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Top-Quark p_T-Spectra at LHC and Flavor Independence of z-Scaling

Mikhail Tokarev[1,a] , and Imrich Zborovsky[2,b]

[1] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[2] *Nuclear Physics Institute, Academy of Sciences of the Czech Republic 250 68 Řež, Czech Republic*

Abstract. New results of analysis of *top*-quark differential cross sections obtained by the CMS and ATLAS Collaborations in pp collisions at the LHC in the framework of z-scaling approach are presented. The spectra are measured over a wide range of collision energy $\sqrt{s} = 7, 8, 13$ TeV and transverse momentum $p_T = 30 - 1000$ GeV/c of *top*-quark using leptonic and jet decay modes. The LHC data on transverse momentum of the *top*-quark spectra are compared with the Tevatron data obtained by the D∅ Collaboration in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ GeV. Flavour independence of the scaling function $\psi(z)$ in pp and $p\bar{p}$ interactions over a wide collision energy range $\sqrt{s} = 19 - 13000$ 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 on self-similarity of *top*-quark production. A tendency to saturation of $\psi(z)$ at low z for *top*-quark is demonstrated. We anticipate that data on low- and high-p_T inclusive spectra of *top*-quark production at 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.

1 Introduction

The *top*-quark is the heaviest known elementary particle. It was discovered at the Tevatron $p\bar{p}$ collider in 1995 by the CDF and D∅ Collaborations [1, 2] at a mass of around 170 GeV. The first measurements of the differential cross section as a function of the transverse momentum of the *top*-quark were presented by the D∅ Collaboration in [3]. It is expected that *top* physics is extremely important to search for new and study of known symmetries in high-p_T region. One of them is self-similarity related to scale transformations in the space of momentum fractions. The symmetry related to the ideas of self-similarity of hadron interactions at a constituent level is manifested by the z-scaling [4, 5]. The scaling was used for analysis of inclusive spectra obtained at the accelerators U70, S$\bar{p}$pS, SPS, ISR, Tevatron and RHIC [6, 7]. The scaling is treated as manifestation of self-similarity of the structure of the colliding objects (hadrons or nuclei), the interaction mechanism of their constituents, and the process of fragmentation into real hadrons. In the framework of this approach, the transverse momentum spectra of inclusive particles are described in therms of the scaling function $\psi(z)$ in dependence

[a] e-mail: tokarev@jinr.ru
[b] e-mail: zborovsky@ujf.cas.cz

on self-similarity parameter z. Both are expressed via experimentally measurable quantities (inclusive cross section, multiplicity density, momenta and masses of the colliding and produced particles). The shape of the scaling function was found to be independent of the collision energy, multiplicity density, detection angle and hadron type including production of particles with heavy flavor content. The power behavior $\psi(z) \sim z^{-\beta}$ was established in the high-z (high-p_T) range. At low z (low p_T), a saturation of the scaling function was found [7, 8]. The z-scaling reflects self-similarity of hadron structure, interaction of hadron constituents and hadronization process. The energy, angular, and multiplicity independence of the scaling function $\psi(z)$ gives strong constraints on the values of the model parameters c, δ, and ϵ entering in the definition of z. The parameter c is interpreted as a "specific heat" of the produced medium associated with the production of an inclusive particle. It controls the behavior of $\psi(z)$ at low z. The structure of the colliding protons at high momenta is characterized by the parameter δ interpreted as a fractal dimension. The fragmentation process is described in terms of the fragmentation dimension ϵ_F. Universality of the shape of the scaling function is given by its flavour independence. It means that spectra of particles with different flavour content can be described by the same function $\psi(z)$ with values of z and ψ rescaled by a scale factor α_F.

In the present paper we analyze the data on transverse momentum spectra of *top*-quark production in pp collisions at the energy $\sqrt{s} = 7, 8$ and 13 TeV in the middle rapidity range obtained by the CMS [9–11] and ATLAS [12, 13] Collaborations at the LHC in the framework of z-scaling approach. The results of analysis of the *top*-quark spectra obtained in pp collisions at the LHC are compared with similar spectra [14] measured by the D∅ Collaboration in $\bar{p}p$ collisions at the Tevatron energy $\sqrt{s} = 1.96$ TeV and with the reference curve for π-mesons. We verify the flavor independence of $\psi(z)$ for *top*-quark production in pp collisions in the new kinematic range. A tendency to saturation of $\psi(z)$ for the process at low z is demonstrated. A power-law behavior of $\psi(z)$ at high z is also observed. The measurements of high-p_T spectra of the *top*-quark production at highest LHC energy is of interest for verification of the self-similarity of particle production, understanding flavor origin and search for new physics symmetries with *top*-quark probe.

