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z-SCALING OF JET PRODUCTION
AT THE TEVATRON

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Токарев М. В., Дедович Т. Г.   E2-2004-188
z-скейлинг в рождении струй на тэватроне

Анализируются новые данные, полученные коллаборациями CDF и D0, по рождению струй на тэватроне (сеанс II) в рамках z-скейлинга. Обсуждаются свойства z-представления этих данных. Обосновывается интерпретация скейлинговой функции как плотности вероятности рождения частицы на длине формирования z. Отмечается, что величина z обладает свойством фрактальной меры. Показано, что эти экспериментальные данные подтверждают z-скейлинг.

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New data on jet production obtained by the CDF and D0 Collaborations at the Tevatron (Run II) are analyzed in the framework of z-scaling. Properties of data z-presentation are discussed. Physics interpretation of the scaling function $\psi(z)$ as a probability density to produce a particle with the formation length z is argued. The quantity z is noted to have a property of fractal measure. These experimental data are shown to confirm z-scaling.

INTRODUCTION

The production of very large transverse momentum hadron jets in hadron–hadron collisions at high energies at SpS (CERN) observed by UA2 and UA1 Collaborations confirming the hints of jet production in the experiment of AFS Collaboration at ISR was a convincing experimental proof of quarks and gluons existence confirming the theory of strong interaction — Quantum ChromoDynamics (QCD). The wide study of the phenomena is performed in $\bar{p} - p$ collisions at the highest energy at the Tevatron [1, 2].

Jets are experimentally observed as a strong correlated group of particles in space–time which are copiously produced at hadron colliders. They are result of hard scattering of quarks and gluons and their subsequent transformation into real particles.

New era of QCD precision measurements is starting at hadron colliders RHIC, Tevatron and LHC. The study of the energy and angular dependencies of jet and dijet cross sections, invariant mass distribution of jets, structure and content of jets and their fragmentation properties is considered to give enough information both for verification of the theory (QCD and SM) and search for new physics phenomena in new kinematical domain.

Fragmentation of partons into hadrons is one of the least understanding feature of QCD. Even though the primary scattering process is described in term of perturbative QCD the hadronization chain contains very low, respective to the parent parton, $p_{\perp}$ hadrons. Therefore the whole process is clearly a non-perturbative phenomena involving final-state interactions which have to conserve color and baryon number. The quarks and gluons carry color charge and are essentially massless in the theoretical calculations. A hadron jet has no color charge and often large invariant mass. Thus jets are ambiguous objects and should be treated in such a way that these unavoidable ambiguities do not play an important role [3].

A search for general properties of jet production in hadron–hadron collisions is of great interest, especially in connection with commissioning such large accelerators of nuclei and proton as the RHIC at BNL and the LHC at CERN. The main physical goals of the investigations at these colliders are to search for and study Quark Gluon Plasma (QGP) — the hot and extremely dense phase of the nuclear matter, Higgs boson and particles of new generation predicted by supersymmetry theories, and to understand origin of the proton spin.

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Jets are traditionally considered to be one of the good probes for study the hard interaction between quarks and gluons in the surrounding nuclear matter and search for indication on phase transition. Jet production in collisions of polarized protons at the RHIC give a new tool for study of enigmatical Nature of particle spin as well.

In our work we present the results of analysis of new data on jet production obtained by the CDF and D0 Collaborations at the Tevatron in Run II in the framework of z-scaling concept. The concept is based on the fundamental principles such as self-similarity, locality and fractality of structure of colliding objects, interaction of their constituents and mechanism of particle formation.

The scaling function $\psi(z)$ and scaling variable z used for presentation of experimental data are expressed via the observable quantities, such as an inclusive cross section and multiplicity density. The function ψ has simple physical interpretation as the probability density to form a jet with formation length z.

We would like to emphasize that the properties of z-presentation for jet production give evidence on fractality of jet formation mechanism at very small scale up to 10^{-4} fm. This is the region where the geometry of space–time itself could play an important role for search for general regularities of all fundamental interactions.

The results of our new analysis are found to be in good agreement with the previous ones [5] and are considered as a new confirmation of z-scaling at the Tevatron.

