Suppression of elliptic flow without viscosity

Denes Molnar (molnar@physics.purdue.edu) and **Adam Takacs** (adam.takacs@uib.no)

Purdue University, Indiana, USA University of Bergen, Norway

Motivation

Comparison of hydrodynamics with data requires the conversion of hydro fields to particles [1], and thus knowledge of the momentum distributions $f_i(\mathbf{p})$ of the hadron species. It is known that picking f_i is ambiguous for dissipative fluids. Infinitely many different choices can reproduce the same fluid fields [2, 3, 4], leading to systematic uncertainties in the extraction of transport coefficients from data [4, 5].

An **analogous ambiguity exists for ideal fluids too** because it is not known *a priori* that hadron distributions are Boltzmann or close to Boltzmann in local equilibrium:

- interacting systems have in general non-Boltzmann single-particle distributions [6, 7]
- it is not clear whether heavy-ion collisions lead to local thermalization, or only some steady-state distribution is reached
- far-from-equilibrium evolution can still obey hydrodynamic equations of motion, if the system is (nearly) conformal and locally isotropized [8]

Goal of this study:

- investigate the conversion from ideal hydro to a hadron gas with non-Boltzmann, but isotropic, local equilibrium distributions
- study how power-law tails at high momenta affect differential elliptic flow

We use the q-exponential (Tsallis) distribution to characterize power-law deviations from the local Boltzmann form which might occur in finite-size systems that expand rapidly. One can investigate other distributions as well, the general idea stays the same.

Four-source model with power-law corrections

For analytic estimates, we **adapt the simple four-source model** by Huovinen *et al* [9] in which four uniform, non-expanding fireballs of equal volume and temperature move symmetrically in back-to-back pairs along the x and y axes in the transverse plane.

The momentum distribution is given by

$$f^{(4s)} = f_{v_x} + f_{-v_x} + f_{v_y} + f_{-v_y} \, .$$

For Boltzmann sources,

$$f_{\mathrm{B},\boldsymbol{v}} \propto e^{-E_{\mathrm{LR}}/T} \, , \quad E_{\mathrm{LR}} \equiv p \cdot u = \gamma \left(E(\boldsymbol{p}) - \boldsymbol{v}\boldsymbol{p} \right) \, .$$

We include power-law corrections by replacing the Boltzmann factor with

$$f_\alpha(E_{\mathrm{LR}}) = A \left(1 + \frac{\alpha}{\Lambda} E_{\mathrm{LR}} \right)^{-\frac{1}{\alpha}} \, . \qquad (1)$$

For $\alpha \to 0$, f_α becomes Boltzmann with $T = \Lambda$.

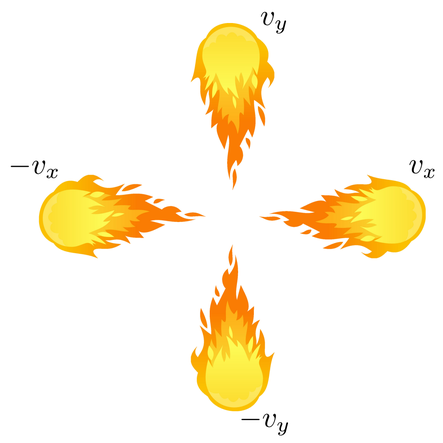

Fig. 1: Illustration of 4-source model.

Despite having zero(!) viscosity, we find that power-law corrections suppress anisotropic flow

$$v_n(p_T, y=0) = \frac{\int_0^{2\pi} d\phi \, \cos(n\phi) \, f^{(4s)}(p_T, \phi, y=0)}{\int_0^{2\pi} d\phi \, f^{(4s)}(p_T, \phi, y=0)}$$

compared to the Boltzmann result at high p_T.

