ON SATURATION OF CHARGED HADRON PRODUCTION IN PP COLLISIONS AT LHC

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First results on charged hadron transverse momentum spectra in pp collisions obtained by the CMS Collaboration at LHC were analyzed in \( z \)-scaling approach. The first LHC data confirm \( z \)-scaling. The saturation regime of the scaling function \( \psi(z) \) observed in pp and \( p\bar{p} \) interactions at lower energy \( \sqrt{s} = 19 - 1600 \) GeV is verified. The saturation of \( \psi(z) \) for charged hadrons is found down to \( z \approx 0.05 \) at the highest energy \( \sqrt{s} = 2360 \) GeV reached till now at colliders. A microscopic scenario of hadron production is discussed in connection with search for new signatures of phase transitions in hadron matter. Constituent energy loss and its dependencies on the transverse momentum and collision energy are estimated. The beam energy scan at LHC in the saturation region is suggested.

I. INTRODUCTION

Commissioning of the Large Hadron Collider (LHC) at CERN aimed to discover new physics beyond Standard Model (SM) gives a unique possibility \([1, 2, 3, 4, 5, 6, 7]\) to verify various theoretical models and experimental properties of hadron interactions established at ISR, SppS, SPS, RHIC, and Tevatron over the range \( \sqrt{s} = 19 - 1600 \) GeV \([8, 9, 10, 11, 12]\). Phenomenological features of particle production experimentally found and theoretically predicted are extremely important for scientific search on high energy physics frontier \([13, 14, 15, 16, 17, 18, 19, 20, 21]\).

One of such features is a new scaling (\( z \)-scaling) of hadron production in pp and \( p\bar{p} \) collisions suggested in \([22]\) (see also \([23, 24, 25]\) and references therein). It was used as a method allowing systematic analysis of data on inclusive cross sections and search for new physics. The scaling function \( \psi(z) \) and scaling variable \( z \) are expressed via experimentally measurable quantities. The shape of the scaling function was shown to be independent of the energy, multiplicity density of collisions, 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-\( z \) range. At low \( z \), a saturation \([24, 25]\) of the scaling function was found down to \( z \approx 10^{-3} \). The single parameter \( \beta \) which controls the behavior of \( \psi(z) \) at low \( z \) is interpreted as a "specific heat" of the produced medium associated with inclusive particle. The scaling in pp and \( p\bar{p} \) collisions is consistent with a constant value of \( \beta \). Possible change in this parameter is assumed to be an indication of a phase transition of the matter produced in high energy collisions. Investigation of the non-perturbative regime and phase transitions in non-Abelian theories is considered to be preferred in the softly region (low-\( p_T \) and high multiplicity) of hadron production. It was concluded that \( z \)-scaling reflects self-similarity of particle structure, interaction of constituents, and hadronization process.

In the present paper we analyze the first data \([26]\) on transverse momentum spectra of charged hadrons produced in pp collisions at the energy \( \sqrt{s} = 900 \) and \( 2360 \) GeV in the middle rapidity range obtained by the CMS Collaboration at LHC. The saturation of \( \psi(z) \) at the LHC energies is verified. The results are compared with ISR, SppS, SPS, RHIC, and Tevatron data. The microscopic scenario of hadron production in the \( z \)-scaling approach is used to estimate the energy loss and recoil mass at the constituent level in dependence of the collision energy and transverse momentum of the inclusive hadron. The change of collision and particle reconstruction conditions (energy, multiplicity, type of particle, transverse momentum) is discussed in connection with possibility for a Beam Energy Scan (BES) program at the LHC to expand research area in search of strongly pronounced signatures of phase transitions. We consider that systematic analysis of particle production as a function of the collision energy and multiplicity towards searching for clear signatures of phase transition from quark and gluon to hadron degrees of freedom as well as location of the Critical Point (CP) on the QCD phase diagram is possible at energies achieved at the LHC now.

II. \( z \)-SCALING

Here we briefly remind the basic ideas of the \( z \)-scaling concept \([24, 25]\). 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). A single interaction of the constituents is illustrated in Fig.1. Structures
of the colliding objects are characterized by the parameters $\delta_1$ and $\delta_2$. The constituents of the incoming objects (hadrons or nuclei) with the masses $M_1, M_2$ and momenta $P_1, P_2$ carry their fractions $x_1, x_2$. The inclusive particle carries the momentum fraction $y_a$ of the object produced in the constituent collision into the observed direction. Its fragmentation is characterized by a parameter $\epsilon_a$. The fragmentation in the recoil direction is described by a parameter $\epsilon_b$ and the momentum fraction $y_b$. Multiple interactions of the constituents are considered to be similar. This property reflects a self-similarity of the hadronic interactions at the constituent level.

