Towards a quantitative understanding of the quark–gluon plasma

Jon-Ivar Skullerud[1], for the FASTSUM collaboration

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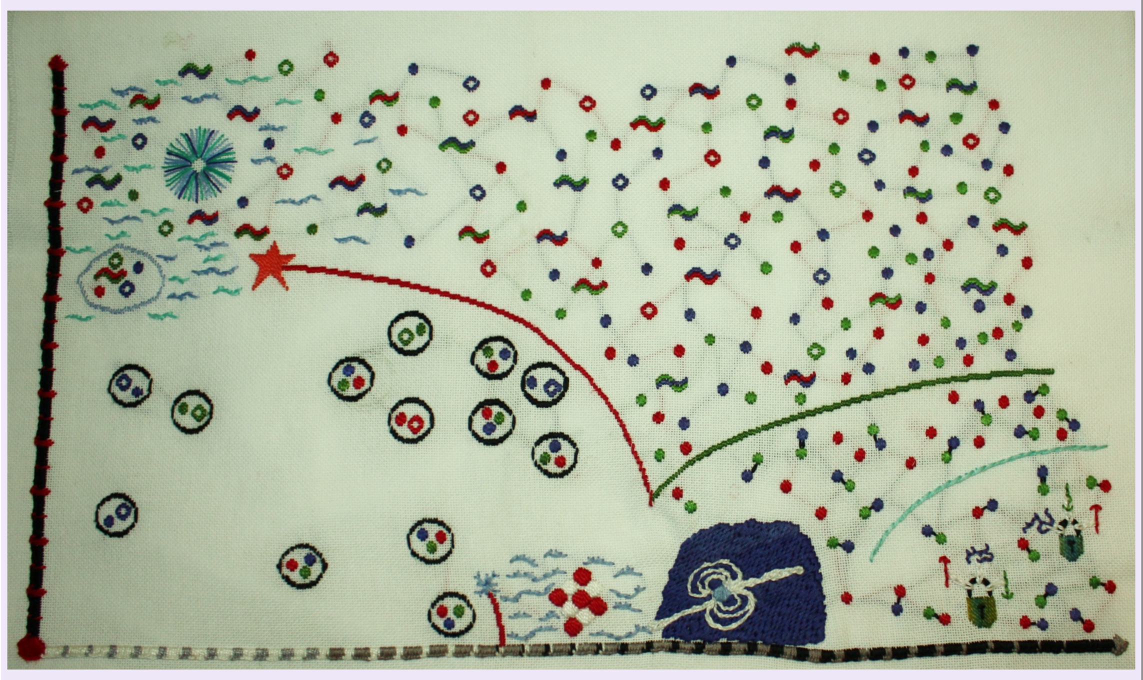
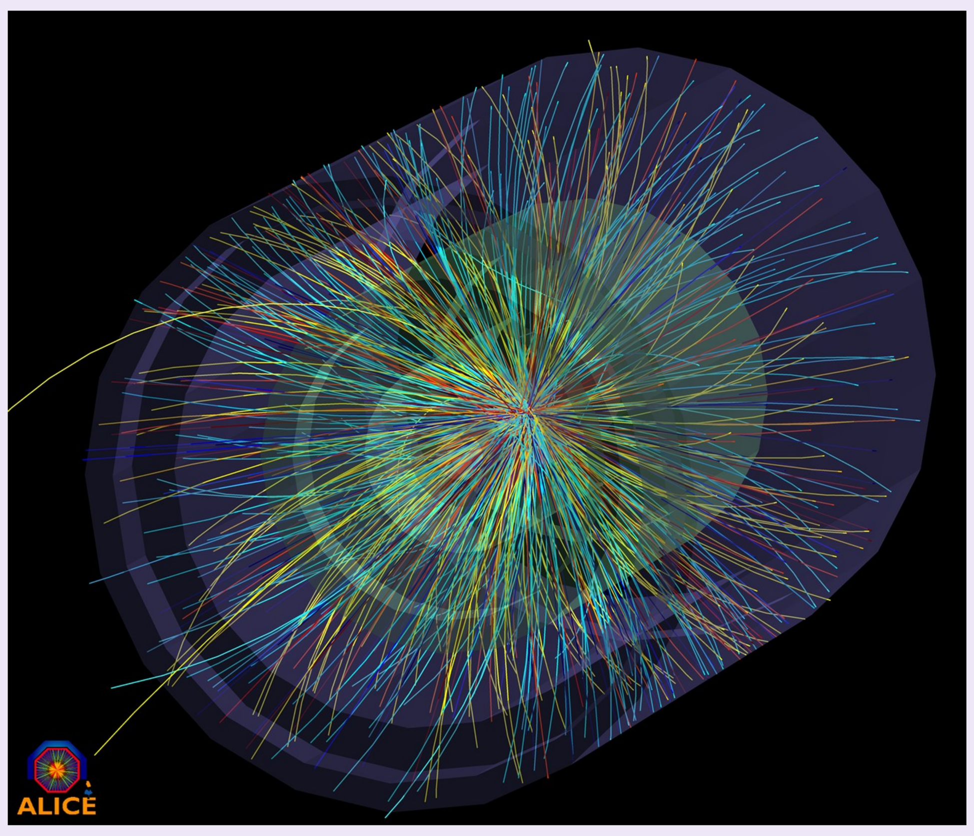
Motivation



