E2-2012-12

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ON SELF-SIMILARITY OF TOP PRODUCTION AT TEVATRON

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О самоподобии рождения top-кварка на тэватроне

Представлены результаты анализа в рамках z-скейлинга данных по дифференциальным сечениям рождения top-кварка в $p\bar{p}$-столкновениях при энергии $\sqrt{s} = 1960$ ГэВ на тэватроне, полученные D0-коллаборацией. Проверяется флейворная независимость скейлинговой функции $\psi(z)$, установленная ранее для рождения адронов, от π- до Υ-мезонов, в pp- и $p\bar{p}$-столкновениях в области энергий $\sqrt{s} = 19{-}1960$ ГэВ. Экспериментальное подтверждение этого свойства рассматривается как указание на самоподобие рождения top-кварка. Получено также указание на режим насыщения скейлинговой функции $\psi(z)$ при малых z. Изучается зависимость доли импульса сталкивающегося (анти)протона x_1 от приведенного поперечного импульса p_T/m частицы. Мы предполагаем, что данные по инклюзивным спектрам рождения top-кварка и других частиц на тэватроне и LHC при малых и больших p_T могли бы дать новую информацию о самоподобии рождения адронов с разными массами и флейворным составом.

Работа выполнена в Лаборатории физики высоких энергий им. В. И. Векслера и А. М. Балдина ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 2012

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On Self-Similarity of Top Production at Tevatron

Results of analysis of D∅ 1.0 fb^{-1} data on top-quark differential cross section measurements at the Fermilab Tevatron collider at $\sqrt{s} = 1960$ GeV in the framework of z-scaling approach are presented. Flavour independence of the scaling function $\psi(z)$ observed in pp and $p\bar{p}$ interactions over a wide collision energy range $\sqrt{s} = 19{-}1960$ GeV is verified. This property of $\psi(z)$ was found for different hadrons from π meson up to Υ particle. The flavour independence of $\psi(z)$ is used as indication to self-similarity of top-quark production. A tendency to saturation of $\psi(z)$ at low z for top-quark is demonstrated. The momentum fractions x_1 of the incoming (anti)protons as a function of the scaled transverse momentum p_T/m and masses of heavy mesons are studied. We anticipate that data on low- and high-p_T inclusive spectra of top-quark production at Tevatron and LHC energies could be of interest for verification of the self-similarity over a wide range of masses and different flavour content of produced particles.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2012

1. INTRODUCTION

The measurements [1] of the top quark transverse momentum distribution have been performed at the Fermilab Tevatron collider at $\sqrt{s} = 1800$ and 1960 GeV by the CDF and D∅ Collaborations, respectively. The integrated luminosities of CDF and D∅ data samples are 106 pb^{-1} and 1 fb^{-1}. The top-quark is the heaviest known elementary particle and was discovered at the Tevatron $p\bar{p}$ collider in 1995 by the CDF and D∅ Collaborations [2, 3] at a mass of around 170 GeV. It is expected [4–11] that top physics is extremely important for scientific search in the high-energy physics frontier.

