FEYNMAN SCALING VIOLATION ON BARYON SPECTRA IN $pp$ COLLISIONS AT LHC AND COSMIC RAY ENERGIES

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Abstract

A significant asymmetry in baryon/antibaryon yields in the central region of high energy collisions is observed when the initial state has non-zero baryon charge. This asymmetry is connected with the possibility of baryon charge diffusion in rapidity space. Such a diffusion should decrease the baryon charge in the fragmentation region and translate into the corresponding decrease of the multiplicity of leading baryons. As a result, a new mechanism for Feynman scaling violation in the fragmentation region is obtained. Another numerically more significant reason for the Feynman scaling violation comes from the fact that the average number of cutted Pomerons increases with initial energy. We present the quantitative predictions of the Quark-Gluon String Model (QGSM) for the Feynman scaling violation at LHC energies and at even higher energies that can be important for cosmic ray physics.

PACS. 25.75.Dw Particle and resonance production
1 Introduction

The problem of Feynman scaling violation has evident both theoretical and practical interest. In particular, this question is very important [1, 2] for cosmic ray physics, where the difference from the primary radiation to the events registered on the ground or mountain level is determined by the multiple interactions of the so-called leading particles (mainly baryons) in the atmosphere.

Despite the lack of direct measurements of Feynman scaling violation for secondary baryon spectra in nucleon-nucleon collisions at energies higher than those of ISR, some experimental information from cosmic ray experiments seems to confirm [3, 4, 5] the presence of significant Feynman scaling violation effects. Now the LHCf Collaboration has started the search [6, 7] of Feynman scaling violation effects for the spectra of photons ($\pi^0$) and neutrons in the fragmentation region at LHC energies.

In principle, the violation of Feynman scaling in the fragmentation region should exist due to the energy conservation, since the spectra of charged particles increase in the central region. However, no quantitative predictions can be made without some model of the particle production.

The Additive Quark Model [8, 9] predicts the violation of Feynman scaling in the fragmentation region due to the increase of the interaction cross sections. However, to make a description of the energy dependences of the spectra as a function of $x_F$ additional assumptions and parameters are needed.

The QGSM [10, 11] allows the calculation of the spectra of secondaries at different initial energies in the whole $x_F$ region. The QGSM is based on Dual Topological Unitarization (DTU), Regge phenomenology, and nonperturbative notions of QCD. This model is successfully used for the description of multiple production processes in hadron-nucleon [12, 13, 14, 15], hadron-nucleus [16, 17], and nucleus-nucleus [18] collisions. The quantitative predictions of the QGSM depend on several parameters which were fixed by comparison of the calculations to the experimental data obtained at fixed target energies. The first experimental data obtained at LHC [19, 20] show that the model predictions are in reasonable agreement with the data.

We will consider the energy dependences of the spectra of secondary baryons in the projectile fragmentation region which we determine as the interval $0.05 < x_F < 0.8$. These values of $x_F$ are larger than the typical values for central production and smaller than the values where triple-Reggeon diagrams dominate.

In the frame of QGSM several reasons for the Feynman scaling violation in the fragmentation region exist [21]. The first one is the increase of the average number
of exchanged Pomerons with the energy, which leads to the corresponding increase of the yields of hadron secondaries in the central region and to their decrease in the fragmentation region. This effect is present even at asymptotically high energies. The preliminary estimation of this effect was provided in [22, 23].

In the case of nuclear (air) targets, the growth of the $hN$ cross section with energy leads to the increase of the average number of fast hadron inelastic collisions inside the nucleus. Thus, the average number of Pomerons is additionally increased, resulting in a stronger Feynman scaling violation [22, 23].

In [24] these predictions were taken into account to calculate the penetration of fast hadrons into the atmosphere, leading to a better description of the cosmic ray experimental data.

The differences in the yields of baryons and antibaryons produced in the central (midrapidity) region of high energy $pp$ interactions [15, 19, 20, 25, 26, 27, 28] are significant. Evidently, the appearance of the positive baryon charge in the central region of $pp$ collisions should be compensated by the decrease of the baryon multiplicities in the fragmentation region that leads to an additional reason for Feynman scaling violation. This effect has a preasymptotical behaviour and it is saturated at very high energies (see section 4).

In the present paper we consider the effects of Feynman scaling violation, i.e. the energy dependences of the spectra of secondary protons, neutrons, and Λ produced in $pp$ collisions in the fragmentation region.

In our estimations the role of the nuclear factor for air nuclei should be similar to that presented in [22, 23].

2 Inclusive spectra of secondary hadrons in the Quark-Gluon String Model

The QGSM [10, 11] allows us to make quantitative predictions for different features of multiparticle production, in particular, for the inclusive spectra of different secondaries, both in the central and in fragmentation regions. In QGSM high energy hadron-nucleon collisions are considered as taking place via the exchange of one or several Pomerons, all elastic and inelastic processes resulting from cutting through or between Pomerons [29].

