Mass Hierarchy in Identified Particle Distributions in Proton-Lead Collisions

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We study the mass dependence for identified particle average transverse momentum and harmonic flow coefficients in proton-lead (p-Pb) collisions, recently measured at the LHC. The collective mechanism in the p-Pb system predicts a specific mass ordering in these observables: the growth of the average transverse momentum with the particle mass and a mass splitting of the elliptic flow coefficient, i.e., smaller differential elliptic flow of protons than pions for $p_T < 2$ GeV. This provides an opportunity to distinguish between the collective scenario and the mechanism based on the initial gluon dynamics in the evolution of the p-Pb system.

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In this Letter, we analyze the mass hierarchy in proton-lead (p-Pb) collisions for average transverse momentum, harmonic flow coefficients, and the "ridge" correlations [1–5], recently measured for identified particles at the LHC [6–8]. We show that the flow generated with hydrodynamics is capable of uniformly explaining these data for the most central p-Pb collisions, where collective effects are expected to be most important.

The fact that the (identified particle) average transverse momentum $\langle p_T \rangle$ in p-Pb collisions cannot be explained by a superimposition of p-p production was recently brought up by Bzdak and Skokov [9], thus on general grounds hinting at collectivity, or strong departures from superposition in the p-Pb system. We present below quantitative estimates showing that collective flow effects explain the observed $\langle p_T \rangle$ for identified particles. As arguments based on saturation and on geometric scaling [10,11] lead to similar phenomena, other observables are needed for the verification, in particular, the particle-identified harmonic flow. The elliptic and triangular flow coefficients [12,13] in relativistic nuclear collisions (A-A) arise as a result of the collective expansion of an azimuthally asymmetric fireball. In high-multiplicity A-A collisions, the flow asymmetry is routinely analyzed in terms of the harmonic flow coefficients v_n

$$\frac{dN}{d^3p} = \frac{dN}{2\pi p_T dp_T d\eta}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T, \eta)\cos[n(\phi - \Psi_n)]\right]. \quad (1)$$

In proton-proton (p-p) and p-Pb reactions at the LHC energies, the two-particle distributions in relative azimuthal angle $\Delta\phi$ and relative pseudorapidity $\Delta\eta$ have been analyzed [1,3,4,14]. The observation of a sizable same-side ($\Delta\phi \simeq 0$) and a away-side ridge ($\Delta\phi \simeq \pi$) in the highest-multiplicity p-Pb events resembles the effect noticed previously in the A-A case, where the same-side ridge and the broader away-side ridge occur as a result of the azimuthally asymmetric collective expansion of the formed fireball [15]. The two-particle correlation function, including the ridges, can be successfully decomposed in Fourier components involving the squares of the harmonic flow coefficients v_n^2. The same coefficients (up to the nonflow effects and flow fluctuations) are obtained from the flow analysis with respect to the event plane angles Ψ_n, or with cumulants [16]. The coefficients v_n reflect the structure of the Fourier components of the initial transverse energy density, whose eccentricity coefficients are determined by the geometry of the collision and the fluctuations of the initial density in the transverse plane.

Hydrodynamic expansion of the small fireball formed in p-Pb collisions generates relatively large elliptic and triangular flow [17] and may as well be behind the origin of the same-side ridge observed in p-Pb experiments at the LHC [18]. The direct measurement of the elliptic flow, and especially of the triangular component v_3, strongly suggests a collective origin of the effect [2,5,7,17–22].

In another class of models, the ridge is generated by local partonic dynamics [23,24], which in the saturated regime leads to long range correlations in rapidity between the produced particles [25]. The away- and same-side ridges are generated by the interplay of the ladder and interference diagrams [24,26]. The elliptic flow component in the two-particle correlations can be explained in both scenarios. The existence of the two alternative scenarios of the dynamics in the p-Pb collisions which explain the observed ridge correlations calls for the evaluation of additional experimental observables, able to disentangle different sources of two- or many-particle correlations.

In this Letter, we discuss how a further insight into the mechanism of particle production can be gained from the analysis of spectra and flow correlations for identified particles. In particular, we present the results for the average transverse momentum and the flow coefficients for identified particles, and compare them to very recent experimental results [7,8]. It has been well known from the experience in the A-A studies that the flow generates a mass hierarchy in the p_T spectra, where the transverse motion pushes heavier hadrons to higher momenta [27]. The origin of the effect is very simple. When an expanding hydrodynamic fluid freezes, it emits particles according to the Frye-Cooper [28] formula

$$\frac{dN}{d^3p} = \int_\Sigma dS(x, p), \tag{2}$$

where the emission function is integrated over some freeze-out hypersurface. Explicitly, the "boosted" source element is [28]

$$dS(x, p) = d\Sigma_\mu p^\mu f\left(-\frac{p_\mu u^\mu(x)}{T}\right), \tag{3}$$

where f denotes the statistical distribution function at the freeze-out temperature T, and u is the flow four-velocity. The statistical hadronization also includes the important resonance contributions, but the qualitative aspects remain simple: the momenta of heavier particles are affected more strongly by the collective flow; in particular, due to expansion, the protons will, on average, acquire higher momentum than kaons, and those, in turn, higher than pions.