In the present paper, we analyse D∅ data using the method known as z scaling [12, 13]. Main features of the approach in pp and $p\bar{p}$ interactions at FNAL, CERN, and BNL (RHIC) energies were presented and discussed in [14,15]. Some results of analysis of the LHC data on the charged hadron [16], K_S^0 meson [17], and jet [18, 19] production are presented in [20–22]. The method allows us to perform systematic analysis of data on inclusive cross sections of hadrons, direct photons, and jets in different kinematic conditions. The scaling function $\psi(z)$ and the scaling variable z are expressed via experimentally measurable quantities (inclusive and total inelastic cross sections, multiplicity density, momenta and masses of colliding and produced particles) using some parameters which allow physical interpretation. The shape of the scaling function was found to be independent of the collision energy, multiplicity density of particles, detection angle, and hadron type including the production of particles with heavy flavor content. A power behavior of the function $\psi(z) \sim z^{-\beta}$ was established in the high-z (high-p_T) range. At low z (low-p_T), a saturation of the scaling function was found down to a value of $z \simeq 10^{-3}$ [15, 21]. It was concluded that z scaling reflects self-similarity of the hadron structure, interaction of the constituents, and hadronization process. The analyzed experimental data cover a wide range of the collision energies, transverse momenta, and angles of the produced particles. The energy, angular, and multiplicity independence of the scaling function $\psi(z)$ gives strong constraints on the values of the parameters c, δ, and ϵ entering into the definition of z. The single parameter c which controls the behavior of $\psi(z)$ at low z is interpreted as a «specific heat» of the produced medium associated with the production of an inclusive particle. The scaling in pp and $p\bar{p}$ collisions is consistent with a constant value of $c = 0.25$. Possible change of this parameter is assumed to be an indication of a phase transition of the matter produced in high energy collisions. The structure of the interacting objects at high momenta is characterized by a parameter δ interpreted as nucleon fractal dimension. The scaling is consistent with a constant value of $\delta \simeq 0.5$ for all types of the analyzed inclusive hadrons. The fragmentation process is parameterized in terms of the fragmentation dimension ϵ_F which increases with the hadron mass.

In the present paper, we analyze the data [1] on transverse momentum spectra of top-quark production in $p\bar{p}$ collisions at the energy $\sqrt{s} = 1960$ GeV in the middle rapidity range obtained by the D∅ Collaboration at the Tevatron. The measurements select events with an isolated lepton with a transverse momentum p_T of at least 20 GeV and a pseudorapidity of $|\eta| < 1.1(e + \mathrm{jets})$ or $|\eta| < 2.0(\mu + \mathrm{jets})$. A cut on the missing transverse energy of 20 GeV is applied. Furthermore, at least four jets are required with $p_T > 20$ GeV/c and $|\eta| < 2.5$, an additional cut of $p_T > 40$ GeV/c is applied for the leading jet. Finally, at least one jet needs to be identified as a b jet. For the reconstruction of the event kinematics additional constraints are used: the masses of the two W bosons are constrained to 80.4 GeV. The masses of the two reconstructed top quarks are assumed to be equal.

The results on the top-quark production are compared with other Tevatron data [23–25] on $J/\psi, D^0, B$, and Υ particle spectra at $\sqrt{s} = 1960$ and 1800 GeV in the z presentation. We verify flavour independence of $\psi(z)$ including the inclusive top-quark measurements in this region. The microscopic scenario of hadron production in the z-scaling approach is used to estimate the energy loss and recoil mass at a constituent level in dependence on the transverse momentum of the inclusive particle. This gives specific dependencies of the momentum fraction x_1 characteristic for different types of the produced hadrons. The p_T behavior of the fraction x_1 for the top quark is compared with other particles.

We anticipate that systematic measurements of the inclusive differential spectra of the top quark as a function of the transverse momentum at LHC energies could give new information on self-similarity of the heavy flavour production in the superhigh energy domain.

2. z SCALING

Here we follow to the basic ideas of the z-scaling concept [14, 15]. The collision of extended objects (hadrons, nuclei) at sufficiently high energies is considered as an ensemble of individual interactions of their constituents (partons, quarks, gluons). Structures of the colliding objects are characterized by the parameters δ_1 and δ_2. The constituents of the incoming objects (hadrons or nuclei) with masses M_1, M_2 carry the fractions x_1, x_2 of their momenta P_1, P_2. The inclusive particle has a fraction (denoted by y_a) of the momentum of the object produced in the constituent collision in the observed direction. Its fragmentation is characterized by a parameter ϵ_a. The fragmentation in the recoil direction is described by a parameter ϵ_b and the momentum fraction y_b. Multiple interactions of the constituents are considered to be similar. This property reflects a self-similarity of the hadron interactions at the constituent level.