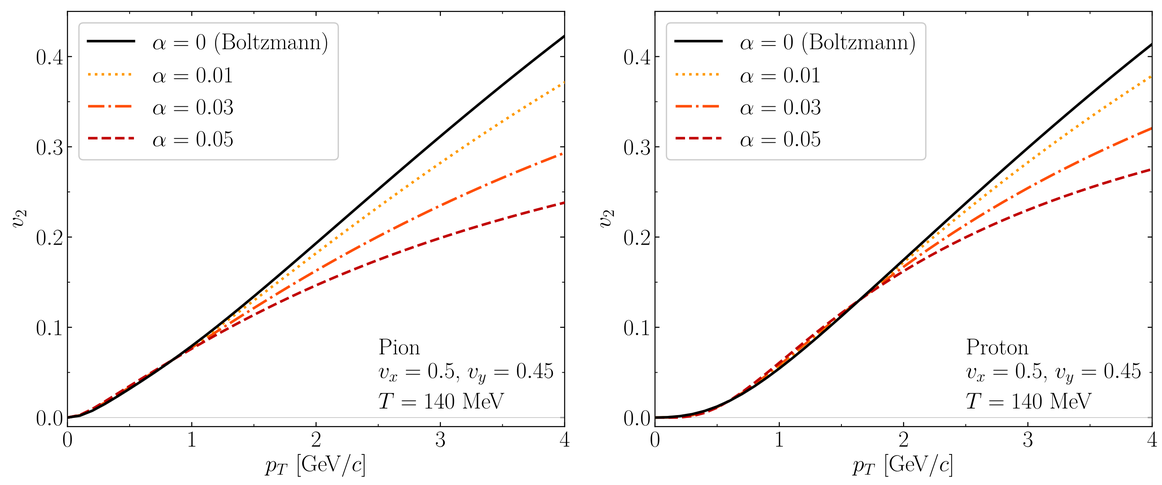

Fig. 2: Elliptic flow $v_2(p_T)$ suppression from the four-source model for different exponents α, relative to the Boltzmann case ($\alpha = 0$). The suppression is stronger for pions (left) than for protons (right).

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Results using 2+1D hydrodynamics

As in Ref. [4], we study Au+Au collisions at RHIC using the 2+1D ideal hydro code AZHYDRO[10]. The fluid is converted to particles on a $T = 140$ MeV space-time hypersurface via the **Cooper–Frye approach**:

$$E \frac{dN_i(x, \boldsymbol{p})}{d^3p} = p^\mu \, d\sigma_\mu(x) \, f_{i,eq}(x, \boldsymbol{p}) \, ,$$

where $d\sigma(x)$ is the normal of the local surface element at x.

Hadron distributions were set by matching A and Λ in (1), for each species, to reproduce the Boltzmann values of the partial pressure and energy density for the given species (the exponent α was a fixed parameter). This ensures that the ideal fluid energy-momentum tensor is matched perfectly with a mixture of hadrons that have power-law distributions, i.e.,

$$T^{\mu\nu}(x) = \sum_i \int \frac{d^3p}{E_i} p^\mu p^\nu f_{i,eq}(p, x) \, . \qquad (2)$$

Figure 3 shows that pion, kaon, and proton spectra are quite reasonable from this simple ideal hydro calculation, especially if we use a modest $\alpha \sim 0.05$ exponent.

More importantly, we find in Fig. 4 much the same $v_2(p_T)$ suppression for power-law distributions as in the analytic four-source calculation earlier. *We emphasize that viscosity is zero in this calculation.*

