Evidence for flow in pPb collisions at 5 TeV from \( v_2 \) mass splitting

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We show that a fluid dynamical scenario describes quantitatively the observed mass splitting of the elliptical flow coefficients \( v_2 \) for pions, kaons, and protons. This provides a strong argument in favor of the existence of a fluid dynamical expansion in pPb collisions at 5 TeV.

One of the strongest signals of collective flow in heavy ion collisions is the fact that the transverse momentum dependence of the elliptical flow coefficient \( v_2 \) (measuring the azimuthal asymmetry) depends in a very characteristic way on the mass of the observed hadrons. This has been predicted \(^{[1]}\) and impressively confirmed experimentally later \(^{[2,3]}\). Can we also “prove” the existence of flow in small systems like proton-lead collisions, where such a collective behavior has not been expected?

Information about flow asymmetries can be obtained via studying two particle correlations as a function of the pseudorapidity difference \( \Delta \eta \) and the azimuthal angle difference \( \Delta \phi \). So-called ridge structures (very broad in \( \Delta \eta \)) have been observed first in heavy ion collisions, later also in pp \(^{[4]}\) and very recently in pPb collisions \(^{[5–7]}\). In case of heavy ions, these structures appear naturally in models employing a hydrodynamical expansion, in an event-by-event treatment.

To clearly pin down the origin of such structures in small systems, one needs to consider identified particles. In the fluid dynamical scenario, where particles are produced in the local rest frame of fluid cells characterized by transverse velocities, large mass particles (compared to low mass ones) are pushed to higher transverse momenta, visible in \( p_t \) distributions, but also in the dihadron correlations. Both effects are clearly seen in experimental data. In this paper, we focus on dihadron correlations and the \( v_2 \) coefficients.

The following discussion is based on ALICE results on dihadron correlations \(^{[5,8]}\) and EPOS3 simulations. EPOS3 is a major update of the work described in \(^{[11]}\) (EPOS2). Here, we introduced a theoretical scheme which accounts for hydrodynamically expanding bulk matter, jets, and the interaction between the two. The whole transverse momentum range is covered, from very low to very high \( p_t \). In \(^{[11]}\), we show that this approach can accommodate spectra of jets with \( p_t \) up to 200 GeV/c in pp scattering at 7 TeV, as well as particle yields and harmonic flows with \( p_t \) between 0 and 20 GeV/c in PbPb collisions at 2.76 TeV. To our knowledge, this is the only model able to describe the famous lambda to kaon enhancement correctly over the whole \( p_t \) range. New features of EPOS3 are: an event-by-event 3D+1 viscous hydrodynamical evolution, and a new treatment of high parton densities, via an individual parton saturation scale \( Q_s \) for each elementary scattering. More details will be given in the appendix. All results in this paper are based on EPOS3.074.

As in \(^{[11]}\), the basis of our approach is multiple scattering (even for pp), where a single scattering is a hard elementary scattering plus initial state radiation, the whole object being referred to as parton ladder or Pomeron. The corresponding final state partonic system amounts to (usually two) color flux tubes, being mainly longitudinal, with transversely moving pieces carrying the \( p_t \) of the partons from hard scatterings. These flux tubes constitute eventually both bulk matter, also referred to as “core” (which thermalizes, flows, and finally hadronizes) and jets (also referred to as “corona”), according to some criteria based on the energy of the string segments and the local string density.

In p-Pb collisions, the “violence” of a collision is no

![Figure 1: (Color online) Example of a semi-peripheral p-Pb scattering, with 8 Pomerons, showing the transverse plane at space-time rapidity \( \eta_s = 1 \). The positions of the Pomerons are indicated by the black dots. String segment having enough energy to escape (corona) are marked green, the red ones constitute the core.](image.png)
longer characterized by the impact parameter, but by the multiplicity, or in the multiple scattering approach, by the number of Pomerons – being proportional to the multiplicity. In fig. [1] we show a simulation of a semi-peripheral p-Pb scattering, with 8 Pomerons. We consider the transverse plane at space-time rapidity $\eta_s = 1$. The positions of the Pomerons are indicated by the black dots. String segment having enough energy to escape are marked green, the red ones constitute the core.

The positions of the Pomerons, and therefore also the positions of the string segments, are generated randomly. In the current example, the overall shape of the core part (the red circles) happens to be elongated along the $y$ axis, so we have generated randomly an elliptical shape (indicated by the blue ellipse, to guide the eye). This will lead to a preferred expansion along the $x$ axis, and a $\cos(2\Delta\phi)$ shape of the correlation function. The question is only, if the fluctuations are sufficiently big and sufficiently frequent to provide a quantitative agreement with the observed correlation functions. In fig. [2] we plot the dihadron correlation function for charged particles, from ALICE (upper plot) and EPOS3 simulations. We observe in theory and experiment the “jet peak” as well as a near side and a away side ridge structure.

To get rid of, the jet correlations, one subtracts the low multiplicity correlation function (assuming that the jet correlation is the same). In fig. [3] we show the results for ALICE measurement and the corresponding EPOS3 simulations. Indeed, a double ridge structure is visible, essentially flat in the $\Delta\eta$ directions. The origin of the double ridge are random azimuthal asymmetries, as shown in fig. [1] which lead to asymmetric flow and to a double

Figure 2: (Color online) Dihadron correlation function for charged particles, from ALICE (upper plot) and EPOS3 simulations, for high multiplicity (0-20%) events.

