Do we see change of phase in proton-proton collisions at the Large Hadron Collider?

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I. INTRODUCTION

The minuscule universe of high energy-density and temperature, immediately after the Big Bang, evolved through a state of an exotic phase of matter, the Quark-Gluon Plasma (QGP) [1], that survived for some microseconds only. The QGP - the plasma state in quantum chromodynamics (QCD) [2], the theory of strong interaction - can be created also in the laboratory [3–6] in relativistic heavy-ion collisions. The formation of the QCD plasma necessitates accomplishment of thermodynamic equilibrium. As the system formed in the high energy collision starts expanding almost instantaneously, it remains far from turning to a homogeneous system and so cannot reach the global thermodynamical equilibrium. However, strong interactions of a large number of particles in a small volume, where the mean free path of constituent particles is much smaller than the dimensions of the system, lead to the local thermodynamical equilibrium. In heavy-ion collisions, the local thermodynamic equilibrium is assumed to obtain the equation of state for the space-time evolution of the system in the framework of the relativistic hydrodynamics [7]. Eventually, the formation of QGP in heavy-ion collisions is established mainly by characterizing the system in the hydrodynamic model. The proton-proton (pp) collision, on the other hand, is considered as the elementary interaction by most of the topical models which do not endorse formation of any medium, whatsoever. One may also question if the mean free path of the constituent particles, the size and the lifetime of the produced medium, if any, in pp collisions are conducive to the formation of QGP or not. Nevertheless, the recent data of pp collisions, particularly for the high-multiplicity events, at the Large Hadron Collider (LHC) at CERN show certain features [8,10] which are typical of the hydrodynamic medium formed in the relativistic heavy ion collisions. Several of subsequent phenomenological studies with the LHC pp data indicate the formation [11,13] of collective medium. Further, while some theoretical approaches [14,16] support applicability of relativistic hydrodynamics in high multiplicity pp collisions, formation of a non-hadronic medium has been shown [14] to be energetically possible in pp collisions at the LHC. A study [17] in search for the change in phase in pp collisions, analyzing a wide range of centre-of-mass energy, includes the LHC data also. The prima facie observations from all these studies in pp collisions at the LHC are quite encouraging for one to follow the approach adopted in search for the QGP in heavy-ion collisions - assume local thermal equilibrium and search for signals for formation of QGP. We analyze the data of pp collisions at the LHC to search for a signal of change of phase from thermalized partonic matter, the QGP, to hadronic one, in terms of change in effective number of degrees of freedom of the system formed in the collision as a function of temperature. The signal has been predicted [18–23] by the Lattice Quantum Chromodynamics (LQCD), the well accepted tool for non-perturbative calculations in QCD.

II. THE SIGNAL FOR CHANGE OF PHASE

The LQCD - predicted signal for the phase transition or for the crossover in high energy heavy-ion and pp collisions involves the temperature (T) and the energy-density (ε) or the entropy-density (σ = ε/T) of the system. The energy-density (ε) for an ideal gas is proportional to T⁴, where the proportionality constant reflects the effective number of degrees of freedom. The prediction calls for a fast rise of ε/T⁴ or σ/T³ over a small change in temperature, reflecting rapid increase in the effective number of degrees of freedom indicating a change in phase. While a sharp, step-like increase manifests the first order phase transition, a smooth but rapid rise indicates to either the crossover or a second order phase transition. The lattice QCD simulation is continuously progressing [21] towards more realistic calculations, in terms of number of quark flavors and their masses, minimization of lattice spacings etc. The latest LQCD calculations result in a crossover [23] in the QCD transition. At temperature lower than the critical region of rapid rise, the system is populated mainly by pions, forming a hadron gas. In this temperature range, however, the lattice calculation of ε and so σ is difficult as they are exponentially suppressed [21]. At
temperature higher than the critical region, where the ideal gas limit of degrees of freedom is reached asymptotically, the system corresponds to ideal gas consisting of partons. In absence of a straightforward method of estimation of temperature from data, the predicted behavior of temperature dependence of $\epsilon/T^4$ and $\sigma/T^3$ as a signal for the phase transition or the crossover is still a far from convincing experimental verification even for the heavy-ion collisions. Adding to the complexity, in the real-life scenario of experiments, the finite size effect \(23, 26\) of the system formed in the collision, may cause widening of the width of transition or smoothening of singularities in the LQCD-predicted dependence of the degrees of freedom.

### III. METHODOLOGY

The experimental search for the phase transition or for the crossover in the data of high energy collisions involves connecting thermodynamical variables with measurable observables. The rapidity density, \(dN_{ch}/d\eta\), (where \(N_{ch}\) is the number of charged hadrons, the rapidity, \(y = (1/2) \ln(E+\not{p}_E-p_L)\), \(E\) and \(p_L\) are respectively the energy and longitudinal component of momentum of a particle) or the pseudorapidity density, \(dN_{ch}/d\eta\), (where the pseudorapidity, \(\eta = -\ln[tan(\theta/2)]\) and \(\theta\) is the polar angle of the particle with respect to the beam direction) and the transverse momentum, \(p_T\), of produced charged hadrons are primary measurable observables in high energy experiments which are connected to thermodynamic variables involved in the LQCD-predicted signal for the change in phase.

