Extracting freeze-out parameters from cumulant ratios of electric charge and strangeness fluctuations

F. Karsch[1], Swagato Mukherjee[2], C. Schmidt[1] and D. Bollweg[1]

[1]Bielefeld University, [2]Brookhaven National Lab

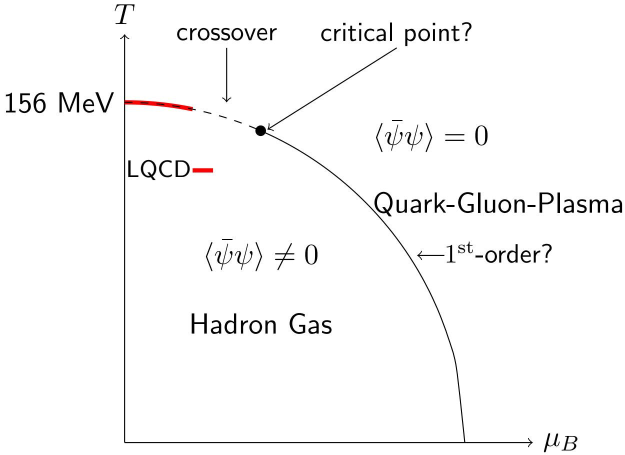
Strangeness in Quark Matter, BNL/ZOOM | 20.05.2021

Outline

UNIVERSITÄT BIELEFELD
Faculty of Physics

QCD phase diagram

- Exploration of QCD phase diagram poses long-standing open problem in heavy ion research.
- Search for a critical endpoint is the focus of many large scale collider experiments: RHIC, upcoming FAIR...
- Signs of a CEP might be found in higher order cumulants of conserved charge fluctuations.
- **Our Goal: Provide first-principle QCD baselines for conserved charge fluctuations.**



Fluctuations via lattice QCD

$M/\sigma^2, S\sigma, \kappa\sigma^2$ are accessible via *generalized susceptibilities* χ:

$$\chi_{ijk}^{BQS} \equiv \frac{1}{VT^3} \frac{\partial^{i+j+k} \log \mathcal{Z}}{\partial \hat{\mu}_B^i \partial \hat{\mu}_Q^j \partial \hat{\mu}_S^k}, \quad \hat{\mu}_X \equiv \frac{\mu_X}{T}$$

$$M_X/\sigma_X^2 = \frac{\chi_1^X}{\chi_2^X}, S_X\sigma_X = \frac{\chi_3^X}{\chi_2^X}, \kappa_X\sigma_X^2 = \frac{\chi_4^X}{\chi_2^X} \text{ with } X = B, Q, S$$

- Finite-density sign problem renders direct simulations at $\mu_B > 0$ impossible.
- Use constrained Tayor-Expansion in μ to access cumulants at finite density.
- Impose strangeness neutrality $n_S = 0$ and $\frac{n_Q}{n_B} = 0.4$ order by order - corresponds to thermal conditions in HIC (e.g. Pb + Pb or Au + Au).

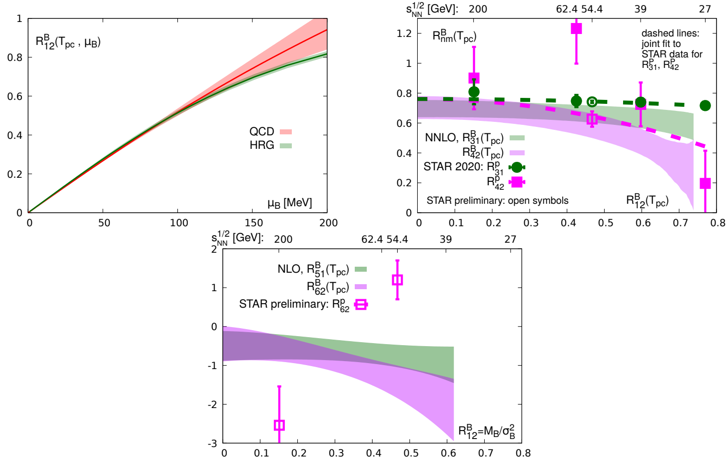
Fluctuations via lattice QCD - Setup

- Dynamical Fermions (HISQ) with $N_f = 2 + 1$: two light Quarks (up + down) and a strange Quark with mass ratio $\frac{m_s}{m_l} = 27$. ⇒ physical meson masses in the continuum limit!
- Lattice sizes $32^3 \times 8$, $48^3 \times 12$ and $64^3 \times 16$ with $T = 135 - 175$ MeV.
- Simulation campaigns 2020 & 2021 focused on $N_t = 16$ lattices, ∼ doubling the statistics.
- Exploration of $T = 125$ MeV with $N_t = 8$.

