

Progress Report for Project A02

Lattice QCD at non-vanishing density

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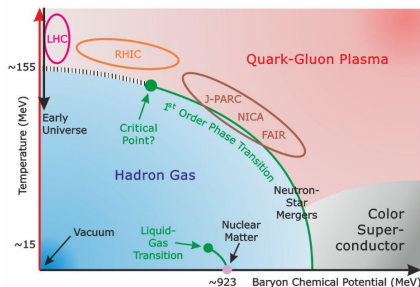


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PLs	Current YSs	Former YSs
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- ▶ Phase boundary and the order of the transition at high temperatures and densities
- ▶ Nuclear liquid-gas transition and the nuclear-matter phase
- ▶ Further developments of the effective theories



(Figure taken from funding proposal of the CRC-TR 211)

Goals:

- ▶ Establish a region of overlap between the effective theories in the $\mu_B - T$ phase diagram
- ▶ Dual representation: determine the β -dependence of the chiral critical endpoint
- ▶ 3-dimensional effective theory: extend to and simulate at smaller quark masses

Timeline:

- 2021** Dual representation: extend phase diagram to $m_q, \beta > 0$
Both: Determine baryon mass as a function of (m_q, β)
3-dimensional effective theory: evaluate with static quarks via series expansion techniques
- 2022** 3-dimensional effective theory: extend to and simulate for light quark masses

Goals:

- ▶ Establish a region of overlap between the effective theories in the $\mu_B - T$ phase diagram
- ▶ Dual representation: determine the β -dependence of the chiral critical endpoint
- ▶ 3-dimensional effective theory: simulate at smaller quark masses

Timeline:

2023 (none)

2024 (none)

2025 Dual representation: investigate chiral transition at sufficiently large values of β

Both: possibly make contact with parameter regime of project A01

- ▶ Dual representation: obtained simulation results at NLO (published)
- ▶ 3-dimensional effective theory: evaluation with static quarks via series expansion techniques done (publication in preparation, delayed due to lack of personnel)
- ▶ 3-dimensional effective theory: evaluation method substituted by mean-field
 - Derived mean-field equations (proceedings out, publication in preparation)
 - Conclusion: NNLO effective action insufficient to gain qualitative insights of the QCD phase diagram for light quark masses

Compared to planned timeline, we are behind.

Goals:

- ▶ Dual representation: aim for lower T and larger β
- ▶ Both: study the nuclear equation of state and nuclear interactions
- ▶ Both: obtain the canonical phase diagram
- ▶ Both: extend to $\mu_I \neq 0$

Timeline:

2021 (none)

2022 Dual representation: extend to $\mu_I \neq 0$ via implementation of quantum Hamiltonian

2023 Dual representation: perform quantum simulations for $\mu_B \neq 0 \neq \mu_I$ and investigate enlarged phase diagram

Goals:

- ▶ Dual representation: aim for lower T and larger β
- ▶ Both: study the nuclear equation of state and nuclear interactions
- ▶ Both: obtain the canonical phase diagram
- ▶ Both: extend to $\mu_I \neq 0$

Timeline:

- 2024 Both: investigate nuclear transition and nuclear interactions for moderate pion masses and determine nuclear critical endpoint
- 2025 (none)

- ▶ Dual representation:
 - Set up detailed strategy for quantum simulations at $\mu_I \neq 0$ (proceedings out)
 - Mapping out of phase diagram in $\mu_B - \mu_I - T$ -space work in progress
- ▶ 3-dimensional effective theory: extended NNLO action to $\mu_I \neq 0$; evaluation was delayed due to lack of personnel
- ▶ Investigated the nuclear transition in
 - the dual formulation at NLO with $\mu_I = 0$ (published)
 - 3-dimensional effective theory via mean-field (publication in preparation)

Compared to planned timeline, we are behind.

Goals:

- ▶ Dual representation: derive for Wilson fermions
- ▶ Dual representation: implement simulation algorithms
- ▶ 3-dimensional effective theory: improved effective couplings

Timeline:

2021 Dual representation: extend to Wilson fermions

2022 Dual representation: algorithmic improvements for simulation and evaluation at large values of β

Goals:

- ▶ Dual representation: derive for Wilson fermions
- ▶ Dual representation: implement simulation algorithms
- ▶ 3-dimensional effective theory: improved effective couplings

Timeline:

- 2023** Dual representation: simulate at lower T and larger β
3-dimensional effective theory: generalize relations for numerical projection of couplings to include quarks
- 2024** 3-dimensional effective theory: numerically simulate projected couplings
- 2025** (none)

- ▶ Dual representation: switched topic from extension to Wilson fermions to evaluation at NNLO
 - Developed the simulation strategy (proceedings out for gauge group $U(3)$, extension to $SU(3)$ in progress)
 - Parallelized simulation code is work in progress
- ▶ Dual representation: tested simulation methods on a quantum annealer at LO (published)
- ▶ Numerical matching procedure for 3-dimensional effective theory:
 - Analytical relations for matching of couplings generalized to include static quarks
 - Simulation code for projected couplings finished, but simulations are not being worked on due to lack of personnel

Compared to planned timeline, we are behind

- ▶ Extension of 3-dimensional effective theory to light quark masses
 - Analytical derivation of higher order corrections done
 - Implementation for evaluation via mean-field is in progress

- ▶ We are behind in all components of the project due to lack of personnel and modifications of some topics
- ▶ Changed from extending dual formulation to Wilson fermions to evaluation at NNLO
- ▶ 3-dimensional effective theory: changed evaluation method from simulation to mean-field
 - Very flexible way for evaluating the effective theory
 - Possibility to evaluate effective theory with higher order corrections (work in progress), interesting for the light quark regime