$$u_{ud}(x, n) = C_{ud} x^{1.5} (1-x)^{n-1.5}, \quad (6)$$

$$u_u(x, n) = C_u x^{-0.5} (1-x)^{n+0.5}, \quad (7)$$

$$u_d(x, n) = C_d x^{-0.5} (1 - x)^{n+1.5}, \quad (8)$$

$$u_{\bar{u}}(x, n) = u_{\bar{d}}(x, n) = C_{\bar{u}} x^{-0.5} [(1 + \delta/2)(1 - x)^{n+0.5}(1 - x/3) - \delta/2(1 - x)^{n+1}], \quad n > 1, \quad (9)$$

$$u_s(x, n) = C_s x^{-0.5} (1 - x)^{n+1}, \quad n > 1, \quad (10)$$

and in the case of a π^- meson beam:

$$u_d(x, n) = u_{\bar{u}}(x, n) = C_d x^{-0.5} (1 - x)^{n-1.5}, \quad (11)$$

$$u_u(x, n) = u_{\bar{d}}(x, n) = C_u x^{-0.5} (1 - x)^{n-1.5} (1 - \delta\sqrt{1-x}), \quad n > 1, \quad (12)$$

$$u_s(x, n) = C_s x^{-0.5} (1 - x)^{n-1}, \quad n > 1, \quad (13)$$

where $\delta = 0.2$ is the relative probability to find a strange quark in the sea and the factors C_i are determined from the condition:

$$\int_0^1 u_i(x, n) dx = 1. \quad (14)$$

The functions of quark and diquark fragmentation to charmed mesons and baryons have been slightly modified with respect to [15, 16] so as to obtain a better agreement with the existing experimental data. We use these functions in the form:

$$G_u^{\bar{D}^0} = G_d^{D^-} = a_0(1 - z)^{\lambda - \alpha_\psi(0)}(1 + a_1 z^2), \quad (15)$$

$$G_u^{D^-} = G_u^{D^+} = G_u^{D^0} = G_d^{D^+} = G_d^{D^0} = G_d^{\bar{D}^0} = a_0(1 - z)^{1 + \lambda - \alpha_\psi(0)}, \quad (16)$$

$$G_{uu}^{D^+} = G_{uu}^{D^-} = G_{uu}^{D^0} = G_{ud}^{D^+} = G_{ud}^{D^0} = a_0(1 - z)^{3 + \lambda - \alpha_\psi(0)}, \quad (17)$$

$$G_{uu}^{\bar{D}^0} = a_0(1 - z)^{2 + \lambda - \alpha_\psi(0)}(1 + a_2 z^2), \quad (18)$$

$$G_{ud}^{\bar{D}^0} = a_0(1 - z)^{2 + \lambda - \alpha_\psi(0)}(1 - z + a_2 z^2/2), \quad (19)$$

$$G_{uu}^{\Lambda_c} = G_{ud}^{\Lambda_c} = a_{01}(1 - z)^{6 + \lambda - \alpha_\psi(0)}, \quad (20)$$

$$G_u^{\Lambda_c} = G_d^{\Lambda_c} = a_{01}(1 - z)^{2 + \lambda - \alpha_\psi(0)}, \quad (21)$$

$$G_u^{\Lambda_c} = G_d^{\Lambda_c} = G_u^{\Lambda_c}(1 - z), \quad (22)$$

with

$$\alpha_\psi(0) = -2, \quad \lambda = 0.5, \quad a_0 = 0.02, \quad a_{01} = 0.016, \quad a_1 = 20, \quad a_2 = 100. \quad (23)$$

