Towards a quantitative understanding of the quark–gluon plasma

Jon-Ivar Skullerud, for the FASTSUM collaboration
Gert Aarts, Chris Atton, Simon Hands, Maria-Paola Lombardo, Sejong Kim, Sinéad Ryan, JIS
1Department of Mathematical Physics, Maynooth University, Ireland; 2Department of Physics, Swansea University, UK; 3INFN – Laboratori Nazionali di Frascati, Italy; 4Department of Physics, Sejong University, Korea; 5School of Mathematics, Trinity College Dublin, Ireland

Motivation

Phase diagram of QCD in $T - \nu$ plane

- At extremely high temperatures, quarks and gluons become deconfined → quark–gluon plasma (QGP)
- Chiral symmetry restoration: quarks become nearly massless
- The QGP is created and studied in heavy ion collisions at CERN and Brookhaven
- Precise understanding of spectral and transport properties as well as thermodynamics required to interpret experiments

Left: Experimental results from CMS [6] at high temperature (bottom) the $\Upsilon$ (2S) and (3S) states are suppressed relative to pp collisions (top).

Right: Spectral functions from FASTSUM [7] above $T_c$, $\Upsilon$ (2S) melts, but the ground state remains robust.

Methods

Path integral in euclidean space:

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}[\psi] \mathcal{D}[\bar{\psi}] e^{-S}\mathcal{O}$$

- Discretise space-time → Lattice QCD
- Generate gauge configurations $\Gamma$ with probability weight $e^{-\beta S(\Gamma)}$
- using Markov Chain Monte Carlo
- Temperature $T = \frac{1}{\beta} = (N a_0)^{-1}$
- Anisotropic lattices: $a_0 = \xi a$ → $a$ → non-trivial tuning [1, 2]

Real-time quantities encoded in spectral function $\rho(\omega, T)$

$$G_\mathcal{O}(\tau, T) = \int_0^{\infty} d\omega \mathcal{N}(\omega, T) \rho(\omega, T)$$

Maximum Entropy Method to determine $\rho(\omega, T)$ given $G_\mathcal{O}(\tau, T)$

Conductivity and charge diffusion

- Conductivity $\sigma$ and diffusion coefficient $D_\mathcal{O}$ are both determined from the electromagnetic (vector) current correlator

$$G_{\mathcal{O}}^{\mathcal{A}}(\tau, T) = \int d^4x e^{i\mathcal{A}(\tau, x)} G_{\mathcal{O}}(\tau, x)$$

Kubo relation

$$\sigma = \lim_{\omega \to 0} \frac{G_{\mathcal{O}}^{\mathcal{A}}(\tau, T)}{\omega}$$

$$D_\mathcal{O} = \frac{\sigma}{\mathcal{A}^2}$$

Outlook

- Very high precision (sub-permille) and fine temporal resolution required to determine spectral information
- Anisotropic lattice QCD is in a position to achieve this, thanks to improved algorithms and HPC resources
- Promising results for heavy quarkonium and conductivity
- "Third generation" ensembles with twice the temporal resolution in progress

References


Acknowledgments

This work has been supported by PRACE Call 3 and Call 5 awards, as well as a UK STFC DiRAC award and Irish Centre for High-End Computing Class A and B awards.

Conductivity signal

Electric current spectral function

Conductivity (left) and charge diffusion coefficient (right) as function of temperature [5].

Charm and beauty

- $J/\psi$ suppression — a probe of the quark–gluon plasma?
- charm and beauty quarks created in primordial collisions, hard probes?
- Sequential suppression observed at CMS

Use non-relativistic QCD (NRQCD) for beauty quarks:
- No temperature-dependent kernel, $G_T = f_T / u_e^{-c T}$
- Longer euclidean time range
- Appropriate for probes not in thermal equilibrium
- Does not incorporate transport properties

Nucleons

If chiral symmetry is restored, the nucleon and its parity partner are degenerate. We find that as the temperature increases, this degeneracy emerges.

Conductivity and charge diffusion

Nucleon correlators at different temperatures [10]. The forward and backward propagating parts are positive and negative parity states.