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RIDGES AND v_2 WITHOUT USING HYDRODYNAMICS*

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Azimuthal anisotropy at low $p_{\rm T}$ in heavy-ion collisions is studied in an approach that avoids the assumption of fast thermalization. What generates the asymmetry in momentum space is the ridge formation due to semi-hard scattering near the surface of the medium created in non-central collisions. Phenomenological input from ridge studies is used to derive analytical formulas for elliptic flow without using hydrodynamics. The result of this simple study is in accord with data for $p_{\rm T} < 1.5$ GeV/c.

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The prevailing paradigm on azimuthal anisotropy at low $p_{\rm T}$ in heavy-ion collisions is hydrodynamical flow. Good agreement with data on both hadron spectra and elliptic flow has been achieved if the initial conditions are set at $\tau_0 = 0.6\,{\rm fm}/c$, which is a very short thermalization time [1]. No successful dynamical scheme has so far been found to explain the rapid thermalization process. If none can be found, how much do we have to give up on the results of hydrodynamical studies? Is there any justification to regard the dense medium as a perfect fluid?

In hydrodynamics (hydro) if pressure is built up quickly before the spatial asymmetry in non-central collisions disappears by radial expansion, then the higher pressure near the reaction plane can generate eccentricity in momentum space to give rise to the observed v_2. But concepts in hydro cannot be applied unless the system is equilibrated. Thus what hydro needs cannot be found within hydro. Short-time physics is usually associated with hard scattering processes. If one can capture a part of that dynamics that can affect the bulk behavior of the system without early time hydro (ETH), and then let the system evolve hydrodynamically after equilibration is achieved,

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we would have azimuthal anisotropy as well as collective flow describable by late time hydro (LTH). In that way we can not only circumvent rapid thermalization, but also include a piece of physics that is missing in the usual hydro.

That physics involves jets. In the continuum of transverse momentum $p_{\rm T}$ ranging from 0 to over $10\,{\rm GeV}/c$ different processes are important in different regions. At very high $p_{\rm T}$, say $> 8\,{\rm GeV}/c$, jets are important and can be calculated in pQCD, but they are rare occurrences that do not affect the bulk. At very low $p_{\rm T}$, say $< 1.5\,{\rm GeV}/c$, hydro is effective, but the system must first be equilibrated before the theory can be applied. In between is the intermediate $p_{\rm T}$ region where exact calculation from first principles is difficult, but what takes place there can be crucially important, and must be taken into account even if only phenomenologically. As the virtuality of hard scattering is lowered in the continuum, the probability of semi-hard scattering increases. There must come a point when it is hard enough to be sensitive to the initial configuration, for example, $p_{\rm T} \sim$ 2–3 GeV/c, corresponding to $\tau \sim 0.1$ fm/c, but soft enough to have a high rate of occurrence, since the corresponding longitudinal momentum fraction is only about $x \sim 0.03$, at which the parton density is high. Those semi-hard jets are what drive the azimuthal anisotropy.

Weak jets created in the interior of the dense medium are absorbed and in time become a part of the bulk. Those created near the surface have a chance to escape, but not without losing some energy first to the environment of their trajectories. The energy lost enhances the thermal energy of the partons in the neighborhood, which in turn manifest themselves as a ridge for each semi-hard parton that leaves the medium. Properties of ridges have been investigated in recent years [2], and should not be ignored by any study of hadronic observables $< 3\,{\rm GeV}/c$. Whereas the experimental study of ridges involves the use of triggers, we consider many weak jets (without triggers) emitted throughout the surface of the almond-shaped overlap region. Their angles of emission are on average normal to the surface of the initial spatial configuration, and are therefore constrained by $\phi \in \mathcal{R}$, where

$$\mathcal{R} \Rightarrow \{|\phi| < \Phi,\ |\pi - \phi| < \Phi\}\,, \qquad \Phi = \cos^{-1}\left(\frac{b}{2R_A}\right)\,, \tag{1}$$

b being the impact parameter, R_A the nuclear radius. The formation of hadrons in the ridge may take some time and may be describable by LTH, but the initiation of ϕ asymmetry is by semi-hard partons that do not require fast thermalization and is not describable by ETH. Without a code to track the time evolution of the system, I use phenomenological input to describe the bulk (B) and the ridge (R). Both B and $B+R$ have thermal distributions of the form $\exp(-p_{\rm T}/T)$ and $\exp(-p_{\rm T}/T')$, respectively, T' being slightly higher than T due to the enhancement of thermal partons by energy loss. The values of T and T' are taken from data. By so doing we do not exclude the relevance of LTH. A hydro calculation of the problem would require careful attention given to the presence of semi-hard jets at early time, unlike what have been done so far. Not using hydro in our study does not mean that collective flow cannot develop at later time.