2.1. Momentum Fractions x_1, x_2, y_a, and y_b. The elementary subprocess is considered to be a binary collision of the constituents with masses x_1M_1 and x_2M_2 resulting in the scattered and recoil objects with masses m/y_a and $x_1M_1+x_2M_2+\bar{m}/y_b$ in the final state. The produced secondary objects transform into real particles after the constituent collisions. The registered particle with mass m and 4-momentum p is produced with its hadron counterpart with mass $\bar{m}$ carrying the momentum fractions y_b of the produced recoil. The momentum conservation law of the constituent subprocess is written in the form

$$(x_1P_1 + x_2P_2 - p/y_a)^2 = M_X^2, \tag{1}$$

with the recoil mass $M_X = x_1M_1 + x_2M_2 + \bar{m}/y_b$. The production of the associated particle with mass $\bar{m}$ ensures conservation of the additive quantum numbers. Equation (1) is an expression of the locality of the hadron interaction at a constituent level. It represents a kinematic constraint on the momentum fractions x_1, x_2, y_a, and y_b which determine the underlying elementary subprocess.

Structure of the colliding objects and fragmentation of the systems formed in the scattered and recoil directions are characterized by the parameters δ_1, δ_2, and ϵ_a, ϵ_b, respectively. The parameters δ_1, δ_2, and ϵ_a, ϵ_b are connected with the corresponding momentum fractions by the function

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\epsilon_a}(1-y_b)^{\epsilon_b}. \tag{2}$$

The quantity Ω is proportional to the relative number of all such constituent configurations in the inclusive reaction, which contain the configuration defined by the fractions x_1, x_2, y_a, and y_b. The Ω plays the role of a relative volume which occupies these configurations in the space of the momentum fractions. The parameters δ_1, δ_2, and ϵ_a, ϵ_b are interpreted as fractal dimensions in the parts of the space of the momentum fractions which correspond to the colliding objects and fragmentation processes, respectively. For given values of δ_1, δ_2, and ϵ_a, ϵ_b, the fractions x_1, x_2, y_a, and y_b are determined in a way to maximize the function Ω, simultaneously fulfilling the condition (1).

In the case of pp ($p\bar{p}$) interactions, we have $M_1 = M_2 = m_N$ and set $\delta_1 = \delta_2 \equiv \delta$. We assume that the fragmentation of the objects moving in the scattered and recoil directions can be described by the same parameter $\epsilon_a = \epsilon_b \equiv \epsilon_F$ which depends on the type of the inclusive particle. The relation $m = \bar{m}$ is used for each particle species. Values of the parameters δ, and ϵ_F are determined in accordance with the self-similarity requirements and the experimental data. They were found to have constant values in pp and $p\bar{p}$ collisions at high energies.

2.2. Scaling Variable z and Scaling Function $\psi(z)$. The self-similarity of hadron interactions reflects the property that hadron constituents and their interactions are similar. The self-similarity variable z is defined as follows

$$z = z_0 \Omega^{-1}, \tag{3}$$

where $z_0 = \sqrt{s_\perp}/(dN_{ch}/d\eta|_0)^c \, m_N$, and Ω is maximal value of (2) with the condition (1). For a given inclusive reaction the quantity z is proportional to the transverse kinetic energy $\sqrt{s_\perp}$ of the constituent subprocess consumed for the production of the inclusive particle and its counterpart with masses m and $\bar{m}$, respectively. The quantity $dN_{\mathrm{ch}}/d\eta|_0$ is the corresponding multiplicity density of charged particles in the central region of the reaction at the pseudorapidity $\eta = 0$. The parameter c characterizes properties of the produced medium. It is interpreted as a «specific heat» of the medium in the state with the respective value of $dN_{\mathrm{ch}}/d\eta|_0$. The constant m_N is the nucleon mass.

