<u>Teaser:</u> Using the vast computing power of the GPU accelerators on the JUWELS Booster of JSC, an international team of physicists – the HotQCD Collaboration – calculated up to eighth order expansion coefficients of Taylor series that allows to describe properties of strong-interaction matter at high densities. Results obtained through a Pade resummation of this series provide stringent bounds on the possible existence of a phase transition occurring at high temperature and high baryon number density.

High order cumulants of conserved charge fluctuations

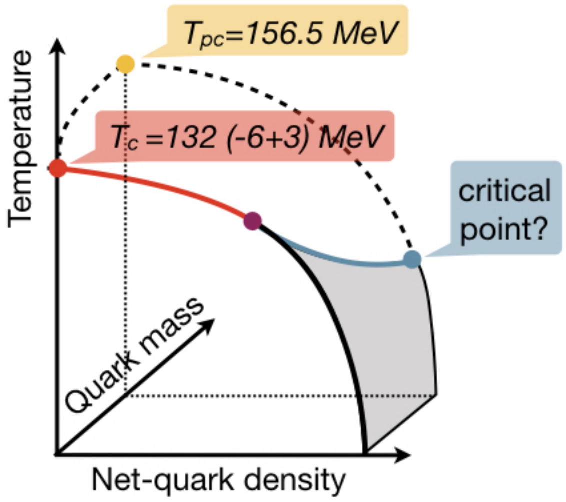

***Figure 1**: Schematic phase diagram of QCD. Indicated are the pseudo critical transition temperature (T_{pc}) of QCD with massive quarks and the critical transition temperature (T_c) in the massless limit. Dashed lines indicate the crossover transition, solid lines are lines of second order phase transitions, and the gray surface is a surface of first order phase transition points. A hypothetical critical point at physical quark masses is also shown.*

The theory of strong-interaction physics is called Quantum Chromodynamics (QCD). At low temperatures it describes properties of matter formed by hadrons such as the proton, neutron or lighter particles like the pion. It is widely believed that this matter undergoes a phase transition at high temperature and/or high net-baryon number density. During this transition the fundamental constituents of hadrons, quarks and gluons, are expected to get liberated. They form a new state of matter, the Quark Gluon Plasma (QGP).

While this transition is well studied in large scale numerical simulation and evidence for the existence of such a transition has been established at vanishing net-baryon number densities, studies at non-vanishing values of the net-baryon number, or equivalently non-zero values of the relevant control parameter – so-called chemical potentials – is much more difficult. As direct numerical simulations are not possible in this case, the effect of non-vanishing chemical potentials is incorporated by performing, for instance, Taylor series expansion in terms of the chemical potentials. The expansion coefficients in these series are the so-called cumulants. Expansions are being performed in terms of three different chemical potentials, which couple to three operators reflecting three conserved quantum numbers of QCD, i.e. baryon number, electric charge and strangeness.

In a series of scientific studies using various HPC systems around the world the HotQCD Collaboration calculated Taylor expansion coefficients (cumulants) in QCD. Using resources on the JUWELS Booster, which is equipped with powerful A100 GPUs, these expansions could be extended up to eighth order in the chemical potentials. This allowed, for the first time, to analyze also Pade-approximants, which provide a systematic resummation of the Taylor series. The poles of the Pade-approximants typically occur at complex values of the chemical potentials. They are known to provide insight into the convergence properties of Taylor series and can provide evidence for the existence of phase transitions, if such poles occur on the real axis. Using our new eighth

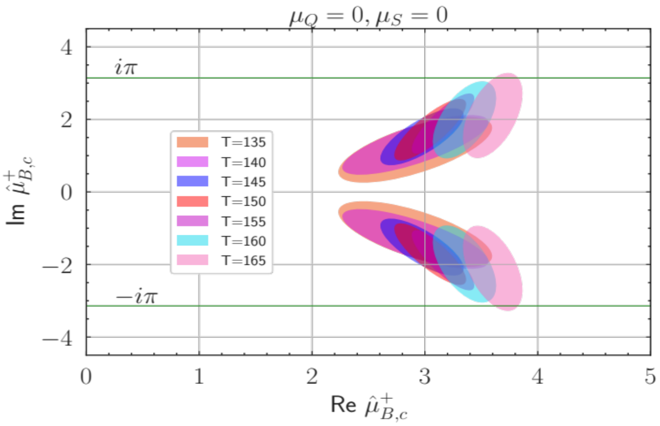

Figure 2: *Location of poles in the complex chemical potential plane. Shown is the temperature dependence of the positive pole nearest to the origin obtained from the [4,4] Pade approximants. With decreasing temperature the poles tend to approach the real axis.*