1. z-SCALING

In this section we would like to remind some basic ideas and definitions of z-scaling. As shown in [4–6] self-similarity of high-p_T particle formation reveals itself as possibility to describe physical process in terms of the scaling function $\psi(z)$ and scaling variable z. The function is expressed via the invariant cross section $Ed^3\sigma/dp^3$ and the multiplicity density $dN/d\eta$ as follows:

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

Here, s is the center-of-mass collision energy squared, σ_{in} is the inelastic cross section, J is the corresponding Jacobian. The factor J is the known function of the kinematic variables, the momenta and masses of the colliding and produced particles.

The normalization equation

$$\int_0^\infty \psi(z)dz = 1$$ (2)

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allows us to interpret the function $\psi(z)$ as a probability density to produce a particle with the corresponding value of the variable z.

The variable z as established in [4–6] reveals property of fractal measure. It can be written in the form

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

The finite part z_0 is the ratio of the transverse energy released in the binary collision of constituents and the average multiplicity density $dN/d\eta|_{\eta=0}$. The divergent part Ω^{-1} describes the resolution at which the collision of the constituents can be singled out of this process. The quantity $\Omega(x_1, x_2) = m(1-x_1)^{\delta_1}(1-x_2)^{\delta_2}$ represents relative number of all initial configurations containing the constituents which carry fractions x_1 and x_2 of the incoming momenta. The δ_1 and δ_2 are the anomalous fractal dimensions of the colliding objects (hadrons or nuclei). The momentum fractions x_1 and x_2 are determined in a way to minimize the resolution $\Omega^{-1}(x_1, x_2)$ of the fractal measure z with respect to all possible subprocesses satisfying the momentum conservation law. The variable z is interpreted as a particle formation length.

The general regularities of z-scaling for jet production in $p - p$ and $\bar{p} - p$ collisions at the ISR, SpS and Tevatron were established in [5]. In the present work the regularities are verified by using new experimental data obtained by the D0 and CDF Collaboration at the Tevatron in Run II.

2. JETS AT HADRON COLLIDERS

A jet is experimentally observed as a strong correlated group of particles in space–time. At low collision energies only high-p_T hadrons were observed and considered as a result of hard scattering of elementary hadron constituents. At high collision energy $\sqrt{s}$ jets are copiously produced at hadron colliders such as SpS and Tevatron. They are considered as an experimental signature of quarks and gluons interactions.

Figure 1 demonstrates the high-p_T spectra of π^0 mesons produced at the ISR and azimuthal correlations of jets produced in $\bar{p} - p$ collisions at the SpS and Tevatron and in $p - p$ collisions at the RHIC.

2.1. Jet Definition. In interaction of colliding hadrons two (or more) highly collimated collection of particles having approximately equal transverse momentum are observed. These collimated beams of particles in space–time are called jets. The strong correlation of high-p_T particles from the jets in the azimuthal plane is one of main features of jet production. The high-p_T hadrons are considered to be produced by hadronization of quarks and gluons. A typical dijet event is assumed to consist of hard interaction and underlying event. The last one includes initial and final gluon and quark radiation, secondary semi-hard interactions, interaction between remnants, hadronization and jet formation. Thus the
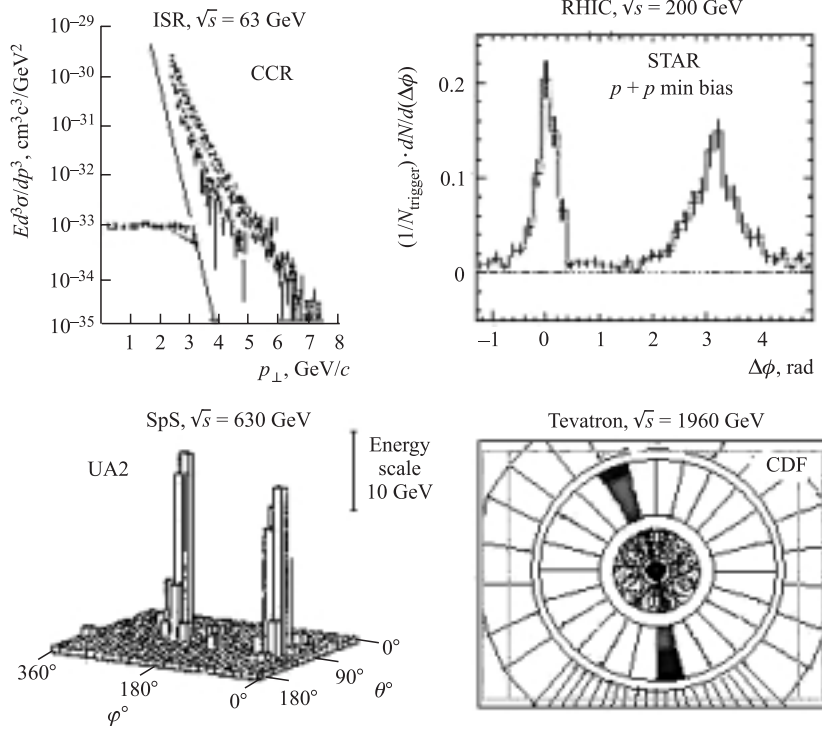
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Fig. 1. Jets at the ISR, RHIC, SpS and Tevatron colliders