As far as Λ_c production is concerned, there are two different contributions [10]. The first one corresponds to the central production of $\Lambda_c \bar{\Lambda}_c$ pairs and can be described by the formulae presented above. The second contribution is connected with the direct fragmentation of the initial baryon into Λ_c with string junction conservation. To account for this possibility we input into eq. (2) two additional terms, $f_{qq2}(x_+, n)$ and $f_{qq2}(x_-, n)$, which are not multiplied by $f_q(x_-, n)$ and $f_q(x_+, n)$. The functions $f_{qq2}(x_+, n)$ and $f_{qq2}(x_-, n)$ are determined by the corresponding fragmentation functions:

$$G_{uu2}^{\Lambda_c} = a_{02} z^2 (1 - z)^{1 + \lambda - \alpha_\psi(0)}, \quad (24)$$

$$G_{ud2}^{\Lambda_c} = a_{02} z^2 (1 - z)^{\lambda - \alpha_\psi(0)}, \quad (25)$$

with

$$a_{02} = 2. \quad (26)$$

The probabilities of processes with n cut pomerons were calculated from quasi-eikonal approximation [10, 25]:

$$w_n = \sigma_n / \sum_{n=1}^{\infty} \sigma_n, \quad \sigma_n = \frac{\sigma_P}{nz} (1 - e^{-z} \sum_{k=0}^{n-1} \frac{z^k}{k!}), \quad (27)$$

$$z = \frac{2C\gamma}{R^2 + \alpha'\xi} e^{\Delta\xi}, \quad \sigma_P = 8\pi\gamma e^{\Delta\xi}, \quad \xi = \ln(s/1\text{GeV}^2) \quad (28)$$

with parameters:

$$\Delta = 0.139, \quad \alpha' = 0.21\text{GeV}^{-2}, \quad \gamma_{pp} = 1.77\text{GeV}^{-2}, \quad \gamma_{\pi p} = 1.07\text{GeV}^{-2},$$

$$R_{pp}^2 = 3.18\text{GeV}^{-2}, \quad R_{\pi p}^2 = 2.48\text{GeV}^{-2}, \quad C_{pp} = 1.5, \quad C_{\pi p} = 1.65.$$

4. COMPARISON OF QGSM AND LUND MODEL PREDICTIONS WITH EXPERIMENTAL DATA

4.1 Total cross-sections for charm and beauty

In table 2 we present the total cross-sections for charm production measured in pp collisions at $\sqrt{s} = 27$ GeV [24] and $\sqrt{s} = 39$ GeV [26] and for both charm [27] and beauty [28] production in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV, together with the results of our calculations for pp interactions²⁾ using PYTHIA with different structure functions. The "old" sets (EHLQ and DO) agree with the low-energy data and have a rather weak energy dependence. Several "modern" sets produce too small cross-sections at low energies. Of course, the experimental errors are large and we cannot be sure that the K-factors used are appropriate although analytical calculations (see for instance [21]) show that usually K-factors have a weak dependence on the initial energy. Set GRV1 is in disagreement with the data. Sets MT3 and GRV2 also give too small cross-sections at low energies, which suggests that the corresponding gluon structure functions in the intermediate x -region are possibly underestimated. On the other hand, all "modern" sets are known to be in good agreement with the existing Deep Inelastic Scattering (DIS) data. Therefore the data on heavy flavour production in hadron collisions turn out to be useful for an additional test of parton structure functions.

In the case of QGSM the cross-sections for charm and beauty production cannot be calculated independently from the experimental data because the values of the parameters a_0 , a_1 and a_2 in eqs. (15)-(22) are to be determined. In other words, we need some experimental input for normalization. One can see from table 2 that the results of QGSM

2) Our results can be used for $p\bar{p}$ 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.

calculations are a little higher than the experimental ones, and this is connected with the tuning of the above mentioned parameter values. Let us discuss this tuning.

The QGSM and PYTHIA cross-section calculations for different charm hadrons produced in pp (or πp) interactions at different energies are presented in table 3, together with the corresponding experimental data. The QGSM cross-sections for D -meson production are in fair agreement with the data relative to pp at $\sqrt{s} = 27$ GeV [24] and $\sqrt{s} = 39$ GeV [26], and to πp at $\sqrt{s} = 26$ GeV [30]. However when looking at each meson state individually, the QGSM values for $\sigma(D^0)$ and $\sigma(D^+)$ are somehow too large with respect to the pp measurements at $\sqrt{s} = 27$ GeV [24], whereas those for $\sigma(\bar{D}^0)$ and $\sigma(D^-)$ are too small. And QGSM is unable to reproduce the condition $\sigma(D^0/\bar{D}^0) > \sigma(D^+/D^-)$, as measured in πp at $\sqrt{s} = 26$ GeV [30]. The reason for this discrepancy is the choice of large values for the parameters a_1 and a_2 in eqs. (15), (18) and (19), which is connected with our wish to obtain a comparatively large value of $\sigma(\Lambda_c)$ for pp at $\sqrt{s} = 62$ GeV in order to match the ISR results [29]. As a consequence, the calculation of $\sigma(\Lambda_c)$ for pp at $\sqrt{s} = 27$ GeV turns out to be too large with respect to the experimental limits given in [24]. However the QGSM cross-section for Λ_c production in pp interactions as a function of $\sqrt{s}$ (see fig. 8, where the experimental points are taken from [29]) does not seem to be high in comparison with other measurements at different energies.