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

- At extremely high temperatures, quarks and gluons become deconfined $\longrightarrow$ 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



A central Pb–Pb collision in the ALICE detector

Methods

Path integral in euclidean space:

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

- Discretise space-time $\longrightarrow$ Lattice QCD
- Generate gauge configurations U with probability weight
$$e^{-S[U]} = \det M[U] e^{-S_G[U]}$$
using Markov Chain Monte Carlo
- Temperature $T = \frac{1}{L_\tau} = (N_\tau a_\tau)^{-1}$
- Anisotropic lattices: $a_s = \xi a_\tau \gg a_\tau \longrightarrow$ non-trivial tuning [1, 2]
- Chroma [3] with BAGEL [4] optimisation for BlueGene

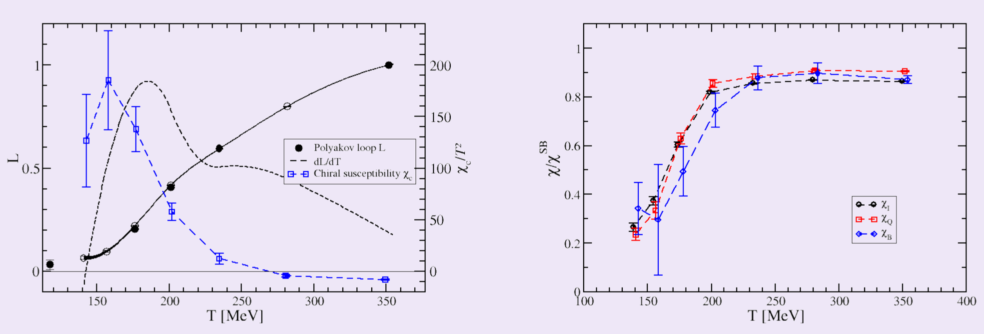
Real-time quantities encoded in spectral function $\rho(\omega; T)$

$$G_E(\tau; T) = \int_0^\infty d\omega K(\omega, \tau; T) \rho(\omega; T)$$

Maximum Entropy Method to determine $\rho(\omega; T)$ given $G_E(\tau; T)$

Deconfinement transition

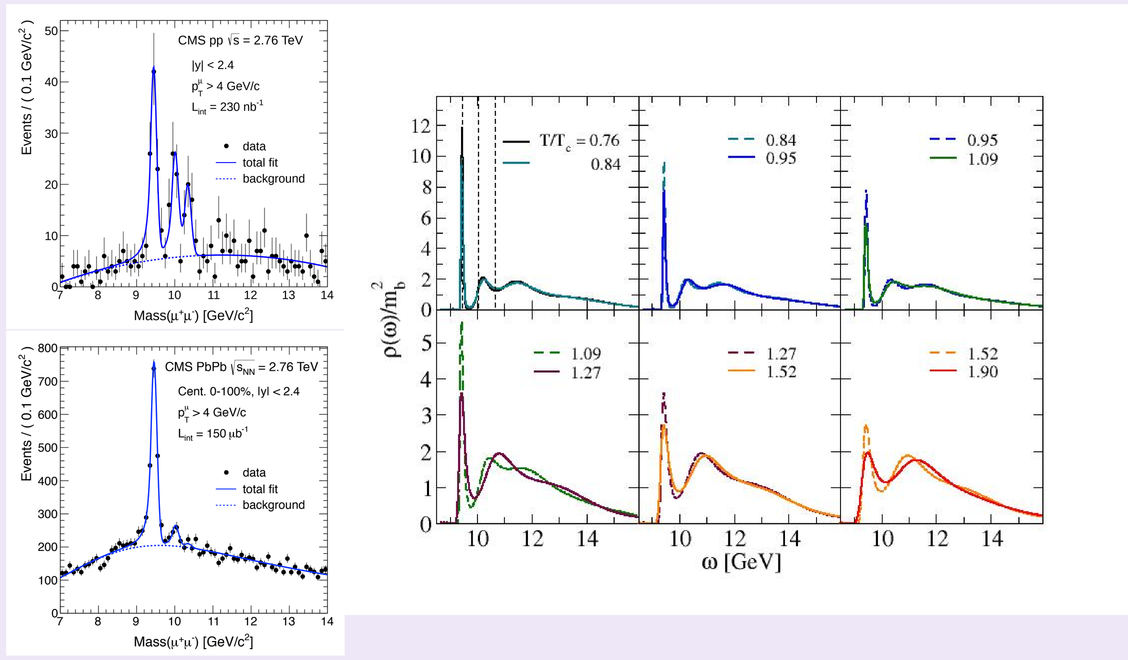
The transition to the QGP is characterised by a rapid increase in the Polyakov loop $L = e^{-F_q/T}$ and the baryon number susceptibility χ_B, as well as a peak in the chiral susceptibility.