	$N_t = 8$	$N_t = 12$	$N_t = 16$
No. of Conf.	$1.2 \cdot 10^6$	$2 - 4 \cdot 10^5$	$2 \cdot 10^4$

- High statistics data enable us to calculate cumulants up to $\mathrm{N}^3\mathrm{LO}$ in μ_B.
- New $N_t = 16$ data allows for continuum extrapolations of up to fourth order cumulant ratios.
- **All data on fluctuations in this presentation are HotQCD preliminary.**

Previous results: Baryon fluctuations



[Phys.Rev.D 101 (2020) 7, 074502] & [Nucl.Phys.A 1005 (2021) 121835]

UNIVERSITÄT BIELEFELD
Faculty of Physics

- R_{12}^Q dominated by leading order contribution $\sim \mu_B$.
- NLO contributions smaller by an order of magnitude.
- Mild temperature dependence.
- Ideal for extracting freeze-out chemical potential $\mu_{B,f} \Rightarrow$ "Baryometer"

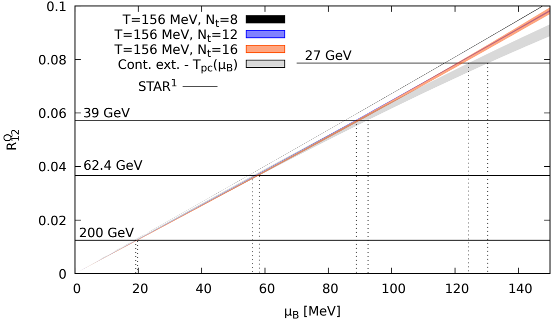


Figure: R_{12}^Q along T_{pc}.

[1] [PRL 113, 092301 (2014)]

Electric charge fluctuations - R_{31}^{Q}

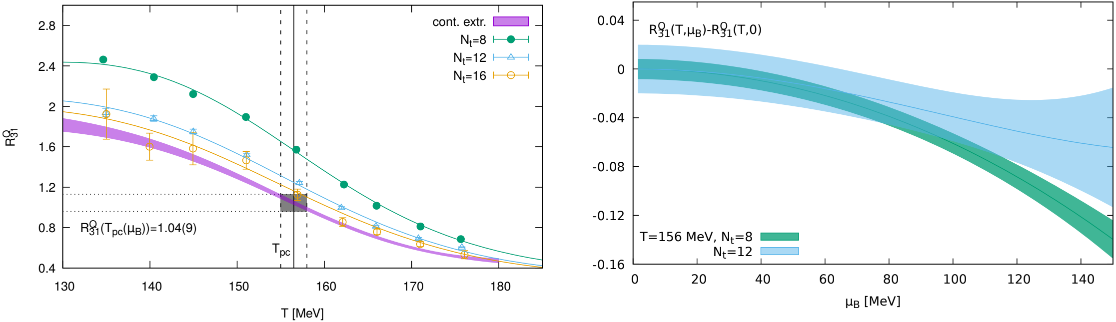
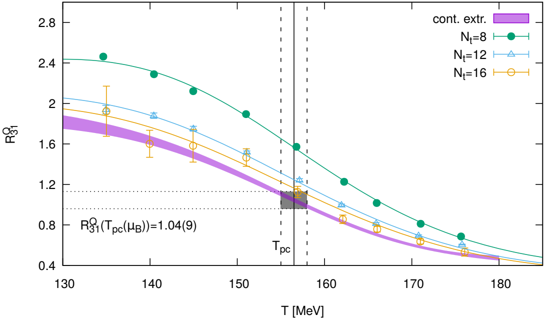


Figure: Left: R_{31}^{Q} at $\mu_B = 0$. Right: μ_B dependence around T_{pc}.

- Strong temperature dependence/ weak μ_B dependence $\Rightarrow$ "Thermometer"

Electric charge fluctuations - R_{31}^Q



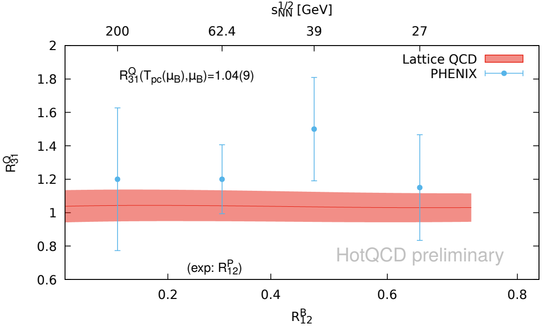


Figure: Continuum extrapolation of $R_{31}^Q(T_{\text{pc}}(\mu_B))$.

