How To Measure the Diffusivity of Light Quarks

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Overview and Motivation

A principal goal of relativistic heavy ion physics is to determine bulk properties of the quark-gluon plasma (QGP), i.e., matter where the density exceeds the point at which individual hadrons can be defined. Several of these properties can be reliably extracted from lattice gauge theory, but even in those cases it is important to extract the properties from experiment to test whether the idealization of a locally equilibrated QGP has indeed been realized in the collision. Careful comparisons of experiment to theoretical models have so far constrained several of these properties, including the equation of state [1], charge susceptibility [2], viscosity [1, 3, 4], jet-energy loss [5, 6] and the diffusivity for heavy quarks [7]. Here, we describe how the diffusivity for light quarks can be added to this list.

Charge diffusion and balance functions

The charge balance functions (CBFs) naturally probe the physics of diffusion. One begins with the charge current density $\mathbf{j}_a$:

$$\mathbf{j}_a = -D_{ab}\nabla\delta\rho_b, \tag{1}$$

where ρ_a is the charge density and D_{ab} is the diffusivity for light quark flavors a and b. The electric conductivity D_E, i.e. the response to a gradient of the charge density for uniform strangeness and baryon number, can be written at high T as $D_E \approx D_{uu} \approx D_{dd} \approx D_{ss}$.

Theoretically, diffusion is probed by the charge correlator in coordinate space

$$C_{ab}(\vec{r}_1, \vec{r}_2, t) \equiv \langle \rho_a(\vec{r}_1)\rho_b(\vec{r}_2)\rangle. \tag{2}$$

Correlations indexed by charge, C_{ab}, translate into correlations, $C_{hh'}$, indexed by hadron species using thermal arguments,

$$\delta n_h = \chi_{ab}^{-1} n_h q_{ha} \delta\rho_b, \tag{3}$$

where n_h is the density of hadrons of type h.

Experimentally, diffusive correlations are probed at the hadronic level by the momentum-space correlator

$$B(\Delta\phi) \equiv \frac{\langle N_{+-}(\Delta\phi) + N_{-+}(\Delta\phi) - N_{++}(\Delta\phi) - N_{--}(\Delta\phi)\rangle}{(N_+ + N_-)}. \tag{4}$$

$B(\Delta\phi)$ is known as the *charge balance function* and is studied here as a function of $\Delta\phi$, the angular separation between a given pair of charged-particle momenta.

Charge balance functions in hydrodynamics

In order to compute the CBFs derived from hydrodynamics, we decouple the long-wavelength hydrodynamic evolution from the short-wavelength stochastic-diffusive dynamics. The hydrodynamic evolution is assumed to be boost-invariant and deterministic [8, 9]. The evolution of the charge correlations are then obtained by splitting the charge correlator into local (equilibrated) and non-local (inequilibrated) pieces:

$$C_{ab}(\vec{r}_1, \vec{r}_2, t) = \chi_{ab}(\vec{r}_1, t)\delta(\vec{r}_1 - \vec{r}_2) + C'_{ab}(\vec{r}_1, \vec{r}_2, t). \tag{5}$$

The non-local piece C'_{ab}, which probes the effects of diffusion in an evolving system, is evolved according to the following diffusion equation:

$$\partial_t C'_{ab}(\vec{r}_1, \vec{r}_2, t) = D(\nabla_1^2 + \nabla_2^2)C_{ab}(\vec{r}_1, \vec{r}_2, t) + S_{ab}(\vec{r}_1, t)\delta(\vec{r}_1 - \vec{r}_2), \tag{6}$$

where the "source function" is

$$S_{ab}(\mathbf{r}, t) = (\partial_t + \mathbf{v}\cdot\nabla + \nabla\cdot\mathbf{v})\chi_{ab}(\mathbf{r}, t) \tag{7}$$

and χ_{ab} is the susceptibility for light quark flavors a and b.

After decoupling, the charge correlations are converted to hadronic correlations and subsequently evolved further using a hadronic afterburner [10].

