QCD phase diagram physics opportunities at EIC

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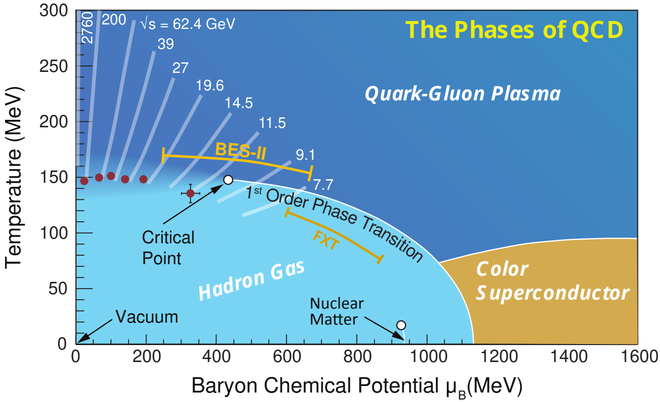
QCD phase diagram and RHIC

- What is the order of the finite T transition in QCD?
  (Pisarski-Wilczek 84')
  - Lattice: at $\mu_B = 0$ — crossover *(Aoki et al, Nature 06')*
- Does the order depend on μ_B? Critical point? At what μ_B? Can it be discovered in HIC experiments? *(MS-Rajagopal-Shuryak 98')*
- The desire to answer these questions has been a major motivation for BES at RHIC and a driving force behind new theory developments of RHIC era.
- These parallel developments of theory and experiment lay the groundwork for exploration of the QCD phase diagram at future facilities, such as EIC.

Phase diagram of QCD in RHIC era



- What is the nature of the QCD state at crossover?
  - Strongly-coupled perfect fluid
- Where on the QCD phase boundary is the critical point?
  - Not at $\mu_B \lesssim 400$ MeV

Theory in RHIC ERA: BEST Framework

The goal of BES theory: connect observables to QCD phase diagram.

BEST framework: An et al (40+ authors, 100+ pp, 369 refs) 2108.13867

BES theory review: Du, Sorensen, MS 2402.10183

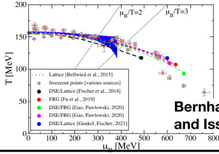
- Lattice EOS + CP $\rightarrow$ parametric EOS
- EOS $\rightarrow$ Hydrodynamics with (non-gaussian) fluctuations.
- Freezeout, including fluctuations. *review: 2403.03255, 2410.02861*
- Comparison with experiment. Bayesian analysis (AI/ML). Determine/constrain EOS, critical point parameters.

Locating QCD critical point

- CP location: estimates converging around $\mu_B \sim 400 - 650$ MeV.

  Caution: systematic errors poorly known.
  Sign problem is still a challenge.

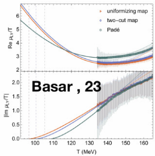
Latest theory developments on locating CP



FRG/ DSE

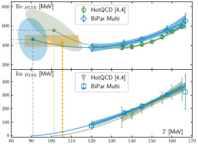
Bernhardt, Fischer and Isserstedt, 23

$$(\mu_{BC}, T_c) = (495 - 654, 108 - 119)\ \text{MeV}$$



Basar , 23

$$(\mu_{BC}, T_c) \approx (580, 100)\ \text{MeV}$$



Clarke et al., 24

$$(\mu_{BC}, T_c) = (422^{+80}_{-35}, 105^{+8}_{-18})\ \text{MeV}$$

Font Color

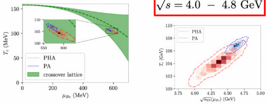
Bayesian Holography + Lattice input at $\mu = 0$

Hippert et al, e-Print: 2309.00579 [nucl-th]

Predict CEP (95% confidence level):

$T_c = 101 - 108$ MeV $\quad \mu_c = 560 - 625$ MeV

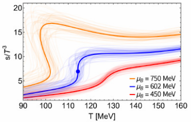
$\sqrt{s} = 4.0 \;-\; 4.8$ GeV



Extrapolations of Lee-Yang edge singularities to real axis

Thermodynamic analysis of a lattice QCD extrapolated EoS

Shah et al., 24



$$(\mu_{BC}, T_c) = (602.1 \pm 62.1\,,\, 114.3 \pm 6.9)$$

From Maneesha Pradeep's talk, CPOD 2024

Different approaches, but broadly similar results: $\mu_c \sim 420 - 650$ MeV.

All critical points are equal, but some a more equal ...

- While critical equation of state is universal, there are also important non-universal characteristics.
- Critical point is characterized not only by its position, but also by the strength and the shape of the singularity.
- BEST collaboration standardized the parameters quantifying these non-universal properties: w, ρ, α_1, α_2.
- Equation of state with given critical point parameters
  and matching lattice QCD data:
  Parotto et al 18', Karthein et al 22', Kahangirwe et al 24'

Quantifying theory predictions for fluctuations

- Translating fluctuations in hydrodynamics into fluctuations of particle multiplicites has been a major challenge.
- Solution developed in RHIC era: maximum entropy freezeout

  (Pradeep-MS 22')

  - Satisfies all conservation laws (baryon number, energy, etc.)
  - Maximizes fluctuation entropy of correlated hadron gas.
  - Model-independent, minimally biased prediction.

