CRC-TR 211
Strong-interaction matter under extreme conditions

Progress Report for Project A06:

Hadronic excitations and spectral functions in the medium

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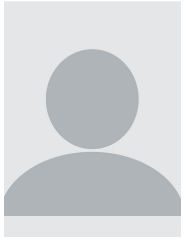
Goals of Project A06

(i) Hadronic correlation functions from lattice QCD

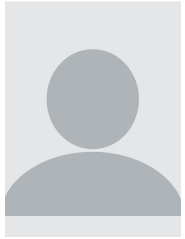

S. Ali


D. Bala


P. Lowdon

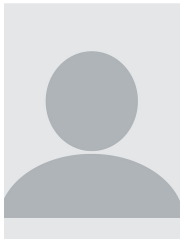

J. Turnwald


T. Ueding


N. Wink


Y. Zhang

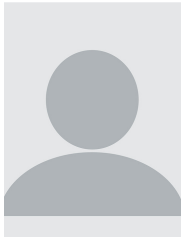
(ii) Critical behavior of mesonic correlators

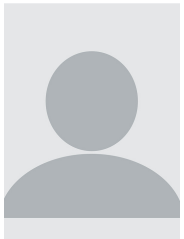

M. Harhoff


F. Klette


L. Sieke

(iii) Effective theories and real-time methods for spectral functions


P. Niekamp


F. Rennecke


J. Roth


M. Spier


Y. Ye

Hadronic Correlation Functions: Goals and Timeline

Goals:

- Dilepton and photon rates from light-quark vector-meson correlators
- Extend the methodology developed for quarkonium from quenched to full QCD
- In-medium properties of D/B-mesons in the hadronic and the QGP phase

Timeline:

2021 Generate gauge-field configurations, tune quark masses, and perform first calculations of hadronic correlators on coarse lattices

2022 Compute and analyse light- and heavy-quark correlation functions with dynamical light quark

2023 Perform continuum extrapolations of all hadronic correlation functions

2024 Reconstruct hadronic spectral functions

2025 Analyze thermal modifications of quarkonia and open heavy-flavor meson

Hadronic Correlation Functions: Where Are We? I

Dilepton and photon rates from light-quark vector-meson correlators

- ✓ Extracted thermal photon rate from the Transverse-Longitudinal ($T - L$) meson correlator and the Gaussian process regression (Bala, Ali, et al., 2023; Ali, Bala, Francis, et al., 2024)
- ... Ongoing: dilepton rates

Hadronic Correlation Functions: Where Are We? II

Extend the methodology developed for quarkonium from quenched to full QCD

- ✓ Reconstructed spectral functions for charmonium and bottomonium in the pseudo-scalar channel with $\frac{m_s}{m_l} = 5$ (Ali, Bala, Kaczmarek, et al., 2023a; Ali, Bala, Kaczmarek, et al., 2023b)
- ✓ Developed complex non-perturbative potential (this is connected to subproject (iii)) (Hoying et al., 2022; Bala, Kaczmarek, Larsen, et al., 2022; Parkar et al., 2022)
- – $2 + 1 + 1$ configurations not necessary yet since effects of dynamical charm negligible at current temperatures of interest

In-medium properties of D/B-mesons in the hadronic and the QGP phase

- – Data is available but not analyzed yet

Compared to planned timeline, we are on time.

Critical Mesonic Correlators: Goals and Timeline I

Goals:

- Dynamic scaling functions for $O(4)$ chiral transition
- Critical behavior of meson correlators in the chiral limit and at finite density
- Non-equilibrium phase transitions

Timeline:

2021
- Set up classical-statistical simulations for $O(4)$ chiral transition at finite spatial momenta and for non-equilibrium phase transitions with Z_2 scalar fields

2022
- Determine dynamic critical exponents of $O(4)$ model with Hamiltonian and Langevin dynamics and of universal scaling functions for spectral function of chiral order parameter
- Calculate meson correlators on configurations with smaller-than-physical light-quark masses