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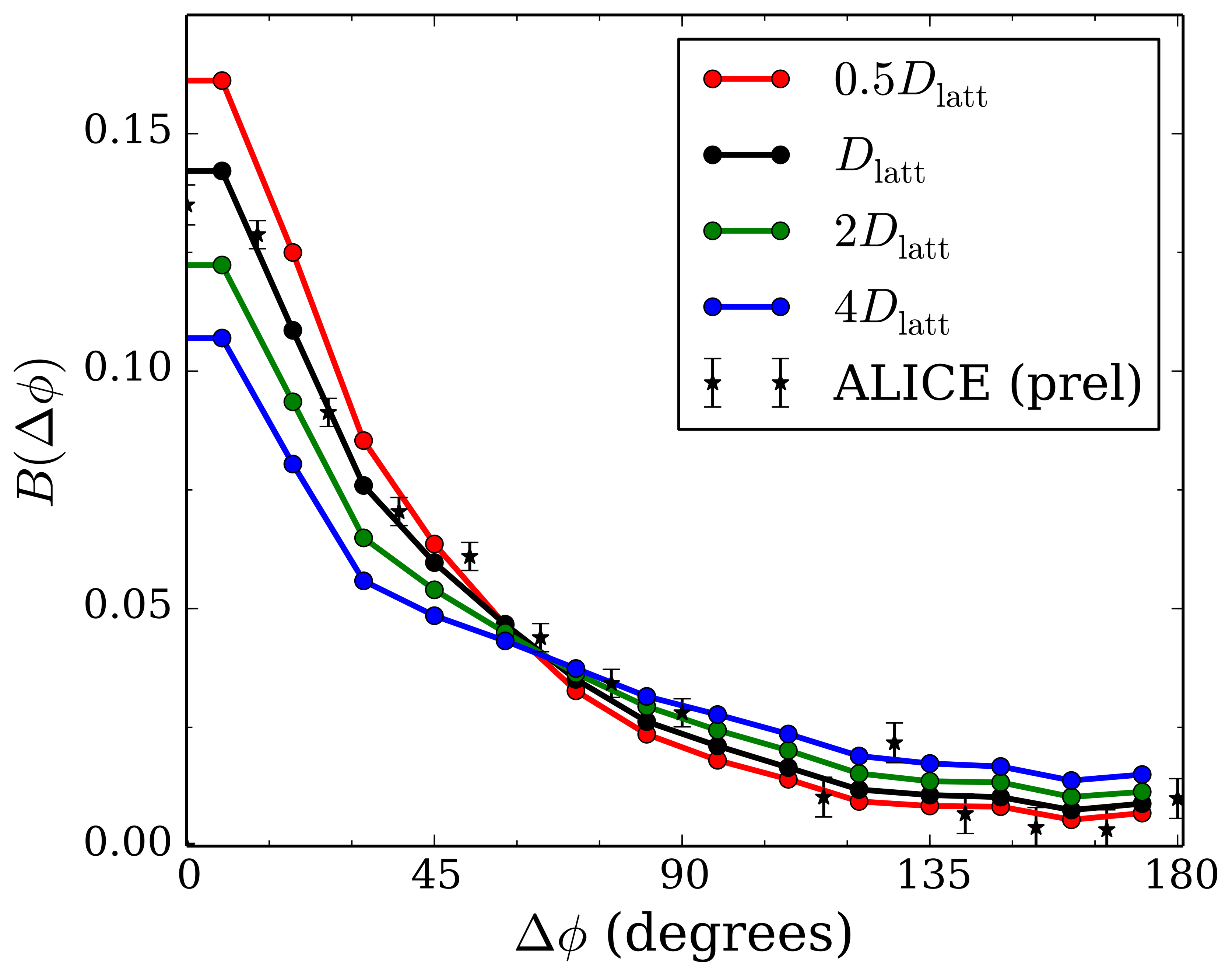
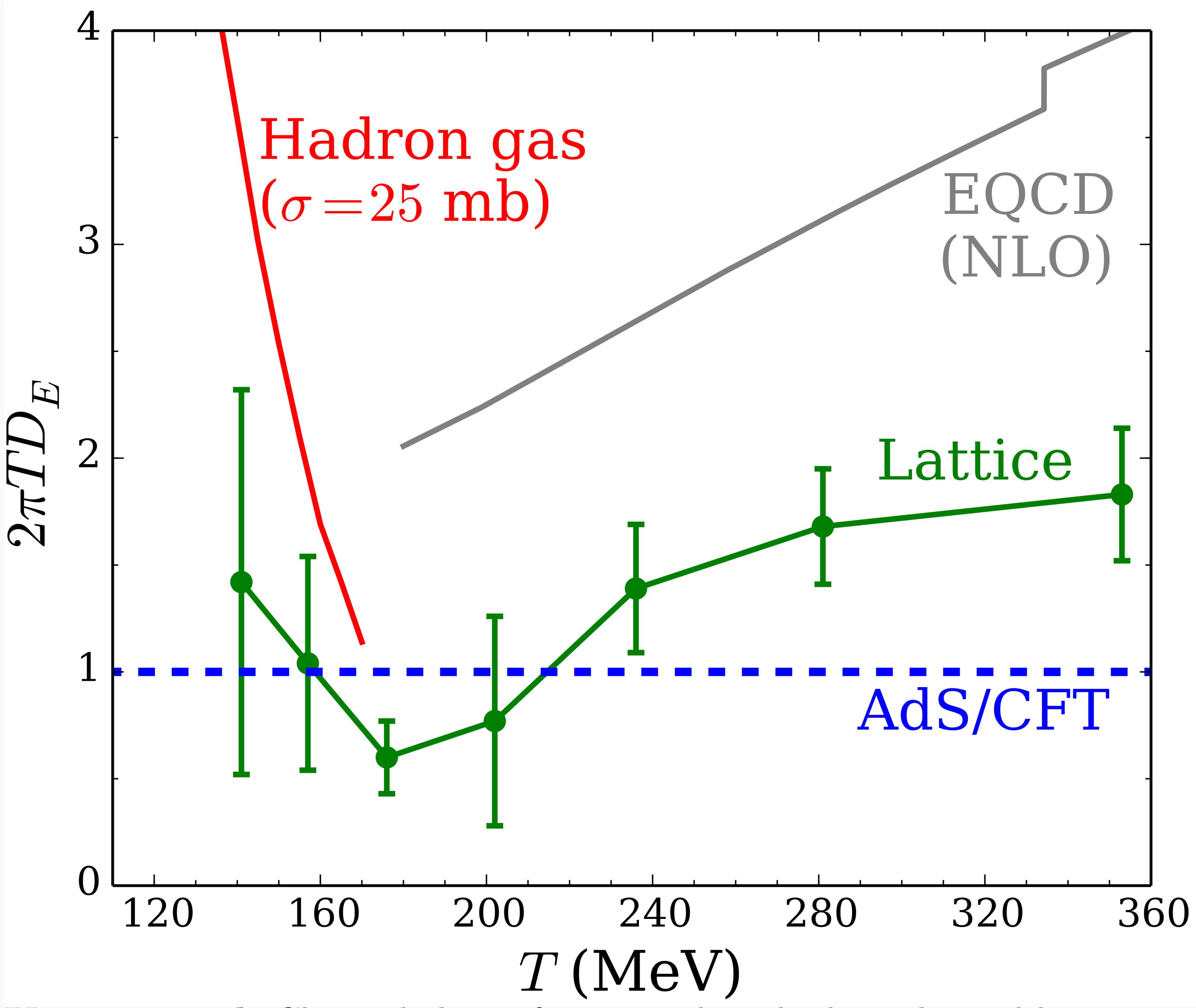
Modeling Charge Correlations in Hydrodynamics

We consider Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as modeled by boost-invariant hydrodynamics and we neglect initial-state fluctuations. The results [11] of our theoretical formalism are shown below for several different scalings of the lattice diffusion coefficient and compared with the corresponding (preliminary) ALICE data [12].





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Upper panel: Charge balance functions describe how charged kaon pairs are separated as a function of azimuthal angle for four choices of the diffusivity. The heavy black line shows results using the $D_E(T)$ from lattice calculations in [13], while results with half (red dashes), double (green dotted) and quadruple (blue dot-dashed) those values illustrate how higher diffusivities result in larger angular spreads. The sensitivity to the diffusivity derives from the strength of the electric charge source function at hadronization.

Lower panel: The electric diffusivity, scaled by $2\pi T$, from lattice gauge theory as calculated in [13] (green points). A hadron gas with a fixed 25-mb cross section (red line) has significantly higher diffusivity, as does a perturbative approach, EQCD, to next-to-leading order [14] (grey line). For AdS/CFT, the value is unity (blue dashes).

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