Universality in hadronic and nuclear collisions at high energy

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Recent experimental results in proton-proton and in proton-nucleus collisions at Large Hadron Collider energies show a strong similarity to those observed in nucleus-nucleus collisions, where the formation of a quark-gluon plasma is expected. We discuss the comparison between small colliding systems and nucleus-nucleus collisions, for (a) the strangeness suppression factor γ_s and yields of multi-strange hadrons; (b) the average transverse momentum, p_t, with particular attention to the low p_t region where soft, nonperturbative effects are important; and (c) the elliptic flow scaled by the participant eccentricity. The universal behavior in hadronic and nuclear high energy collisions emerges for all these observables in terms of a specific dynamical variable which corresponds to the entropy density of initial system in the collision and which takes into account the transverse size of the initial configuration and its fluctuations.

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I. INTRODUCTION

Recent experimental results in proton-proton (pp) and proton-nucleus (pA) collisions at the Large Hadron Collider (LHC) and Relativistic Heavy Ion Collider (RHIC) show a strong similarity to those observed in nucleus-nucleus (AA) collisions, where the formation of a quark-gluon plasma is expected. Many different signatures [1–9] support the conclusion that the system created in high energy, high multiplicity collisions with "small" initial settings, i.e., pp and pA, is essentially the same as that one produced with "large" initial AA configurations.

The ALICE Collaboration reported [1] the enhanced production of multistrange hadrons, previously observed in PbPb collisions [10], in high energy, high multiplicity, pp events. The strangeness enhancement was suggested to be present in high-multiplicity pp collisions on theoretical grounds in Refs. [11,12] by considering a specific dynamical variable corresponding to the initial entropy density of the collisions, which takes into account the transverse size (and its fluctuations) of the initial configuration in high multiplicity events [13,14]. Noticeably, the energy loss in AA collisions was also shown to scale in the same dynamical variable [15].

An important similarity between pp, pA, and AA collisions was identified also in several measurements of long-range dihadron azimuthal correlations [3,4,6,16] indicating universally present flowlike patterns.

The similarity of the average transverse momentum (p_t) between pp, pA, and AA collisions was discussed in Refs. [17–19], where the scaling of p_t as a function of the variable $N_{\rm track}/A_T$ ($N_{\rm track}$ being the multiplicity and A_T the transverse area of the initial system) was explored in the framework of color glass condensate (CGC), where also the geometrical scaling of direct-photon production in hadron collisions at RHIC and LHC energies has been obtained in terms of the saturation scale, proportional to the transverse entropy density [20].

The previously discussed similarities indicate that a few dynamical ingredients, common to the different initial settings, drive the particle production, independently of the complexity of the nonequilibrium dynamics with annihilation and creation of many interacting quarks and gluons and hadronization of final partons.

In this paper, we discuss some pieces of the mosaic of this universal behavior in a unified way. More precisely, for small colliding systems versus AA collisions, we compare (a) the strangeness enhancement, refining previous analyses [13,14]; (b) the mean p_t, with particular attention to the low p_t region where the soft, nonperturbative effects are important; and (c) the elliptic flow, v_2, where a scaling behavior has been already observed [21–23] for different nuclei (Au, Cu, and Pb) by considering the ratio $v_2/\epsilon_{\rm part}$, where $\epsilon_{\rm part}$ is the participant eccentricity, defined for example in [23–26]. All the comparisons speak in favor of the universal, initial entropy density driven mechanism for the particle production across different colliding systems.

II. EMERGENT UNIVERSALITY

Let us recall that the initial entropy density s_0 is given in the one-dimensional hydrodynamic formulation [27] by the form

$$s_0\tau_0 \simeq \frac{1.5}{A_T}\frac{dN_{ch}^x}{dy} = \frac{1.5}{A_T}\frac{N_{\text{part}}^x}{2}\frac{dN_{ch}^x}{dy}\bigg|_{y=0}, \tag{1}$$

with $x \simeq pp,\ pA,\ AA$. Here A_T is the transverse area, $(dN_{ch}^x/dy)_{y=0}$ denotes the number of produced charged secondaries, normalized to half the number of participants N_{part}^x, in reaction x, and τ_0 is the formation time. The initial entropy density is directly related to the number of partons per unit of transverse area and, due to the large fluctuations in high multiplicity events, one needs a reliable evaluation of the transverse area for different collisions.

