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Hydrodynamic models of particle production - p-Pb collisions

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Abstract. Viscous hydrodynamics gives a satisfactory description of the transverse momentum spectra, of the elliptic and triangular flow, and of the femtoscopic correlations for particles produced in relativistic heavy-ion collisions. On general grounds, a similar collective behavior has been predicted for proton-lead (p-Pb) collisions at the LHC. We present results of the hydrodynamics calculation of the elliptic and triangular flow in p-Pb. We discuss the mass dependence of flow coefficients and of the average transverse momentum for identified particles.

1. Hydrodynamic model

The observation of the jet quenching and of the strong azimuthally asymmetric flow shows that in a high energy heavy-ion collision at ultrarelativistic energies a dense and hot droplet of matter is formed. Event-by-event hydrodynamic calculations [1, 2, 3, 4, 5, 6] are used to provide the response of the collective flow to the deformations of the fluctuating initial state. The eccentricity and triangularity of the initial density result in the formation of the elliptic and triangular flow in the spectra [3, 7]. Not only the average, but the whole distribution of the harmonic flow coefficients v_n [8] can be reproduced [9] for the IP-Glasma initial conditions. The event-by-event distribution of the hydrodynamic response shows that the distributions of v_2 and v_3 follow the initial distributions of ϵ_2 and ϵ_3.

Non-flow correlations between particles with soft momenta can be included in the simulation giving correlations between unlike-sign particles, mainly at small relative angle and relative pseudorapidity [10]. The hydrodynamic model gives predictions for the spectra of identified particles that are in satisfactory agreement with experiment at LHC energies [11, 12, 13, 14, 15]. Advanced hydrodynamic calculations are used to extract the properties of the quark-gluon plasma at different temperatures [16, 17, 18, 9, 19] and baryonic densities [20, 21]. The hard equation of state of the quark-gluon plasma leads to a rapid build up of the transverse flow, which implies a strong dependence of the femtoscopic radii on the pion pair momentum [22, 23].

The p-Pb collisions have been proposed as a laboratory to study the initial state effects and to obtain reference data for Pb-Pb collisions [24]. On the other hand, it has been predicted that the collective expansion of the fireball formed in central p-Pb collisions is significant and can lead to observable elliptic and triangular flow [25]. Experiments with p-Pb collisions at the

LHC measure the two-particle correlation function in relative pseudorapidity $\Delta\eta$ and relative azimuthal angle $\Delta\phi$ [26, 27, 28]. The two-dimensional correlation function presents two ridge-like structures, elongated in pseudorapidity, with pairs collimated in the same direction (same-side ridge, $\Delta\phi \simeq 0$) and in the opposite direction (away-side ridge, $\Delta\phi \simeq \pi$). The azimuthal structure in the two-dimensional correlation function can be understood as an effect of the azimuthally asymmetric collective flow and of the transverse momentum conservation [29], in a similar way as in heavy-ion collisions [30, 31]. The formation of the two ridges is predicted in the color glass condensate approach as well [32, 33, 34]. In Ref. [25] it has been proposed to look for collectivity in small systems using d-A collisions. In central d-A collisions the density profile in the transverse plane is determined by the deuteron wave-function, hence the eccentricity ϵ_2 is large $\simeq 0.5$, which gives a large elliptic flow [25]. The analysis of correlation functions in d-Au collisions at RHIC shows a strong v_2 component [35], but quantitative conclusions are difficult due to large non-flow contributions in the low multiplicity environment at the RHIC energies.

2. Transverse flow in p-Pb interactions

The multiplicity in central p-Pb collisions is comparable to peripheral Pb-Pb collisions. The source size can be estimated using the Glauber Monte Carlo model [36, 37]. The value of the root mean square radius, 1-2 fm, depends on the details of the energy deposition in the model, and grows for more central collisions. The expansion of the large energy density deposited in the

