Early stage momentum anisotropy and electromagnetic probes of quark-gluon plasma

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Abstract

Various microscopic models suggest that local rest frame momentum anisotropies can be large during the early stages of evolution of the quark-gluon plasma (QGP). In recent years, the framework of relativistic anisotropic hydrodynamics (aHydro) has been developed in order to incorporate momentum anisotropic distributions of the QGP constituents into the phenomenological studies of ultra-relativistic heavy-ion collision experiments. In this work, the question of how much we can learn about the early-time momentum anisotropies by studying the yield and flow of electromagnetic probes will be addressed. In particular, we compare the sensitivity of hadronic and electromagnetic probes to the initial momentum anisotropy used in hydrodynamic calculations.

Dilepton Production Rate

From kinetic theory, the differential production rate of thermal dileptons from the QGP is given by

$$\frac{dN}{d^4x d^4P} = \int \frac{d^3\mathbf{k}_1}{(2\pi)^3}\frac{d^3\mathbf{k}_2}{(2\pi)^3} f_q(\mathbf{k}_1) f_{\bar{q}}(\mathbf{k}_2) v_{q\bar{q}} \sigma_{q\bar{q}}^{l^- l^+} \delta^4(k_1 + k_2 - P), \quad (1)$$

where $P = (E, \mathbf{p})$, $k_1 = (E_1, \mathbf{k_1})$, and $k_2 = (E_2, \mathbf{k_2})$ are the four-momenta of the lepton pair, quarks, and anti-quarks respectively, $v_{q\bar{q}} = \sqrt{(k_1.k_2)^2 - m_q^4} \Big/ (E_1 E_2)$ is the relative velocity of the incoming $q\bar{q}$ pair, and $\sigma_{q\bar{q}}^{l^- l^+}$ is the cross section for the production of the dilepton from a quark-antiquark pair. We neglect the rest masses of both quarks and leptons, and as a result the leading order cross section for producing a dilepton of mass M is

$$\sigma_{q\bar{q}}^{l^- l^+} = \frac{4\pi}{3} N_c (2s+1)^2 \frac{\alpha^2}{M^2} \sum_{i=1}^{N_f} e_i^2 \,, \quad (2)$$

which becomes $\sigma = 80\pi\alpha^2 \big/ 9M^2$ when considering only the u and d flavors. Also, one has $v_{q\bar{q}} = \frac{M^2}{E_1 E_2} = \frac{M^2}{|\mathbf{k_1}||\mathbf{k_2}|}$ with the assumption of massless fermions.

Momentum anisotropic distributions

For the quarks and anti-quarks, we consider the same anisotropic LRF distributions which we parametrize by an ellipsoidal deformation of the isotropic distribution as

$$f_q(\mathbf{k}) = f_{\bar{q}}(\mathbf{k}) = f(\mathbf{k}) = f_{\rm iso}\left(\frac{1}{\lambda}\sqrt{\frac{k_x^2}{\alpha_x^2} + \frac{k_y^2}{\alpha_y^2} + \frac{k_z^2}{\alpha_z^2}}\right), \quad (3)$$

where λ is a temperature-like scale, and the α_i parameters determine the shape and strength of the ellipsoidal anisotropic deformation. In the framework of 3+1d aHydro, λ and α_i's all depend on space-time. For fermions, we use the Fermi-Dirac distribution $f_{\rm FD}(k) = 1/\left(1 + e^k\right)$ for $f_{\rm iso}$.

One can change the parameters as

$$\Lambda = \lambda\alpha_y, \qquad \xi_1 = \left(\frac{\alpha_y}{\alpha_z}\right)^2 - 1, \qquad \xi_2 = \left(\frac{\alpha_y}{\alpha_x}\right)^2 - 1, \quad (4)$$

to obtain an anisotropic distribution of the form

$$f(\mathbf{k}) = f_{\rm iso}\left(\frac{|\mathbf{k}|}{\Lambda}\sqrt{1 + \xi_1(\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{k}})^2 + \xi_2(\hat{\mathbf{n}}_2 \cdot \hat{\mathbf{k}})^2}\right). \quad (5)$$

Convolving with 3+1d aHydro evolution

Integrating over space-time evolution of the QGP, the differential yield of dileptons becomes

$$\frac{dN}{M dM p_T dp_T dy d\phi_p} = \int d^4x \, \frac{dN}{d^4x d^4P} \,. \quad (6)$$