Turning now to PYTHIA calculations, in the case of D -meson production, again the agreement is fair except for GRV2 parametrization giving too small cross-sections. As far as the Λ_c -baryon is concerned, the results from PYTHIA are consistent with the experimental upper bound of [24] but strongly contradict the data of [29].

4.2 Inclusive x_F -distributions for charmed hadrons

Let us now look at the QGSM predictions for the inclusive x_F -spectra of charmed hadrons. In pp collisions at $\sqrt{s} = 27$ GeV, the experimental data [24] for all D -mesons are shown in fig. 9. The QGSM theoretical curve superimposed is in reasonable agreement with the data. In fig. 10 the x_F -distributions of the different D -mesons are presented separately: some disagreement with the theoretical curves is evident, although not so large, as already pointed out.

The inclusive x_F -spectra of D -mesons produced in π^-p collisions at $\sqrt{s} = 26$ GeV [30] are compared with the present QGSM calculations in fig. 11. The agreement for all D -mesons (fig. 11a), as well as separately for "non-leading", i.e. D^+ and $\bar{D}^0$, (fig. 11b) and "leading", i.e. D^- and D^0 , (fig. 11c) mesons seems to be quite reasonable.

The x_F -spectrum of Λ_c , as measured in pp interactions at $\sqrt{s} = 62$ GeV [29], is presented in fig. 12. The theoretical curve obtained from QGSM has the right shape and lies only slightly below the data points. The PYTHIA model predictions, also shown in fig. 12, are in total disagreement with the data [29]. Moreover the shape of the x_F -spectrum is also completely different.

4.3 Structure of events with charm production

It is assumed in PYTHIA that heavy flavour production occurs only in hard interactions via $q\bar{q} \rightarrow Q\bar{Q}$ or $gg \rightarrow Q\bar{Q}$ processes. The experimental multiplicity distributions of charged secondaries produced in events with and without charm, as measured in pp collisions at $\sqrt{s} = 27$ GeV [31], give a possibility to check this assumption. These are shown in fig. 13: the distributions are similar at large values of N_{ch} but significantly differ at small N_{ch} where, in the case of charm production, the multiplicity distribution is significantly lower.

In fig. 13 we also compare the experimental distributions with PYTHIA predictions. In events without charm, i.e. in standard or "minimum-bias" events (fig. 13a), PYTHIA reasonably agrees with the data except in the region of very high multiplicities where the theoretical distribution decreases significantly faster than the experimental one. This difference is likely connected with the absence of multiparton interactions (which could be analogous to multipomeron exchanges [25]) in PYTHIA at this energy. The dependence on the choice of a particular structure function parametrization is not significant.

Another situation takes place in the case of charm events (fig. 13b). The average multiplicity values are close enough, $\langle N_{ch} \rangle = 11.0 \pm 0.5$ in the experiment and $\langle N_{ch} \rangle = 12.1$ in PYTHIA (practically the same for different structure functions). The dispersions of the experimental and theoretical distributions are also similar: $D_{ch} = 3.9 \pm 0.2$ and 3.3, respectively. However here we have a good agreement of PYTHIA predictions with the data at moderate and high multiplicities and a serious disagreement at small multiplicities. Let us note that at high multiplicities, $N_{ch} \geq \langle N_{ch} \rangle$, the experimental distributions in events with and without charm production are similar whereas the calculated one in the case of charm production decreases more slowly.

