FLOW IN p–Pb COLLISIONS AT THE LHC*

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We present the predictions of a hydrodynamic model for the flow observables recently measured in the highest-multiplicity p+Pb collisions at the LHC. We focus on the "ridge" phenomenon, which provides an important probe of the long-range dynamics and may be used to support the collective interpretation of the p+A data.

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In this paper, we review our recent predictions [1–3] concerning the possibility of soft collective dynamics in the highest-multiplicity p+Pb collisions at the LHC energies of $\sqrt{s_{NN}} = 5.02$ TeV. Indeed, one of the most important findings of the heavy-ion program at RHIC, now confirmed at the LHC, is the collective flow appearing in the A+A collisions [4]. It results, *inter alia*, in the *ridge* phenomenon in the two-particle two-dimensional correlations in the relative azimuth and pseudorapidity in the high multiplicity A+A collisions [5–10], as well as in the *highest* multiplicity p+A collisions and even the p+p collisions [6, 11–14].

The appearance of the ridge in A+A collisions found a convincing explanation in terms of the collective harmonic flow [15, 16]. Indeed, if the created fireball in the transverse plane is approximately boost-invariant, *i.e.*, if the resulting flow patterns in the transverse directions are similar over a range of pseudorapidity (typically, experiments cover from a few units), then

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a collimation effect appears, extending over a few units of rapidity. One may imagine surfers on a long wave: they all move in the same directions due to the flow, even if they are two miles away!

The pertinent question now is if the flow idea may also be applied to a much smaller system than the one formed in central $A+A$ collisions, namely, the fireball in p+Pb collisions. We use a three-stage approach which became popular in the $A+A$ studies, where it describes successfully numerous aspects of the soft-physics data. The three phases are:

1. The fluctuating initial state, obtained here with the Glauber simulations [17], where the initial density is obtained by placing smeared sources in the centers of the participating nucleons.
2. The subsequent event-by-event hydro simulations with the 3+1D viscous dynamics [3, 18], with the shear viscosity $\eta/s = 0.08$, the bulk viscosity, and the early hydro ignition time of $\tau = 0.6$ fm.
3. The statistical hadronization [19], carried out at the constant freeze-out temperature $T_{\rm f} = 150$ MeV.

The physical object of our study is the per-trigger correlation function in relative pseudorapidity and azimuth, defined as [20]

$$C_{\rm trig}(\Delta\eta, \Delta\phi) \equiv \frac{1}{N}\frac{d^2N^{\rm pair}}{d\Delta\eta\, d\Delta\phi} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}\,, \tag{1}$$

where $\Delta\eta$ and $\Delta\phi$ are the relative pseudorapidity and azimuth of the particles in the pair. The signal is defined via the pairs from the same event,

$$S(\Delta\eta,\Delta\phi) = \left\langle \frac{1}{N}\frac{d^2N^{\rm same}}{d\Delta\eta\, d\Delta\phi}\right\rangle_{\rm events}\,, \tag{2}$$

whereas the mixed-event background distribution is

$$B(\Delta\eta,\Delta\phi) = \left\langle \frac{1}{N}\frac{d^2N^{\rm mix}}{d\Delta\eta\, d\Delta\phi}\right\rangle_{\rm mixed\ events}\,. \tag{3}$$

The variable N denotes the number of charged particles in a given centrality class and acceptance bin. To make quantitative comparisons, one introduces the projected correlation function

$$Y(\Delta\phi) = \frac{\int B(\Delta\phi)d(\Delta\phi)}{\pi N} C(\Delta\phi) - b_{\rm ZYAM}\,, \tag{4}$$

where $S(\Delta\phi)$ and $B(\Delta\phi)$ are averages of $S(\Delta\eta, \Delta\phi)$ and $B(\Delta\eta, \Delta\phi)$ over the chosen range in $\Delta\eta$ avoiding the central region, in particular, $2 < |\Delta\eta| < 5$ in the ATLAS analysis, and the constant b_{ZYAM} is such that the minimum of $Y(\Delta\phi)$ is at zero.