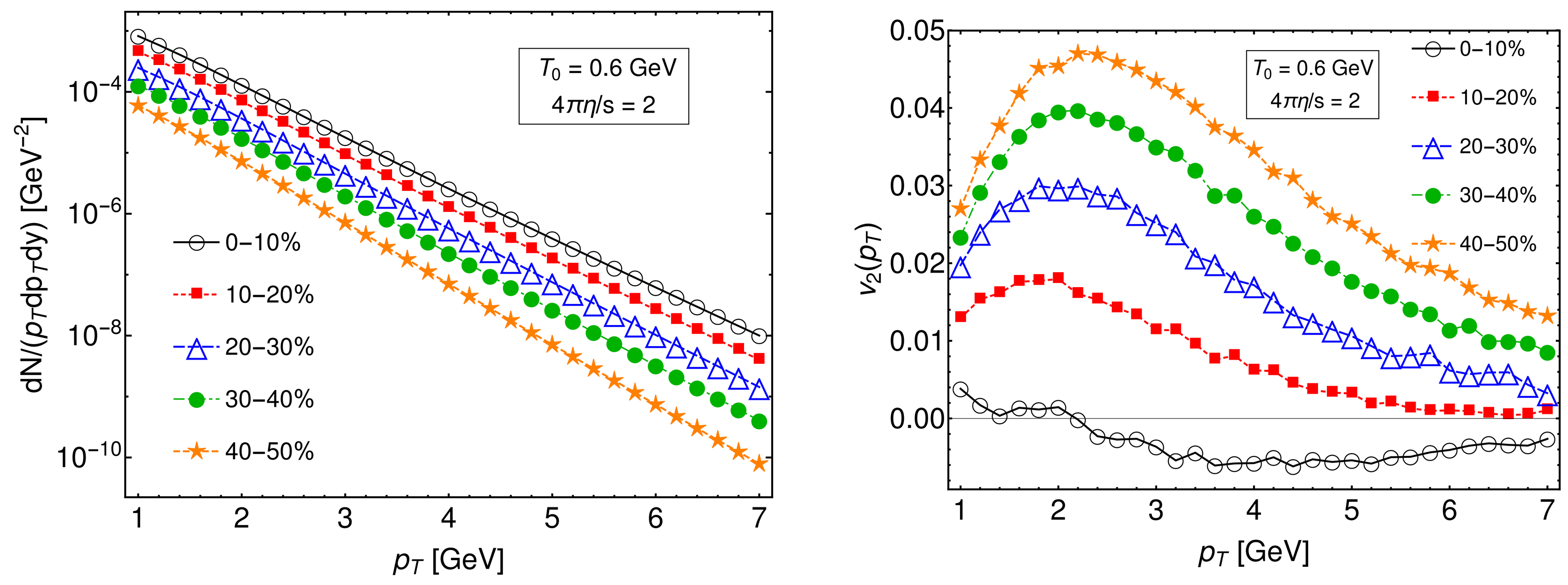
In aHydro calculations, non-equilibrium anisotropic distributions are evolved through the moments of Boltzmann equation

$$p_\mu \partial^\mu f = -C[f], \quad (7)$$

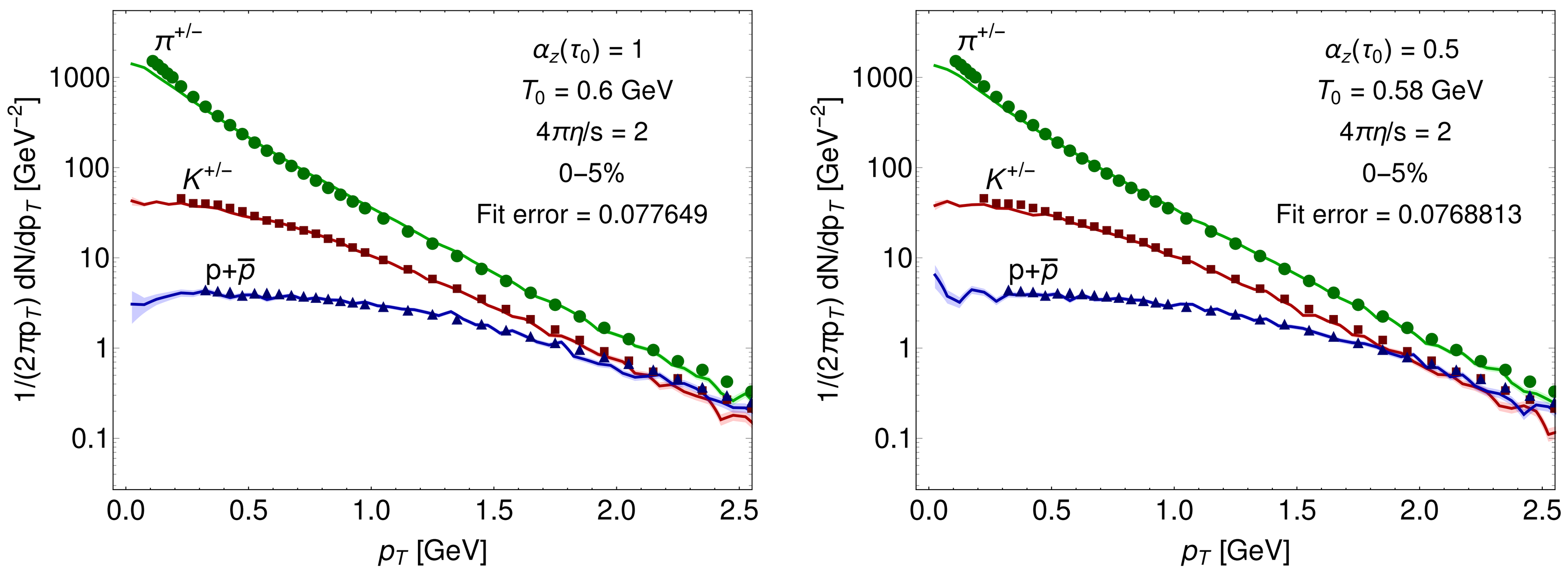
with relaxation time approximation for the collision kernel.