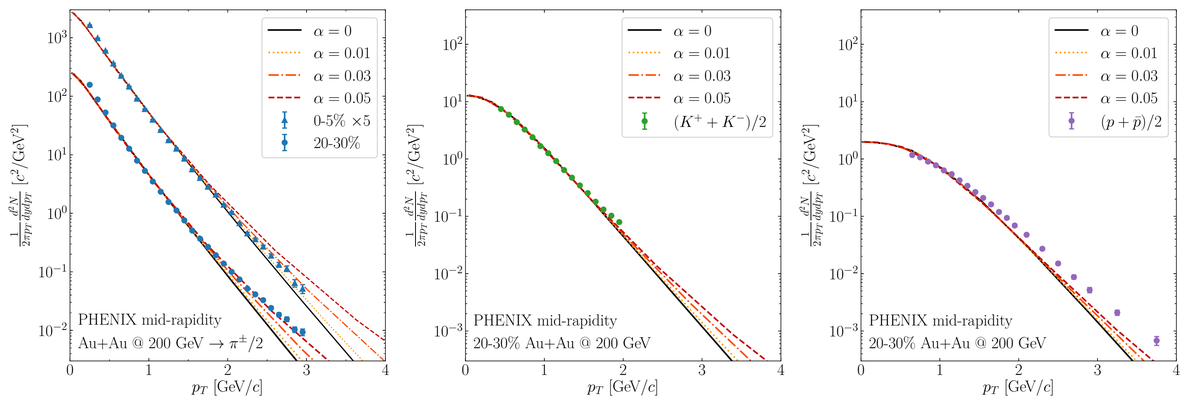

Fig. 3: Spectra at midrapidity measured by PHENIX [11], compared to spectra from 2+1D ideal hydrodynamic simulations using power-law-like equilibrium distributions. The impact parameters are $b = 2.3$ and 7.3 fm, corresponding to 0-5% and 20-30% centrality. Increasing α results in bigger deviations from the Boltzmann case ($\alpha = 0$), building up a power-law tail in the spectra that is also seen in experimental data.

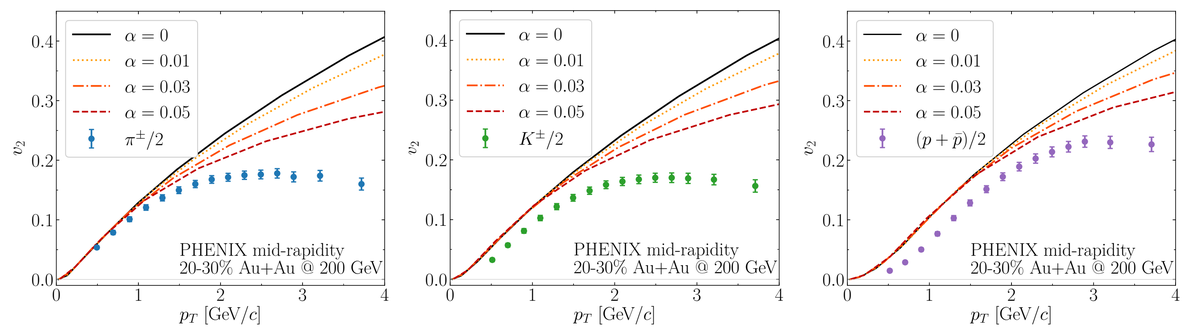

Fig. 4: The elliptic flow at midrapidity from PHENIX [11] with impact parameter $b = 7.3$ fm, and calculation from 2+1D ideal hydrodynamic simulations, but with different hadron phase space distributions. For increasing α, the suppression of v_2 relative to the Boltzmann case ($\alpha = 0$) becomes stronger. Panels are for pions, kaons and protons (from the left to the right).

Conclusions

- We investigated fluid-to-particle conversion using the **Cooper-Frye approach with power-law corrections** to the usual Boltzmann distributions, and found **elliptic flow suppression** at high transverse momenta.
- The suppression is qualitatively **similar to that due to shear viscosity, even though viscosity is zero in our case**.
- The suppression comes from power-law tails at high momenta. If power-law-like local equilibrium distributions play a role, then shear viscosity extracted from anisotropic flow data at RHIC and the LHC may be overestimated.

Our results question whether all of the v_2 suppression seen in the data can be attributed to viscous effects, or part of the suppression comes from non-Boltzmann equilibrium distributions.

- It would be interesting to study the effect in hydro+transport models too (e.g., [12]), as well as in kinetic theory with non-Boltzmann fixed point (such as [13]).

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