In Fig. 1, we show the typical results of our simulations. We note the two ridges, as well as the central peak, here formed due to included charge balancing [21], and to a lesser extent by the decays of resonances. In Fig. 2, we show the projected and ZYAM-subtracted correlation function for two variants of the model, with the standard and compact sources (*cf.* Ref. [3]). We note a fair agreement of the hydrodynamical model with the data. Other results, such as the obtained harmonic flow coefficients, are given in Ref. [3].

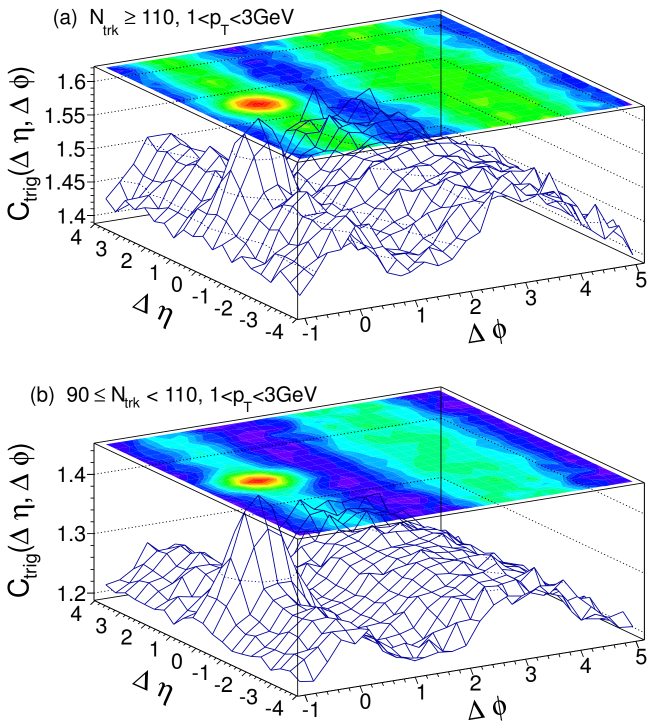

Fig. 1. The per-trigger-particle correlation function $C_{\mathrm{trig}}(\Delta\eta, \Delta\phi)$ of Eq. (1) for the two most central centrality classes corresponding to $N_{\mathrm{track}} \geq 110$ (panel (a)) and $90 \leq N_{\mathrm{track}} \leq 110$ (panel (b)) for the p+Pb collisions used by the CMS Collaboration. The transverse momentum of each particle belongs to the relatively soft range $1.0 < p_{\mathrm{T}} < 3.0$ GeV.

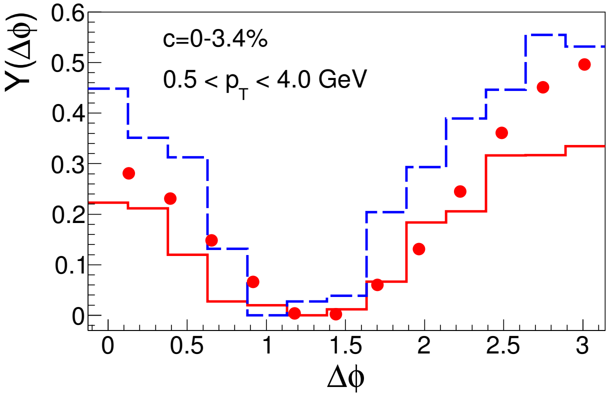

Fig. 2. The projected and ZYAM-subtracted correlation function $Y\Delta(\phi)$ for the most central p–Pb collisions for the standard source (solid line) and compact source (dashed line), compared to the most central ATLAS data (points). The total transverse momentum is approximately conserved with the condition for the total transverse momentum, $p_{\mathrm{T}} < 5$ GeV. Charge balancing is imposed.

In conclusion, we note that the correlation and flow data for the highest multiplicity p+Pb collisions at the LHC may be satisfactorily described with the approach incorporating hydrodynamics, thus based on collectivity of the dynamics. Thus we offer an explanation following the path of the A+A analyses. For scenarios based on the Color Glass Condensate theory, see [22–27]. The discrimination of the two approaches may be made in the future with the particle-identified data.

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REFERENCES

[1] P. Bożek, W. Broniowski, *Phys. Lett.* **B718**, 1557 (2013) [arXiv:1211.0845 [nucl-th]].