According to the relativistic hydrodynamics, the rapidity or the pseudorapidity density reflects the entropy-density \(\langle \sigma \rangle\) created early in the collision. The \(\sigma\) depends only on the initial energy-density \(\langle \epsilon \rangle\) and remains constant throughout the evolution of the system. Even for \(d\langle N_{ch}\rangle/d\eta \approx 6\), the \(\epsilon\) has been shown \(14\) to be sufficient for formation of a non-hadronic medium in \(pp\) collisions at $\sqrt{s} = 7$ TeV. The Compact Muon Solenoid (CMS) experiment has recorded \(27, 28\) sufficient statistics of high multiplicity \(pp\) events with \(d\langle N_{ch}\rangle/d\eta\) going up to \(\approx 30\), providing a wide range of data to look for effects of variation in observables involving energy-density. As the objective of this study does not include evaluation of the absolute value of the energy-density, the following simple formalism \(14\) as proposed by Bjorken could be sufficient for estimation of the energy-density and then the entropy-density:

\[
\epsilon_{BJ} \simeq \frac{dN_{ch}}{d\eta} \frac{1}{2} (p_T)^2 \frac{V}{\langle S_{ch} \tau \rangle}
\]

where, \(V\) is the effective volume occupied by the particles and is given by \(S_{ch} \tau \), \(S\) being the interaction area and \(c.\tau\), a longitudinal dimension, considered to be about 1 fm in Bjorken model. The estimate of entropy density, therefore, comes as:

\[
\sigma \simeq \frac{dN_{ch}}{d\eta} \frac{3}{2} \frac{\langle p_T \rangle}{S}
\]

where \(\sigma = \epsilon/\langle p_T \rangle\) and \(S = \pi R^2\), \(R\) is the radius of the interaction area.

The \(p_T\) spectra produced particles from high energy collisions contain information on temperature as well as on transverse expansion of the system. In the context of the present work, it is important to note that the temperature of a thermalized partonic medium, if formed, should ideally be reflected by the low \(p_T\) particles (usually \(p_T < 2\) GeV/c, as has been considered in heavy-ion collisions). As disentangling the effect of the temperature and the contribution from the transverse expansion in the \(p_T\) spectra is not possible, instead of exclusive measure of temperature, experimental analysis deal with parameters that reflect the temperature of the system. Either the mean transverse momentum, \(\langle p_T \rangle\), as proposed \(15\) by Van Hove, or the slope of the transverse mass (\(m_T\)) - spectra, obtained from the \(p_T\) spectra (for a particle of mass \(m\), \(m_T = (m^2 + p_T^2)^{1/2}\)), can be used for comparing thermal states of the system.

The investigation of the LQCD predicted signal for change in phase in terms of effective number of degrees
of freedom in pp collisions has been studied in terms of the \( \langle p_T \rangle \) dependence of \( \sigma/(p_T)^3 \). On the other hand, the \( m_T \) - spectra corresponding to low - \( p_T \) particles are usually satisfactorily fitted with exponential function of the form, \( dN/m_T dp_T = C.\exp(-m_T/T_{\text{effective}}) \), where \( T_{\text{effective}} \), known as the inverse slope parameter. Increase in inverse slope parameter, \( T_{\text{effective}} \), with mass, \( m \), for the most commonly measured identified particles (\( \pi^\pm \), \( K^\pm \), \( p \) and \( \bar{p} \)), as has been observed in heavy-ion collisions as well as in the recent pPb collisions at CERN is a well known phenomenon, attributed to the collective transverse flow of the medium formed in the collision.

### IV. ANALYSIS & RESULTS

The CMS experiment at the LHC has measured \( p_T \)-spectra of pions (\( \pi^\pm \)), kaons (\( K^\pm \)), and protons (\( p \) and \( \bar{p} \)) over the rapidity range \( |y| < 1 \) for the pp collisions at \( \sqrt{s} = 0.9, 2.76 \) and 7 TeV for several event classes selected on the basis of mean number of charged particles, \( \langle N_{ch} \rangle \) in the pseudo-rapidity interval, \( |y| < 2.4 \) or, in other words, as a function of pseudo-rapidity density, \( d\langle N_{ch} \rangle/d\eta \), reflecting "centrality" in pp collisions. The measured \( p_T \) - ranges are (0.1 to 1.2) GeV/c for \( \pi^\pm \), (0.2 to 1.050) GeV/c for \( K^\pm \) and (0.35 - 1.7) GeV/c for \( p \) and \( \bar{p} \). It is worth mentioning that the same set of data, on analysis in the hydrodynamics motivated Boltzman-Gibbs blast-wave model, revealed collective transverse flow for the high multiplicity events. To check if the previously observed indication of the formation of collective medium in pp collisions is revealed in the statistical model also, we look for the mass dependence of inverse slope parameter with the data at \( \sqrt{s} = 7 \) TeV from the CMS experiment. To avoid the effect of resonance decays, the pions with \( p_T < 0.45 \) GeV/c were excluded from the calculations. The increase of \( T_{\text{effective}} \) with mass of identified particles for event classes of high \( \langle N_{ch} \rangle \) reiterates (Figure 1) the finding of collective medium in high-multiplicity pp collisions. The collectivity, however, does not confirm formation of the QGP.