procedure for extraction information on hard constituent interactions and comparison with theoretical calculation in the framework of QCD is an indirect one and sophisticated algorithms of data analysis are required.

2.2. Cone Algorithm. A standard definition of a jet to facilitate comparisons of measurements from different experiments and with theoretical predictions was accepted in the Snowmass Accord [11].

The Snowmass Jet Algorithm defines a jet as a collection of partons, particles or calorimeter cells contained within a cone of an open angle R. All objects in an event have a distance from the jet center $\Delta R_i = \sqrt{(\phi_i - \phi_{\text{jet}})^2 + (\eta_i - \eta_{\text{jet}})^2}$, where $(\phi_{\text{jet}}, \eta_{\text{jet}})$ define direction of the jet and ϕ_i, η_i are the coordinates of the parton, particle or center of the calorimeter cell. If $\Delta R_i \leq R$ then the object is a part of jet. The transverse energy E_T and direction of jet are defined by formulas

$$E_T = \sum_{i \in R_i \leq R} E_T^i,$$

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$$\eta_{\text{jet}} = (1/E_T) \cdot \sum_{i \in R_i \leq R} \eta^i \cdot E_T^i, \tag{4}$$

$$\phi_{\text{jet}} = (1/E_T) \cdot \sum_{i \in R_i \leq R} \phi^i \cdot E_T^i.$$

An iterative procedure for finding the jets given by the Snowmass algorithm includes determination of jet seeds, jet cone formation, determination of the transverse energy and direction of jet. The definition of jet seed is not given by the algorithm. The Snowmass Accord does not deal with jet overlap.

At the parton level seeds could be partons, points lying between pairs of partons, a set of points randomly located in the $\eta - \phi$ space. Experimentally the seed could be defined as any cell in calorimeter or clusters of calorimeter cells. Therefore there are different treatment of jets at the parton and calorimeter level. To accommodate the difference between the jet definitions at the parton and calorimeter level in the modified Snowmass algorithm a purely phenomenological parameter R_{sep} has been suggested [12]. At the parton level R_{sep} is the distance between two partons when the clustering algorithm switches from one jet to two final-state jets, even though both partons are contained within the jet defining cone. The maximum allowed distance ΔR between two partons in a parton jet divided by the cone size used: $R_{\text{sep}} = \Delta R/R$. The value of R_{sep} depends on details of the jet algorithm used and the experimental jet splitting and merging scheme.

2.3. Clustering k_T-Algorithm. Clustering algorithms in contrast to cone algorithms, which globally find the jet direction, successively merge pairs of nearby vectors. The order in which vectors are recombined into jets defines the algorithm. The k_T-algorithm combines vectors based on their relative transverse momentum.

Several variants of the clustering k_T-algorithm for hadron collisions have been proposed [13]. It is designed to be independent of the order in which the seeds are processed. It is infrared and collinear safe. The initial seeds are all charged particles with $k_{T,i}$ in a given η-range. Each seed is labeled as prejet. Measure or closeness criterion in phase space is defined for each prejet and pair of prejets as follows:

$$d_i = k_{T,i}^2, \tag{5}$$

$$d_{i,j} = \min\{k_{T,i}^2, k_{T,j}^2\} \cdot \Delta R_{i,j}^2 / R^2. \tag{6}$$

Here R is a jet cone size, $\Delta R_{i,j}$ is the distance between two prejets (i and j) in (η, ϕ) space. The procedure of jet finding includes the next steps: computation of the measure of all prejets and all pairs of prejets; finding of the prejet or pair of prejets with the smallest measure $d_{\min}$; promotion it to a jet and remove its particles from considerations if $d_{\min}$ arises from a single prejet; combination the pair into a new prejet and recompute measure for all prejets and pairs of prejets

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if $d_{\min}$ arises from a pair of prejets; continuation previous steps until all prejets have been promoted to jet.