Each Pomeron corresponds to a cylindrical diagram (see Fig. 1a), and thus, when cutting one Pomeron, two showers of secondaries are produced as it is shown in Fig. 1b. The inclusive spectrum of a secondary hadron $h$ is then determined by the convolution
of the diquark, valence quark, and sea quark distributions, \( u(x, n) \), in the incident particles, with the fragmentation functions, \( G^h(z) \), of quarks and diquarks into the secondary hadron \( h \). These distributions, as well as the fragmentation functions, are constructed by using the Reggeon counting rules [30]. Both the diquark and the quark distribution functions depend on the number \( n \) of cut Pomerons in the considered diagram. The details of the model are presented in references [10, 11, 12, 13, 15].

For a nucleon target, the inclusive rapidity (\( y \)), or Feynman-\( x \) (\( x_F \)), spectrum of a secondary hadron \( h \) has the form [10]:

\[
\frac{dn}{dy} = \frac{1}{\sigma_{\text{inel}}} \cdot \frac{d\sigma}{dy} = \frac{x_E}{\sigma_{\text{inel}}} \cdot \frac{d\sigma}{dx_F} = \sum_{n=1}^{\infty} w_n \cdot \phi_n^h(x) + w_0 \cdot \phi_D^h(x) ,
\]

where \( x_F = 2p_\parallel/\sqrt{s} \) is the Feynman variable, and \( x_E = 2E/\sqrt{s} \), and the functions \( \phi_n^h(x) \) determine the contribution of the diagram with \( n \) cut Pomerons and \( w_n \) is the relative weight of this diagram \( \sum_{n=1}^{\infty} w_n = 1 \). The last term in Eq. (1) accounts for the contribution of diffraction dissociation processes that are determined by the cuts between Pomerons \( (n = 0) \).

For \( pp \) collisions

\[
\phi_{pp}^h(x) = f_{qq}^h(x_+, n) \cdot f_q^h(x_-, n) + f_q^h(x_+, n) \cdot f_{qq}^h(x_-, n) + 2(n - 1) f_s^h(x_+, n) \cdot f_s^h(x_-, n) ,
\]

\[
x_\pm = \frac{1}{2} \left[ \sqrt{4m_T^2 + x^2} \pm x \right] ,
\]
where \( f_{qq}, f_q, \) and \( f_s \) correspond to the contributions of diquarks, valence quarks, and sea quarks, respectively.

These functions are determined by the convolution of the diquark and quark distributions with the fragmentation functions, e.g., for the quark one can write:

\[
 f_q^h(x_+, n) = \int_{x_+}^{1} u_q(x_1, n) \cdot G_q^h(x_+/x_1) dx_1 .
\]

The fragmentation functions \( G^h(z) \) are independent on the number of cutted Pomerons \( n \). On the contrary, the diquark and quark distributions \( u(x, n) \) (which are normalized to unity) become softer when \( n \) increases. Thus, for example in [10] it was assumed that the diquarks distributions depend on \( n \) as:

\[
 u_{qq}(x) \sim (1 - x)^{-\alpha_R + (n-1)} .
\]

If the intercept of the Pomeron trajectory is larger than unity,

\[
 \alpha_P(0) = 1 + \Delta , \quad \Delta > 0 ,
\]

the average number of Pomerons which should be accounted for increases with energy. The probabilities for cutting different numbers of Pomerons, \( n, w_n \) in Eq. (1), can be calculated in the quasiclialional approach [31]. The results of the calculation at four different energies, \( \sqrt{s} = 17.3 \text{ GeV}, 200 \text{ GeV}, 8 \text{ TeV} \) (the current LHC energy), and 100 TeV (significant energy for the Pierre Auger cosmic ray observatory, see, for example [32]) are presented in Fig. 2.

3 Baryon/antibaryon asymmetry in the QGSM

In the string models, baryons are considered as configurations consisting of three connected strings (related to three valence quarks) called string junction (SJ) [33, 34, 35]. Such a baryon structure is supported by lattice calculations [37]. In the case of inclusive reactions the baryon number transfer to large rapidity distances in hadron-nucleon reactions can be explained [15, 25, 38, 39, 40] by SJ diffusion.

The production of a baryon-antibaryon pair in the central region occurs via \( SJ-S\bar{J} \) (SJ has upper color indices whereas \( S\bar{J} \) has lower indices) pair production, which then combines with sea quarks and sea antiquarks into a \( B\bar{B} \) pair [35, 41], as it is shown
Figure 2: The calculated probabilities for cutting different number of Pomerons at energies $\sqrt{s} = 17.3$ GeV (dotted curve), 200 GeV (dash-dotted curve), 8 TeV (dashed curve), and 100 TeV (solid curve).

in Fig. 3a, the contributions of these processes to the inclusive spectra of secondary baryons being determined by Eq. (2).