In studying the strangeness enhancement and the average p_t, we use results from Glauber Monte Carlo (MC) [28] to obtain A_T as a function of multiplicity for AA and for pPb collisions. For pp collisions the effective transverse area is sensitive to the fluctuations of the gluon field configurations and therefore we apply the CGC parametrization of the transverse size as a function of multiplicity [17–19].

On the other hand, for the scaling behavior of the elliptic flow, namely of the ratio $v_2/\epsilon_{\text{part}}$, the effective transverse area, S, of the initial setting is the one related to ϵ_{part}. The S is evaluated by MC simulations in Refs. [22,26] for AA and in Ref. [29] for pp collisions.

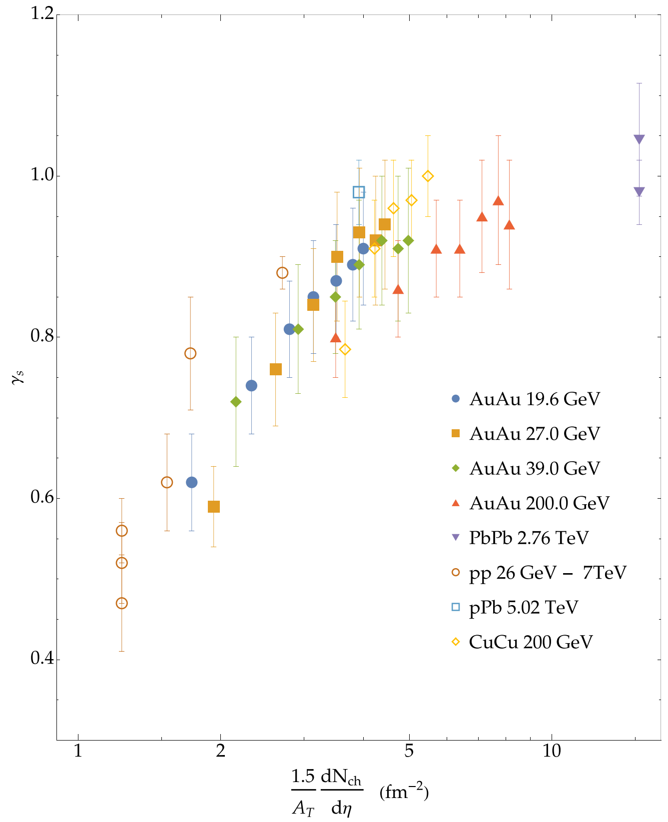

FIG. 1. The strangeness suppression factor γ_s as a function of initial entropy density evaluated for data from Refs. [31,32,34,35]. The Phobos parametrization [36] for the relation between charge multiplicity, energy and the number of participants is applied for RHIC data.

III. UNIVERSALITY IN STRANGENESS PRODUCTION

In Refs. [13,14] the parameter $\gamma_s \leqslant 1$, which describes the strangeness suppression in the statistical hadronization model (SHM) [30], was studied as a function of the variable from Eq. (1), by using an approximate evaluation of the transverse area for pp, pPb, and AA collisions.

Here we use an improved evaluation of the transverse area for AA, pPb, and pp collisions as described in the previous section. The resulting scaling behavior for the strangeness production is reported in Fig. 1, where γ_s for AA at different energies and centralities are shown along with those for pPb and pp collisions. The data refer to pp at energy $\sqrt{s} = 26$ GeV to 7 TeV [31,32], to pPb at $\sqrt{s} = 2.76$ TeV [11–14,33], to PbPb at $\sqrt{s} = 2.76$ TeV [34], to AuAu at $\sqrt{s} =$ 19.6, 27, 39 and 200 GeV [35], and to CuCu at $\sqrt{s} = 200$ GeV [32].