The mentioned difference at small multiplicities allows one to obtain an upper limit for the diffraction-dissociation contribution to charm production processes. The total cross-section of events with $N_{ch} = 2$ and 4 in fig. 13b is about 7 mb. So the contribution of single-diffraction dissociation is about 2/3. If we assume that in the case of charm production the difference between PYTHIA results and experimental data at these small N_{ch} values is due to the absence of diffraction-dissociation processes in PYTHIA, we can estimate the upper bound of the contribution from diffraction dissociation to charm production to be of the order of 5%.

5. QGSM AND LUND MODEL PREDICTIONS FOR SUPERCOLLIDER ENERGIES

The PYTHIA predictions for D -meson and Λ_c -baryon production distributions in pp interactions at $\sqrt{s} = 630$ GeV are presented in figs. 14-16 for different sets of structure functions. The x_F -distributions refer to one hemisphere only, while the p_T^2 ones to the full phase-space. The QGSM predictions in terms of x_F are superimposed in fig. 14a. Let us note here that the x_F -spectra of D^+ and D^0 -mesons are the same in QGSM³⁾. In fig. 14a

3) The same holds true for $\bar{B}^0$ and B^- -mesons whose spectra are degenerate.

a significant difference shows up between QGSM and PYTHIA. On the other hand, as shown in figs. 14-16, the shapes of the PYTHIA x_F -distributions for different structure functions (EHLQ1, MT2 and GRV2) are very close and the differences appearing are mainly connected with normalization (i.e. with different total cross-section values for charm production). For the p_T^2 -distributions, the situation is similar. However GRV2 structure functions predict a slightly faster decrease of the cross-section with p_T^2 .

Analogous predictions for B -meson and Λ_b -baryon production are presented in figs. 17-19 for PYTHIA and in fig. 17a for QGSM. Here also there is significant difference between QGSM and PYTHIA. The shapes of the PYTHIA distributions for different structure functions are very similar.

In fig. 20 we present PYTHIA predictions for the charged particle multiplicity distribution relative to standard events without heavy flavour (charm or beauty) production, to events with charm and to those with beauty, again in pp interactions at $\sqrt{s} = 630$ GeV. Here too the dependence on structure functions is weak. But the three considered cases differ significantly from each other. In charm and beauty events, the N_{ch} distributions are slightly narrower than in standard events because of the absence of a diffraction-dissociation contribution to heavy quark production. For the same reason the corresponding mean multiplicity in the case of charm production is slightly higher than in standard events (see table 4). In the case of beauty production, the mean multiplicity is significantly higher than in the previous cases and the distribution is shifted towards the high multiplicity region. All these effects can be related to the structure of PYTHIA where standard non-diffractive events correspond to multiple mini-jet production processes whose hardness at the considered energy is of the order of the charmed quark mass. In the case of beauty production, the hardness is significantly higher leading to higher multiplicities of secondaries.

Theoretical predictions for heavy flavour production at the energies of future supercolliders seem to be interesting in connection with experimental plans. Most important is to understand the possible cross-section levels at superhigh energies. In this respect we present in fig. 21 the QGSM and PYTHIA predictions for charm and beauty total cross-sections in pp interactions in the energy interval 0.63-200 TeV. Let us point out that PYTHIA predictions using "new" sets of parton distributions (MT2 and GRV2) give significantly higher cross-sections than using the "old" ones (EHLQ1 in this case). For example, the GRV2 parametrization predicts $c\bar{c}$ production practically in every inelastic pp collision at the ELOISATRON energy. Also interesting is that the "new" sets predict the b/c yield ratio not to exceed the 0.1 level even at the highest energy considered whereas the "old" sets give significantly larger values. The reason for this difference is the x -dependence of the structure functions in the small x -region (see table 1) since the x -values of the interacting quarks or gluons are essentially:

$$x_1 \approx x_2 \approx 2m_Q/\sqrt{s}, \quad (29)$$

where m_Q is a heavy quark mass. The QGSM cross-sections are higher than those obtained using "old" sets in PYTHIA although the b/c ratio turns out to be practically the same.

Concerning now the event structure, as the energy increases, the influence of different structure functions becomes significant as one can see in fig. 22 showing the PYTHIA-simulated charged hadron multiplicity distribution for standard events at $\sqrt{s} = 40$ TeV.