Quantifying theory predictions for fluctuations

- Quantifying effects on non-universal parameters on fluctuations using maximum entropy approach to freezeout *(Karthein et al 25')*
  - w controls magnitude (width of critical region);
  - ρ — location of signatures in μ_B (shape of the CR)
- Estimates for fluctuations from critical point parameters constrained to the region indicated by Padé approach *(Basar et al 26')*.

Hydrodynamics of fluctuations

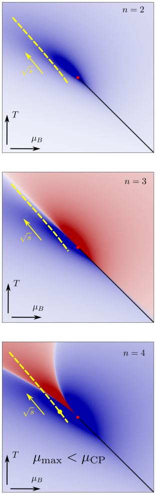
- The RHIC era ushered in major advances in **hydrodynamics.**
- The quest for quantifying non-equilibrium effects on fluctuations lead to development of hydrodynamics **with fluctuations.**
  - Two parallel and complementary approaches: stochasitic and deterministic (Hydro+).

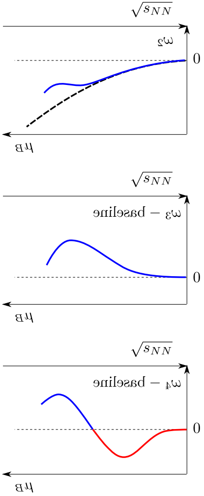
    (Akamatsu et al, MS-Yin, An et al, Martines et al, Chattopadhyay et al, . . .)
- In Hydro+, the evolution of fluctuation can be described with minimum of modeling, from EOS + transport coefficients only.
- Together with maximum entropy freezeout, this allows, in principle, translating experimental data into the quantitative knowldge of the fundamental properties of the QCD phase diagram in the least model biased manner.

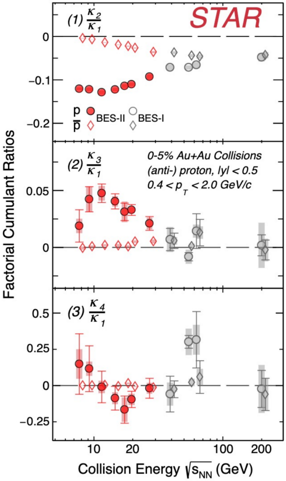
Theory vs BES-II data

(universal EOS) critical χ_n:

(irreducible correlations) $\mathrm{FC}_n[N_p] \sim \chi_n$ (Pradeep, MS 2211.09142), $\omega_n \equiv \mathrm{FC}_n/\mathrm{FC}_1$







Bzdak et al review 1906.00936

Expected signatures: bump in ω_2 and ω_3, dip then bump in ω_4 for CP at $\mu_B > 420$ MeV

Observations

- Significant deviations from monotonic baseline(s) in all FC.
- Qualitatively, consistent with expectations from CP.
- To produce such signatures the CP has to be at $\mu_B > 420$ MeV.
- In line with recent theory estimates by different approaches.

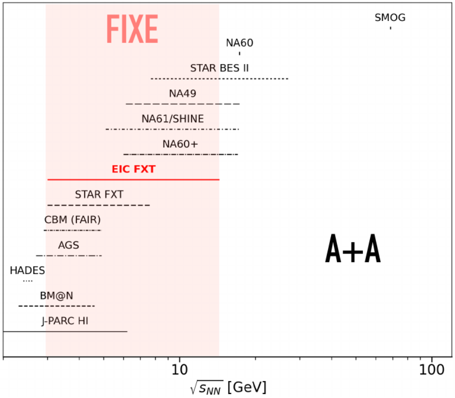
But

- Non-equilibrium effects – conservation laws, memory – are not yet fully taken into account and are important.
- Hydro at FXT energies is a challenge *(L. Du talk)*

Summary

- The RHIC era brought significant advances in our understanding of the QCD phase diagram physics.
- Theory advances include novel approaches to locating the critical point, major developments of relativistic hydrodynamics, in particular, with fluctuations, and maximum entropy freezeout.
- With RHIC BES data on hand, we learned that the critical point, if it exists, is at $\mu_B \gtrsim 400$ MeV.
- RHIC BES-II data shows interesting qualitative features (deviations from baseline) broadly in line with theoretical expectations for the CP at $\mu_B > 400$ MeV.

Outlook



Naim, CPOD2026

- Fixed Target @ EIC covers the interesting range of the QCD phase diagram:

  $\mu_B \sim 300 - 700$ MeV.

- Bridging the gap between the STAR BES-II collider and FXT mode

- With RHIC-era theory advances and knowledge gained from BES at RHIC, EIC has an opportunity to make a lasting mark on the QCD phase diagram.