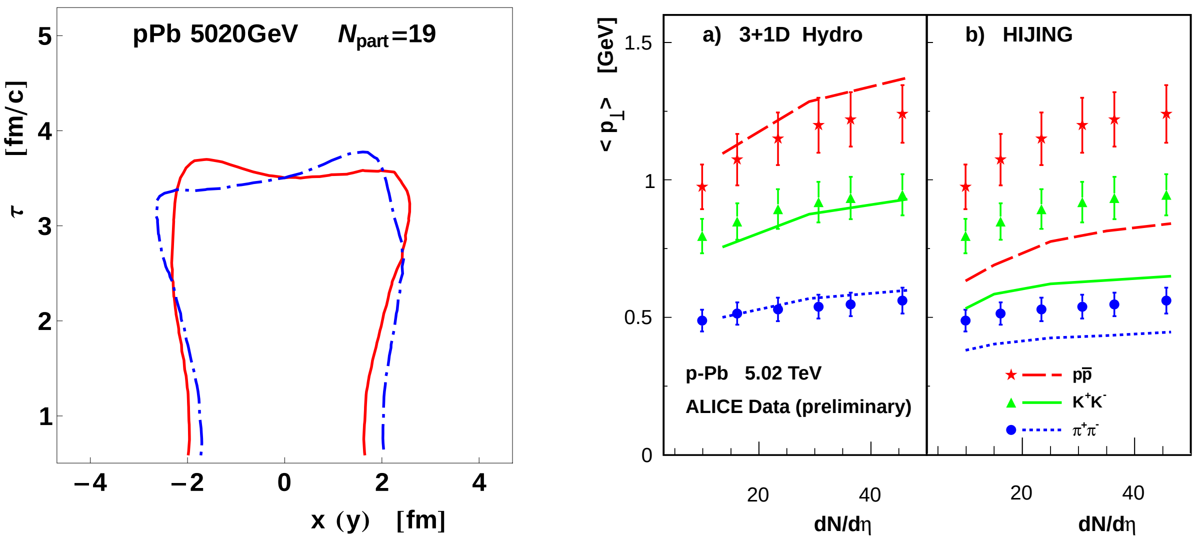

Figure 1. Left: The freeze-out isotherms in the $x-\tau$ plane (solid) and the $y-\tau$ plane (dashed) in a sample event. Right: Mean transverse momentum of identified particles as a function of charged particle density from hydrodynamics (panel (a), lines) and HIJING (panel (b), lines), ALICE Collaboration data [38] (symbols in panels a) and b)).

small volume generates large transverse collective flow [36, 37, 39, 40]. In the left panel of Fig. 1 is shown the freeze-out hypersurface for an event with 19 participant nucleons. The transverse size increases during the freeze-out and can be measured using interferometry radii. The values of the interferometry radii grow as a power of the multiplicity $N^{1/3}$ [41]. The slope of this dependence is different for A-A and for p-p collisions. It may suggest that the dynamics of typical p-p interactions is different than in peripheral A-A collisions. It would be very interesting to investigate experimentally this dependence also for p-Pb collisions to see, whether the space-time development of the p-Pb system is similar to p-p or to Pb-Pb interactions. The hydrodynamic model predicts for the p-Pb system the interferometry radii are close to those corresponding to A-A interactions [39].

The average transverse momentum of particles produced in the p-p, p-Pb and A-A interactions increases with the event multiplicity [38, 42]. For p-p interactions this increase can be explained as a color reconnection effect [43]. Modeling the particle production in p-Pb and A-A collisions as a superposition of nucleon-nucleon interactions one finds the average transverse momentum below the measured value [44, 38]. This effect is visible in the right panel of Fig. 1, where the HIJING model, based on the superposition of nucleon-nucleon collisions, underpredicts the average transverse momentum. This difference leaves room for additional collective transverse velocity to be generated during the expansion phase in p-Pb collisions. An important characteristic of the collective transverse flow is the mass hierarchy. The average transverse momentum from collective flow is larger for heavier particles. The data for π, K, and p transverse momenta can be reproduced naturally in the hydrodynamic framework [45] (Fig. 1 right panel). The consistency of the hydrodynamic calculations with the experimental data validates the collective flow interpretation, while we note that the mass hierarchy of the average transverse momentum can also be understood as coming from geometrical scaling [46]. The transverse momentum spectra in p-Pb collisions contain a soft component coming from the collective expansion with statistical emission at freeze-out [25, 40, 47]. The spectra can be reproduced in the region of intermediate $p_\perp$ in the EPOS LHC model [40, 47, 42].

3. Elliptic and triangular flow in p-Pb interactions

The most important evidence for the collective expansion in A-A collisions is the observation of elliptic and triangular flow. The elliptic flow coefficient v_2 has been measured using 2- and 4-particle cumulants in p-Pb collisions [48, 49]. The data is consistent with the predictions of the hydrodynamic model [25, 36, 50, 51] (Fig. 2 left panel). In p-Pb interaction the model