The same distribution at $\sqrt{s} = 200$ TeV for standard events, events with charm and events with beauty is shown in fig. 23. The general features actually change with respect to fig. 20. The dependence on the structure function used is now dramatic because, as already mentioned above, the main contribution to the production cross-section (of light and heavy quarks) at this energy is given by x -values of the order of 10^{-6} or less, where parton distributions are really unknown. In particular for standard events, the multiplicity distribution is now split into a "narrow" component at low N_{ch} (corresponding to single and double diffraction-dissociation processes) and a "broad" component at large N_{ch} whose width and peak position can increase by factor ~ 3 depending on the structure function parametrization used. It is worth to point out that this "broad" component better compares with the N_{ch} distribution of events with beauty (fig. 23b) than with charm (fig. 23c), thus indicating, when comparing figs. 13, 20 and 23, that the hardness of standard interactions in PYTHIA increases with the energy. This is not the case in the QGSM approach where, moreover, the splitting of the N_{ch} distribution does not show up. For details, we refer the reader to [32].

6. CONCLUSION

PYTHIA and QGSM models reasonably describe most of the existing data on charm hadroproduction. Some contradictions exist and these are essentially related to some significant differences in the experimental results. In the QGSM approach, an appropriate parameter tuning (for a_1 and a_2 in eqs. (15), (18) and (19)) allows to reproduce the well-known "leading" baryon effect, clearly appearing in the x_F -distribution of Λ_c measured at $\sqrt{s} = 62$ GeV [29] (see fig. 12), and to predict it, for both charm and beauty baryons, at higher energies⁴⁾. On the other hand PYTHIA has a serious problem to describe the same Λ_c data, although its predictions in terms of cross-sections at lower energies seem to better match the experimental values (see table 3). All this translates into some significant differences in the predictions from QGSM and Lund models at higher energies.

In addition, at superhigh energies ($\sqrt{s} = 200$ TeV), the dependence of PYTHIA results on the choice of a particular structure function parametrization becomes critical, not only for heavy flavour production, but for the whole bulk of soft inelastic processes.

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4) Let us recall that, apart from possible violations in the central region, the $x_E/\sigma_{in} \cdot d\sigma/dx_F$ distributions are expected to scale with the energy [32].

Table 1

Compilation of structure function parametrizations in the small x and Q^2 region.

Name in PYTHIA	Name in ref.	$xG(x \rightarrow 0, Q^2 = Q_0^2)$
EHLQ1	EHLQ set 1 [17]	const.
EHLQ2	EHLQ set 2 [17]	const.
DO1	DO set 1 [18]	const.
DO2	DO set 2 [18]	const.
MT1	absent in [19]	$x^{-0.17}$
MT2	MT fit S-DIS [19]	$x^{-0.33}$
MT3	MT fit B2-DIS [19]	$x^{-0.72}$
MT4	MT fit E-DIS [19]	$x^{-0.33}$
GRV1	GRV (LO) [20]	$x^{-0.40}$ for $10^{-4} < x < 10^{-3}$
GRV2	GRV (HO) [20]	$x^{-0.33}$ for $10^{-4} < x < 10^{-3}$

Table 2

Total cross-sections (in μb) for charm and beauty production. The present calculations for pp interactions with PYTHIA (referred in the table according to the set of structure functions used) and QGSM are compared to the experimental results relative to pp ($\sqrt{s} = 27, 39$ GeV) and $p\bar{p}$ ($\sqrt{s} = 630$ GeV) collisions.

$\sqrt{s}$	27 GeV, $c\bar{c}$	39 GeV, $c\bar{c}$	630 GeV, $c\bar{c}$	630 GeV, $b\bar{b}$
EHLQ1	19	35	310	11
EHLQ2	26	45	260	12
DO1	15	26	160	8.3
DO2	26	37	180	12
MT1	14	31	450	10
MT2	25	33	610	11
MT3	9	21	960	9.3
MT4	12	27	440	9.1
GRV1	9	21	1900	12
GRV2	9	20	940	10
QGSM	36	58	530	40
Experiment	14-23	29-55	$680 \pm 560 \pm 250 \pm 210$	$19.3 \pm 7 \pm 9$

Table 3

Comparison of the experimental cross-sections (in μb) of different charmed hadrons produced in pp and πp interactions at low energy, with the results of our present QGSM and PYTHIA calculations. The PYTHIA predictions are referred according to the structure function parametrization used. In the case of πp collisions, the cross-sections are given only in the region $x_F > 0$ (i.e. in the outgoing π hemisphere).

