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M. Tokarev [1], I. Zborovský [2]

TOP-QUARK p_T-SPECTRA AT **CMS** AND FLAVOR INDEPENDENCE OF z-SCALING

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[1] E-mail: tokarev@jinr.ru
[2] Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež, Czech Republic; E-mail: zborovsky@ujf.cas.cz

Токарев М., Зборовский И. E2-2017-2

Спектры рождения топ-кварка на CMS и флейворная независимость z-скейлинга

Представлены результаты анализа, в рамках теории z-скейлинга, дифференциальных сечений рождения топ-кварка в протон-протонных столкновениях, полученных коллаборацией CMS на LHC. Анализируемые спектры измерены в широком диапазоне энергий столкновения $\sqrt{s} = 7$, 8 и 13 ТэВ и поперечного импульса топ-кварка $p_T = 30-500$ ГэВ/c в каналах с рождением лептонов и струй. Проверена флейворная и энергетическая независимость скейлинговой функции $\psi(z)$ в новой кинематической области. Результаты анализа спектров рождения топ-кварка на LHC сравниваются с аналогичными данными, полученными на тэватроне в протон-антипротонных столкновениях при энергии $\sqrt{s} = 1{,}96$ ТэВ. Получены указания о режиме насыщения функции $\psi(z)$ в области малых и степенном поведении в области больших значений z. Отмечается, что измерения спектров рождения топ-кварка при максимальной энергии pp-столкновений на LHC и при больших значениях поперечного импульса кварка представляют интерес для проверки принципа самоподобия в рождении частиц, понимания природы флейвора и поиска новых симметрий в процессах с рожденим топ-кварка в качестве пробника.

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

We present new results of the analysis of top-quark differential cross sections obtained by the CMS Collaboration in pp collisions within the z-scaling approach. The spectra are measured over a wide range of collision energy $\sqrt{s} = 7$, 8, 13 TeV and transverse momentum $p_T = 30-500$ GeV/c of top-quark using leptonic and jet decay modes. Flavor independence of the scaling function $\psi(z)$ is verified in the new kinematic range. The results of analysis of the top-quark spectra obtained at the LHC are compared with similar spectra measured in $p\bar{p}$ collisions at the Tevatron energy $\sqrt{s} = 1.96$ TeV. A tendency to saturation of $\psi(z)$ for the process at low z and a power-law behavior of $\psi(z)$ at high z is observed. The measurements of high-p_T spectra of the top-quark production at the highest LHC energy is of interest for verification of self-similarity of particle production, understanding the flavor origin, and search for new physics symmetries with top-quark probe.

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

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INTRODUCTION

The top-quark was discovered at the Tevatron $p\bar{p}$ collider in 1995 by the CDF and DØ 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 DØ Collaboration in [3]. It is expected that top-quark physics is extremely important to search for new and study known symmetries at high-p_T region. One of them is self-similarity which is related to scale transformations in space of the 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 the analysis of inclusive spectra obtained at the accelerators U70, S$\bar{\text{p}}$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 this approach, inclusive momentum spectra are described in terms of a scaling function $\psi(z)$ and a self-similarity parameter z. Both are expressed via measurable quantities (inclusive cross section, multiplicity density, momenta and masses of 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. A 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 $\psi(z)$ was found [7, 8]. The energy, angular, and multiplicity independence of the scaling function gives strong constraints on the values of the model parameters c, δ, and ϵ_F entering 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 a 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 flavor independence. It means that spectra of particles with different flavor content can be described by the same function $\psi(z)$ with values of z and ψ rescaled by a scale factor α_F.

1. z-SCALING

Here we follow the basic ideas of the z-scaling concept [6, 7]. A collision of extended objects (hadrons, nuclei) is considered at sufficiently high energies as an ensemble of individual interactions of their constituents (partons, quarks, gluons). Structures of the objects are characterized by parameters δ_1 and δ_2. The constituents of the colliding 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 with the mass m 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 self-similarity of hadron interactions at the constituent level.

1.1. Momentum Fractions x_1, x_2, y_a, and y_b. The elementary sub-process 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 $x_1M_1+x_2M_2+\overline{m}/y_b$ 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 of the constituent sub-process is written in the form

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

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

1.2. 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 $z_0 = \sqrt{s_\perp}/[(dN_{\rm ch}/d\eta|_0)^c m_N]$ and Ω is maximal value of (2) with the condition (1). For the given inclusive reaction the quantity z is proportional to the transverse kinetic energy $\sqrt{s_\perp}$ of the constituent sub-process consumed for the production of the inclusive particle and its counterpart with masses m and $\overline{m}$, respectively. The quantity $dN_{\rm ch}/d\eta|_0$ is the corresponding multiplicity density of charged particles in the central region of the reaction 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 $dN_{\rm ch}/d\eta|_0$. The constant m_N is the nucleon mass.