In the processes with incident baryons, e.g. in $pp$ collisions, another possibility to produce a secondary baryon in the central region exists. This possibility is the diffusion in rapidity space of any SJ existing in the initial state and it can lead to significant differences in the yields of baryons and antibaryons in the midrapidity region even at high energies [15]. The most important experimental fact in favour of this process is the rather large asymmetry in $\Omega$ and $\Omega$ baryon production in high energy $\pi^-p$ interactions [12].

The theoretical quantitative description of the baryon number transfer via SJ mechanism was suggested in the 90’s and used to predict [13] the $p/\bar{p}$ asymmetry at HERA energies.

In order to obtain the net baryon charge we consider, following ref.[15] three different possibilities. The first one is the fragmentation of the diquark giving rise to a leading

\footnote{There is some freedom [16] in how to account for this effect.}
baryon (Fig. 3b). A second possibility is to produce a leading meson in the first break-up of the string and a baryon in a subsequent break-up (Fig. 3c). In these two first cases the baryon number transfer is possible only for short distances in rapidity. In the third case, shown in Fig. 3d, both initial valence quarks recombine with sea antiquarks into mesons $M$ while a secondary baryon is formed by the SJ together with three sea quarks.

The fragmentation functions for the secondary baryon $B$ production corresponding to the three processes shown in Figs. 3b, 3c, and 3d, can be written as follows \cite{15}:

\[ G_{qq}^B(z) = a_N \cdot v_{qq}^B \cdot z^{2.5}, \]  
(7)

\[ G_{qs}^B(z) = a_N \cdot v_{qs}^B \cdot z^2 \cdot (1 - z), \]  
(8)

\[ G_{ss}^B(z) = a_N \cdot \varepsilon \cdot v_{ss}^B \cdot z^{1-\alpha_{SJ}} \cdot (1 - z)^2, \]  
(9)

where $a_N$ is the normalization parameter, and $v_{qq}^B$, $v_{qs}^B$, $v_{ss}^B$ are the relative probabilities for different baryons production that can be found by simple quark combinatorics \cite{44,45}. Their numerical values for different secondary baryons were presented in \cite{28}.

The first two processes shown in Figs. 3b and 3c, Eqs. (7) and (8), determine the spectra of leading baryons in the fragmentation region. The third contribution shown
in Fig. 3d, Eq. (9), is essential if the value of the intercept of the SJ exchange Regge-trajectory, \( \alpha_{SJ} \), is not too small. In QGSM the weight of this third contribution is determined by the coefficient \( \varepsilon \) which fixes the small probability for such a baryon number transfer to occur.

In the case of \( pp \) collisions the most sensitive ratios to the values of parameters \( \alpha_{SJ} \) and \( \varepsilon \) are the ratios of \( \bar{B}/B \) in the central region. If the initial energy is high enough, one can neglect the contributions of the processes of figs. 3b and 3c, so the \( \bar{B}/B \) ratio is determined by the contributions of figs. 3a and 3d.

The spectra of antibaryons are described by QGSM [12, 13, 15] with reasonable accuracy, so the values of the parameters which determine the contributions of Fig. 3d can be extracted from the experimental data.

The energy dependence of \( \bar{p}/p \) produced in \( pp \) collisions in midrapidity region \( (y_{cm} \sim 0) \) is shown in Fig. 4. The theoretical curve has been normalized to the experimental point at \( \sqrt{s} = 27.5 \) GeV, where the error bar is minimal and the \( \chi^2 \) analyses gives [27]:

\[
\alpha_{SJ} = 0.5 \pm 0.1, \text{ with } \varepsilon = 0.0757.
\] (10)

Unfortunately, four experimental points at RHIC energy \( \sqrt{s} = 200 \) GeV are in evident disagreement with each other, the calculation performed with values of the

![Figure 4: The QGSM description of the energy dependence of the \( \bar{p}/p \) in the midrapidity region. Solid curve correspond to the value \( \alpha_{SJ} = 0.5 \) and dashed curve to the value \( \alpha_{SJ} = 0.9 \).](image)
parameters $\alpha_{SJ} = 0.9$ and $\varepsilon = 0.024$ being in agreement with the lowest RHIC point (see dashed curve in Fig. 4).