Here we would like to note that different modifications of cone and clustering algorithms have been used in analysis of experimental and theoretical jet data to obtain their compatibility [11, 13–15]. It is especially important for study of soft and hard processes contribute to jet formation [16]. Transformation of quarks and gluons into real particles is considered to include evolution of constituent structure and their interactions at different scales. It corresponds to different scheme used for evolution of parton distribution functions [17–19]. Therefore general regularities which can be extracted from experimental data could give complementary constraints on theoretical models of jet formation and new insight into origin of particle mass as well.

3. z-SCALING AND JET PRODUCTION AT TEVATRON IN RUN II

In this section we analyze new data on inclusive cross section of jet production in $\bar{p}-p$ collisions at $\sqrt{s} = 1960$ GeV obtained by the D0 [20,22] and CDF [21,23] Collaborations at the Tevatron in Run II and compare them with our previous results [5].

3.1. Energy Independence of ψ. The production hadron jets at the Tevatron probes the highest momentum transfer region currently accessible and thus potentially sensitive to a wide variety of new physics. The information on inclusive jet cross section at high transverse momentum range is the basis to test QCD, in particular to extract the strong coupling constant $\alpha_S(Q^2)$, the parton distribution functions and to constrain uncertainties for gluon distribution in the high-x range. In Run II, as mention in [23], the measurement of jet production and the sensitivity to new physics will profit from the large integrated luminosity and the higher cross section, which is associated with the increase in the center-of-mass energy from 1800 to 1960 GeV. Therefore the test of z-scaling for jet production in $\bar{p} - p$ collisions in new kinematic range is of great interest to verify scaling features established in our previous analysis [5].

The D0 and CDF Collaborations have carried out the measurements [20, 21] of transverse spectra of single inclusive cross sections of jet production at $\sqrt{s} = 1960$ GeV. In the D0 [20] and CDF [21] experiments single jets were registered in the $0.0 < |\eta| < 0.5$ and $0.1 < |\eta| < 0.7$ ranges, respectively. The data were used in the present analysis.

New data on inclusive cross sections of jet production in $\bar{p} - p$ collisions obtained by the D0 Collaboration at the Tevatron in Run II are presented in Fig. 2, a [20]. Spectrum of jet production is measured at $\sqrt{s} = 1960$ GeV in the pseudorapidity and transverse momentum ranges $|\eta| < 0.5$ and $p_T = 60 - 560$ GeV/c, respectively. Data of p_T- and z-presentations are shown in

Fig. 2, *b*, *c*. Note that results of the present analysis of new D0 data are in good agreement with our results [4] based on the data [14] obtained by the same Collaboration in Run I. The energy independence and the power law (the dashed line in Fig. 2, *c*) of the scaling function $\psi(z)$ are found to be as well.