The scaling function $\psi(z)$ is expressed in terms of the experimentally measured inclusive cross section $Ed^3\sigma/dp^3$, the multiplicity density $dN/d\eta$, and the total inelastic cross section σ_{inel} as follows [14]:

$$\psi(z) = -\frac{\pi s}{(dN/d\eta)\sigma_{\mathrm{inel}}} J^{-1} E \frac{d^3\sigma}{dp^3}, \tag{4}$$

where s is the square of the center-of-mass energy, and J is the corresponding Jacobian. The multiplicity density $dN/d\eta$ in (4) depends on the center-of-mass energy, centrality, and on the production angles at which the inclusive spectra were measured. The above expression can be rewritten in the central interaction region in the form

$$\psi(z) = \frac{1}{N\sigma_{\mathrm{inel}}} \left(\frac{dz}{dp_T}\right)^{-1} \frac{d\sigma}{dp_T}. \tag{5}$$

The scaling function is normalized as follows

$$\int_0^\infty \psi(z) dz = 1. \tag{6}$$

It allows us to interpret $\psi(z)$ as a probability density of the production of an inclusive particle with the corresponding value of the variable z.

3. FLAVOR INDEPENDENCE OF $\psi(z)$ AND SELF-SIMILARITY OF TOP PRODUCTION

The flavour independence of hadron production means that spectra of particles with the different flavour content can be described by an universal scaling function $\psi(z)$ in z presentation [14,15]. Our previous analysis was based on the observation that simultaneous energy, angular, and multiplicity independence of the z scaling for negative pions, kaons, and antiprotons produced in proton–proton collisions gives the same shape of the scaling function. The flavor independence of $\psi(z)$ was confirmed also for other inclusive particles including the heavy quarkonia, J/ψ [23], and Υ [25], measured at the Tevatron energies $\sqrt{s} = 1960$ and 1800 GeV. The property is observed for very small values of $z \simeq 10^{-3}$. In the region $z \lesssim 0.1$ we observe a saturation of the scaling function $\psi(z)$ which can be approximated by a constant.

In the present paper, we analyze the data [1] on differential cross section of top-quark production measured by the DØ Collaboration at the Tevatron as a function of the transverse momentum p_T at middle rapidity. We show that the flavor independence of the z presentation of hadron spectra is valid for the top-quark production as well. We exploit the scaling transformation

$$z \to \alpha_F z, \quad \psi \to \alpha_F^{-1}\psi \tag{7}$$

for comparison of the shape of the scaling function $\psi(z)$ for different hadron species. The parameter α_F is scale-independent quantity. The transformation does not change the shape of $\psi(z)$. It preserves the normalization equation (6) and does not destroy the energy, angular, and multiplicity independence of the z presentation of particle spectra.

Figure 1, *a* shows the z presentation of the spectra of heavy hadrons (J/ψ, D^0, B, and Υ) [23–25] obtained in $p\bar{p}$ collisions at the Tevatron energies $\sqrt{s} = 1960$ and 1800 GeV in the central rapidity region. The experimental data are shown by

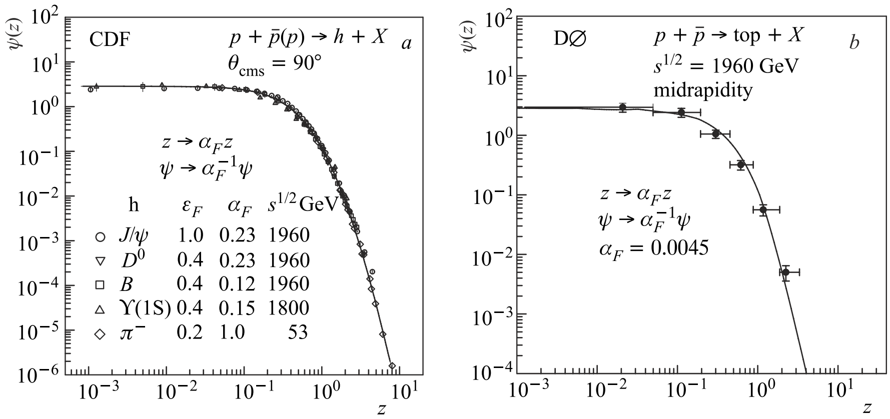

Fig. 1. The flavor independence of z scaling. The spectra of $J/\psi, D^0, B, \Upsilon$ mesons (*a*), and top-quarks (*b*) produced in $p\bar{p}$ collisions at the Tevatron in z presentation. The spectra of π^- mesons were measured in pp collisions at ISR. Data are taken from [1,23–26]. The solid line in Fig. 1, *b* is the same as in Fig. 1, *a*