order Taylor series we located the zeroes of the largest diagonal Pade-approximant P[4,4]. We found that in the temperature range explored in our simulations only complex valued poles exist. However, with decreasing temperature these poles move closer to the real axis, suggesting that a phase transition at non-zero values of the baryon chemical potential may occur at temperatures below T=140 MeV and at values of the chemical potential larger than 400 MeV. These findings strengthen evidence for the existence of a possible phase transition in QCD with its physical quark mass spectrum at non-vanishing baryon chemical potentials and temperatures that are below that of the chiral phase transition temperature at vanishing values of the quark masses and vanishing chemical potentials that is found to be at $T_c = 132^{+3}_{-6}\, MeV$. This result is not only of academic interest but has also important phenomenological consequences. It can be seen as an upper bound for the long discussed and searched for critical point in the QCD phase diagram at non-vanishing net-quark densities. Our findings suggests that such a critical point cannot be found in currently performed collider experiments at the relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory, but will require dedicated fixed target experiments that allow to generate strong-interaction matter at higher densities. Such experiment started at RHIC and will also be performed in future experiments at GSI, Darmstadt.

References

[1] D. Bollweg, D. A. Clarke, J. Goswami, O. Kaczmarek, F. Karsch, S. Mukherjee, P. Petreczky, C. Schmidt and Sipaz Sharma, Equation of state and speed of sound of (2+1)-flavor QCD in strangeness-neutral matter at non-vanishing net baryon-number density, submitted to Physical Review D, [arXiv:2212.09043 [hep-lat]]

[2] D. Bollweg, J. Goswami, O. Kaczmarek, F. Karsch, S. Mukherjee, P. Petreczky, C. Schmidt and P. Scior, Taylor expansions and Pade approximants for cumulants of conserved charge fluctuations at non-vanishing chemical potentials, Physical Review D 105 (2022) 7, 074511, [arXiv:2202.09184 [hep-lat]]

[3] D. Bollweg, J. Goswami, O. Kaczmarek, F. Karsch, S. Mukherjee, P. Petreczky, C. Schmidt and P. Scior, [HotQCD Collaboartion], Second order cumulants of conserved charge fluctuations revisited: Vanishing chemical potentials, Phys. Rev. D 104 (2021) no.7, 074512, doi:10.1103/PhysRevD.104.074512 [arXiv:2107.10011 [hep-lat]]

[4] Dennis Bollweg, PhD thesis, Higher order cumulants of net conserved charge distributions in lattice QCD, Bielefeld, November 2021, https://pub.uni-bielefeld.de/record/2959588.

Project-ID: chbi20

HPC Plattform used: JUWELS Booster (A100 GPUs)

Principal Investigator: Frithjof Karsch, karsch@physik.uni-bielefeld.de

Affiliation: Universität Bielefeld, Faculty of Physics

Project Contributors:

Dennis Bollweg, Bielefeld University, dennis.bollweg@physik.uni-bielefeld.de

David Clarke, Bielefeld University, dclarke@physik.uni-bielefeld.de

Jishnu Goswami, Bielefeld University, jishnu@physik.uni-bielefeld.de

Olaf Kaczmarek, Bielefeld University, okacz@physik.uni-bielefeld.de

Anirban Lahiri, Bielefeld University, alahiri@physik.uni-bielefeld.de

Philipp Scior, Bielefeld University, scior@physik.uni-bielefeld.de

Mugdha Sarkar, Bielefeld University, mugdha@physik.uni-bielefeld.de

Swagato Mukherjee, Brookhaven National Laboratory, swagato@bnl.gov

Christian Schmidt, Bielefeld University, schmidt@physik.uni-bielefeld.de