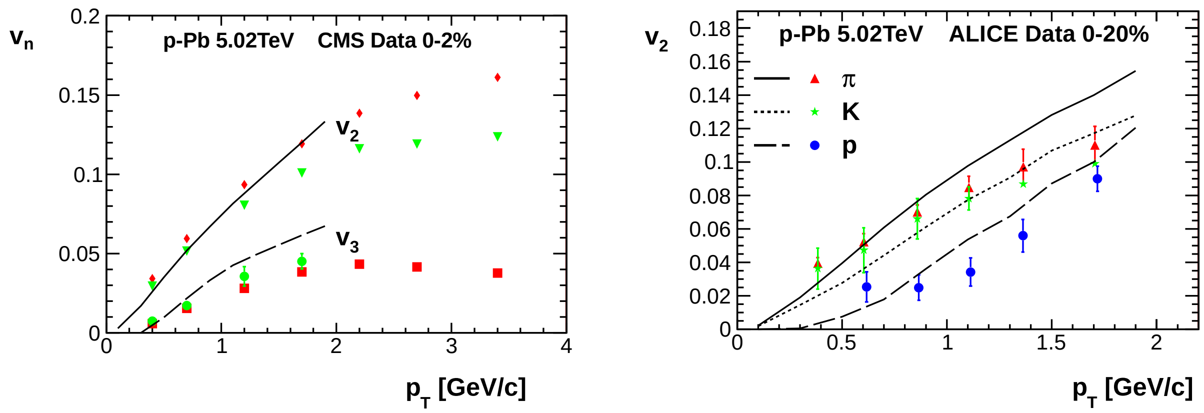

Figure 2. Left: v_2 and v_3 for charged particles from the hydrodynamic calculation, CMS Collaboration data [49]. Right: $v_2(p_\perp)$ for pions, kaons and protons from the hydrodynamic model, ALICE Collaboration data [52]).

uncertainty on the value of the initial eccentricity is a more severe problem than for the A-A system [36, 44]. The small size and short lifetime of the system make the final results depend significantly on other parameters of the model as well: the initial time of the expansion, the freeze-out temperature, the shear viscosity. The relativistic viscous hydrodynamics can be reliably applied if the velocity gradients in the system are moderate and if the mean free path is smaller than the size of the system. In small systems the contribution of non-thermal corona is relatively more important, which can reduce the value of the elliptic flow. These assumptions become more and more questionable when applying the model to more peripheral p-Pb collisions. An additional difficulty in comparing to the experimental data is related to the large contribution of non-flow correlations that are not implemented in the models. All of the above mentioned factors mean that the agreement of the calculation with the data can be at best semi-quantitative.

An important experimental result is the observation of mass splitting of the elliptic flow in p-Pb interactions [52]. The smaller value of the elliptic flow coefficient $v_2(p_\perp)$ for heavy particles is a characteristic of the collective elliptic flow. This feature is reproduced by the calculation [45, 51] (Fig. 2 right panel). The observation of triangular flow in p-Pb interactions is a strong argument for the collective expansion scenario. The predictions of the hydrodynamic model, with fluctuating initial conditions are consistent with measurements [25, 36, 50] (Fig. 2 right panel). This means that the model captures correctly the fluctuations of the initial state and describes realistically its collective expansion. The mass splitting for the triangular flow v_3 in p-Pb collisions is smaller than for v_2, moreover, it is distorted by resonance decays.

4. Collectivity in p-Pb

The formation of a fireball of strongly interacting fluid in ultrarelativistic heavy-ion collisions is well established. The observation of elliptic and triangular flow in agreement with predictions of nearly prefect fluid hydrodynamics, the quantitative description of transverse momentum spectra, and jet quenching are strong evidence of the creation of the quark-gluon plasma. Quantitatively the hydrodynamic model can be reliably applied in central A-A collisions. Many experimental efforts have been devoted to the study the properties of the matter in the fireball when changing the system size and the energy. The data indicate that a collectively expanding system is formed in peripheral A-A collisions and at different energies of the RHIC beam energy scan.

It has been generally expected that in p-Pb collisions at the LHC, the final state interactions would be negligible [24], but the hydrodynamic model applied to initial conditions extrapolated to the p-Pb system at TeV energies predicted a significant collective expansion [25] that could be observed as the elliptic and triangular flow. Many experimental data from p-Pb interactions are consistent with the collective expansion scenario, the double-ridge [29], the elliptic and triangular flow [25, 36, 50, 51], the mass hierarchy of average transverse momenta [45, 40], and of the elliptic flow [45, 51]. The observed appearance of the flow in low multiplicity p-Pb events [49] and general arguments suggest that the p-Pb system can be used as a testing ground for the onset of collectivity in small systems.

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References

[1] Schenke B, Jeon S and Gale C 2011 *Phys. Rev. Lett.* **106** 042301
[2] Petersen H, Qin G Y, Bass S A and Muller B 2010 *Phys.Rev.* **C82** 041901
[3] Gardim F G, Grassi F, Luzum M and Ollitrault J Y 2012 *Phys. Rev.* **C85** 024908
[4] Bożek P and Broniowski W 2012 *Phys. Rev.* **C85** 044910
[5] Qiu Z, Shen C and Heinz U 2012 *Phys. Lett.* **B707** 151
[6] Pang L, Wang Q and Wang X N 2012 *Phys.Rev.* **C86** 024911
[7] Niemi H, Denicol G, Holopainen H and Huovinen P 2013 *Phys.Rev.* **C87** 054901
[8] Aad G *et al.* (ATLAS Collaboration) 2013 (*Preprint* 1305.2942)