The data by the ALICE Collaboration [46] for $\bar{p}/p$ ratios in $pp$ collisions at $\sqrt{s} = 900$ GeV and 7 TeV in midrapidity region are presented in Table 1, together with the QGSM predictions. These data confirm the asymmetry in the ratio $\bar{p}/p$ and they are in agreement with the QGSM predictions for the value $\alpha_{SJ} = 0.5$.

| SJ exchange | $\sqrt{s} = 900$ GeV | $\sqrt{s} = 7$ TeV |
|-------------|----------------------|---------------------|
| $\alpha_{SJ} = 0.9$ | 0.89 | 0.95 |
| $\alpha_{SJ} = 0.5$ | 0.95 | 0.99 |
| $\varepsilon = 0$ | 0.98 | 1.0 |
| ALICE Collaboration | $\pm 0.006 \pm 0.014$ | $\pm 0.005 \pm 0.014$ |

Table 1. The QGSM predictions for $\bar{p}/p$ in $pp$ collisions at LHC energies and the corresponding data by the ALICE Collaboration. The value $\varepsilon = 0$ corresponds to the case without C-negative exchange.

The LHCb Collaboration measured the ratios of $\bar{\Lambda}$ to $\Lambda$ in the rapidity interval $2 < y < 4$ at $\sqrt{s} = 900$ GeV and 7 TeV [47]. These preliminary data are also incompatible [48] with the QGSM calculation without SJ contribution ($\varepsilon = 0$). Though the errorbars are too large to make any conclusion, the QGSM calculations with the value $\alpha_{SJ} = 0.9$ seem to be in a slightly better agreement with the data than the calculations with $\alpha_{SJ} = 0.5$.

So, we can conclude that the transfer of baryon charge in large rapidity distances occurs up to the LHC energies, and it can probably be described by the QGSM by taking the values of the parameters $\alpha_{SJ}$ and $\varepsilon$ presented in Eq. (10).

4 Energy dependence of secondary proton spectra in the fragmentation region

As it was mentioned above, the inclusive spectra of secondary net baryons $B$ produced in the processes of Figs. 3b, 3c, and 3d are determined by the convolution of the diquark distribution $u(x, n)$ in the incident particles with the fragmentation functions $G^h(z)$ presented in Eqs. (7)–(9). The baryon charge of all secondary particles is determined by the integral over these spectra and it should be exactly equal to two (i.e. to the baryon charge of the initial $pp$ state). In the case the process in Fig. 3d is absent, the integral over the spectra of secondary net baryons totally saturates at the distance of
several units of rapidity from the projectile. Thus, in the absence of the process in Fig. 3d the Feynman scaling violation in the fragmentation region can only be due to effects connected with the increase of the average number of exchanged Pomerons.

The SJ contribution to the inclusive cross section of secondary baryon production (Fig. 3d) at large rapidity distance $\Delta y$ from the incident nucleon can be estimated as

$$\frac{1}{\sigma} \frac{\sigma_B^B}{d y} \sim a_B \cdot \varepsilon \cdot e^{(1-\alpha_{SJ}) \cdot \Delta y} , \quad a_B = a_N \cdot v_{ss}^B . \quad (11)$$

At asymptotically high energies, the baryon charge transferred to large rapidity distances can be determined by integration of Eq. (11), and it turns out to be of the order of

$$\langle n_B(s \to \infty) \rangle_{SJ} \sim a_B \cdot \varepsilon \cdot \frac{1}{1 - \alpha_{SJ}} , \quad (12)$$

only the left part of the initial baryon charge being available for the production of the leading baryons.

The only free parameter in eqs. (7)-(9) is the normalization $a_N$, that should be modified at asymptotically high energies in the presence of the SJ mechanism for the baryon charge as

$$\tilde{a}_N(s \to \infty) = a_N \cdot \frac{\langle n_B \rangle_{\varepsilon=0}}{\langle n_B \rangle_{\varepsilon=0} + \langle n_B(s \to \infty) \rangle_{SJ}} , \quad (13)$$

to guarantee the conservation of the baryon charge. One can see that $\langle n_B(s \to \infty) \rangle_{SJ}$ is finite if $\alpha_{SJ} < 1$ (see Eq (12)), so the Feynman scaling violation due to the discussed effects has a preasymptotical behaviour.

To obtain the QGSM predictions for the spectra of leading baryons at finite energy $s$ we have to calculate the value of $\langle n_B(s) \rangle_{SJ}$ at this energy for the renormalized value of $\tilde{a}_N(s)$ in Eq. (13). This can be provided by the numerical integration of the convolution of the diquark distribution $u(x, n)$ in the incident protons with the fragmentation functions $G_h^B(z)$. By this way we account for the rather complicate shape of $(1/\sigma) \cdot d\sigma_B^{B}/dy$ at small $\Delta y$.

Though currently the value of $\alpha_{SJ} = 0.5$ seems more plausible [46], the value of $\alpha_{SJ} = 0.9$ cannot be excluded [47, 49]. Thus, in this paper we present the calculation obtained with these two values of $\alpha_{SJ}$, and also without any SJ contribution ($\varepsilon = 0.$).