- Lattice QCD prediction: $R_{31}^Q(T_{\text{pc}}(\mu_B)) = 1.04(9)$.
- PHENIX[1] Measurements of R_{31}^Q consistent with freeze-out at T_{pc}.

[1] [Phys. Rev. C 93, 011901(R) (2016)]

Electric charge fluctuations - R_{42}^{Q}

UNIVERSITÄT BIELEFELD
Faculty of Physics

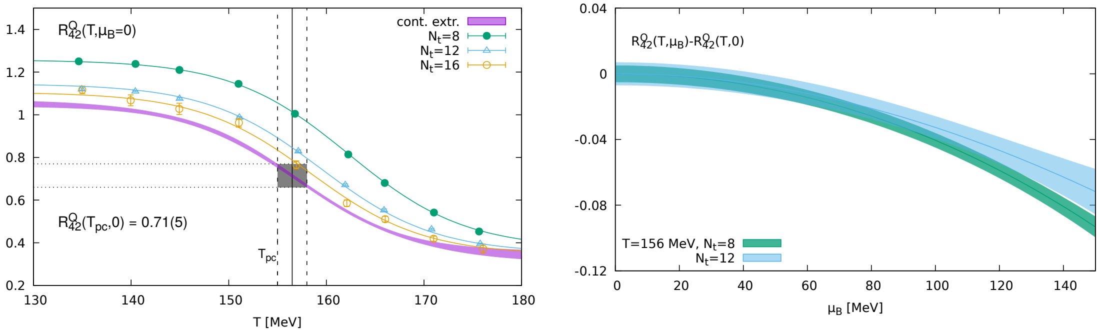
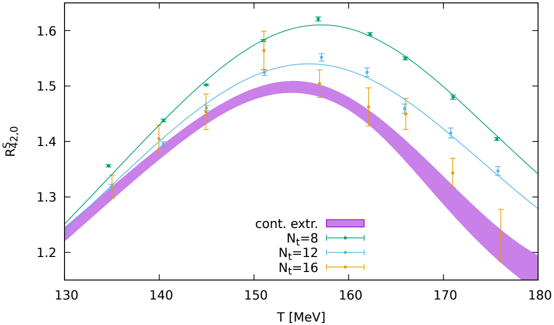


Figure: Left: R_{42}^{Q} at $\mu_B = 0$. Right: μ_B dependence around $T_{\rm pc}$.

- Significantly smaller errors compared to R_{31}^{Q} since noisy baryon correlations do not contribute to LO. LQCD Prediction: $R_{42}^{Q}(T_{pc}, 0) = 0.71(5)$.

UNIVERSITÄT BIELEFELD
Faculty of Physics



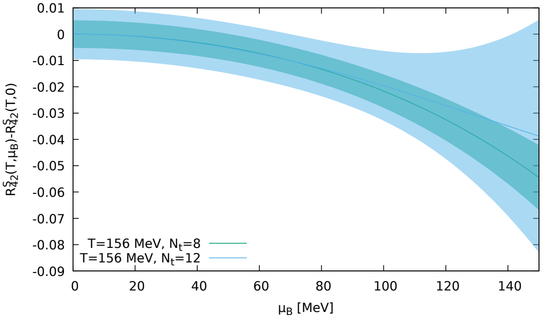


Figure: Left: R_{42}^S at $\mu_B = 0$. Right: μ_B dependence around $T_{\rm pc}$.

UNIVERSITÄT BIELEFELD
Faculty of Physics

- Constraint $n_S(\mu_B, \mu_S) \stackrel{!}{=} 0$ determines μ_S:

$$\frac{\mu_S}{\mu_B} = s_1(T) + s_3(T)\left(\frac{\mu_B}{T}\right)^2 + \mathcal{O}\left(\left(\frac{\mu_B}{T}\right)^4\right).$$

- $s_n(T)$: Consists of combinations of χ_{ijk}^{BQS} directly accessible in LQCD.
- Main contribution to $s_1(T)$ comes from $\frac{\chi_{11}^{BS}}{\chi_2^S}$.
- s_n with $n \geq 3$ almost negligible.
- QCD result on μ_S/μ_B sensitive to strangeness content (in a HRG model).

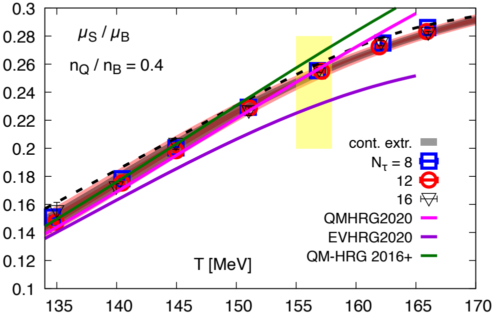


Figure: $s_1(T)$ from lattice QCD and HRG.