The dependence of single jet cross section on transverse momentum of jet in $\bar{p} - p$ collisions at $\sqrt{s} = 630, 1800$ and 1960 GeV is shown in Fig. 3, *a*. The data [15, 21] covers momentum range $p_T = 10 - 560$ GeV/c. The energy
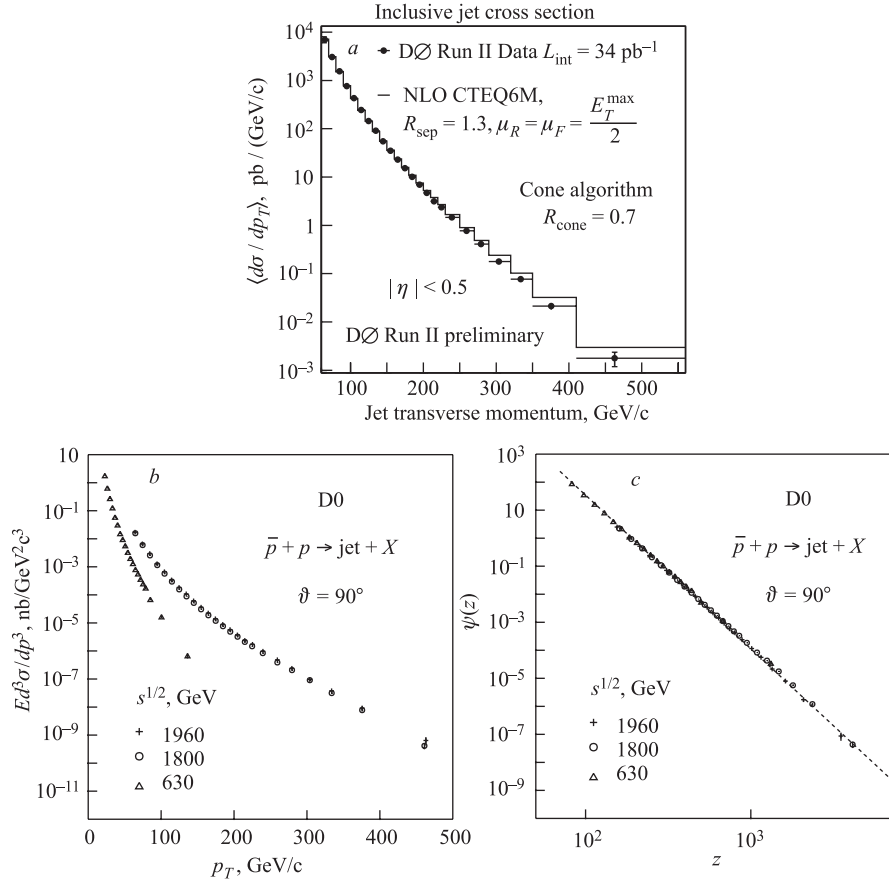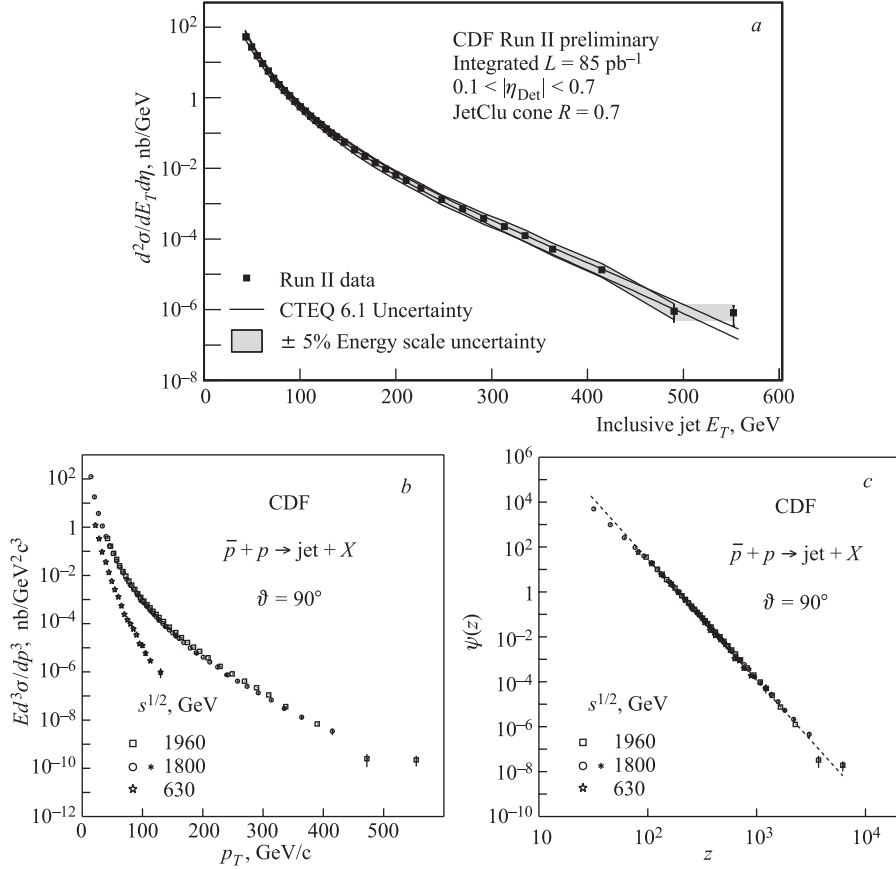

Fig. 2. *a*) The preliminary D0 data [20] on inclusive spectrum $d\sigma/dp_T$ of one jet produced in $\bar{p} - p$ collisions at $\sqrt{s} = 1960$ GeV in the central pseudorapidity range $|\eta| < 0.5$ as a function of the transverse momentum. *b*) The D0 data on invariant cross section $Ed^3\sigma/dp^3$ of jet production at $\sqrt{s} = 630, 1800$ GeV [14] and 1960 GeV [20] in p_T- and *c*) z-presentations. The dashed line represents the power fit to the data

