TOP QUARK p_{rmT}-SPECTRA AT TEVATRON AND LHC: FLAVOR INDEPENDENCE OF z-SCALING*

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New LHC data on top quark p_{T}-spectra obtained by the CMS Collaboration in pp collisions at $\sqrt{s} = 7000$ GeV are analyzed in the framework of z-scaling. The results are compared with DØ data on top quark differential cross section measurements at the Fermilab Tevatron collider at $\sqrt{s} = 1960$ GeV. 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 on self-similarity of top quark production. A tendency to saturation of $\psi(z)$ at low z for the top quark is demonstrated.

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1. Introduction

Measurements and properties of top quark production cross sections have played a major role in testing the Standard Model (SM) and in searches for new physics [1–8]. Launch of the Large Hadron Collider (LHC) opens a new realm for top quark physics [9, 10]. For the first time, the $t\bar{t}$ pair production rate is sufficiently high to determine differential cross sections as a function of top quark transverse momentum with high precision [11]. It is noted that these measurements are vital to verify the top quark production mechanism at a new energy scale within the scope of the SM and perturbative quantum chromodynamics (QCD).

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In the present paper, we analyse the new data [11] on differential cross section of top quark production in pp collisions at $\sqrt{s} = 7000$ GeV obtained by the CMS Collaboration 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^0_{S}-meson [17], and jet [18, 19] production were presented in [20–22]. 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 $\psi(z)$ was found to be independent of the collision energy, multiplicity density and detection angle of inclusive particles. A power behaviour $\psi(z) \sim z^{-\beta}$ 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 its constituents and hadronization process. Analyses of experimental data show that the scaling function $\psi(z)$ has the same shape for different hadron species including the production of particles with heavy flavour content (from π mesons up to Υ particle). The property is called flavour independence of z-scaling.

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 DØ Collaborations [23, 24] at a mass of around 170 GeV. First data on the top quark transverse momentum distribution have been obtained at the energies $\sqrt{s} = 1800$ and 1960 GeV [25, 26]. The CMS Collaboration presented [11] differential cross sections of $t\bar{t}$ pair production in pp collisions at $\sqrt{s} = 7000$ GeV. The measurements were performed in the fully leptonic (electrons and muons) and the semileptonic (single electron and muon with jets) $t\bar{t}$ decay channels. The differential distributions were measured as function of the transverse momentum, (pseudo-)rapidity and invariant mass of the final state leptons, top quarks and the $\bar{t}t$ system in the visible phase space.

The experimental data give us unique possibility to test properties of the z-scaling using the top quark as a new probe. We anticipate that systematic measurements of inclusive spectra of the top quarks as a function of the transverse momentum could give important information on self-similarity of heavy flavour production in the LHC energy range and allow us to study the flavour independence of particle production at small scales ($\sim 10^{-4}$fm).

2. z-scaling

Here, we remind some 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 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 momentum fraction (denoted by y_a) of the object produced in the underlying constituent collision in the observed direction. Its fragmentation is characterized by a parameter ϵ_a. The fragmentation in the recoil direction is described by 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.

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) 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 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 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 these configurations occupy 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 this space and 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 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 $\epsilon_a = \epsilon_b \equiv \epsilon_{\rm F}$ depending on the type of the inclusive particle. Values of the parameters δ, and $\epsilon_{\rm F}$ are determined in accordance with the self-similarity requirements. They were found to have constant values in pp and $p\bar{p}$ collisions at high $\sqrt{s}$. The relation $m = \overline{m}$ is used for all particle species.