### A. Momentum fractions $x_1, x_2, y_a, \text{and } y_b$

The elementary subprocess is considered to be a binary collision of the constituents $(x_1 M_1)$ and $(x_2 M_2)$ resulting in the scattered $(m_1/y_a)$ and recoil $(x_1 M_1 + x_2 M_2 + m_2/y_b)$ objects in the final state. The produced secondary objects transform into real particles after the constituent collisions. The registered particle with the mass $m_1$ and the 4-momentum $p$ is produced with its hadron counterpart $(m_2)$ carrying the momentum fractions $y_b$ of the produced recoil. The momentum conservation law of the constituent subprocess is written in the form

$$ (x_1 P_1 + x_2 P_2 - p/y_b)^2 = M_X^2, \quad (1) $$

with the recoil mass $M_X = x_1 M_1 + x_2 M_2 + m_2/y_b$. The associate production of $(m_2)$ 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 kinematical constraint on the momentum fractions $x_1, x_2, y_a$, and $y_b$ which determine the underlying elementary subprocess.

The structural parameters $\delta_1, \delta_2$ and $\epsilon_a, \epsilon_b$ are connected with the corresponding momentum fractions by the function

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

The quantity $\Omega$ is proportional to 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 $\Omega$ plays the role of a relative volume which occupy these configurations in the space of the momentum fractions. The parameters $\delta_1, \delta_2$ and $\epsilon_a, \epsilon_b$ 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 $\delta_{1,2}$ and $\epsilon_{a,b}$ the fractions $x_1, x_2, y_a$, and $y_b$ are determined in a way to maximize the function $\Omega$, simultaneously fulfilling the condition (1).

In the case of proton-proton interactions we 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 $\epsilon_a = \epsilon_b \equiv \epsilon$ which depends on the type of the inclusive particle. Values of the parameters $\delta$ and $\epsilon$ are determined in accordance with the self-similarity requirements and experiment. They were found to have constant values in $pp$ and $\bar{p}p$ collisions at high energies.

### B. Scaling variable $z$ and scaling function $\psi(z)$

The self-similarity of hadron interactions reflects a property that hadron constituents and their interactions are similar. The self-similarity variable $z$ is defined as follows

$$ z = z_0 \Omega^{-1}, \quad (3) $$

where

$$ z_0 = \frac{\sqrt{s_0}}{(dN_{ch}/d|y|)_0 \epsilon m} \quad (4)$$

and $\Omega$ is maximal value of (2) with the condition (1). For a given inclusive reaction the quantity $z$ is proportional to the transverse kinetic energy $\sqrt{\not{p}_T}$ of the constituent subprocess consumed on the production of the inclusive particle $(m_1)$ and its counterpart $(m_2)$. The quantity $dN_{ch}/d|y|_0$ is the corresponding multiplicity density of charged particles in the central region of the inclusive reaction at pseudorapidity $\eta = 0$. The parameter $c$ characterizes properties of the produced medium and is interpreted as a "specific heat". The mass constant $m$ is arbitrary and we fix it at the value of nucleon mass.

The scaling function $\psi(z)$ is expressed in terms of the experimentally measured inclusive cross section $E^3 \sigma / dp^3$, the multiplicity density $dN / d|y|$, and the total inelastic cross section $\sigma_{inel}$ as follows

$$ \psi(z) = \frac{\pi s}{(dN / d|y|) \sigma_{inel}} J^{-1} \bigg| \frac{E^3 \sigma}{dp^3} \bigg|, \quad (5)$$

FIG. 1: Diagram of the constituent subprocess of the reaction $p + p \rightarrow h + X.$
where $s$ is the square of the center-of-mass energy and $J$ is the corresponding Jacobian. The multiplicity density $dN/dq$ in Eq. (5) depends on the center-of-mass energy, centrality, and on the production angles at which the inclusive spectra were measured. The function $\psi(z)$ is normalized to unity. It is interpreted as a probability density to produce an inclusive particle with the corresponding value of the variable $z$.