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

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

where J is the Jacobian for the transformation from $\{p_T^2, y\}$ to $\{z, \eta\}$. The scaling function is normalized to unity,

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

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.

2. FLAVOR INDEPENDENCE OF $\psi(z)$

The flavor independence of hadron production means that spectra of particles with the different flavor content can be described by a universal scaling function $\psi(z)$ [6, 7]. Our previous analyses were based on the observation that

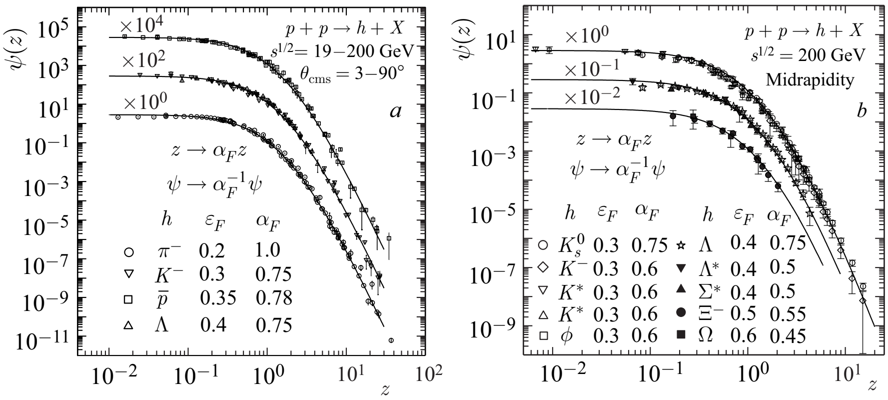

Fig. 1. Inclusive spectra of hadrons produced in pp collisions shown in z-presentation. The symbols correspond to experimental data measured at the CERN, FNAL, and BNL. The plots are taken from [7, 9]. The solid line is a reference curve for π^- mesons

simultaneous energy, angular, and multiplicity independence of the z-scaling for different particles produced in pp collisions gives the same shape of $\psi(z)$. This was obtained for constant values of $\delta = 0.5$, $c = 0.25$, and ϵ_F depending on the type of inclusive hadrons.

Figure 1, a shows the spectra of negative pions, kaons, antiprotons, and Λ's produced in pp collisions over the range $\sqrt{s} = 19{-}200$ GeV and $\theta_{\rm cms} = 3{-}90°$ in the z-presentation [7]. The symbols correspond to data on differential cross sections measured in the central and fragmentation regions. One can see that the distributions of different hadrons are sufficiently well described by a single curve over a wide z-range. 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. For this purpose we exploit the scaling transformation

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

It does not change the shape of $\psi(z)$ in the log-log scale, preserves the normalization equation (5), and does not destroy the energy, angular, and multiplicity independence of the z-scaling.

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 RHIC [9]. The symbols representing data include baryons which consist of one, two, and three strange valence quarks. The z-presentation of the data is shown separately for mesons, single-strange (Λ, Λ^*, Σ^*) and multistrange (Ξ^-, Ω) baryons. The shape of $\psi(z)$ for all these particles is described by the single curve (solid line) which is the same as in Fig. 1, a. Based on the obtained results we have concluded that the RHIC data confirm flavor independence of the z-scaling in pp collisions.

3. SELF-SIMILARITY OF TOP-QUARK PRODUCTION

The first analysis of top-quark spectra [3] within z-scaling approach was performed in [10]. Figure 2, a shows the transverse momentum distribution of top-quark production [11] measured by the CMS Collaboration in pp collisions in the lepton + jets channel at $\sqrt{s} = 7$ TeV. The distribution was obtained in the mid-rapidity region in the range $2 < p_T < 400$ GeV/c. The data were accumulated at the integrated luminosity of 5.0 fb^{-1}.