2 z-Scaling

Here we follow the basic ideas of the z-scaling concept [6, 7]. At sufficiently high energies, a collision of hadrons or nuclei is considered as an ensemble of individual interactions of their constituents (partons, quarks, gluons). Structures of the colliding objects are characterized by parameters δ_1 and δ_2. Interacting constituents carry the fractions x_1, x_2 of the momenta P_1, P_2 of the incoming hadrons (or nuclei). The inclusive particle with mass m carries the fraction y_a of momentum of the produced object in constituent interaction. The object moves in the observed direction and its fragmentation is characterized by parameter ϵ_a. The fragmentation in the recoil direction is described by parameter ϵ_b and the momentum fraction y_b. Multiple interactions of the constituents are considered to be similar. This property reflects self-similarity of hadron interactions at the constituent level.

2.1 Momentum fractions x_1, x_2, y_a, and y_b

The elementary sub-process is considered as 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 $x_1M_1 + x_2M_2 + \overline{m}/y_b$ 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 $\overline{m}$ carrying the momentum fractions y_b of the produced recoil. The momentum conservation law in the constituent sub-process is subject to the condition

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

with the recoil mass $M_X = x_1M_1 + x_2M_2 + \overline{m}/y_b$. The production of associated particle with mass $\overline{m}$ ensures conservation of the additive quantum numbers. The conservation law expresses locality of the hadron interactions 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 sub-process. 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 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 occupy 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 relevant parts of the space 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 $m = \overline{m}$ is used for each particle species. The parameters δ, and ϵ_F are determined in accordance with self-similarity requirements and experimental data. They were found to have constant values in pp and $p\bar{p}$ collisions at high energies.

2.2 Scaling function $\psi(z)$ and self-similarity parameter 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 sub-process consumed on the production of the inclusive particle and its counterpart with masses m and $\overline{m}$, respectively. The quantity $dN_{ch}/d\eta|_0$ is the corresponding multiplicity density of charged particles in the central interaction region at the pseudo-rapidity $\eta = 0$. 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 $dN_{ch}/d\eta|_0$. The constant m_N is the nucleon mass.

The scaling function $\psi(z)$ is expressed in terms of the experimentally measured inclusive cross section $Ed^3\sigma/dp^3$, multiplicity density $dN/d\eta$, and the total inelastic cross section σ_{in} as follows [6]

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

where s is the square of the center-of-mass energy and J is the Jacobian for the transformation from $\{p_T^2, y\}$ to $\{z, \eta\}$. 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 scaling function is normalized as follows

$$\int_0^\infty \psi(z)dz = 1. \tag{5}$$

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 $\psi(z)$

Universality of z-scaling is given by its flavour independence. It means that spectra of particles with the different flavour content can be described by an universal scaling function $\psi(z)$ in z-presentation [6, 7]. Our previous analysis was based on the observation that simultaneous energy, angular, and multiplicity independence of the z-scaling for negative pions, kaons, and anti-protons produced in proton-proton collisions gives the same shape of the scaling function. We exploit the scaling transformation

$$z \to \alpha_F z, \quad \psi \to \alpha_F^{-1}\psi \tag{6}$$

for comparison of the shape of the scaling function $\psi(z)$ for different hadron species. The parameter α_F is a scale dependent quantity. The transformation does not change the shape of $\psi(z)$. It preserves the normalization equation (5) and does not destroy the energy, angular, and multiplicity independence of the z-presentation of particle spectra.

Figure 1(a) shows spectra of negative pions, kaons, antiprotons, and $\Lambda's$ produced in pp collisions over the range $\sqrt{s} = 19 - 200$ GeV and $\theta_{cms} = 3^0 - 90^0$ in z-presentation. The symbols correspond to the data on differential cross sections measured in the central and fragmentation regions. The solid lines represent the same curve shifted by multiplicative factors for reasons of clarity. One can see that the distributions of different hadrons are sufficiently well described by a single curve over a wide z-range. The function $\psi(z)$ changes more than ten orders of magnitude. The indicated values of the parameter ϵ_F are consistent with the energy, angular, and multiplicity independence of z-presentation of particle spectra. The scale factors α_F are constants which allow us to describe the scaling function for different hadron species by a single curve.

Figure 1(b) shows z-presentation of the transverse momentum spectra of strange mesons and baryons measured by the STAR and PHENIX Collaborations in pp collisions at $\sqrt{s} = 200$ GeV in the central rapidity region at the RHIC. The symbols representing data on differential cross sections include baryons which consist of one, two and three strange valence quarks. The multiplicative factors $10^0, 10^{-1}$ and 10^{-2} are used to show the data z-presentation separately for mesons, single-strange $(\Lambda, \Lambda^*, \Sigma^*)$ and multi-strange (Ξ^-, Ω) baryons, respectively. The pion distributions obtained