Starting from $B(p_{\rm T})$ being independent of ϕ and $R(p_{\rm T}, \phi) = R(p_{\rm T})\Theta(\phi)$, where $\Theta(\phi) = \theta(\Phi - |\phi|) + \theta(\Phi - |\pi - \phi|)$, we get [3]

$$R(p_{\rm T}) = B(p_{\rm T}) \left(e^{p_{\rm T}/T''} - 1 \right) , \tag{2}$$

where

$$\frac{1}{T''} = \frac{1}{T} - \frac{1}{T'} = \frac{\Delta T}{TT'}, \qquad \Delta T = T' - T\,. \tag{3}$$

It has been found in ridge analysis [2] that $\Delta T \approx 45\,{\rm MeV}$. Using $T = 0.287\,{\rm GeV}$ from fitting the pion distribution [4], we obtain $T'' = 2.12$ GeV [3]. This is the key link between ridge phenomenology and azimuthal anisotropy, because the second harmonic in the ϕ distribution is

$$\begin{aligned} v_2(p_{\rm T}, b) &= \frac{\int d\phi \cos 2\phi [B(p_{\rm T}) + R(p_{\rm T}, \phi)]}{\int d\phi [B(p_{\rm T}) + R(p_{\rm T}, \phi)]} \\ &= \frac{\sin 2\Phi(b)}{\pi B(p_{\rm T})/R(p_{\rm T}) + 2\Phi(b)} = \frac{\sin 2\Phi(b)}{\pi/(e^{p_{\rm T}/T''} - 1) + 2\Phi(b)}\,. \end{aligned} \tag{4}$$

The last expression depends only on T''. In the small $p_{\rm T}$ region it gives

$$v_2^{\pi}(p_{\rm T}, b) \simeq \frac{p_{\rm T}}{\pi T''} \sin 2\Phi(b)\,, \tag{5}$$

which is an explicit analytic expression of the dependence on both $p_{\rm T}$ and b. Fig. 1 (left panel) shows the pion v_2 data from [5] (together with the thin lines from that reference); the result from Eqs. (4) and (5) is shown by the thick (blue) line for $b = \sqrt{2}R_A$, corresponding to $\sim 50\%$ centrality, in good agreement with data. The centrality dependence prescribed mainly by $\sin 2\Phi(b)$ also agrees with data [3].

For proton the mass effect should be taken into account by changing $p_{\rm T}$ to the transverse kinetic energy $E_{\rm T} = (m_{\rm T}^2 + m_p^2)^{1/2} - m_p$ in Eqs. (4) and (5). Without changing anything else the result for 50% centrality is shown by the thick (blue) line in Fig. 1 (right panel) and agrees with the data [4]. The agreement extends to all other more central collisions. For more peripheral collisions the data for v_2 continue to increase, while the simple calculation from (5) saturates in the b dependence, like in the pion case. The reason

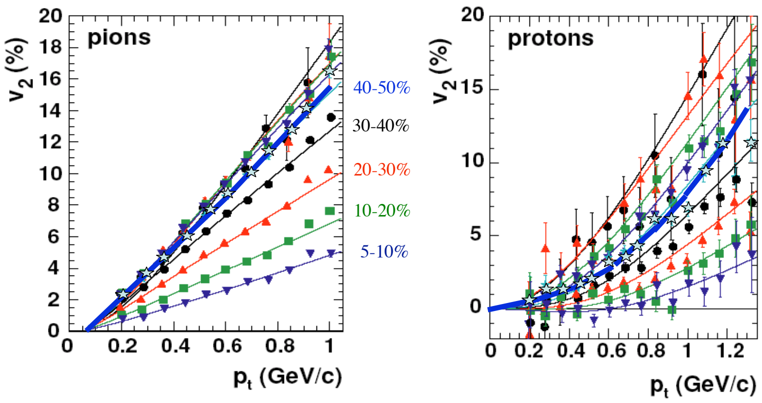

Fig. 1. Calculated $v_2^\pi(p_{\rm T})$ and $v_2^p(p_{\rm T})$ for 50% centrality are indicated by the thick (blue) lines. The data are from [5] for Au–Au collisions at 200 GeV, together with the light lines from that reference.

for the discrepancy is that in peripheral collisions there is low density of thermal partons, so proton production is more complicated to treated than can be done in the simple way presented here. A more elaborate treatment can reproduce the data [6].

In summary we have found that semi-hard scattering of partons is the dynamical mechanism sensitive to the spatial configuration at early time and responsible for the development of ridges at late time. It is pervasive in all collisions and is the natural cause for azimuthal asymmetry in the physics at short time scale. By taking the ridges into account we have shown that the properties of elliptic flow at low $p_{\rm T}$ can be reproduced in a very simple way. There is no need for fast thermalization and no basis to infer any connection with perfect fluid.

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REFERENCES

[1] P.F. Kolb, U. Heinz, *Quark–Gluon Plasma 3*, Ed. R.C. Hwa, X.-N. Wang, World Scientific, Singapore 2004.
[2] J. Putschke, [STAR Collaboration], *Nucl. Phys.* **A783**, 507 (2007).
[3] R.C. Hwa, `arXiv:0708.1508`.
[4] S.S. Adler *et al.* [PHENIX Collaboration], *Phys. Rev.* **C69**, 034909 (2004).
[5] J. Adams *et al.* [STAR Collaboration], *Phys. Rev.* **C72**, 014904 (2005).
[6] R.C. Hwa, C.B. Yang, work in progress.