All results shown in this Letter follow from the three-stage approach described in detail in Refs. [17,20]. The fluctuating initial state is obtained with the Glauber simulations [29], where the initial density is constructed by placing a smeared source in the center of mass of the colliding proton and the participating nucleon (the *compact* source prescription of Refs. [20,21]). We stress that the longitudinal elongation of the initial fireball in space-time rapidity is an assumption of the model that reproduces the observed pseudorapidity densities and leads to long range correlations in the relative pseudorapidity of two particles. The subsequent event-by-event hydro simulations are for the $3 + 1$-dimensional viscous dynamics, with the shear viscosity $\eta/s = 0.08$ and the hydrodynamic ignition time of $\tau = 0.6$ fm$/c$. The statistical hadronization [30] is carried out at the constant freeze-out temperature $T_f = 150$ MeV.

Some explanation of the centrality selection is in place. Exactly the same cuts in centrality as used by the experimental groups cannot be applied in model calculations due to limited statistics. A cut in the initial entropy of the source, which is the prescription we adopt, is an approximation of the experimental procedure. This method works for global average flow observables, especially in the range where their centrality dependence is mild, but cannot be applied to very specific cases, such as the ultrahigh-multiplicity cuts of the CMS Collaboration, or used to estimate the nuclear attenuation factors. In the version of the Glauber model used in this Letter, for simplicity, the initial entropy is proportional to the number of participants, and we define centrality classes via the number of the participant nucleons in the Glauber Monte Carlo event [17]. We note that using alternative scenarios [20] for the initial entropy does not affect the centrality dependence of the bulk observables studied in this Letter.

Figure 1 shows the mean transverse momenta of identified particles in two different approaches: hydro with the Cooper-Frye freeze-out (the model and its parameters are described in detail in Ref. [17]) and the HIJING model [31]. We note a large mass hierarchy in the hydro case, in agreement with the experiment and supporting the collective scenario of the evolution. The hydrodynamic calculations are done for a range of centralities 0%–60%. While the scenario assuming the collective expansion of the source is justified only in the most central p-Pb collisions, our calculation reproduces the observed mass hierarchy and the multiplicity dependence of $\langle p_\perp \rangle$ for all centralities. The HIJING model has no collective flow and cannot reproduce the measured mass splitting in the average transverse momentum. The fact that the superposition models do not reproduce the p-Pb data is visible when using the experimental data for $\langle p_\perp \rangle$ in p-p [9]. This also means that the color reconnection mechanism which reproduces the $\langle p_\perp \rangle$

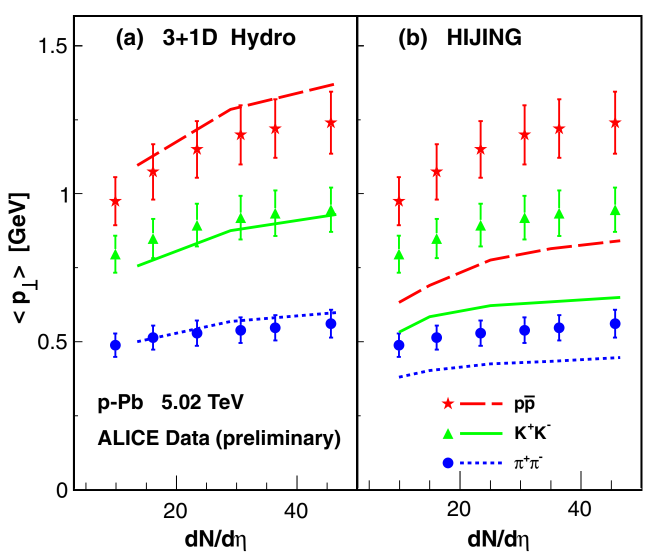

FIG. 1 (color online). Mean transverse momentum of identified particles as a function of the charged particle density in the p-Pb collisions, following from (a) hydrodynamics and (b) HIJING 2.1. The lines show the model calculations, while the data points come from Ref. [8].