The diamond symbols in Fig. 2, *b* show the data in z-presentation. The similar data in the lepton + lepton channel [11] are depicted by the empty squares. The solid line corresponding to π^--meson production describes the experimental data well. The scaling variable (3) was calculated with the parameters $\delta = 0.5$ and $c = 0.25$ which are the same as found in our previous analyses of the inclusive spectra [6, 7, 16]. We have set $\epsilon_{\rm top} = 0$ 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 scaling function $\psi(z)$ was calculated according to Eq. (4). An indication on saturation of $\psi(z)$ at $z < 0.3$ for the top-quark distribution is clearly visible. The value of α_F in the transformation (6) is found to be $\alpha_{\rm top} \simeq 0.0045$. No other parameters were used.

Figure 2, c shows the p_T distribution [12] of top-quark production in the lepton + jets channel at the energy $\sqrt{s} = 8$ TeV. The distribution was measured by the CMS Collaboration in the central rapidity region in the range $20 < p_T < 500$ GeV/c. Figure 2, d demonstrates the same data by the triangles down in the z-presentation. The other symbols correspond to the CMS data [12] in the dilepton (squares), low-p_T (circles), and high-p_T (triangles up) jet + jet decay modes. The scaling function for π^- mesons is depicted by the solid line. As seen from Fig. 2, *d*, the function $\psi(z)$ changes more than five orders of magnitude in the region $10^{-2} < z < 8$. A deviation of the data points from the solid line at $z > 2$ is visible. At low $z < 0.3$, the effect of saturation of $\psi(z)$ becomes apparent.

Figure 2, e shows the p_T distribution [14] of top-quark production in the dilepton channel at the energy $\sqrt{s} = 13$ TeV. The distribution was measured by the CMS Collaboration in the central rapidity region in the range $20 < p_T < 500$ GeV/c. The data were accumulated at an integrated luminosity of 2.2 fb^{-1}. Figure 2, *f* demonstrates the same data in z-presentation by the black circles. The LHC data are compared with new data [15] on the top-quark production spectra in $p\bar{p}$ collisions obtained by the DØ Collaboration at the energy $\sqrt{s} = 1.96$ TeV. The z-presentation of the spectrum obtained at the Tevatron is shown by the triangles down in Fig. 2,*f*. The solid line corresponding to π^--meson production in pp collisions describes the experimental data well. There is also an indication of power behavior at low and high z.