The results of the calculations of the secondary proton spectra produced in $pp$ collisions are presented in Fig. 5, together with experimental data [50] by the NA49 Collaboration on proton spectra in $pp$ collisions at 158 GeV/c beam momentum ($\sqrt{s} = 17.3$ GeV) and the data [51] at 100 GeV/c ($\sqrt{s} = 14$ GeV) and 175 GeV/c ($\sqrt{s} = 19$ GeV).
Figure 5: The QGSM predictions for the spectra of secondary protons produced in \( pp \) collisions at \( \sqrt{s} = 17 \) GeV (left) and 8 TeV (right), compared to the corresponding experimental data by the NA49 collaboration [50] at \( \sqrt{s} = 17 \) GeV (points) and data [51] at \( \sqrt{s} = 14 \) (triangles) and 19 (squares) GeV. Calculations without SJ contribution are shown by solid curves, results for \( \alpha_{SJ} = 0.5 \) by dashed curves, and for \( \alpha_{SJ} = 0.9 \) by dash-dotted curves.

As it is seen on Fig. 5, the comparison of the QGSM calculations to the experimental data in ref. [50, 51] is rather good. The data of these two experimental groups are in good agreement at \( x_F < 0.6 \) and in some disagreement at larger \( x_F \). The calculated spectra of secondary protons produced at \( \sqrt{s} = 17 \) GeV and 8 TeV are significantly different. The calculated spectrum at \( \sqrt{s} = 17 \) GeV increases with \( x_F \) rather monotonically, in agreement with the existing experimental data. This spectrum only weakly depends on the SJ contributions, the reason being that the value of \( \langle n_B(s) \rangle_{SJ} \) at this energy is rather small. With the increase of the energy until \( \sqrt{s} = 8 \) TeV the rapidity region accessible for the baryon number transfer increases, increasing also the value of \( \langle n_B(s) \rangle_{SJ} \) and making the SJ effects more visible.

The peak appearing at \( \sqrt{s} = 8 \) TeV and \( x_F < 0.06 \) is connected with the protons produced together with antiprotons via the mechanism shown in Fig. 3a.

The proton spectra shown in Fig. 5 at both (low and high) energies depend on the values of several QGSM parameters. These considered values were determined from the comparison of the model calculations to the experimental data, but since there is some small disagreement between the calculations and the data. The main part of the uncertainty being connected with the normalization), the values of parameters, as well as the absolute values of the calculated spectra, can be known on the accuracy of the order of, say, 20%. Consequently, the difference between the calculations with and
without SJ contribution at the same energy can be estimated on the level of the 20% of this difference, in agreement with Eq. (10).

Similar situation appears when we consider the ratios of the spectra of the same secondary $h$ at different energies:

$$R_h \left( \frac{\sqrt{s_1}}{\sqrt{s_2}} \right) = \left[ \frac{x_E}{\sigma_{inel}} \cdot \frac{d\sigma}{dx_F} \right]_{s_1} / \left[ \frac{x_E}{\sigma_{inel}} \cdot \frac{d\sigma}{dx_F} \right]_{s_2}. \quad (14)$$

In Fig. 6 the QGSM predictions for the ratio $R_p(8\text{TeV}/17\text{GeV})$ are presented. Here again the normalization uncertainties are canceled and the accuracy of the model predictions is good enough.

![Figure 6: The QGSM predictions for the ratios of the spectra of secondary protons produced in $pp$ collisions at $\sqrt{s} = 17$ GeV and 8 TeV. Calculations without SJ contribution are shown by solid curves, results for $\alpha_{SJ} = 0.5$ by dashed curves, and for $\alpha_{SJ} = 0.9$ by dash-dotted curves.](image)

When the initial energy increases the spectra of secondary protons with $x_F > 0.3$ decrease, mostly due to the increase of the average number of cut Pomerons (see Fig. 2). The same effect increases the spectra at $x_F < 0.3$. Some additional contribution to these Feynman scaling violations comes from the SJ effects which transfer the baryon charge to the low-$x_F$ region resulting in the renormalization of the parameter $a_N$ (see Eq. (13)).
It is also interesting to consider the spectra of secondary protons at fixed points of \( x_F \) as functions of initial energy. Here again, the absolute normalization of the curve contains some uncertainties, but their relative change with the energy and their dependence on the SJ effects can be calculated with reasonable accuracy. The results of such calculations for secondary protons with \( x_F = 0.7, 0.5, 0.2, \) and \( 0.05 \) produced in \( pp \) collisions at different energies are shown in Fig. 7.

Figure 7: The QGSM predictions for the spectra of secondary protons as functions of the energy at fixed values of \( x_F \). The left top bold curves show the spectra of net protons, i.e. the values of the \( p - \bar{p} \) differences. For the four panel, solid curves correspond to the calculation without SJ contribution, dashed curves to the value \( \alpha_{SJ} = 0.5 \), and dash-dotted curves to the value \( \alpha_{SJ} = 0.9 \).