III. SELF-SIMILARITY OF HADRON PRODUCTION

Main features of the $z$-scaling in $pp$ interactions at FNAL, CERN, and BNL energies were presented and discussed in Refs. 24, 25. The experimental data cover a wide range of the collision energy, transverse momenta, and angles of the produced particles. The energy, angular, and multiplicity independence of the scaling function $\psi(z)$ gives strong constrains on the values of the parameters $\epsilon$, $\delta$, and $c$. The scaling is consistent with $c = 0.25$ and $\delta = 0.5$ for all types of the analyzed inclusive hadrons. The value of $\epsilon$ increases with hadron mass. The behavior of $\psi(z)$ is found to be described by the power law, $\psi(z) \sim z^{-\beta}$, in the asymptotic high-$z$ (high-$p_T$) region. At low-$z$ (low-$p_T$), the scaling function flattens out and becomes a constant for $z < 0.1$.

A typical example of $z$-presentation of the inclusive spectra is shown in Fig. 2. It demonstrates the energy independence of the scaling function $\psi(z)$ of charged hadron production in $pp$ collisions at $\sqrt{s} = 19 - 200$ GeV, transverse momenta $p_T = 0.2 - 10$ GeV/c, and $\theta_{\text{cms}} = 90^\circ$. As seen from the figure the function $\psi(z)$ changes within the range of 11 orders of magnitudes. The result manifests applicability of the $z$-scaling over a wide kinematical range.

IV. NEW LHC DATA VS. SATURATION OF $\psi(z)$ AT LOW $z$

The new data on charged hadrons production measured by the CMS Collaboration at LHC confirm $z$-scaling for $z \leq 3$ at midrapidity.

Figure 3(a) shows the charged hadron spectra in $pp$ collisions at $\sqrt{s_{NN}} = 19 - 2360$ GeV and $\theta_{\text{cms}} \approx 90^\circ$ as a function of transverse momentum $p_T$. The results are shown for the minimum bias events. The distributions are measured in the momentum range $0.15 < p_T < 10$ GeV/c. As seen from Fig. 3(a) the spectra demonstrate strong dependence on the collision energy. The ratio of yields at RHIC and IS are shown to increase with the transverse momentum. It is of the order of $10^4$ at $p_T \approx 6$ GeV/c. The shape of the spectra is characterized by the power behavior at $p_T > 1$ GeV/c. The CMS data reveal similar tendencies as data at lower energies.

Figure 3(b) demonstrates $z$-presentation of the same spectra $8, 10, 11, 12, 26$. As seen from the figure the first LHC data confirm the energy independence of the scaling function with the same values of the parameters $\delta, \epsilon$ and $c$. The universal shape of the scaling function is examined in the new energy range. Evidence of saturation of $\psi(z)$ at low $z < 0.2$ is observed. The minimal values of $z = 0.2$ and $z = 0.045$ at $\sqrt{s} = 63$ GeV and $2360$ GeV correspond to $p_T = 0.30$ GeV/c and $p_T = 0.15$ GeV/c, respectively. At higher $z > 2$ indication on the power behavior $\psi(z) \sim z^{-\beta}$ is seen.

The behavior of $\psi(z)$ at still lower $z$ can be investigated by increasing the collision energy $\sqrt{s}$, multiplicity density $dN_{ch}/d\eta$ or by decreasing the transverse momentum $p_T$. For minimum bias events, the multiplicity density at $\sqrt{s} = 7$ and $14$ TeV is estimated to be $5.5$ and $6.36$, respectively. Using Eq. (4) for $p_T = 0.15$ GeV/c ($\Omega 
\simeq 1$), it gives $z = 0.0419$ and $z = 0.042$ for charged hadrons produced at these energies at midrapidity. The increase of energy does not change the values of $z$ too much in this region.

Special selection of events with a high multiplicity density ($dN_{ch}/d\eta \simeq 20$) allows us to reach smaller value of $z \simeq 0.03$ at $p_T = 0.15$ GeV/c. The value is however still much higher than $z \simeq 10^{-3}$ achieved at the ISR and RHIC for the identified hadrons. Therefore study of production of hadrons with heavy flavors such as $J/\psi$ or $\Upsilon$ is more preferable for verification of the saturation of $\psi(z)$. It allows to reach the values $z \simeq 10^{-3}$ at $\sqrt{s} = 7$ TeV for $p_T = 0.15$ GeV/c. It was assumed in Ref. 22 that the asymptotic behavior of $\psi(z)$ at $z \rightarrow 0$ reflects general properties of the produced system consisting of many constituents. The universal scaling behavior in this region suggests that mechanism of particle production at low $p_T$ is governed by soft self-similar processes which reveal some kind of a mutual equilibrium leading to the observed saturation.