The universal trend shows that γ_s increases with the parton density in the transverse plane, up to the fixed point $\gamma_s = 1$, where any suppression disappears.

The result in Fig. 1 has been obtained by estimating γ_s in a specific SHM [31,32,34,35]. On the other hand, different versions of the model, which take into account various dynamical aspects of the hadron resonance gas in thermal equilibrium (e.g., set of included resonances or excluded volume) [37,38] could give slightly different values for γ_s. While the impact of this can be further tested using different SHM, we checked the universality by a model independent analysis. In Fig. 2, ratios of yields of K, Λ, Ξ, and Ω hadrons to pions were evaluated as a function of initial entropy density for PbPb [10,39–41], pPb [2,42], and pp [1,43] data. The production of particles containing strangeness exhibits universality for all the tested collision systems.

Figures 1 and 2 represent two different aspects of universality, since the first one presents a large range of collision energy, whereas the second one, at fixed LHC energy, is a more genuine indication of the role of the system size.

IV. UNIVERSALITY IN MEAN TRANSVERSE MOMENTUM

As recalled, the scaling of the average p_t as a function of the variable N_{track}/A_T has been discussed in [17–19]. Here we analyze the average p_t in the low transverse momentum region where the soft, nonperturbative effects in the particle production are more important due to running of the strong coupling constant than in the higher p_t range. The behavior of the average p_t is evaluated in the region $0.15 < p_t < 1.5$ GeV for different colliding systems as a function of the dynamical variable from Eq. (1). The results are shown in Fig. 3 for the data from Refs. [44–47]. One can see that the average p_t for soft particle production follows the same slowly increasing

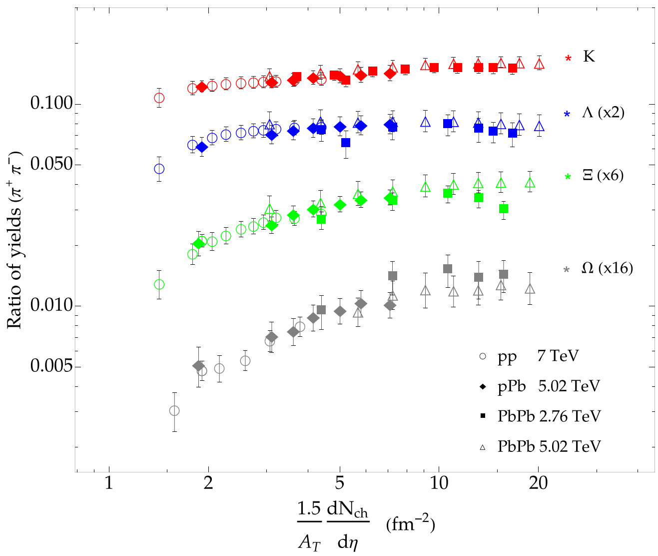

FIG. 2. The strangeness production quantified in terms of the ratio of yields of K, Λ, Ξ, and Ω hadrons to pions evaluated as a function of initial entropy density for data from Refs. [1,2,10,39–43].

trend for all the collisional systems. Discussion of a possible scaling of the hard component has been carried out, e.g., in Ref. [48].

V. UNIVERSALITY IN THE ELLIPTIC FLOW

In noncentral collisions, the beam direction and the impact parameter vector define a reaction plane for each event. If the nucleon density within the nuclei is continuous, the initial nuclear overlap region has an "almondlike" shape and the impact parameter determines uniquely the initial geometry of the collision.