These spectra increase with energy at comparatively low \( x_F = 0.05 \) and \( 0.2 \) (except for the calculation with \( \alpha_{SJ} = 0.9 \) in the last case), and they decrease with energy at \( x_F = 0.5 \) and \( 0.7 \). This change in the energy dependence is explained by the growth of the average number of exchanging Pomerons (see Fig. 2).
The important feature is that at low $x_F$ (about 0.05 and less) one should discriminate between the total yield of secondary protons and the yield of net protons, i.e. the values of the $p - \overline{p}$ differences, by comparing the upper and lower sets of curves in the left top panel of Fig. 7. The spectra of antibaryons are not affected by SJ effects, so after subtraction of $\overline{p}$ spectra the SJ effects are more visible in the spectra of net protons.

5 Predictions for the spectra of neutrons and Λ in $pp$ collisions

The LHCf Collaboration plans to investigate the Feynman scaling violation for neutral secondaries in the fragmentation region. In this perspective, the QGSM predictions for the spectra of secondary neutrons and Λ-hyperons produced in $pp$ collisions at $\sqrt{s} = 8$ TeV are presented in Fig. 8.

![Figure 8: The QGSM predictions for the spectra of secondary neutrons and of Λ-hyperons produced in $pp$ collisions at $\sqrt{s} = 8$ TeV. Calculations without SJ contribution are shown by solid curves, results for $\alpha_{SJ} = 0.5$ by dashed curves, and for $\alpha_{SJ} = 0.9$ by dash-dotted curves.](image)

The spectra of neutrons are similar to the spectra of secondary protons presented
in Fig. 5 but the fragmentation maxima are not so stressed. The spectra of Λ-hyperons do not present such a maxima due to the additional suppression of fast strange particle production with respect to the non-strange secondaries, what leads to a faster decrease of $uu$ and $ud$ fragmentation functions into Λ at large $z$ in comparison with the fragmentation into secondary nucleon.

In both neutron and Λ production cases the SJ effects lead to similar corrections of the spectra than for secondary protons.

The ratios $R_n(8\text{TeV}/17\text{GeV})$ and $R_\Lambda(8\text{TeV}/17\text{GeV})$ of the spectra of neutrons and of Λ-hyperons produced in $pp$ collisions, defined by Eq. (14), are shown in Fig. 9. These ratios show the expected effects of the Feynman scaling violation in different $x_F$-regions. The ratios for secondary neutrons are similar to the corresponding ratios for secondary protons presented in Fig. 6. The ratios for secondary Λ are slightly different due to the difference in the fragmentation functions.

The energy dependences of the spectra of neutrons and Λ-hyperons at $x_F = 0.05$ and 0.5 are presented in Fig. 10. For both secondary neutron and Λ the spectra increase with energy at $x_F = 0.05$ and they decrease at $x_F = 0.5$. The predicted spectra of net baryons have a more complicated energy dependence at $x_F = 0.05$, at $x_F = 0.5$ practically coinciding with the total baryon spectra.

Sometimes it is more suitable to compare the spectra in the rapidity variable. In
Figure 10: The QGSM predictions for the spectra of secondary neutrons (top) and $\Lambda$-hyperons (low) as the functions of energy at fixed values of $x_F$. The bold curves (lower sets of curves) on the two left panels show the spectra of net neutrons and $\Lambda$-hyperons. For the four panel solid curves correspond to the calculation without SJ contribution, dashed curves to the value $\alpha_{SJ} = 0.5$, and dash-dotted curves to the value $\alpha_{SJ} = 0.9$.

Fig. 11 we present the spectra of secondary protons, neutrons, and $\Lambda$ at $\sqrt{s} = 17$ GeV and 8 TeV, as functions of the rapidity measured from the beam, $y_{beam} - y$, defined in the c.m. frame. If Feynman scaling would be preserved, the curves in the left-hand region of Fig. 11 (i.e. in the beam fragmentation region) should coincide at different energies, the appearing differences between curves showing the violation of Feynman scaling. All curves are terminated at the point $y_{cm} = 0$.  


Figure 11: The QGSM predictions for the spectra of secondary protons, neutrons, and Λ-hyperons produced in $pp$ collisions at $\sqrt{s} = 8$ TeV (solid and dashed curves), and at $\sqrt{s} = 17$ GeV (dash-dotted and dotted curves with $\alpha_{SJ} = 0.5$).