Figure 3: (Color online) Dihadron correlation function for charged particles, from ALICE (upper plot) and EPOS3 simulations, for high multiplicity (0-20%) events, after subtraction of the result for the 60-80% class.
peak structure in $\Delta \phi$. The translational invariance of the structure finally leads to a double ridge. The simulation result is an absolute prediction, it is the yield of associated particles per trigger (and per $\Delta \eta \Delta \phi$). So indeed, the magnitude of the effect is of the right order.

For a more quantitative analysis, one considers the projections onto $\Delta \phi$, for $|\Delta \eta| > 0.8$, as shown in fig. 4 for ALICE measurement and the corresponding EPOS3 simulations (the latter ones have been multiplied by 1.07). The solid red line represents a Fourier decomposition, $\frac{1}{N_{\text{trig}}} \frac{dN}{d\Delta \phi \{\text{per} \Delta \eta\}} = \sum_{n=0}^{5} 2a_n \cos(n \Delta \phi)$.

The results for the second harmonics (elliptical flow) are shown in fig. 5. Clearly visible in data and in the simulations: a separation of the results for the three hadron species: in the $p_t$ range of 1-1.5 GeV/c, the kaon $v_2$ is somewhat below the pion one, whereas the proton result is clearly below the two others. To discuss higher values of $p_t$ (and due to limited statistics), we use a different binning in $p_t$ (0.5-1, 1-2, 2-4 GeV/c), see fig. 6. We compare pion and proton results, and we clearly see (in data and simulations) a “crossing”: the $v_2$ of protons is below the one of pions, below 2 GeV/c, and above beyond 2 GeV/c.

$$v_n^\pi = \frac{v_n^{h-\pi}}{\sqrt{v_n^{h-h}}}, \quad v_n^K = \frac{v_n^{h-K}}{\sqrt{v_n^{h-h}}}, \quad v_n^\rho = \frac{v_n^{h-p}}{\sqrt{v_n^{h-h}}}.$$
Within our fluid dynamical approach, the above results are nothing but a “mass splitting”. The effect is based on an asymmetric (mainly elliptical) flow, which translates into the corresponding azimuthal asymmetry for particle spectra. Since a given velocity translates into momentum as \( m_A \gamma v \), with \( m_A \) being the mass of hadron type \( A \), flow effects show up at higher values of \( p_t \) for higher mass particles.

To summarize: We have shown that a realistic fluid dynamical scenario describes quantitatively the observed mass splitting of the elliptical flow coefficients \( v_2 \) for pions, kaons, and protons. This provides a strong argument in favor of the existence of a fluid dynamical expansion in proton-lead collisions at 5TeV.

Appendix A: Gribov Regge approach with saturation scales

Gribov-Regge approach here means an assumption about the structure of the \( T \) matrix, expressed in terms of elementary objects called Pomerons, occurring in parallel. Squaring the matrix element, the total cross section can be expressed as

\[
\sigma^{\text{tot}} = \sum_{\text{cut} \, P} \int \sum_{\text{uncut} \, P} \int \frac{\text{cut}}{G} \frac{\text{uncut}}{-G} \]

in terms of cut and uncut Pomerons, for pp, pA, and AA. Partial summation provides exclusive cross sections. The diagram corresponds to precisely defined mathematical expressions, see [12]. The expression for a cut Pomeron is

\[
G = \frac{1}{2s} 2 \text{Im} \{FT(T)\}(\hat{s}, b), \quad T = i\hat{s} \sigma_{\text{hard}}(\hat{s}) \exp(R_{\text{hard}}^2),
\]

where \( FT \) means Fourier transform. The parton-parton cross section \( \sigma_{\text{hard}} \) is computed based on DGLAP parton evolutions from both sides and a Born pQCD hard scattering, restricting the virtualities to values bigger than a saturation scale \( Q_s \propto N_{\text{part}}^{\gamma} \). This scale is individual for each Pomeron, \( N_{\text{part}} \) is the number of participating nucleons attached to this Pomeron, \( \hat{s} \) is its energy.

Appendix B: Viscous hydrodynamics

In EPOS3, we employ an event-by-event treatment of a numerical solution in 3D+1 dimensions of the hydrodynamic equations (in Israel-Stewart formulation), using Milne coordinates [13],

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,
\]

\[
\gamma \left( \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) \right) \Pi = -\frac{1}{\tau_\Pi} \left( \Pi - \Pi_{\text{NS}} \right) + I_\Pi,
\]

where \( \Pi \) and \( \Pi_{\text{NS}} \) are the shear stress tensor and bulk pressure, respectively, \( \Delta^{\mu\nu} = g^{\mu\nu} - u^{\mu} u^{\nu} \) is the projector orthogonal to \( u^\mu \), and

\[
T^{\mu\nu} = \varepsilon u^\mu u^\nu - (p + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu},
\]

\[
\pi^{\mu\nu}_{\text{NS}} = \eta \left( \Delta^{\mu\lambda} \partial_\lambda u^\nu + \Delta^{\nu\beta} \partial_\beta u^\mu \right) - \frac{2}{3} \eta \Delta^{\mu\nu} \partial_\lambda u^\lambda;
\]

\[
\Pi_{\text{NS}} = -\zeta \partial_\lambda u^\lambda,
\]

\[
I_\Pi = -\frac{4}{3} \Pi \partial_\gamma u^\gamma,
\]

We use for the calculation in this paper always \( \eta/S = 0.08 \), \( \zeta/S = 0 \).

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