Critical Mesonic Correlators: Goals and Timeline II

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2023
- Perform classical-statistical calculations of critical contributions to electric conductivity, shear and bulk viscosity in the vicinity of $O(4)$ and Z_2 critical points
- Study critical behavior of meson correlators in the chiral limit

2024
- Develop protocols for critical-point searches in non-equilibrium phase transitions and of lattice-Boltzmann simulations for Model-H dynamics

2025
- Assess corrections to classical-statistical results for $O(4)$ and Z_2 models with different dynamics
- Study Kibble-Zurek scaling for systems evolving along trajectories close to Z_2 QCD critical point

Critical Mesonic Correlators: Where Are We? I

Dynamic scaling functions for $O(4)$ chiral transition:

- ✓ Performed various scans of the phase diagram in Models A and G
- ✓ Observed clearly different dynamic critical exponents z between Model A and G as expected
- ... Ongoing: Explore effective theory describing interplay of order parameter and $O(4)$ charges $\rightsquigarrow$ improve z extraction and help determine scaling functions

Critical behavior of meson correlators in the chiral limit and at finite density:

- – Results from lattice QCD close to chiral limit and classical-statistical simulations not yet compared

Critical Mesonic Correlators: Where Are We? II

Non-equilibrium phase transitions:

- ✓ Determined non-equilibrium scaling functions and dynamic critical exponent z of Model A from quench through Z_2 critical point (Sieke, Harhoff, Schlichting, and von Smekal, in preparation)
- ... Follow up study of 1st-order transition in Model A in progress
- ... Continuation to Model B planned
- ... Model H with stochastic hydrodynamics under development (alternative to lattice-Boltzmann) (Harhoff, in preparation)

Compared to planned timeline, we are on time.

Real-Time Effective Theories: Goals and Timeline

Goals:

- Investigate reliability and limitations of effective theories
- Spectral functions from FRG on closed-time path
- Real-time simulations beyond classical-statistical limit

Timeline:

2021 Setup FRG in symmetric phase of $O(4)$ model,
calculate spectral functions of Z_2 scalar field theory in GSA

2022 Extend FRG to symmetry-broken phase of $O(4)$ model,
benchmark GSA against classical-statistical simulations

2023 Include dynamical fermions in FRG

2024 Derive flow equations for Quark-Meson model on CTP

2025 Calculate spectral functions for Quark-Meson model

Real-Time Effective Theories: Where Are We? I

Spectral functions from FRG on closed-time path:

- ✓ Compared various real-time methods for spectral functions in quantum-mechanical testbed system (Roth, Schweitzer, Sieke, and von Smekal, 2022)
- ✓ Developed causal regulators, calculated critical spectral functions of Models A, B & C (Roth and von Smekal, 2023)
- ✓ Formulated symmetry-preserving FRG flow for $O(4)$ Model G, confirmed $z = d/2$, and calculated dynamic scaling function for isovector and isoaxial-vector charge diffusion coefficient (Roth, Ye, Schlichting, and von Smekal, 2024)
- ... Ongoing: Derive real-time flow equations for Quark-Meson model

Real-Time Effective Theories: Where Are We? II

Real-time simulations beyond classical-statistical limit:

- ✓ Computed spectral functions of scalar field theory in (2+1)d and (3+1)d using Gaussian-state approximation, verified classical limit, with visible quantum corrections at low temperatures (Sieke, 2022)

Compared to planned timeline, we are on time.

Additional Opportunities and Directions

New ideas/directions which came up in the last years (by subproject):

(i) Hadronic correlation functions from lattice QCD
- Determine spectral function from spatial correlators (Bala, Kaczmarek, Lowdon, et al., 2023)
- Repeat first point for heavy quarks
- $T - L$ correlator for heavy quarks

(ii) Critical behavior of mesonic correlators
- Use Kibble-Zurek mechanism to determine dynamic critical exponent z with high precision

(iii) Effective theories and real-time methods for spectral functions
- Exact solution of $O(N)$ Model G in $N \to \infty$ limit

A06: Outlook

Summary of A06's progress:

- All subprojects (i), (ii) & (iii) on time
- Minor technical changes, but no major deviations from planned goals
- Promising additional opportunities identified in all subprojects

Thank you for your attention!

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