Left: Polyakov loop L and chiral susceptibility χ_c. The peak in dL/dT gives the deconfinement temperature T_c.
Right: Electric charge, isospin and baryon number susceptibility [5].

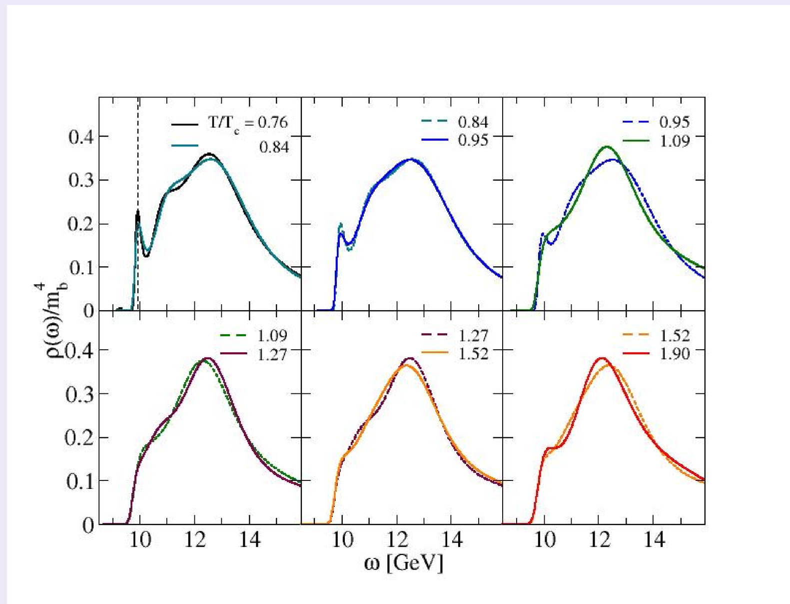
Charm and beauty

- J/ψ suppression — a probe of the quark–gluon plasma?
- c and b quarks created in primordial collisions, hard probes?
- b quarks cleaner probes than c?
- Sequential suppression observed at CMS
- Use non-relativistic QCD (NRQCD) for b quarks:
  - ✓ No temperature-dependent kernel, $G(\tau) = \int \rho(\omega) e^{-\omega\tau} \frac{d\omega}{2\pi}$
  - ✓ Longer euclidean time range
  - ✓ Appropriate for probes not in thermal equilibrium
  - × Does not incorporate transport properties



Left: Experimental results from CMS [6]: at high temperature (bottom) the Υ (2S) and (3S) states are suppressed relative to pp collisions (top).
Right: Spectral functions from FASTSUM [7]: above T_c, Υ (2S) melts, but the ground state remains robust.