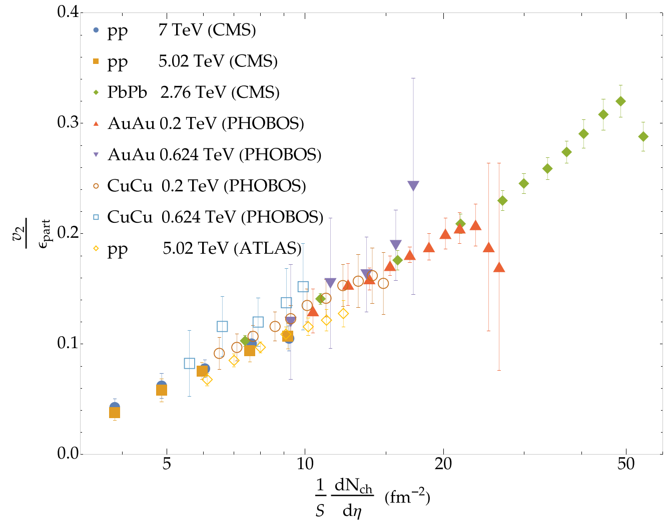

FIG. 4. The $v_2/\epsilon_{\rm part}$ values for pp, PbPb, AuAu, and CuCu evaluated as a function of entropy density for data from Refs. [3,21,22,50].

In a more realistic description, where the position of the individual nucleons that participate in inelastic interactions is considered, the overlap region has a more irregular shape and the event-by-event orientation of the almond fluctuates around the reaction plane [25,49]. Therefore, in the analysis of the elliptic flow where the fluctuations are important, the geometrical eccentricity is replaced by the participant eccentricity, $\epsilon_{\rm part}$, defined using the actual distribution of participants. The size of the fluctuation in $\epsilon_{\rm part}$ and its correlated transverse area S (different from the geometrical one) are evaluated by Glauber MC as previously described.

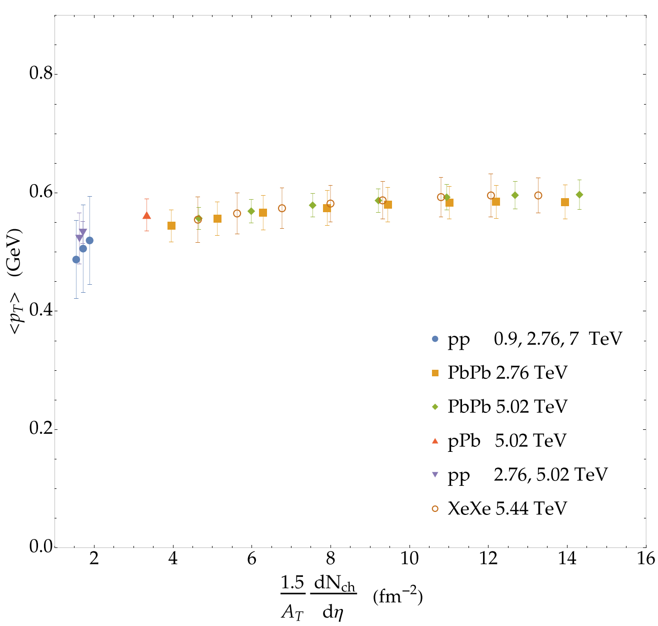

FIG. 3. Average p_t as a function of initial entropy density evaluated in the interval of $0.15 < p_t < 1.5$ GeV for the data from Refs. [44–47].