6 Conclusion

We present the QGSM predictions for Feynman scaling violation in the spectra of leading baryons due both to the increase of the number of cutted Pomerons with the energy and to the baryon charge diffusion at large distances in the rapidity space. The experimental search of the spectra of leading baryons at LHC should allow to confirm or discard these effects. The possible violation of Feynman scaling in the fragmentation region at very high energies was discussed in [6], based on Monte Carlo calculations. In the QGSM these effects exist, but are, as a rule, not numerically large.

We have neglected the possibility of interactions between Pomerons (the so-called enhancement diagrams), since our estimations [52] show that the inclusive density of secondaries produced in $pp$ collisions at LHC energies is not large enough for these diagrams to be significant.

Concerning the LHCf project we can note that the multiplicity of $\Lambda$ in the fragmentation region should be of the order of 10–15% the neutron multiplicity, and so it
should be accounted for. The production of other hyperons should be several orders of magnitude suppressed.

We have also to note that our results are in reasonable agreement with the calculations in ref. [53].

A more detailed version of part of the calculations we include in this paper was already published in ref. [21].

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References

[1] J. Abraham et al., Phys. Rev. Lett. 104, 091101 (2010) and arXiv:1002.0699 [astro-ph.HE].

[2] R. U. Abbasi et al., Phys. Rev. Lett. 104, 161101 (2010) and arXiv:0910.4184 [astro-ph.HE].

[3] E. L. Feinberg, Phys. Report. 50, 237 (1972).

[4] S. N. Vernov et al., J. Phys. C 3, 1601 (1977).

[5] N. N. Kalmykov and G. B. Khristiansen, JETP Lett. 37, 294 (1983); Pisma Zh. Eksp. Teor. Fiz. 37, 247 (1983).

[6] T. Sako (LHCf Collab.), arXiv:1010.0195 [hep-ex].

[7] O. Adriani et al. (LHCf Collab.), arXiv:1012.1490 [hep-ex].

[8] V. V. Anisovich, Yu. M. Shabelski, and V. M. Shekhter, Nucl. Phys. B 133, 477 (1978).

[9] V. V. Anisovich, V. M. Braun, and Yu. M. Shabelski, Z. Phys. C 27, 77 (1985).

[10] A. B. Kaidalov and K.A. Ter-Martirosyan, Sov. J. Nucl. Phys. 39, 979 (1984); Yad. Fiz. 39, 1545 (1984); Sov. J. Nucl. Phys. 40, 135 (1984); Yad. Fiz. 40, 211 (1984).
[11] A. B. Kaidalov, Phys. Atom. Nucl. 66, 1994 (2003); Yad. Fiz. 66, 2044 (2003).
[12] A. B. Kaidalov and O. I. Piskounova, Sov. J. Nucl. Phys. 41, 816 (1985); Yad. Fiz. 41, 1278 (1985); Z. Phys. C 30, 145 (1986).
[13] Yu. M. Shabelski, Sov. J. Nucl. Phys. 44, 177 (1986); Yad. Fiz. 44, 186 (1986).
[14] F. Anselmino, L. Cifarelli, E. Eskut, and Yu.M. Shabelski, Nouvo Cim. 105A, 1371 (1992).
[15] G. H. Arakelyan, A. Capella, A. B. Kaidalov, and Yu. M. Shabelski, Eur. Phys. J. C 26, 81 (2002) and hep-ph/0103337.
[16] A. B. Kaidalov, K. A. Ter-Martirosyan, and Yu. M. Shabelski, Sov. J. Nucl. Phys. 43, 822 (1986); Yad. Fiz. 43, 1282 (1986).
[17] Yu. M. Shabelski, Z. Phys. C38, 569 (1988).
[18] J. Dias de Deus and Yu. M. Shabelski, Phys. Atom. Nucl. 71, 190 (2008).
[19] C. Merino, C. Pajares, M. M. Ryzhinskiy, and Yu. M. Shabelski, arXiv:1007.3206[hep-ph].
[20] C. Merino, C. Pajares, and Yu. M. Shabelski, Eur. Phys. J. C71, 1652 (2011) and arXiv:1105.6026 [hep-ph].
[21] G. H. Arakelyan, C. Merino, C. Pajares, and Yu. M. Shabelski, arXiv:1107.1615[hep-ph].
[22] Yu. M. Shabelski, Sov. J. Nucl. Phys. 45, 143 (1987); Yad. Fiz. 45, 223 (1987).
[23] Yu. M. Shabelski, Z. Phys. C38, 569 (1988).
[24] A. D. Erlykin, N. P. Krutikova, and Yu. M. Shabelski, Sov. J. Nucl. Phys. 45, 668 (1987); Yad. Fiz. 45, 1075 (1987); Sov. J. Nucl. Phys. 47, 1057 (1988); Yad. Fiz. 47, 1667 (1988).
[25] F. Bopp and Yu. M. Shabelski, Phys. Atom. Nucl. 68, 2093 (2005); Yad. Fiz. 68, 2155 (2005) and hep-ph/0406158 Eur. Phys. J. A 28, 237 (2006) and hep-ph/0603193.
[26] G. H. Arakelyan, C. Merino, C. Pajares, and Yu. M. Shabelski, Eur. Phys. J. C 54, 577 (2008) and hep-ph/0709.3174.
[27] C. Merino, M. M. Ryzhinskiy, and Yu. M. Shabelski, Eur. Phys. J. C 62, 491 (2009) and arXiv:0810.1275 [hep-ph].