Strangeness fluctuations - $\mu_{S,f}$

UNIVERSITÄT BIELEFELD
Faculty of Physics

Lattice QCD:

- Constraint $n_S(\mu_B, \mu_S) \overset{!}{=} 0$ determines μ_S:

$$\frac{\mu_S}{\mu_B} = s_1(T) + s_3(T)\left(\frac{\mu_B}{T}\right)^2 + \mathcal{O}\left(\left(\frac{\mu_B}{T}\right)^4\right).$$

- $s_n(T)$: Consists of combinations of χ^{BQS}_{ijk} directly accessible in LQCD.
- Main contribution to $s_1(T)$ comes from $\frac{\chi^{BS}_{11}}{\chi^S_2}$.
- s_n with $n \geq 3$ almost negligible.
- QCD result on μ_S/μ_B sensitive to strangeness content (in a HRG model).

Heavy Ion Collisions:

- HRG relation for $\bar{B}$ to B yields can be used:

$$\frac{\bar{B}}{B}(\sqrt{s}) = \exp\left(-\frac{\mu_B}{T}(2 - 2|S|\frac{\mu_S}{\mu_B})\right)$$

- $\frac{\mu_S}{\mu_B}$ obtainable by fitting yields for different particle species in $|S|$.

Strangeness fluctuations

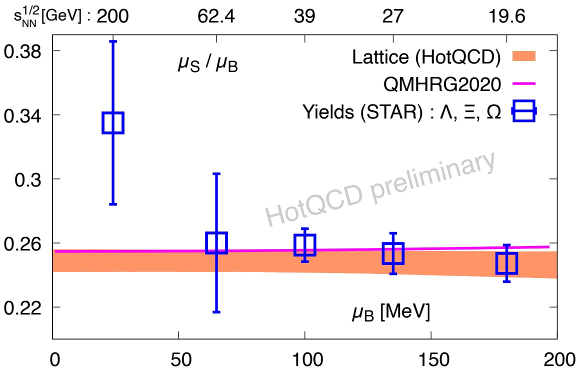
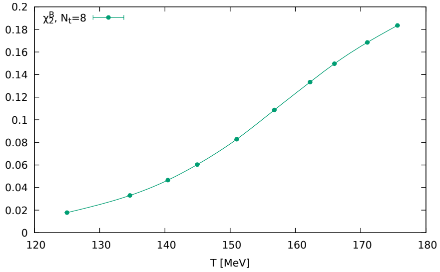


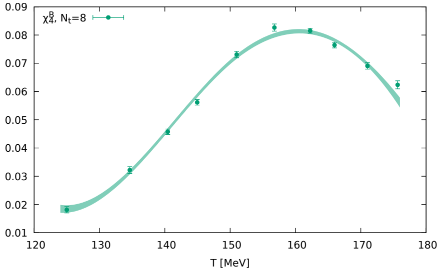
Figure: μ_S/μ_B along $T_{pc}(\mu_B)$ vs. μ_S/μ_B extracted from STAR[1]

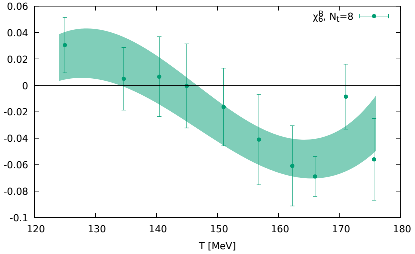
- $\mu_{S,f}/\mu_{B,f}$ from strange baryon yields is consistent with lattice QCD results at T_{pc}!

[1] arXiv:1010.0142 & arXiv:1906.03732

Outlook: new results at $T = 125$ MeV







- expectation: $T_{\text{cep}} < T_c = 132^{+3}_{-6}$ MeV but $T < 135$ MeV unexplored so far.
- New $N_t = 8$ calculations at $T = 125$ MeV.

Summary

- Precise computation of $R_{12}^{Q}(T_{pc}(\mu_B))$ to NNNLO in μ_B.
- Completed continuum extrapolations of R_{31}^{Q}, R_{42}^{Q}, and R_{42}^{S}. $\Rightarrow$ Full set of QCD predictions for M_X/σ_X^2, $S_X\sigma_X^3/M_X$, $\kappa_X\sigma_X^2$ for $X = B, Q, S$.
- μ_S/μ_B lattice QCD results are well described by QM-HRG
- Extraction of $\mu_{S,f}/\mu_{B,f}$ from experimentally measured strange baryon yields consistent with $\mu_S/\mu_B(T_{\mathrm{pc}}(\mu_B))$ from lattice QCD for $\sqrt{s}_{NN} \geq 62.4$ GeV.