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 a 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”. 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 $\sigma_{\rm inel}$ as follows [14]

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

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 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 top quark production

The flavour independence of hadron production means that spectra of particles with the different flavour content can be described by a 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 anti-protons produced in proton–proton collisions gives the same shape of the scaling function (see Fig. 1 (a)). The flavour independence of $\psi(z)$ was confirmed also for other inclusive particles including the heavy quarkonia J/ψ [27] and Υ [28] measured at the energies $\sqrt{s} = 1960$ and 1800 GeV (see Fig. 1 (b)). The scaling transformation $z \to \alpha_F z,\ \ \psi \to \alpha_F^{-1}\psi$ was used for comparison of the shape of the scaling function for different hadron species. The parameter α_F is scale independent quantity. The transformation does not change the shape of $\psi(z)$ and preserves the normalization equation (5). A saturation of $\psi(z)$ is valid in the region $z < 0.1$, where the scaling function can be approximated by a constant. This property is observed up to very small values of $z \simeq 10^{-3}$.

We have analysed [29] the Tevatron data [26] on top quark spectra measured by the DØ Collaboration in $p\bar{p}$ collisions at the energy $\sqrt{s} = 1960$ GeV using the z-scaling approach. Figure 1 (c) demonstrates results of the analysis in 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. (4). The condition (5) is satisfied with the normalization $N\sigma_{\mathrm{inel}} = n\sigma_{t\bar{t}}$ 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 [26]. 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 $\epsilon_{\mathrm{top}} = 0$ 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 is found to be $\alpha_{\mathrm{top}} \simeq 0.0045$. No additional parameters were used.

Figure 1 (d) shows CMS data [11] on top quark spectra in pp collisions at the energy $\sqrt{s} = 7000$ GeV and the central rapidity range in z-presentation. The normalized differential cross sections for the top quark pair production were measured using a dataset recorded in 2011 and corresponding to the integrated luminosity of $L = 1.14 \pm 0.05$ fb^{-1}. The measurements were performed in the semileptonic (e+jets and μ +jets) and dileptonic ($\mu^+\mu^-, e^+e^-$ and $\mu^\pm e^\mp$) final states. Events with top quark pair candidates are selected by requiring the isolated leptons and jets with high transverse momenta. The $t\bar{t}$ candidates themselves and their kinematic properties were obtained with algorithms that reconstruct the event topology. The measured differential cross section distributions are normalized to unity.