Reaction, $\sqrt{s}$	Experiment	QGSM	EHLQ1	MT2	GRV2
$\pi^- p \rightarrow D^+ / D^-$, 26 GeV	5.7 ± 1.6	9.5	7.5	7.4	5.0
$\pi^- p \rightarrow D^0 / \bar{D}^0$, 26 GeV	10.1 ± 2.2	7	17	17	11
$pp \rightarrow D^+ / D^-$, 27 GeV	11.9 ± 1.5	12	9.3	7.5	4.5
$pp \rightarrow D^0 / \bar{D}^0$, 27 GeV	18.3 ± 2.5	30	23	19	11
$pp \rightarrow D^0$, 27 GeV	10.5 ± 1.9	2.8	9.8	8.1	4.7
$pp \rightarrow \bar{D}^0$, 27 GeV	7.9 ± 1.5	27	13	11	6.4
$pp \rightarrow D^+$, 27 GeV	5.7 ± 1.1	2.8	4.7	3.8	2.2
$pp \rightarrow D^-$, 27 GeV	6.2 ± 1.1	9.3	4.6	3.7	2.3
$pp \rightarrow \Lambda_c$, 27 GeV	$< 6.1 (\Lambda_c / D)$	21	2.2	1.5	1.3
—	$< 15 (\Lambda_c / \bar{\Lambda}_c)$	—	—	—	—
$pp \rightarrow D^+ / D^-$, 39 GeV	33 ± 7	23	18	17	10
$pp \rightarrow D^0 / \bar{D}^0$, 39 GeV	26^{+21}_{-13}	45	43	41	24
$pp \rightarrow \Lambda_c$, 62 GeV	$(40 \pm 18) \div (204 \pm 91)$	54	4.9	4.8	4.3

Table 4

PYTHIA predictions for the mean multiplicity and dispersion values of charged secondaries produced in pp collisions at $\sqrt{s} = 630$ GeV, relative to standard (i.e. minimum bias) pp events and to events with charm and beauty production.

Structure function	Standard		With charm		With beauty	
	$\langle N_{ch} \rangle$	D_{ch}	$\langle N_{ch} \rangle$	D_{ch}	$\langle N_{ch} \rangle$	D_{ch}
EHLQ1	26.2	16.0	34.3	10.6	48.0	12.8
MT2	29.7	18.2	34.8	11.4	51.3	13.4
GRV2	30.3	18.3	33.7	11.3	50.3	12.9

Figure captions

- Fig. 1 : K-factors vs. x_F and p_T^2 as calculated in PYTHIA for D -meson production in pp interactions at $\sqrt{s} = 27$ GeV using EHLQ1 (a, b) and MT2 (c, d) structure functions: K1, K2 and K3 are shown as dark circles, dark triangles and open squares, respectively.
- Fig. 2 : Feynman- x and transverse momentum distributions of all D -mesons produced in pp interactions at $\sqrt{s} = 27$ GeV as obtained in PYTHIA using EHLQ1 (a, b) and EHLQ2 (c, d) structure functions. The values calculated with K-factor = 1 (order α_s^2) and with the variants K1, K2 and K3 are shown as dark circles, squares, triangles and open squares, respectively. The corresponding experimental data [24] are shown as open circles.
- Fig. 3 : PYTHIA predictions as in fig. 2 using DO1 (a, b) and DO2 (c, d) structure functions.
- Fig. 4 : PYTHIA predictions as in fig. 2 using MT1 (a, b) and MT2 (c, d) structure functions.
- Fig. 5 : PYTHIA predictions as in fig. 2 using MT3 (a, b) and MT4 (c, d) structure functions.
- Fig. 6 : PYTHIA predictions as in fig. 2 using GRV1 (a, b) and GRV2 (c, d) structure functions.
- Fig. 7 : QGSM diagrams corresponding (a) to the one-pomeron exchange contribution to the elastic pp scattering (cylindrical dyagram), (b) to the cut of one pomeron (which determines the contribution to the inelastic pp cross-section) and (c) to the cut of three pomerons.
- Fig. 8 : Energy dependence of Λ_c^+ production cross-section in pp (and np) collisions. The data points are taken from [29]. The curve superimposed shows the corresponding QGSM calculation.
- Fig. 9 : Inclusive x_F -spectrum for all D -mesons produced in pp interactions at $\sqrt{s} = 27$ GeV [24]. The curve superimposed shows the corresponding QGSM calculation.
- Fig. 10 : Inclusive x_F -spectra for D^+ (a), D^- (b), $\bar{D}^0$ (c) and D^0 (d) mesons produced in pp collisions at $\sqrt{s} = 27$ GeV [24]. The curves superimposed are the corresponding QGSM calculations.
- Fig. 11 : Inclusive x_F -spectrum for all D -mesons (a) produced in π^-p interactions at $\sqrt{s} = 26$ GeV [30] for "non-leading", i.e. D^+ and $\bar{D}^0$, (b) and "leading", i.e. D^- and D^0 , (c) mesons, separately. The $x_F > 0$ region refers here to the outgoing π hemisphere.