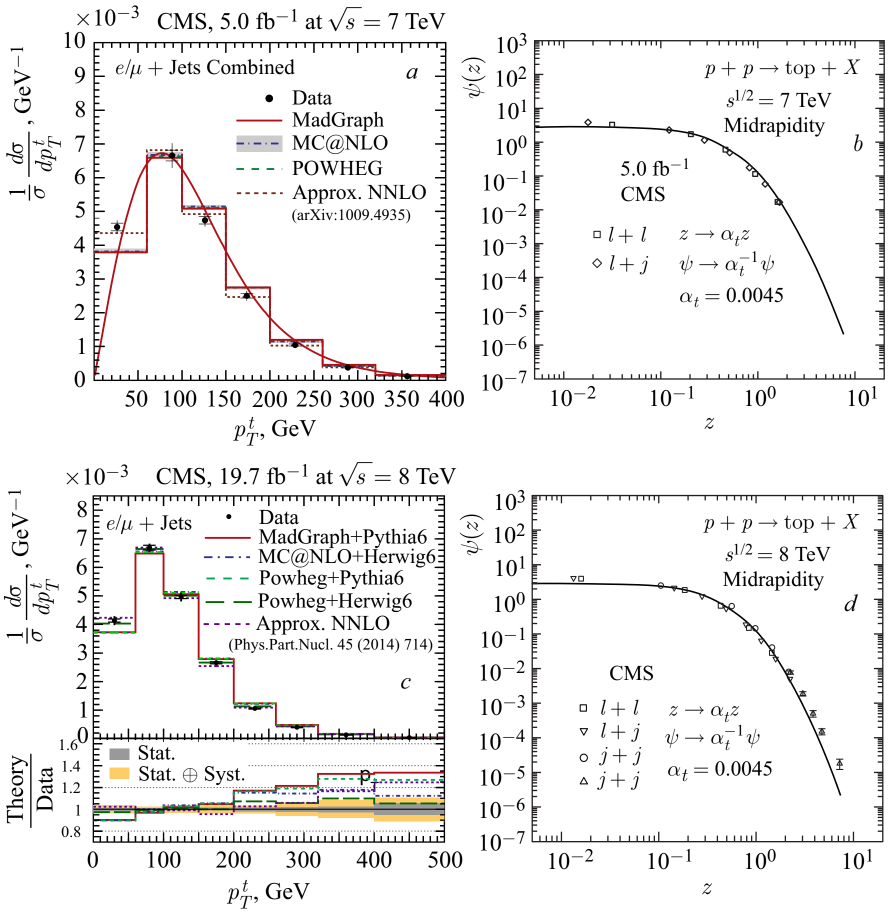

Fig. 2. The normalized differential $t\bar{t}$ production cross section using quoted decay modes in dependence on top-quark transverse momentum at $\sqrt{s} = 7$ TeV [11] (*a*), $\sqrt{s} = 8$ TeV [12] (*c*), and $\sqrt{s} = 13$ TeV [14] (*e*). The scaling function $\psi(z)$ of top-quark production in the indicated combinations of leptonic (l) and jet (j) decay channels at $\sqrt{s} = 7$ TeV (*b*), $\sqrt{s} = 8$ TeV (*d*), and $\sqrt{s} = 13$ TeV (*f*). Experimental data at $\sqrt{s} = 1.96$ TeV are from [15]. The solid line is a reference curve for π^--meson production in pp collisions

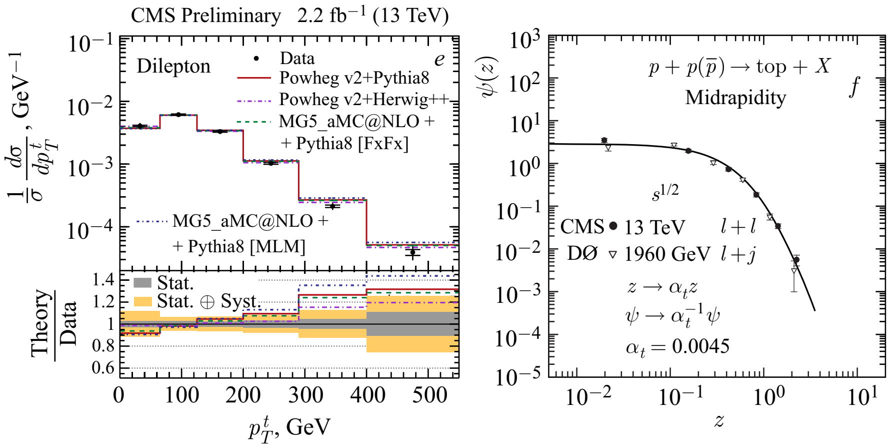

Fig. 2. (continued)

The scaling of the CMS and DØ data on top-quark production at different energies is summarized in Fig. 3. If taking into account wide p_T-bins (not shown in the figure), one can see that z-presentation of the top-quark transverse momentum distribution follows the shape of the z-scaling for other particles in pp collisions sufficiently well. Though the top spectrum is in the limited kinematic region, it is compared with $\psi(z)$ for π^- mesons, which is consistent with the z-scaling for other hadrons. We would like to stress that existing analyses were performed with p_T distributions which depend strongly on the energy, angle, multiplicity, and type of the produced particles. Based on the above comparison, we conclude that recent LHC and Tevatron data on inclusive spectra of the top-quark produc-

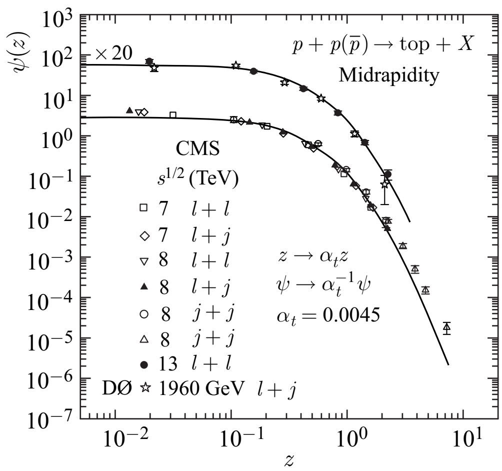

Fig. 3. The scaling function $\psi(z)$ of the top-quark production in pp and $p\bar{p}$ collisions at LHC energies $\sqrt{s} = 7$, 8, 13 TeV and Tevatron energy $\sqrt{s} = 1.96$ TeV. The symbols correspond to experimental data obtained by the CMS [11–14] and DØ [15] Collaborations. The solid line is a reference curve corresponding to π^--meson production in pp collisions

tion give new indication on flavor independence of the scaling function $\psi(z)$ over the range of $z = 0.01{-}8$.

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141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/