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dependence of jet cross section is observed to be strong from $\sqrt{s} = 630$ to 1800 GeV and weak from 1800 to 1960 GeV. Data of p_T- and z-presentations are shown in Fig. 3, b, c. As seen from Fig. 3, c new data [21] are in agreement with that ones obtained in Run I. The energy independence of $\psi(z)$ is observed up to $z \simeq 4000$. Asymptotic behavior of scaling function is described by the power law, $\psi(z) \sim z^{-\beta}$ (the dashed line in Fig. 3, c). The slope parameter β is energy independent over a wide p_T-range.

Fig. 3. a) The preliminary CDF data [21] on inclusive spectrum $d^2\sigma/dE_T d\eta$ of one jet produced in $\bar{p} - p$ collisions at $\sqrt{s} = 1960$ GeV in the central pseudorapidity range $0.1 < |\eta| < 0.7$ as a function of the transverse momentum. b) The CDF data on invariant cross section $Ed^3\sigma/dp^3$ of jet production at $\sqrt{s} = 630, 1800$ GeV [15] and 1960 GeV [21] in p_T- and c) z-presentations. The dashed line represents the power fit to the data

3.2. Angular Independence of ψ. Let us consider the angular dependence of p_T- and z-presentations of new D0 [22] and CDF [23] data. The D0 and CDF Collaborations have carried out the measurements [22, 23] of the angular dependence of the single inclusive cross sections of jet production at $\sqrt{s} = 1960$ GeV. In the D0 experiment [22] a single jet was registered in the range $0.0 < |\eta| < 2.4$. In the CDF experiment [23] jets were registered in the ranges $0.1 < |\eta| < 2.8$.

We would like to note that the strong dependence of the cross sections on the angle of produced jet was experimentally found at the SpS and the Tevatron in Run I.
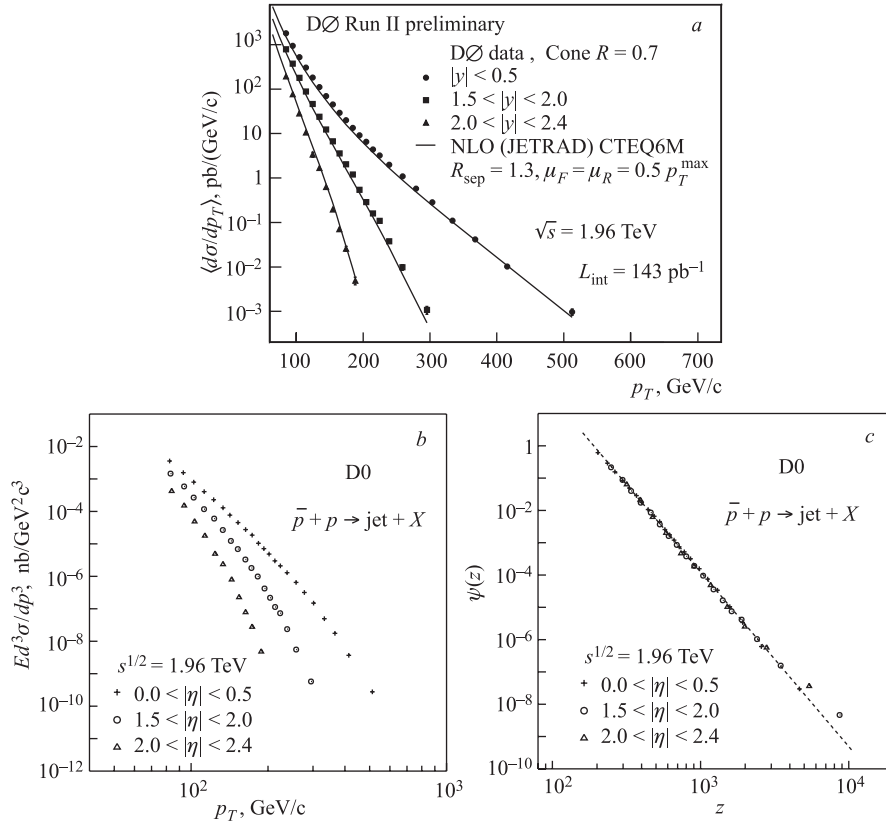