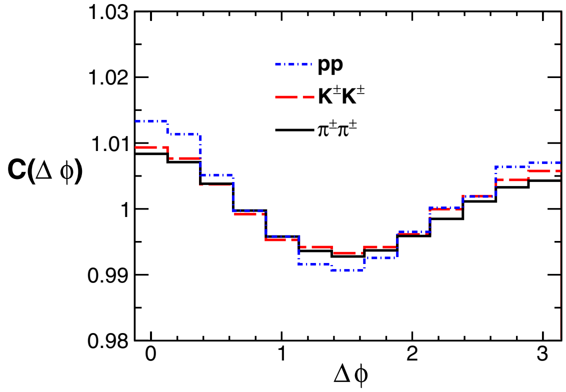

FIG. 2 (color online). The correlation function $C(\Delta\phi)$ in the relative azimuth $\Delta\phi$ for identified particle pairs. The rapidity separation is $|\Delta\eta| > 2$, and the same-sign particles are used to minimize the nonflow effects. The momentum range is the same for all species: $0.3 < \langle p_T \rangle < 3$ GeV. Centrality is defined as $N_{\rm part} \geq 18$, corresponding to 0%–3%.

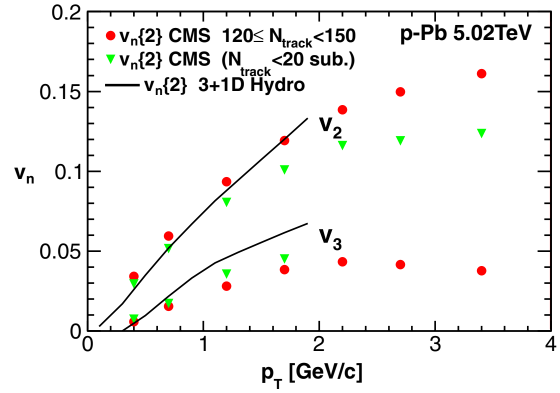

FIG. 3 (color online). v_2 and v_3 for charged particles calculated with the hydrodynamic model. The data come from Ref. [2].

of the identified particles and their multiplicity dependence in p-p interactions [32] would not explain the p-Pb data without additional collective flow or coherence effects.

In Fig. 2, we show our model result for the identified correlations in the azimuthal angle, defined as

$$C(\Delta\phi, \Delta\eta) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)}, \qquad C(\Delta\phi) = \int_{|\Delta\eta|>2} C(\Delta\phi, \Delta\eta), \tag{4}$$

where S is the distribution of signal pairs and B is the mixed-event background. Note that Eq. (4) describes the correlation function between two identified particles, while the flow coefficients $v_n(p_\perp)$ in Figs. 4 and 5 correspond to the correlation of an identified particle with an unidentified charged hadron [7]. We clearly note the two ridges (maxima at $\Delta\phi = 0$ and $\Delta\phi = \pi$) with amplitudes similar for all the studied particle species (the last observation is true only for the particular $p_\perp$ range used). The calculated correlation function should be compared to two-particle correlations extracted from the experiment with the nonflow component subtracted.

Correlations from the collective flow in of Fig. 2 represent the prediction of the hydrodynamic model for correlations between two identical particle species. Thus, in small systems, such flow correlations are present, besides the nonflow correlations from jets, local charge, momentum, or energy conservation, which are also observed in two-hadron correlations in p-p interactions [33].

The hydrodynamic model with Glauber initial conditions from the *compact* source of Refs. [20,21] reproduces the measured elliptic and triangular flow of charged particles for central collisions (Fig. 3), where the CMS experimental centrality bin $120 \leq N_{\rm track} < 150$ is compared to the hydrodynamic calculation with $N_{\rm part} \geq 18$, corresponding to a similar centrality of 0%–3%. We note that quantitative predictions of the hydrodynamic model depend on the assumed initial shape and the parameters of the calculation [17,18,20–22]. Figure 4 shows the p_T dependence of the elliptic flow coefficient v_2 of identified hadrons, with a moderate but systematic mass scaling. The flow coefficients are obtained for events with $N_{\rm part} \geq 14$, using the two-particle cumulant method and the flow vector Q defined by the charged particles. In the experiment, a possible way to reduce the nonflow correlations would be to use the peripheral centrality subtraction method [7] or to use the scalar product method, with the Q vector defined in very forward pseudorapidity bins. In model calculations, the cumulant and the scalar product methods give very similar results [20]. The experimentally observed mass splitting in p-Pb [7] is qualitatively similar to that in the A-A collisions. Within hydrodynamics, the mass splitting appears as a collective flow effect [34]. The magnitude of the mass splitting in the p-Pb collisions can be reproduced with a relatively high freeze-out temperature