symbols. The data include measurements up to small transverse momenta ($p_T \simeq$ 125 MeV/c for charmonia, $p_T \simeq 290$ MeV/c for bottomia, and $p_T \simeq 500$ MeV/c for B mesons). Data on π^--meson spectra at $\sqrt{s} = 53$ GeV [26] are used as a reference data. As is seen from Fig. 1, a, the scaling function is the same for hadrons with light and heavy flavors produced in pp and $p\bar{p}$ collisions in the range $z = 0.001-4$. This is indicated by the solid line. One can see that the distributions of different hadrons are sufficiently well described by a single curve over a wide z range (0.001–10). The function $\psi(z)$ changes more than six orders of magnitude in this region. The values of the parameters α_F and ϵ_F shown in this figure are consistent with the energy, angular, and multiplicity independence of the z presentation of spectra for different hadrons. The parameters were found to be independent of kinematic variables ($\sqrt{s}, p_T$, and $\theta_{\rm cms}$). The scale factors α_F are constants which allow us to describe the z presentation of spectra for different hadron species by a single function. The collapse of data points onto a single curve corresponds to the estimated errors of α_F at the level of 20%.

Figure 1, b demonstrates results of analysis of the Tevatron data [1] on top-quark spectra measured by the D∅ Collaboration in $p\bar{p}$ collisions at the energy $\sqrt{s} = 1960$ GeV and the central rapidity range in z presentation. The solid line is the same curve as depicted in Fig. 1, a. The scaling function $\psi(z)$ for the top-quark distribution was calculated according to Eq. (5). The vertical errors are given by quadratic sum of the statistical uncertainties and the systematic uncertainties on the shape of the cross section in each p_T bin. The horizontal errors refer to the width of the bins. The condition (6) is satisfied with the normalization $N\sigma_{\rm inel} = n\sigma_{t\bar{t}}$ and $n = 2$. This corresponds to two entries per event with the total normalized to the $t\bar{t}$-production cross section $\sigma_{t\bar{t}} = 8.31$ pb [1]. The values of the fractal dimension $\delta = 0.5$ and «specific heat» $c = 0.25$ are the same as used in the previous analyses of the inclusive spectra [14, 15, 20]. We have set $\epsilon_{\rm top} = 0$ in the case of the top quark as no energy loss is assumed in the elementary $t\bar{t}$-production process. This choice corresponds to $y_a = y_b = 1$ in the whole p_T range. The value of α_F in the transformation (7) is found to be $\alpha_{\rm top} \simeq 0.0045$. No additional parameters were used.

As seen from Fig. 1, b, the z presentation of the top-quark transverse momentum distribution follows the shape of the z scaling in pp ($p\bar{p}$) collisions for other particles sufficiently well. Though the top spectrum is in the limited kinematic region and the error bars of the data are large enough, we would like to stress that existing analyses were performed with p_T distributions of the inclusive cross sections $Ed^3\sigma/dp^3$ which reveal strong dependence on the energy, angle, multiplicity, and type of the produced particles. Based on the above comparison, we conclude that the Tevatron data on inclusive spectra of the top-quark production measured by the D∅ Collaboration support the flavor independence of the scaling function $\psi(z)$ over a range of $z = 0.02 - 2$. This result gives us indication on self-similarity of top-quark production in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV.

The method of determination of the momentum fractions allows us to analyze kinematics of the constituent interactions in the framework of the developed approach. Unlike for other particles, the null value of $\epsilon_{\rm top}$ means that the energy loss of the top-quark production is zero or negligible. This is expressed by condition $y_a = y_b = 1$ and by the value of the recoil mass M_X which is practically equal to the mass of the top quark.