[9] Gale C, Jeon S, Schenke B, Tribedy P and Venugopalan R 2013 *Phys.Rev.Lett.* **110** 012302
[10] Bożek P and Broniowski W 2012 *Phys.Rev.Lett.* **109** 062301
[11] Shen C, Heinz U, Huovinen P and Song H 2011 *Phys. Rev.* **C84** 044903
[12] Bożek P and Wyskiel-Piekarska I 2012 *Phys. Rev.* **C85** 064915
[13] Karpenko I, Sinyukov Y and Werner K 2013 *Phys.Rev.* **C87** 024914
[14] Werner K, Karpenko I, Bleicher M, Pierog T and Porteboeuf-Houssais S 2012 *Phys.Rev.* **C85** 064907
[15] Abelev B *et al.* (ALICE Collaboration) 2013 *Phys.Rev.* **C88** 044910
[16] Shen C, Bass S A, Hirano T, Huovinen P, Qiu Z *et al.* 2011 *J.Phys.* **G38** 124045
[17] Niemi H, Denicol G S, Huovinen P, Molnar E and Rischke D H 2011 *Phys. Rev. Lett.* **106** 212302
[18] Bożek P 2010 *Phys. Rev.* **C81** 034909
[19] Luzum M and Ollitrault J Y 2013 *Nucl.Phys.A904-905* **2013** 377c
[20] Steinheimer J, Koch V and Bleicher M 2012 *Phys.Rev.* **C86** 044903
[21] Karpenko I *et al.* 2013 *these proceedings*
[22] Broniowski W, Chojnacki M, Florkowski W and Kisiel A 2008 *Phys. Rev. Lett.* **101** 022301
[23] Pratt S 2009 *Phys. Rev. Lett.* **102** 232301
[24] Salgado C A 2011 *J.Phys.G* **G38** 124036
[25] Bożek P 2012 *Phys. Rev.* **C85** 014911
[26] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Phys. Lett.* **B718** 795
[27] Abelev B *et al.* (ALICE Collaboration) 2013 *Phys.Lett.* **B719** 29
[28] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Rev.Lett.* **110** 182302
[29] Bożek P and Broniowski W 2013 *Phys. Lett.* **B718** 1557
[30] Takahashi J, Tavares B, Qian W, Andrade R, Grassi F *et al.* 2009 *Phys. Rev. Lett.* **103** 242301
[31] Luzum M 2011 *Phys.Lett.* **B696** 499
[32] Dusling K and Venugopalan R 2013 *Phys. Rev. D* **87** 051502
[33] Dusling K and Venugopalan R 2013 *Phys. Rev.* **D87** 094034
[34] Dusling K and Venugopalan R 2013 *Phys. Rev. D* **87** 054014
[35] Adare A *et al.* (PHENIX Collaboration) 2013 (*Preprint* `1303.1794`)
[36] Bożek P and Broniowski W 2013 *Phys. Rev.* **C88** 014903
[37] Bzdak A, Schenke B, Tribedy P and Venugopalan R 2013 *Phys. Rev.* **C87** 064906
[38] Abelev B B *et al.* (ALICE Collaboration) 2013 (*Preprint* `1307.1094`)
[39] Bożek P and Broniowski W 2013 *Phys. Lett.* **B720** 250
[40] Pierog T, Karpenko I, Katzy J, Yatsenko E and Werner K 2013 (*Preprint* `1306.0121`)
[41] Kisiel A (ALICE Collaboration) 2011 *J.Phys.* **G38** 124008
[42] Chatrchyan S *et al.* (CMS Collaboration) 2013
[43] Ortiz A, Christiansen P, Cuautle E, Maldonado I and Paic G 2013 *Phys.Rev.Lett.* **111** 042001
[44] Bzdak A and Skokov V 2013 *Phys.Lett.* **B726** 408
[45] Bożek P, Broniowski W and Torrieri G 2013 *Phys.Rev.Lett.* **111** 172303
[46] McLerran L, Praszalowicz M and Schenke B 2013 *Nucl.Phys.* **A916** 210
[47] Abelev B B *et al.* (ALICE Collaboration) 2013 (*Preprint* `1307.6796`)
[48] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Lett.* **B725** 60
[49] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Phys.Lett.* **B724** 213
[50] Qin G Y and Müller B 2013 (*Preprint* `1306.3439`)
[51] Werner K, Bleicher M, Guiot B, Karpenko I and Pierog T 2013 (*Preprint* `1307.4379`)
[52] Abelev B B *et al.* (ALICE Collaboration) 2013 *Phys.Lett.* **B726** 164