To characterize the collective medium so formed, we study the \( \langle p_T \rangle \) - dependence of \( \sigma/(p_T)^3 \), the effective number of degrees of freedom of the system formed in the collisions. In the study, we also take into consideration some model dependent estimations of the effect due to the transverse expansion on \( \langle p_T \rangle \) to facilitate the study and the interpretation thereof. A model calculation of \( \langle p_T \rangle \) as a function of the temperature for various hadron species show that the change in the shape of the \( p_T \) - spectra or in the value of \( \langle p_T \rangle \) due to the transverse expansion is dependent on the individual hadron species of different mass - while the protons gain most in \( \langle p_T \rangle \), the pions lose some \( \langle p_T \rangle \). According to another model calculation, the protons gain additional \( \langle p_T \rangle \) as the protons decouple from the fireball after pions, experiencing larger flow-effect. Being weakly affected by re-scattering of hadrons and resonance decay, kaons are better observable in the search for change in phase. We, therefore, argue that instead of the \( \langle p_T \rangle \) of several particles together, containing cumulative effect due to the transverse expansion of varying magnitude, the \( \langle p_T \rangle \) of individual species may be more meaningful in reflecting temperature related characteristics of the system. We study the dependence of \( \sigma/(p_T)^3 \) on the \( \langle p_T \rangle \) for pions and kaons from the pp collisions at \( \sqrt{s} = 0.9, 2.76 \) and 7 TeV. We do not study the proton - spectra because of the well known strong proton-flow. To calculate the entropy density, \( \sigma \) following Bjorken’s formalism, the radius of interaction, \( R \), is estimated from the HBT- radius that has dependence on the pair transverse momentum \( k_T \) and multiplicity. For a given \( d\langle N_{ch} \rangle/d\eta \), high \( k_T \) corresponds to the early stage of the collision, while low \( k_T \) relates the final stage, close to the freeze-out, and includes the effect of particle activities in the transverse direction during the expansion. We use the radii for the highest \( k_T \) - range (0.5 to 1.0 GeV/c), as measured by the CMS experiment, to parameterize the radius of interaction as a function of \( \langle N_{ch} \rangle \), as \( R(\langle N_{ch} \rangle) = a.\langle N_{ch} \rangle^{1/3} \), where \( a = 0.504 \pm 0.0097 \) fm.
to be less affected by the flow, that develops with time. In case of early freeze-out, the kaons are likely observed difference in response by the pions and the kaons. A change of phase cannot be concluded out and may provide an alternate explanation to the early kaon-freeze-out as compared to the pion-freeze-out [33, 36, 37] may lead to the freeze-out of hadron species as a consequence of differences in elastic cross-sections.

The shape of the kaon $p_T$-spectrum, therefore, may largely retain the effect of the temperature of the system formed in high energy collisions. One needs to note that, as the $\langle p_T \rangle$ only reflects the $T$ and does not give absolute measure of $T$, the $\sigma/\langle p_T \rangle^3$ also reflects the effective number of degrees of freedom and not necessarily quantitatively match $\sigma/T^3$. Nevertheless, the dependence of $\sigma/\langle p_T \rangle^3$ on $\langle p_T \rangle$ for the kaons reveals the qualitative feature of the LQCD-predicted signal for the change in phase of matter formed in pp collisions in terms of change from high to low degrees of freedom with decreasing $\langle p_T \rangle$, the temperature-related observable. Importantly, the nature of the experimental finding of the change in phase matches the results of the latest LQCD calculations predicting a crossover.

**V. DISCUSSIONS AND CONCLUSIONS**

It is worth mentioning that the idea of formation of thermalized partonic matter in the so-called elementary interactions is not new. There have been several studies [18, 20, 38–40], addressing the de-confinement and formation of hydrodynamic medium in pp collisions. At a very high initial energy-density in pp collisions, even though the system-size is small, one may expect fulfillment of the condition for the local thermal equilibrium - the mean free path sufficiently smaller than the dimensions of the system. In fact, the measured final state particle multiplicity in high-multiplicity pp collisions at LHC, being comparable [15] with that in CuCu collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC, may be adequate enough to fulfill the condition for the equilibrium. We emphasize that the observed dependence of the degrees of freedom on $\langle p_T \rangle$ at large values, equivalent to high temperature, corresponds to the high multiplicity pp events at the LHC. It is noteworthy that the liberation of effective number of degrees of freedom for a given pseudorapidity density and for a given $p_T$ - range, is independent of the centre-of-mass energy. Summarily, the analysis of the data of pp collisions at the LHC, in terms of the nature of dependence of $\sigma/\langle p_T \rangle^3$, the effective number of degrees of freedom, on $\langle p_T \rangle$, reflecting the temperature of the system, corroborates with the LQCD prediction on change in phase. This article, thus, reports a convincing experimental endorsement of the change in phase of matter or equivalently the formation of thermalized partonic matter in pp collisions.

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