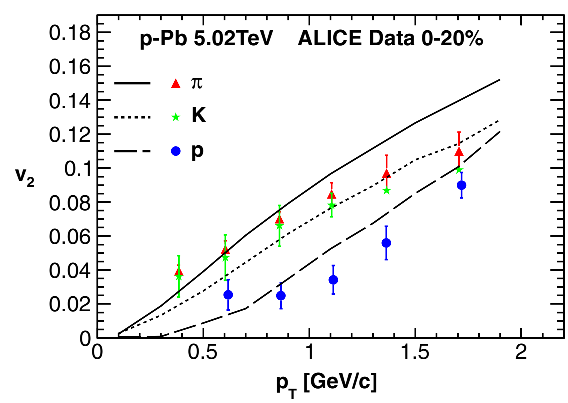

FIG. 4 (color online). $v_2\{2\}$ for pions, kaons, and protons in p-Pb collisions calculated with the hydrodynamic model, as a function of the transverse momentum. The data come from Ref. [7].

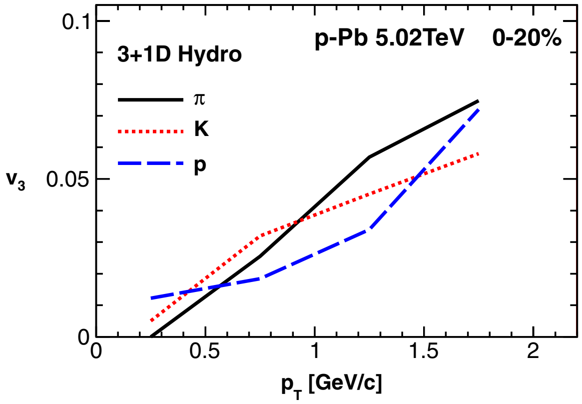

FIG. 5 (color online). Predictions for $v_3\{2\}$ for pions, kaons, and protons in p-Pb collisions calculated with the hydrodynamic model, as a function of the transverse momentum.

$T_f = 150$ MeV, which suggests a relatively short hadronic rescattering phase in the small systems, while a lower freeze-out temperature is used to reproduce the effect in A-A collisions [34].

Figure 5 gives the prediction of the hydrodynamic model for the triangular flow coefficient of identified particles. The magnitude and the mass splitting of the triangular flow for identified hadrons are much smaller than for the elliptic flow (Fig. 4); moreover, the ordering is inverted for small $p_\perp$. We have checked that the inverted mass ordering of v_3 in the range $p_\perp < 500$ MeV comes as a result of resonance decays.

To assess the limits of the applicability of the hydrodynamic picture in p-Pb collisions, we compare the calculated integrated elliptic flow at three centralities to the CMS data (Table I). Clearly, as the systems become smaller, the calculation deviates from the experimental values (especially for v_3), indicating that in peripheral p-Pb collisions, the dissipative effects and the contribution of possible nonthermalized corona increase. Quantitative agreement of the model with the data on flow coefficients can be reached only for the most central interactions, where the system is large enough to sustain a collective expansion phase that can be described through relativistic viscous hydrodynamics.

We note that in small and short-lived systems, part of the flow may be generated in the early prehydrodynamic phase [35,36]. General arguments and numerical simulations show, however, that in many respects, the preequilibrium flow leads to results similar to those of hydrodynamics extended to very early times [37–39]. The p-Pb collisions offer a potential test ground to disentangle these effects.

In conclusion, we restate that the very fact that a strong mass hierarchy is seen in the highest-multiplicity p-Pb collisions at the LHC energies strongly suggests the collective nature of the evolution of the system. We have shown that the experimental results for the average transverse momentum and the elliptic flow coefficient v_2 can be described within the hydrodynamic approach, previously applied to this system.

TABLE I. $v_n\{2, |\Delta\eta| > 2\}$, $n = 2, 3$, for all charged particles for various centrality classes, evaluated with the pseudorapidity gap $|\Delta\eta| > 2$ and the cut $0.3 < p_T < 3$ GeV. The centrality is defined by $\langle N_{\rm track}\rangle$ corrected as in Ref. [6].

	v_2		v_3	
$\langle N_{\rm track}\rangle$	Model	CMS [6]	Model	CMS [6]
154.5	0.057	0.063	0.023	0.02
96	0.059	0.057	0.022	0.016
45	0.061	0.043	0.020	0.006

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Note added.—Recently, very similar qualitative conclusions were reached by Werner *et al.* [40].

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