Spectral functions in the χ_{b1} channel [7]: P-wave states melt above T_c



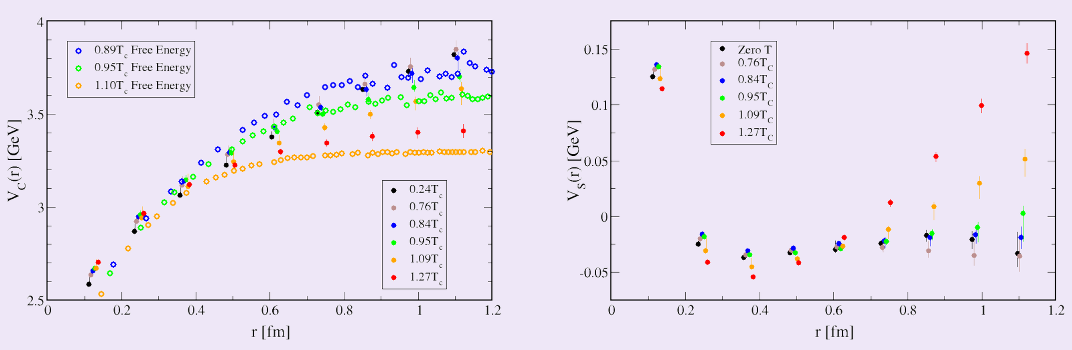
Charmonium potential:

Schrödinger equation for charmonium wavefunctions $\psi_j(\mathbf{r})$:

$$\left[-\frac{1}{2\mu}\frac{\partial^2}{\partial r^2} + V_\Gamma(r)\right]\psi_j(r) = E_j \psi(r), \qquad \mu = \frac{m_c}{2} \approx \frac{M_{J/\psi}}{4}$$

Potential extracted from point-split correlators $C(r, \tau)$

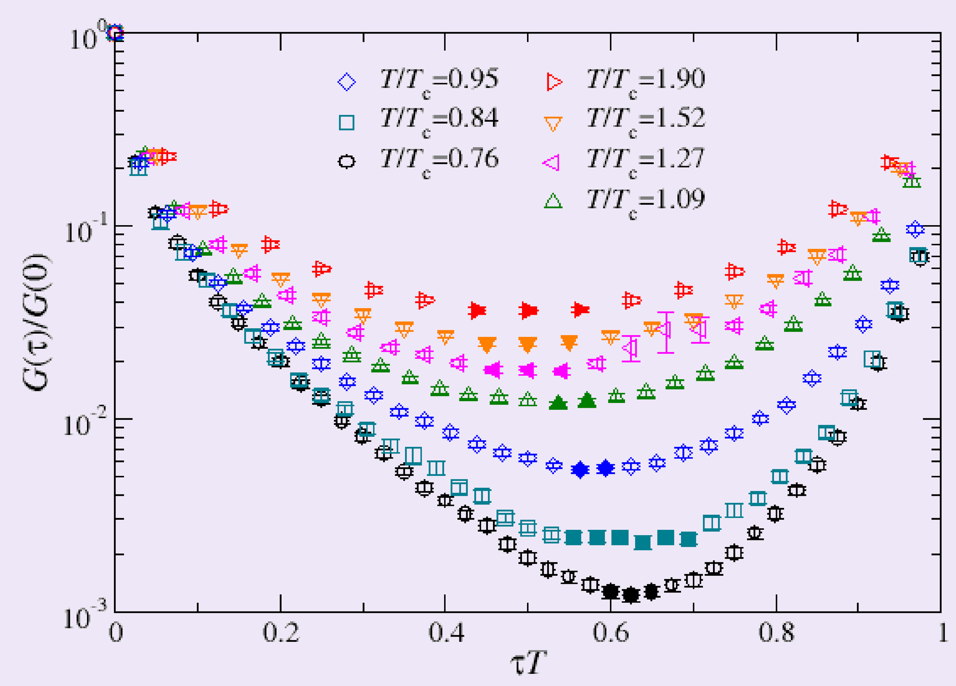
$$\frac{\partial C_\Gamma(r,\tau)}{\partial \tau} = \left(\frac{1}{2\mu}\frac{\partial^2}{\partial r^2} - V_\Gamma(r)\right) C_\Gamma(r,\tau).$$



Central (left) and spin-dependent (right) potential between two charm quarks [8], compared with the free energy of a static $Q\bar{Q}$ pair from [9].