Fig. 4. *a*) The preliminary D0 data [22] on inclusive spectrum $d\sigma/dp_T$ of one jet produced in $\bar{p}-p$ collisions at $\sqrt{s} = 1960$ GeV in the different pseudorapidity ranges $0. < |\eta| < 0.5$, $1.5 < |\eta| < 2.0$ and $2.0 < |\eta| < 2.4$ as a function of the transverse momentum p_T. *b*) The D0 data on invariant cross section $Ed^3\sigma/dp^3$ of jet production at $\sqrt{s} = 1960$ GeV [22] in p_T- and *c*) z-presentations. The dashed line represents the power fit to the data

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Figures 4, *a* and 5, *a* show the dependence of the cross sections of the $\overline{p}+p \rightarrow$ jet $+ X$ process on the transverse momentum $p_\perp$ at $\sqrt{s} = 1960$ GeV for different rapidity intervals, $|\eta| < 2.4$ and $0.1 < |\eta| < 2.8$, measured by the D0 and CDF Collaborations, respectively. The p_T-presentation of new data [22, 23] demonstrates the strong angular dependence as well. The qualitative regularities of jet spectra at $\sqrt{s} = 1960$ GeV are similar to those at $\sqrt{s} = 630$ and 1800 GeV.

We verify the hypothesis of the angular scaling for z-presentation of the data for jet production in $\bar{p} - p$ collisions. The angular scaling of data z-presentation means that the scaling function $\psi(z)$ at given energy $\sqrt{s}$ has the same shape over a wide p_T and pseudorapidity range of produced jets.
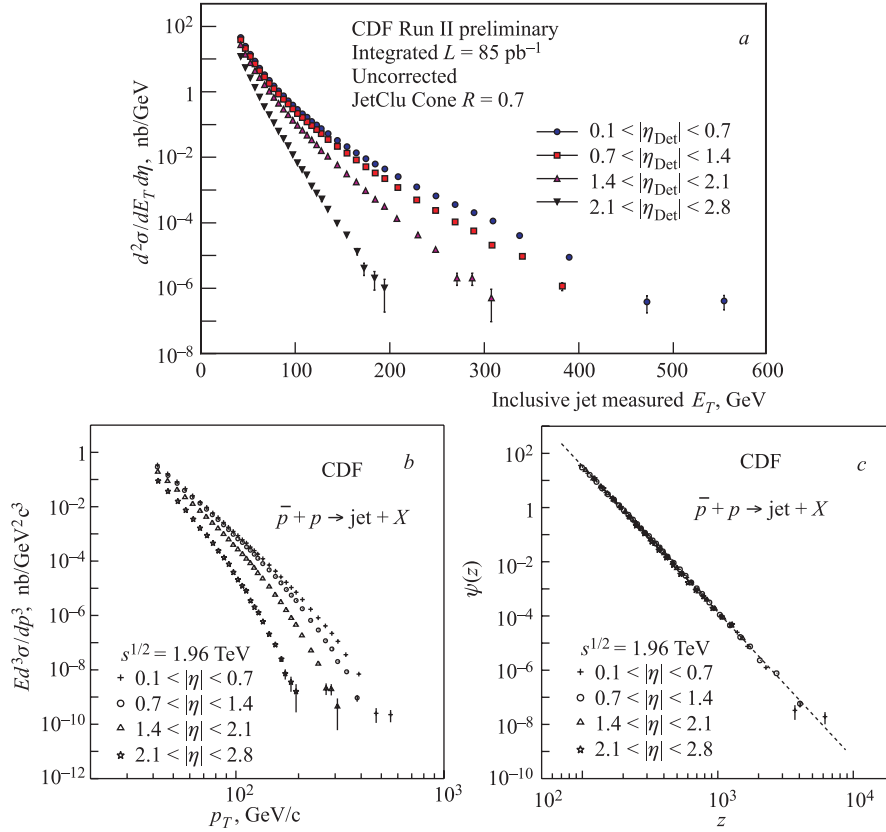

Fig. 5. *a)* The preliminary CDF data [23] on inclusive spectrum $d^2\sigma/dE_T d\eta$ of one jet produced in $\bar{p} - p$ collisions at $\sqrt{s} = 1960$ GeV in the different pseudorapidity ranges $0.1 < |\eta| < 0.7$, $0.7 < |\eta| < 1.4$, $1.4 < |\eta| < 2.1$, and $2.1 < |\eta| < 2.8$ as a function of the transverse momentum p_T. *b)* The CDF data on invariant cross section $E d^3\sigma/dp^3$ of jet production at $\sqrt{s} = 1960$ GeV [23] in p_T- and *c)* z-presentations. The dashed line represents the power fit to the data