[2] P. Bożek, W. Broniowski, *Phys. Lett.* **B720**, 250 (2013) [arXiv:1301.3314 [nucl-th]].

[3] P. Bożek, W. Broniowski, *Phys. Rev.* **C88**, 014903 (2013) [arXiv:1304.3044 [nucl-th]].

[4] J.Y. Ollitrault, *Phys. Rev.* **D46**, 229 (1992).

[5] S. Mohapatra [ATLAS Collaboration], *J. Phys. Conf. Ser.* **389**, 012011 (2012) [arXiv:1109.6721 [nucl-ex]].

[6] S. Chatrchyan *et al.* [CMS Collaboration], *Phys. Lett.* **B724**, 213 (2013) [arXiv:1305.0609 [nucl-ex]].

[7] K. Aamodt *et al.* [ALICE Collaboration], *Phys. Lett.* **B708**, 249 (2012) [arXiv:1109.2501 [nucl-ex]].

[8] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev.* **C78**, 014901 (2008) [arXiv:0801.4545 [nucl-ex]].

[9] B. Abelev *et al.* [STAR Collaboration], *Phys. Rev.* **C80**, 064912 (2009) [arXiv:0909.0191 [nucl-ex]].

[10] B. Alver *et al.* [PHOBOS Collaboration], *J. Phys. G* **35**, 104080 (2008) [arXiv:0804.3038 [nucl-ex]].

[11] V. Khachatryan *et al.* [CMS Collaboration], *J. High Energy Phys.* **09**, 091 (2010) [arXiv:1009.4122 [hep-ex]].

[12] A. Adare *et al.* [PHENIX Collaboration], arXiv:1303.1794 [nucl-ex].

[13] G. Aad *et al.* [ATLAS Collaboration], *Phys. Rev. Lett.* **110**, 182302 (2013) [arXiv:1212.5198 [hep-ex]].

[14] B. Abelev *et al.* [ALICE Collaboration], *Phys. Lett.* **B719**, 29 (2013) [arXiv:1212.2001 [nucl-ex]].

[15] J. Takahashi *et al.*, *Phys. Rev. Lett.* **103**, 242301 (2009) [arXiv:0902.4870 [nucl-th]].

[16] B. Alver, G. Roland, *Phys. Rev.* **C81**, 054905 (2010) [arXiv:1003.0194 [nucl-th]].

[17] W. Broniowski, M. Rybczyński, P. Bożek, *Comput. Phys. Commun.* **180**, 69 (2009) [arXiv:0710.5731 [nucl-th]].

[18] P. Bożek, *Phys. Rev.* **C85**, 014911 (2012) [arXiv:1112.0915 [hep-ph]].

[19] M. Chojnacki *et al.*, *Comput. Phys. Commun.* **183**, 746 (2012) [arXiv:1102.0273 [nucl-th]].

[20] S. Chatrchyan *et al.* [CMS Collaboration], *Phys. Lett.* **B718**, 795 (2013) [arXiv:1210.5482 [nucl-ex]].

[21] P. Bożek, W. Broniowski, *Nucl. Phys.* **A904-905**, 479c (2013) [arXiv:1210.4315 [nucl-th]].

[22] K. Dusling, R. Venugopalan, *Phys. Rev. Lett.* **108**, 262001 (2012) [arXiv:1201.2658 [hep-ph]].

[23] K. Dusling, R. Venugopalan, *Phys. Rev.* **D87**, 054014 (2013) [arXiv:1211.3701 [hep-ph]].

[24] K. Dusling, R. Venugopalan, *Phys. Rev.* **D87**, 051502 (2013) [arXiv:1210.3890 [hep-ph]].

[25] Y.V. Kovchegov, D.E. Wertepny, *Nucl. Phys.* **A906**, 50 (2013) [arXiv:1212.1195 [hep-ph]].

[26] A. Kovner, M. Lublinsky, *Int. J. Mod. Phys.* **E22**, 1330001 (2013) [arXiv:1211.1928 [hep-ph]].

[27] K. Dusling, R. Venugopalan, *Phys. Rev.* **D87**, 094034 (2013) [arXiv:1302.7018 [hep-ph]].