We expect that verification of the saturation of $\psi(z)$ and/or search for violation of the $z$-scaling at low $z$ could give new information on the non-perturbative regime and...
phase transitions in non-Abelian theories. It is assumed that discontinuity of the single parameter $c$ describing the behavior of the scaling function in this region could be a signature of the Critical Point. Search for the location of CP on the QCD phase diagram is the main task of the Beam Energy Scan program at the SPS [27] and RHIC [28]. The scaling assumption makes the CP search relevant for the energies achieved at the LHC as well.

We would like to emphasize that "scaling" and "universality" are the concepts developed to understand critical phenomena. Scaling means that systems near the critical points exhibiting self-similar properties are invariant under transformation of scale. According to universality, quite different systems behave in a remarkably similar fashion near the respective critical points [29]. We see that the $z$-scaling possesses saturation and universality as remarkable properties both in the low $z$ region.

V. SELF-SIMILARITY & ENERGY LOSS

The measured spectrum at the highest collision energy $\sqrt{s} = 2360$ GeV (Fig.3) allows us to estimate the constituent energy loss for charged hadron production in $pp$ collisions and compare it with the similar one at lower energies $\sqrt{s} = 19 - 200$ GeV. The energy dissipation is proportional to the value of $(1 - y_a)$.

Figure 4(a) shows the dependence of the fraction $y_a$ on the transverse momentum at $\sqrt{s} = 19 - 2360$ GeV. The behavior of $y_a$ demonstrates a monotonic growth with $p_T$. It means that the energy loss associated with the produc-
tion of a high-\(p_T\) hadron is smaller than for hadrons with lower transverse momenta. The largest energy loss corresponds to the region of low-\(p_T\). The decrease of \(y_a\) with the collision energy represents larger energy losses for higher collision energies. For \(p_T \approx 4\) GeV/c, the energy loss is estimated to be about 20\% at \(\sqrt{s} = 19\) GeV and about 90\% at \(\sqrt{s} = 2360\) GeV, respectively. The study of evolution of the energy loss with the collision energy has relevance to the evolution of the created nuclear matter and can be useful for searching for signatures of the phase transition and the Critical Point in the region of small \(p_T\).

The energy dissipation in the final state is connected with the recoil mass \(M_X\). This is another characteristic of the constituent interactions. It is function of the momentum fractions \(x_1\) and \(x_2\) of the interacting objects with the masses \(M_1\) and \(M_2\) and the fraction \(y_b\) of the produced recoil object carried by the mass \(m_2\). The recoil mass \(M_X\) depends on the constituent interaction and is connected with the processes of formation of the individual hadrons.

Figure 4(b) demonstrates the dependence of the recoil mass \(M_X\) on the transverse momenta of the charged hadrons produced in \(pp\) collisions at the energy \(\sqrt{s} = 19 – 2360\) GeV in the central rapidity region. The curves for \(\sqrt{s} = 19, 63,\) and 200 GeV demonstrate slow growth with \(p_T\) followed by a successive flattening. The recoil mass at LHC energies is considerably larger than at RHIC and SPS energies. For \(p_T \approx 4\) GeV/c it was found to be about \(M_X = 18\) GeV at \(\sqrt{s} = 2360\) GeV which is much higher than the corresponding value \(M_X = 2\) GeV at \(\sqrt{s} = 19\) GeV. The large recoil mass means that the momentum of the inclusive particle is compensated with the momentum of a high multiplicity system consisting of more particles.

VI. CONCLUSIONS

We have presented results of our analysis of the first data \cite{26} on inclusive spectra of charged hadron production in \(pp\) collisions at the energy \(\sqrt{s} = 900\) and 2360 GeV obtained by the CMS Collaboration at the LHC. The transverse momentum spectra in \(p_T\)- and \(z\)-presentation are compared with data obtained at lower energies at ISR, SppS, SPS, and RHIC.

Based on the results presented here we conclude that the first LHC data on charged hadron production in \(pp\) collision confirm \(z\)-scaling. The energy independence of the scaling function \(\psi(z)\) at the LHC energies in midrapidity range is observed. Results of the analysis of the CMS data support assumption on saturation of \(\psi(z)\) at low \(z\) down to \(z \approx 0.05\). The constituent energy loss and recoil mass \(M_X\) at the LHC energies were estimated as functions of the transverse momentum in the \(z\)-scaling approach. The energy loss increases with \(\sqrt{s}\) and decreases with increasing \(p_T\). The recoil mass \(M_X\) increases with \(\sqrt{s}\) and \(p_T\).