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Figures $4, b$, c and $5, b$, c demonstrate p_T- and z-presentations of the D0 [22] and CDF [23] data sets, respectively. Taking into account errors of the experimental data we can conclude that the data confirm the angular scaling of $\psi(z)$. Nevertheless, it is necessary to note that some points (last five and seven points corresponding to the (1.4), (2.1) and (2.1), (2.8) pseudorapidity ranges of the data [23] and two last points corresponding to the (1.5), (2.0) and (2.0), (2.4) pseudorapidity ranges of the data [22]) deviate from the power law. This is not real indication of z-scaling violation. The reason of the deviation is impossibility to take correctly into account the kinematical conditions of constituent subprocess due to large pseudorapidy bins for reconstructed jets. The smaller angular binning and more higher statistics of data are necessary to resolve the problem.

3.3. Jet Multiplicity Density $dN/d\eta$. The important ingredient of z-scaling is the multiplicity density $\rho(s, \eta) \equiv dN/d\eta$. The quantity is well determined in analysis of high-p_T particle production. The energy dependence of $\rho(s)$ for charged hadrons produced in $p - p$ and $\bar{p} - p$ collisions at $\eta = 0$ is measured up to $\sqrt{s} = 1800$ GeV. The dependence is used to construct z and ψ for different pieces of particles.
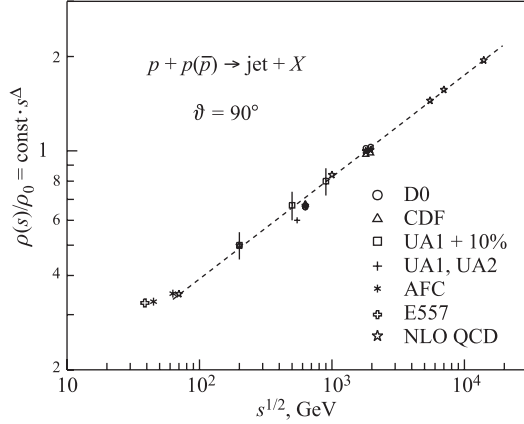

Fig. 6. The dependence of the normalized jet multiplicity density $\rho(s)/\rho_0$ in $\bar{p}(p) - p$ collisions on energy $\sqrt{s}$. The dashed line represents the power fit to the data

In the case of jet production the quantity is not well determined. It is connected with the experimental and theoretical determination of jets. In the analysis [5] the normalized jet multiplicity density $\rho(s)/\rho_0$ has been used. The value of $\rho(s)/\rho_0$ at the normalization point $\sqrt{s} = 1800$ GeV is equal to 1.

Figure 6 shows the dependence of $\rho(s)/\rho_0$ on the collision energy $\sqrt{s}$. At the accessible energy range the dependence is well described by the power law shown in Fig. 6 by the dashed line.

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CONCLUSION

Analysis of new experimental data on jet production in $\bar{p} - p$ collisions obtained at the Tevatron in Run II by the CDF and D0 Collaborations in the framework of data z-presentation was performed.

The scaling function $\psi(z)$ and scaling variable z expressed via the experimental quantities, the invariant inclusive cross section $Ed^3\sigma/dp^3$ and the jet multiplicity density $\rho(s, \eta)$ are constructed. The scaling function ψ is interpreted as a probability density to produce a jet with the formation length z.

The general regularities of jet production (the energy and angular independence of ψ, and the power law) found at the ISR, SpS and Tevatron in Run I are confirmed in new kinematical range ($\sqrt{s} = 1960$ GeV and $p_T = 10 - 550$ GeV/c). Results of our analysis of new experimental data are found to be in good agreement with results obtained by the D0 and CDF Collaborations, in Run I. The obtained results are new evidence that mechanism of jet formation reveals self-similar and fractal properties over a wide transverse momentum range.

Thus we conclude that new data obtained at the Tevatron confirm the general concept of z-scaling. The further inquiry and search for violation of the scaling could give information on new physics phenomena in high-energy hadron collisions and determine domain of validity of the strong interaction theory and the Standard Model itself.

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