- We use 3+1d aHydro for Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV at the LHC.
- The initial state is modeled using a smooth Glauber model.
- The initial proper time is taken to be $\tau_0 = 0.25$ fm/c.
- The freeze-out temperature is taken to be 0.130 GeV.
- A quasiparticle EOS extracted from lattice QCD calculations is used in aHydro.
- Hadronic freeze-out and decays are performed using the THERMINATOR 2 Monte Carlo event generator.
- To consider only the QGP phase contribution to dilepton emission, the rate from regions of fluid with $T_{\rm effective} < T_c$ is set to 0, where T_c is the critical temperature which is taken to be 0.155 GeV.

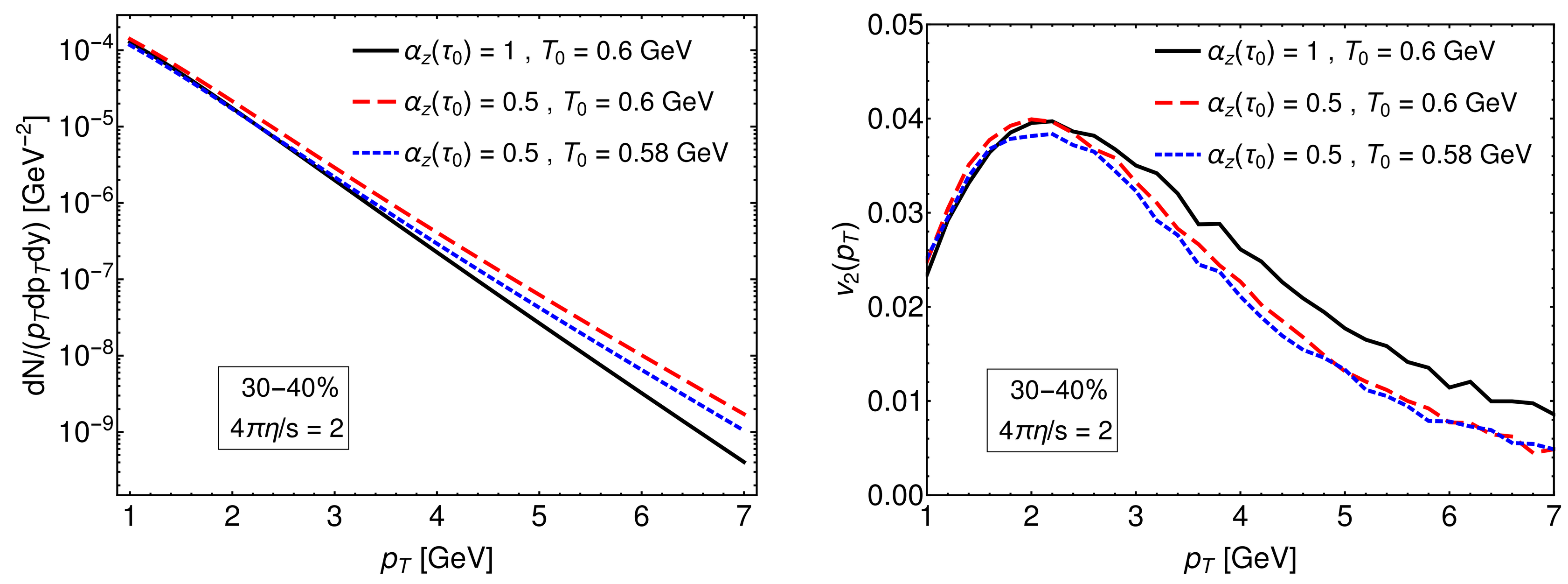
Results



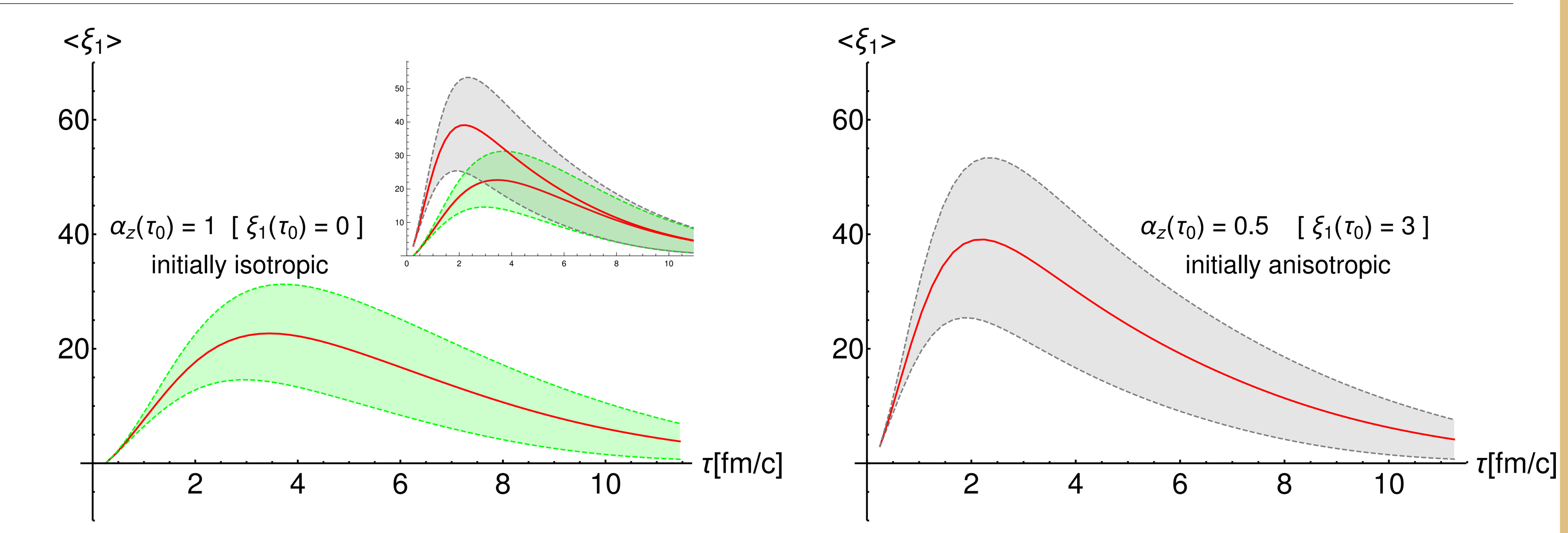
Transverse momentum dependence of mid-rapidity ($y = 0$) thermal dilepton yield (left) and v_2 (right) for different centrality classes, assuming initial momentum isotropy, $4\pi\eta/s = 2$, and initial central temperature of $T_0 = 0.6$ GeV.



Best fits of aHydro results to experimental data for soft hadron spectra ($\sqrt{s} = 2.76$ TeV, $|y| < 1$). Plots are for initially isotropic (left), and initially anisotropic (right) system.



Mid-rapidity ($y = 0$) QGP dilepton yield (left) and v_2 (right) for 30-40% centrality. Three curves are for initially isotropic (solid black) and initially anisotropic with same $T_0 = 0.6$ GeV, (dashed red) and with adjusted $T_0 = 0.58$ GeV based on fits to hadronic spectra (dashed blue).



Evolution of momentum anisotropy with proper time for initially isotropic (left) and initially anisotropic (right) cases. Thick curves show spatial average (in fixed rapidity plane) and the dashed curves show average ± 0.5×standard deviation of the anisotropy parameter ξ_1.

Conclusions

- Using 3+1d relativistic anisotropic hydrodynamics, we calculated the differential yields and elliptic flow of in-medium dileptons from a momentum-anisotropic QGP generated in Pb-Pb collision at $\sqrt{s} = 2.76$ TeV at LHC.
- At larger transverse momentum, the results of the dilepton yield and $v_2(p_T)$ were sensitive to the early stage momentum anisotropy.

Acknowledgements/References

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[1] B. S. Kasmaei and M. Strickland, Phys. Rev. D 99, 034015 (2019) [and refs within].