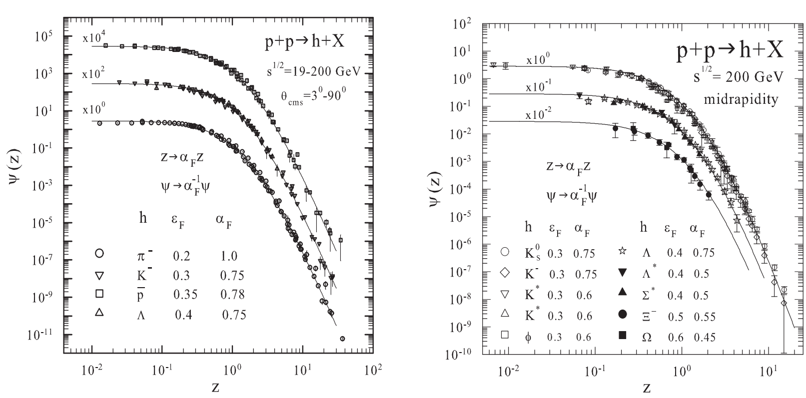

Figure 1. Inclusive spectra of hadrons produced in pp collisions in the z-presentation. The symbols denote the experimental data obtained in the experiments performed at CERN, FNAL, and BNL. The plots are taken from Ref. [7, 15]. The solid line is a reference curve corresponding to π^--meson production in pp collisions.

by the STAR Collaboration are used for comparison as reference points. The shape of $\psi(z)$ for all these particles is described by the same curve (solid line) which is depicted in Fig. 1(a). Based on the obtained results we conclude that the RHIC data confirm the flavor independence of the z-scaling in pp collisions including particles with very small p_T. Next we show that the flavor independence of z-presentation of hadron spectra is valid for the top-quark production as well.

4 Self-similarity of top-quark production

The first analysis of top-quark spectra [3] in the framework of the z-scaling approach was performed in [16]. In the present paper we analyze spectra of top-quark production obtained at the LHC and compare it with data at lower energy from the Tevatron. The differential cross sections were measured in dependence on the top-quark transverse momentum p_T at middle rapidity.

Figure 2 shows the z-presentation of the spectra of top-quark production obtained in pp collisions at the LHC energies $\sqrt{s} = 7, 8$ and 13 TeV in the central rapidity region. The data were obtained by the CMS [9–11] and ATLAS [12, 13] Collaborations. The measurements of the inclusive production cross section were performed in the dilepton and jet channels. The data include measurements over a wide range of the transverse momentum $30 < p_T < 1000$ GeV. The scaling function $\psi(z)$ for the top-quark distributions was calculated according to Eq. (4). Data on π^--meson spectra shown by the solid line serves as a reference data. The values of the fractal dimension $\delta = 0.5$ and the parameter $c = 0.25$ are the same as used in our previous analyses [6, 7, 17]. We have set $\epsilon_{top} = 0$ in the case of the top-quark, as no or negligible 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 scale parameter α_F in the transformation (6) is found to be $\alpha_{top} \simeq 0.0045$. No additional parameters were used.

The new data [14] on spectra of the top-quark production in $p\bar{p}$ collisions obtained by the D∅ Collaboration at the Tevatron energy $\sqrt{s} = 1.96$ GeV are shown for comparison with the data measured at the LHC. As seen from Fig. 2, the scaling function demonstrates the energy independence

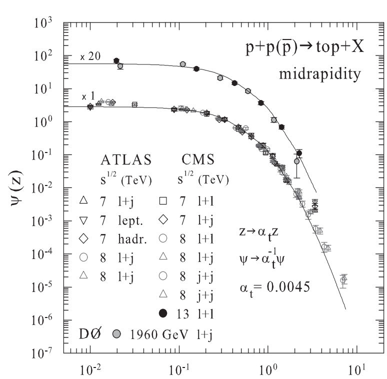

Figure 2. The scaling function $\psi(z)$ of the top-quark production in pp and $p\bar{p}$ collisions at the LHC energies $\sqrt{s} = 7, 8, 13$ TeV and the Tevatron energy $\sqrt{s} = 1.96$ TeV. The symbols denote the experimental data obtained by the CMS, ATLAS and D∅ Collaborations are taken from [9–11],[12, 13] and [14], respectively. The solid line is a reference curve corresponding to π^--meson production in pp collisions.

over a wide range of the self-similarity parameter $z = 0.001 - 8$. The function $\psi(z)$ changes more than five orders of magnitude in this region.

As seen from Fig. 2, 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, we would like to stress that it is compared with existing analyses of p_T-distributions of inclusive cross sections $Ed^3\sigma/dp^3$ for other hadrons which reveal strong dependence on the energy, angle, multiplicity, and type of the produced particles. Based on the above comparison we conclude that the new LHC and Tevatron data on inclusive spectra of the top-quark production support the flavor independence of the scaling function $\psi(z)$ over the interval of $z = 0.001 - 8$. This result gives us indication on self-similarity of top-quark production in pp and $p\bar{p}$ interactions up to the top-quark transverse momentum $p_T < 1000$ GeV and for a wide range of the collision energies $\sqrt{s}$.

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