[28] G. H. Arakelyan, A. B. Kaidalov, C. Merino, and Yu. M. Shabelski, Phys. Atom. Nucl. 74, 426 (2011); Yad. Fiz. 74, 447 (2011) and arXiv:1004.4074 [hep-ph].

[29] V. A. Abramovsky, V. N. Gribov, and O. V. Kancheli, Sov. J. Nucl. Phys. 18, 308 (1974); Yad. Fiz. 18, 595 (1973).

[30] A. B. Kaidalov, Sov. J. Nucl. Phys. 45, 902 (1987); Yad. Fiz. 43, 1282 (1986).

[31] K. A. Ter-Martirosyan, Phys. Lett. B 44, 377 (1973).

[32] P. Abreu et al., In Proceedings of the 32nd International Cosmic Ray Conference, Beijing, China, 2011; arXiv1107.4809[astro-ph.HE].

[33] X. Artru, Nucl. Phys. B 85, 442 (1975).

[34] M. Imachi, S. Otsuki, and F. Toyoda, Prog. Theor. Phys. 52, 346 (1974); 54, 280 (1976); 55, 551 (1976).

[35] G. C. Rossi and G. Veneziano, Nucl. Phys. B 123, 507 (1977).

[36] D. Kharzeev, Phys. Lett. B 378, 238 (1996).

[37] V. G. Bornyanov et al, Uspekhi Fiz. Nauk. 174, 19 (2004).

[38] G. H. Arakelyan, C. Merino, and Yu. M. Shabelski, Yad. Fiz. 69, 911 (2006) and hep-ph/0505100; Yad. Fiz. 70, 1146 (2007); Phys. Atom. Nucl. 70, 1110(2007) and hep-ph/0604103; Eur. Phys. J. A 31, 519 (2007) and hep-ph/0610264.

[39] O. I. Piskounova, Phys. Atom. Nucl. 70, 1107 (2007); Yad. Fiz. 70, 1143 (2007) and hep-ph/0604157.

[40] C. Merino, M. M. Ryzhinskiy, and Yu. M. Shabelski, Proceedings of the XLIII PNPI Winter School on Nuclear and Particle Physics (PNPI-2009), Repino, St.Petersburg, Russia, February 24th-March 1st, 2009, pages 156-185, and arXiv:0906.2659 [hep-ph].

[41] S. E. Vance, M. Gyulassy, and X-N. Wang, Phys. Lett. B 443, 45 (1998).

[42] E. M. Aitala et al. (E769 Collab.), hep-ex/0009016; Phys. Lett. B 469, 9 (2000).

[43] B. Z. Kopeliovich and B. Povh, Z. Phys. C 75, 693 (1997); Phys. Lett. B 446, 321 (1999).
[44] V. V. Anisovich and V. M. Shekhter, Nucl. Phys. B 55, 455 (1973).

[45] A. Capella and C. A. Salgado, Phys. Rev. C 60, 054906 (1999).

[46] K. Aamodt et al. (ALICE Collab.), Phys. Rev. Lett. 105, 072002 (2010) and arXiv:1006.5432 [hep-ex].

[47] F. Dettori et al. (LHCb Collab.), Nucl. Phys. B (Proc. Suppl.) 206-207, 151 (2010) and arXiv:1009.1221 [hep-ex].

[48] C. Merino, C. Pajares, and Yu. M. Shabelski, arXiv:1105.6026 [hep-ph].

[49] C. Merino, C. Pajares, M. M. Ryzhinskiy, and Yu. M. Shabelski, Proceedings of the International Conference on Hadron Structure and QCD-HSQCD 2010, edited by V. T. Kim and L. N. Lipatov, PNPI Publishing Department, Gatchina, Russia, 5-9 July 2010, pages 75-82.

[50] T. Anticic et al. (NA49 Collab.), Eur. Phys. J. C65, 9 (2010) and arXiv:0904.2708 [hep-ex].

[51] A. E. Brenner, Phys. Rev. D26, 1497 (1982).

[52] C. Merino, C. Pajares, and Yu. M. Shabelski, Eur. Phys. J. C59, 691 (2009) and arXiv:0802.2195 [hep-ph].

[53] C. J. Bleibel et al., arXiv:1011.2703 [hep-ph].