Fig. 12 : Inclusive x_F -spectrum for Λ_c^+ -baryon production in pp collisions at $\sqrt{s} = 62$ GeV [29]. The QGSM and PYTHIA (with EHLQ1, MT2 and GRV2 structure functions) predictions are shown as open and black points, respectively, as indicated. We use the well-known scaled variable $x_E/\sigma_{in} \cdot d\sigma/dx_F$, where $x_E = 2E/\sqrt{s}$.

Fig. 13 : Charged particle multiplicity distributions in pp interactions at $\sqrt{s} = 27$ GeV [31] in standard (i.e. minimum bias) events (a) and in events with charm production (b). The experimental points are shown as open circles. The PYTHIA predictions for EHLQ1, MT2 and GRV2 structure functions are shown as dark points, as indicated.

Fig. 14 : PYTHIA (with EHLQ1 structure functions) and QGSM predictions for the x_F (a) and p_T^2 (b) distributions of D^+ , D^0 , D^- , $\bar{D}^0$ and Λ_c^+ produced in pp interactions at $\sqrt{s} = 630$ GeV. The PYTHIA results are shown as different kinds of points, the QGSM ones as different kinds of curves, as indicated. For the x_F -distributions, we use the well-known scaled variable $x_E/\sigma_{in} \cdot d\sigma/dx_F$, where $x_E = 2E/\sqrt{s}$.

Fig. 15 : PYTHIA predictions as in fig. 14 using MT2 structure functions.

Fig. 16 : PYTHIA predictions as in fig. 14 using GRV2 structure functions.

Fig. 17 : PYTHIA (with EHLQ1 structure functions) and QGSM predictions as in fig. 14 for B^+ , B^0 , B^- , $\bar{B}^0$ and Λ_b^0 production in pp interactions at $\sqrt{s} = 630$ GeV.

Fig. 18 : PYTHIA predictions as in fig. 17 using MT2 structure functions.

Fig. 19 : PYTHIA predictions as in fig. 17 using GRV2 structure functions.

Fig. 20 : PYTHIA predictions for the charged particle multiplicity distribution in pp interactions at $\sqrt{s} = 630$ GeV in standard (i.e. minimum bias) events (a), in events with charm (b) and with beauty (c) production using EHLQ1, MT2 and GRV2 structure functions.

Fig. 21 : PYTHIA and QGSM predictions for the energy dependence of the charm (a) and beauty (b) production cross-sections and of the b/c yield ratio (c) in pp collisions. In PYTHIA the EHLQ1, MT2 and GRV2 structure function parametrizations are considered.

Fig. 22 : PYTHIA predictions for the charged particle multiplicity distribution in standard pp interactions at $\sqrt{s} = 40$ TeV, with EHLQ1, MT2 and GRV2 structure functions.

Fig. 23 : PYTHIA predictions as in fig. 20 for pp interactions at $\sqrt{s} = 200$ TeV.

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