We consider that the Beam Energy Scan program in \(pp\) collisions at the LHC could be of interest for searching for scaling violation, phase transition, and location of the Critical Point in the new energy region.

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[1] CMS Collaboration, The CMS experiment at the CERN LHC 2008 JINST 3 S08004. doi:10.1088/1748-0221/3/08/S08004.
[2] The CMS Collaboration, "CMS Physics Technical Design Report", Volume II: Physics Performance 2007 J Phys G: Nucl. Part. Phys. 34 995. doi:10.1088/0954-3899/34/6/S01.
[3] The CMS Collaboration, "CMS Physics Technical Design Report: Addendum on High Density QCD with Heavy Ions", 2007 J. Phys. G: Nucl. Part. Phys. 34 2307. doi:10.1088/0954-3899/34/11/008.
[4] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider. By ATLAS Collaboration (Bentvelsen S et al.) 2008 JINST 3 S08003.
[5] The ATLAS Collaboration, Expected Performance of the ATLAS Experiment. Detector, Trigger and Physics. CERN-OPEN-2008-020, Geneva, December 2008.
[6] ALICE Collaboration, ALICE: physics performance report, volume I, 2004 J. Phys. G 30 1517.
[7] ALICE Collaboration, ALICE: physics performance report, volume II, 2006 J. Phys. G 32 1295.
[8] Alper B et al. (BS Collaboration), 1975 Nucl. Phys. B 100 237.
[9] Drijard D et al. (CDHW Collaboration), 1982 Nucl. Phys. B 208 1.
[10] Antreasyan D et al. 1979 Phys. Rev. D 19 764.
[11] Jaffe D E et al. 1989 Phys. Rev. D 40 2777.
[12] Adams J et al. (STAR Collaboration), 2003 Phys. Rev. Lett. 91, 172302.
[13] Bjorken J D 1969 Phys. Rev. 179 1547; Bjorken J D and Paschos E A 1969 Phys. Rev. 185 1975.
[14] Feynman R P 1969 Phys. Rev. Lett. 23 1415.
[15] Polyakov A M 1970 Zh. Eksp. Theor. Fiz. 59 542; Zh. Eksp. Theor. Fiz. 60 1572.
[16] Koba Z, Nielsen H B and Olesen P 1972 Nucl. Phys. B 40 317.
[17] Mateev V A, Muradyan R M and Tavkhelidze A N 1971 Part. Nuclei 2 7; 1972 Lett. Nuovo Cim. 5 907; 1973 Lett. Nuovo Cim. 7 719.
[18] Brodsky S and Farrar G 1973 Phys. Rev. Lett. 31 1153; 1975 Phys. Rev. D 11 1309.
[19] Bialas A and Peschanski R 1986 Nucl. Phys. B 273 703; 1988 Nucl. Phys. B 308 857.
[20] Dremin I M 1987 JETP Lett. 45 643.
[21] DeWolf E A, Dremin I M and Kittel W 1996 Phys. Rep. 270 1.
[22] Zborovský I, Panebratsev Yu, Tokarev M and Škoro G 1996 Phys. Rev. D 54 5548.
[23] Tokarev M, Zborovský I, Panebratsev Yu and Škoro G 2001 Int. J. Mod. Phys. A 16 1281.
[24] Zborovský I and Tokarev M V 2007 Phys. Rev. D 75 094008.
[25] Zborovský I and Tokarev M V 2009 Int. J. Mod. Phys. A 24 1417.
[26] CMS Collaboration, "Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV", http://www.arxiv.org/abs/1002.0621v2 2010 JHEP 02 041.
[27] NA61 Collaboration, Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS. CERN SPSC-2006-034, SPSC-P-330, November 3, 2006.
[28] Caines H (for the STAR Collaboration), Proceedings for the Rencontres de Moriond 2009 QCD session, [arXiv:0906.0305v1].
Abelev B I et al., [STAR Collaboration] SN0493: Experimental Study of the QCD Phase Diagram and Search for the Critical Point: Selected Arguments for the Run-10 Beam Energy Scan, http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493.
[29] Stanley H E 1999 Rev. Mod. Phys. 71, S358.