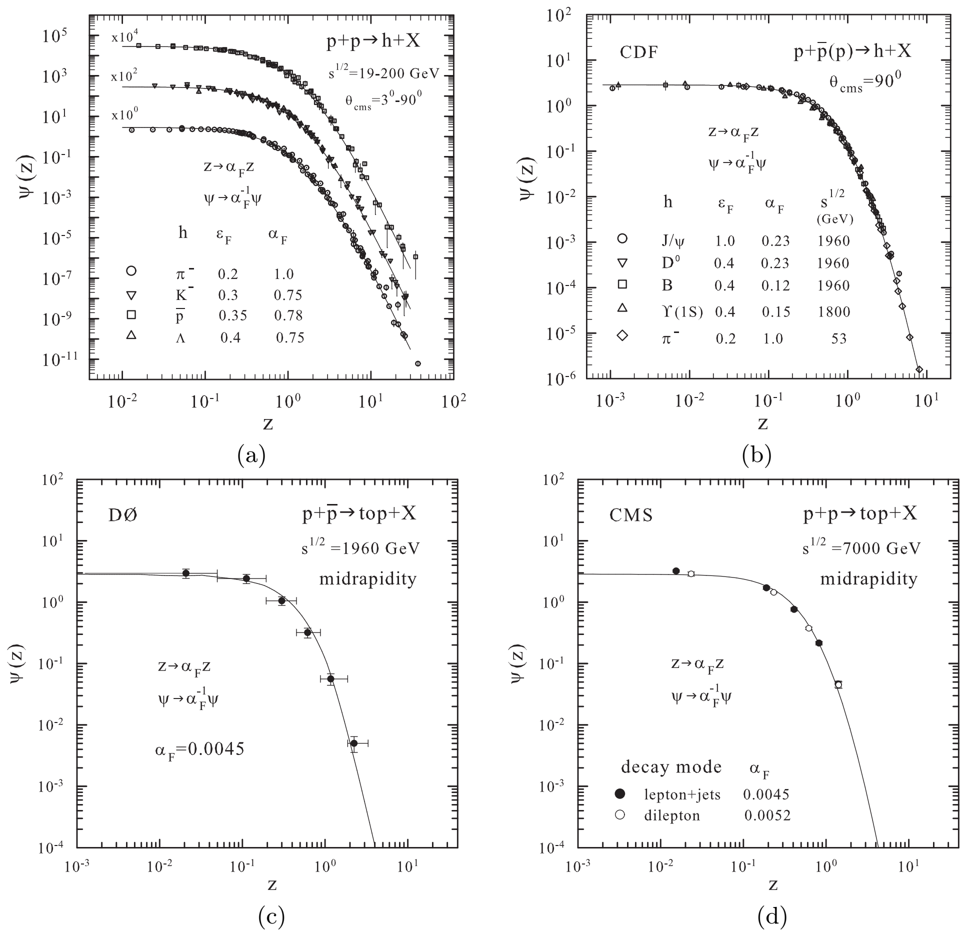

Fig. 1. The flavour independence of z-scaling. The spectra of (a) π^-, K^-, $\bar{p}$, Λ hyperon, (b) J/ψ, D^0, B, Υ mesons, and top quarks produced in (c) $p\bar{p}$ collisions at the Tevatron at $\sqrt{s} = 1960$ GeV, and (d) in pp collisions at the LHC at $\sqrt{s} = 7000$ GeV in z-presentation. The spectra of π^- mesons were measured in pp collisions at ISR. Data are taken from [26–28, 30, 31]. The solid lines shown in Fig. 1 (b)–(d) are the same as in Fig. 1 (a).

As seen from Fig. 1 (d), the data for both decay channels (solid and open circles) are in agreement with the z-scaling curve shown by the solid line. The curve follows the shape of the z-scaling in pp ($p\bar{p}$) collisions for other particles shown in Figs. 1 (a) and 1 (b). The CMS data are consistent with the same values of $\delta, \epsilon_{\rm top}$ and c as found from the analysis of the top spectra in $p\bar{p}$ collisions. The parameter $\epsilon_{\rm top} = 0$ corresponds to zero (or negligible) constituent energy loss in the top quark production with $y_a = y_b = 1$ in the whole p_T range. The values of α_F are found to be $\alpha_{top} \simeq 0.0045$ and 0.0052 for lepton+jet and dilepton decay channels, respectively. The onset of saturation of $\psi(z)$ is confirmed in the low z region for the heaviest known elementary particle at the energy $\sqrt{s} = 7000$ GeV.

We conclude based on the above results that the Tevatron and LHC data on inclusive spectra of the top quark production measured by the DØ and CMS Collaborations support flavour independence of the scaling function $\psi(z)$ over a range of $z = 0.02$–2. The data are consistent with energy independence of the z-scaling and give us indication on self-similarity of the top quark production in $p\bar{p}$ and pp collisions at $\sqrt{s} = 1960$ and 7000 GeV.

4. Conclusions

We have shown results of our analysis of the first data [11] on inclusive spectra of top quark production in pp collisions measured by the CMS Collaboration at the energy $\sqrt{s} = 7000$ GeV. The z-presentation of the transverse momentum spectra obtained at the LHC are compared with data for the light and heavy mesons (including J/ψ, D^0, B, and Υ) in pp and $p\bar{p}$ collisions at the RHIC and Tevatron energies $\sqrt{s}$ =200, 1800 and 1960 GeV in the central rapidity region.

Based on the results presented here, we conclude that the CMS data on top quark production in pp collision are in reasonable agreement with flavour independence of the z-scaling found before. The top quark p_T-distributions measured at the Tevatron and LHC support energy independence of the scaling function in the middle rapidity region for the heaviest known elementary particle. A tendency to saturation of $\psi(z)$ at low z for top quark production is demonstrated as well. We assume that data on top quark differential inclusive cross section over a wider range of transverse momentum and collision energy at the LHC could be of interest for verification of flavour independence of the z-scaling, self-similarity of heavy quark production and search for new physics.

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