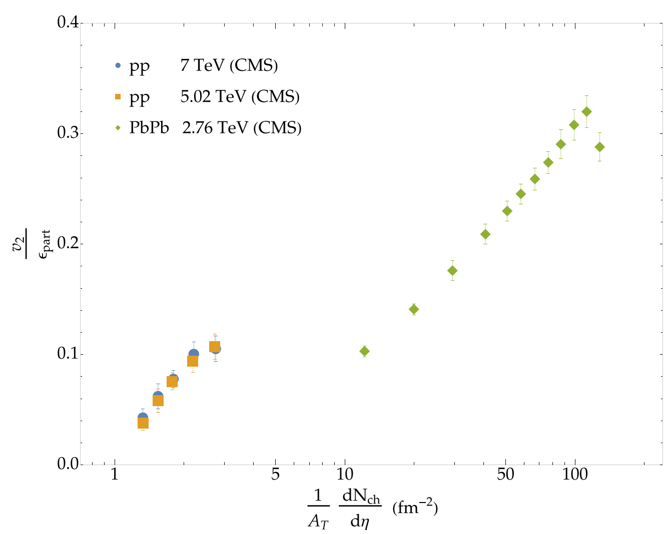

FIG. 5. The $v_2/\epsilon_{\rm part}$ values for pp and PbPb evaluated as a function of entropy density when the geometrical transverse area A_T, rather than S, is used in the evaluation of the initial energy density for data

The scaling of $v_2/\epsilon_{\rm part}$ versus the initial entropy density is depicted in Fig. 4 for *AA* [21,22] and *pp* [3,50]. One can see that the *pp* trend, at lower values, is smoothly followed by the data points from *AA* collisions.

To clarify the different role of A_T versus S, Fig. 5 shows that the scaling in $v_2/\epsilon_{\rm part}$ is not observed if one considers A_T rather than S in evaluating the initial entropy density.

VI. HOW TO CHECK THE UNIVERSAL TREND

The analyses of γ_s, average p_T, and $v_2/\epsilon_{\rm part}$ presented above support the conclusion that at fixed entropy density the "coarse-grain" features of the quark-gluon system formed in high energy collisions are independent of the initial configuration. The scaling variable [Eq. (1)] is a function of multiplicity and the transverse area, and one can evaluate at which multiplicity one can expect the same behavior in high-multiplicity *pp* and PbPb collisions, by solving the equation $(dN/d\eta)_{AA}/A_T^{AA} = x/A_T^{pp}(x)$ for x, which is the multiplicity in *pp*. The result is shown in Table I for PbPb collisions at 5.02 TeV which represent the largest available heavy-ion dataset at the LHC. The values from Table I can be used in subsequent experimental or phenomenological studies aiming to further check the universal trends in hadronic and nuclear collisions using high-multiplicity *pp* collisions at the largest available LHC energies.

VII. COMMENTS AND CONCLUSIONS

High energy and high multiplicity events produced in small colliding systems show dynamical behavior very similar to that present in *AA* collisions. Observations made in this paper suggest that the dynamical behavior is largely driven by the initial entropy density, that is by the parton density in the transverse plane. A clear quantification of limits on the presence of jet quenching in small colliding systems (see, e.g., discussions and new measurements in Refs. [51–53]) or more detailed correlation measurements (see, e.g., recent work in Refs. [54–56]) may help to improve understanding of this similarity. This kind of measurements can be done in detail at the LHC or RHIC or at a 100 TeV *pp* collider which is considered for the future [57] and which would significantly enhance the reach of multiplicities in *pp* collisions.

TABLE I. $dN_{ch}/d\eta$ in PbPb at 5.02 TeV and *pp* for different values of the variable in Eq. (1).

$\frac{1.5}{A_T}\frac{dN_{ch}}{d\eta}$	$\left(\frac{dN_{ch}}{d\eta}\right)_{pp}$	$\left(\frac{dN_{ch}}{d\eta}\right)_{\rm PbPb}$	PbPb centrality
20.1 ± 0.8	100 ± 4	1943 ± 56	0–5%
17.5 ± 1.1	87 ± 5	1587 ± 47	5–10%
15.4 ± 0.9	76 ± 4	1180 ± 31	10–20%
12.2 ± 0.6	60.6 ± 3.1	649 ± 13	20–40%
8.3 ± 0.7	41.2 ± 3.4	251 ± 7	40–60%
5.2 ± 0.8	26 ± 4	70.6 ± 3.4	60–80%
3.1 ± 1.1	12.4 ± 3.0	17.5 ± 1.8	80–90%

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