The kinematics of the underlying subprocess is fully determined by the momentum fractions x_1 and x_2 in this case. The fractions x_1 and x_2 characterize the amount of the energy (momentum) of the incoming protons (antiprotons) carried by the interacting constituents which underlay production of the inclusive particle. In the general case of other particles, x_1 and x_2 are specific functions of y_a and y_b [14]. For the central interaction region, x_1 and x_2 are equal each other. A comparison of the fraction x_1 for the top-quark production with other heavy particles is shown in Fig. 2. The illustration is presented as a function of the scaled transverse momentum p_T/m. One can see a growth of x_1 with p_T/m. The value of x_1 is larger for the production of heavy particles as compared with light ones. The exception for J/ψ meson was observed and discussed in [15]. It is a consequence of the relatively large value of $\epsilon_{J/\psi} \simeq 1$ connected with extra large dissipation of energy in the final state by production of this particle. For a fixed value of p_T/m, the fraction x_1 decreases as the collision energy $\sqrt{s}$ increases. The kinematic limit of the reaction $P_1 + P_2 \to p + X$ corresponds to $x_1 = x_2 = 1$ at any collision energy and for any type of the inclusive particle.

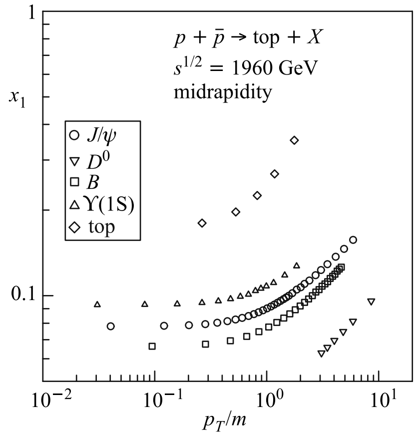

Fig. 2. The momentum fraction x_1 as a function of the scaled transverse momentum p_T/m of hadrons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1800, 1960$ GeV in the middle rapidity region

4. CONCLUSIONS

We have presented the results of analysis of the data on inclusive spectra of top-quark production in $p\bar{p}$ collisions at the energy $\sqrt{s} = 1960$ GeV measured by the D∅ Collaboration at the Tevatron. The transverse momentum spectra in z presentation are compared with data obtained for the heavy mesons $J/\psi, D^0, B$, and Υ at the Tevatron energies $\sqrt{s} = 1960$ and 1800 GeV in the central rapidity range.

Based on the results presented here, we conclude that the D∅ data on the transverse momentum distribution of the top-quark production in $p\bar{p}$ collision are in reasonable agreement with flavour independence of the z scaling. The result supports also the energy independence of the scaling function in the middle rapidity region. A tendency to saturation of $\psi(z)$ at low z for top-quark production is demonstrated as well. The momentum fractions x_1 of the incoming protons for the top-quark were compared with the corresponding values for the heavy mesons measured at the Tevatron. Though production of the top-quark is characterized by no energy loss and constant recoil mass $M_X \simeq m_{\rm top}$, the fractions x_1 reveal similar dependencies on the scaled transverse momentum p_T/m as for the heavy mesons characterized by the constituent energy loss and p_T dependent recoil mass M_X in the production subprocess.

We assume that data on top-quark differential inclusive cross section over a wider range of p_T and collision energy $\sqrt{s}$ at the Tevatron and LHC could be of interest for verification of flavor independence of z scaling, self-similarity of top-quark production and search for new physics.

Acknowledgements. These investigations have been supported by the IRP AVOZ10480505, by the Ministry of Education of the Czech Republic, grants LA08002, LA08015.

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Received on February 8, 2012.

Редактор *Э. В. Ивашкевич*

Подписано в печать 12.04.2012.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,75. Уч.-изд. л. 1,05. Тираж 375 экз. Заказ № 57623.

Издательский отдел Объединенного института ядерных исследований
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