Nucleons

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



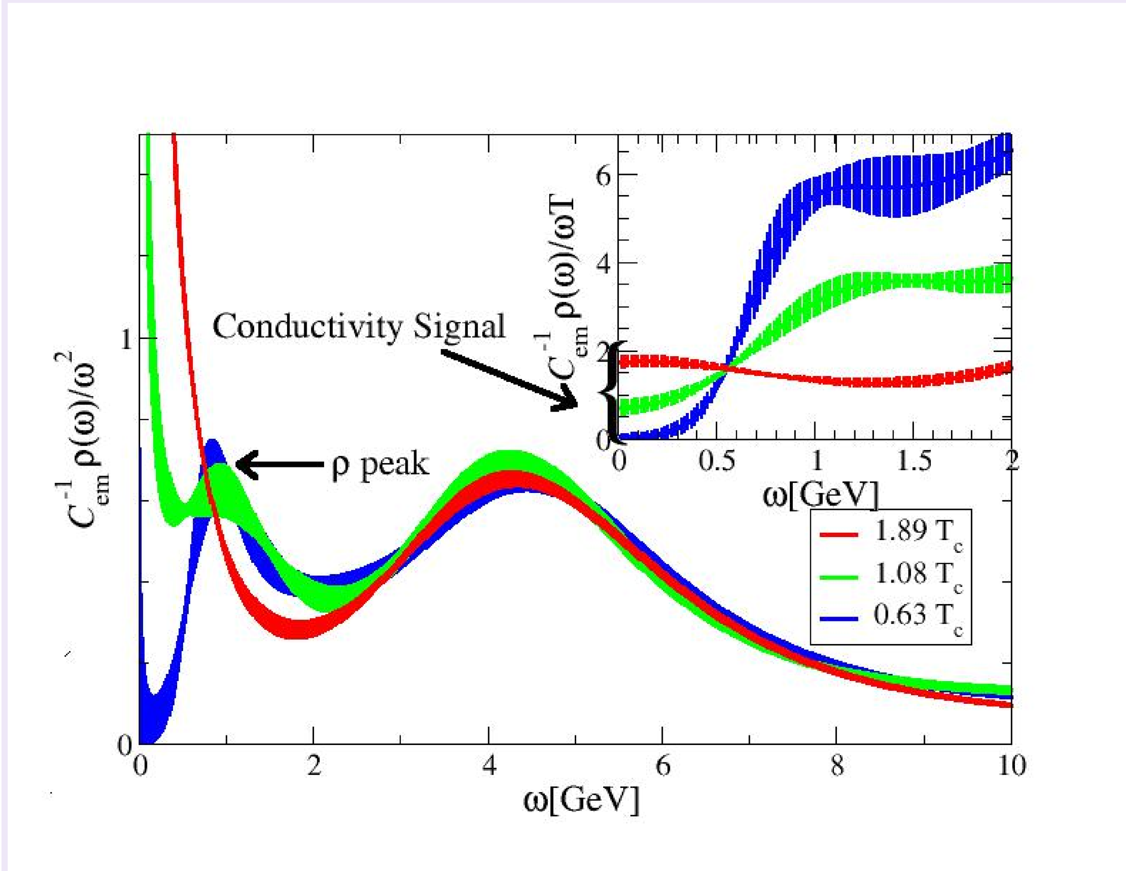
Nucleon correlators at different temperatures [10]. The forward and backward propagating parts are positive and negative parity states.

Conductivity and charge diffusion

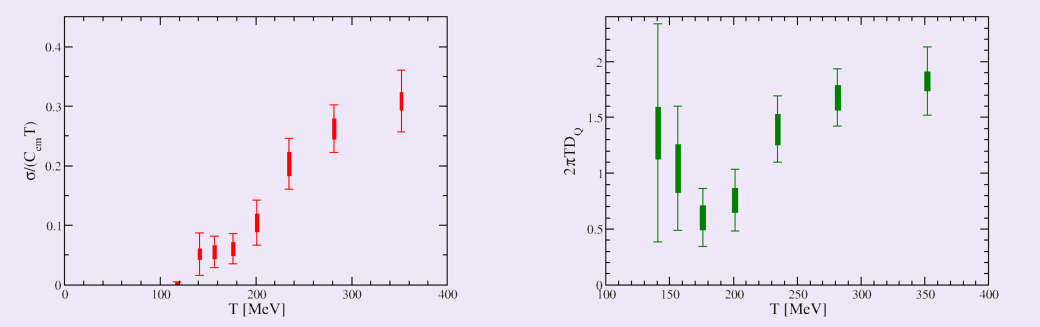
Conductivity σ and diffusion coefficient D_Q are both determined from the electromagnetic (vector) current correlator

$$G_{ij}^{em}(\tau, \vec{p}) = \int d^3x e^{i\vec{p}\cdot\vec{x}} \langle j_i^{em}(\tau, \vec{x}) j_j^{em}(0, \vec{0})\rangle$$

Kubo relation $\quad \sigma = \lim_{\omega \to 0} \frac{\rho_{ii}^{em}(\omega)}{6\omega}; \qquad D_Q = \frac{\sigma}{\chi_Q T}$



Electric current spectral function [11]



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

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 are in progress

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