An Augmented QCD Phase Portrait: Mapping Quark-Hadron Deconfinement for Hot, Dense, Rotating Matter under Magnetic Field

Overview: QCD, deconfinement, QGP, hadron gas

- **QCD matter** created in ultrarelativistic heavy-ion collisions at RHIC, LHC, FAIR, NICA, etc., may sustain extreme **vorticity** and **magnetic fields** for non-central collisions
- **Deconfinement temperature** (T_C) expected to be affected

Phase diagram to be augmented

- ***Hot*** $[T]$, ***Dense*** $[\mu_B]$
- ***Vorticity*** $[\omega]$, ***Magnetic field*** $[eB]$
- Magnetic field, $eB \sim 6m_\pi^2 \sim 0.12$ GeV^2
- Angular velocity, $\omega \sim 0.1$ fm^{-1} ~ 0.02 GeV

Statistical Hadronization or HRG model

- **Hadron resonance gas** (HRG) model framework
- Employed to decode phase structure (T vs. μ_B)
- HRG model modified below as an ideal gas of all hadrons and resonances in a cylindrical volume under parallel (along cylinder z-axis) $\vec{\omega}$ and $\vec{B}$

Augmenting || Rotation + Magnetic field

- Rotating ($\vec{\omega}$) fireball embedded in mag. field $\vec{B}$
- Landau quantization and causality bound: $1/\sqrt{|QB|} \ll R \leqslant 1/\omega$, R=system radius, Q=charge
- **Free energy density** for charged baryons and mesons is then (for a strong enough eB) given by

$$f_{i,c}^{b/m} = \mp \frac{T}{\pi R^2} \int \frac{dp_z}{2\pi} \sum_{n=0}^{\infty} \sum_{l=-n}^{N-n} \sum_{s_z=-s_i}^{s_i} \ln(1 \pm e^{-(\varepsilon_{i,c} - q_i \omega (l+s_z) - \mu_i)/T})$$

$$\varepsilon_{i,c} = \sqrt{p_z^2 + m_i^2 + |Q_i B|(2n - 2s_z + 1)}$$

- Corresponding expression for neutral baryons (b) and mesons (m) is, with only rotation acting,

$$f_{i,n}^{b/m} = \mp \frac{T}{8\pi^2} \int_{(\Lambda_l^{\mathrm{IR}})^2} dp_r^2 \int dp_z \sum_{l=-\infty}^{\infty} \sum_{\nu=l}^{l+2s_i} J_\nu^2(p_r r) \times \ln(1 \pm e^{-(\varepsilon_{i,n} - (l+s_i)\omega - \mu_i)/T}),$$

$$\varepsilon_n = \sqrt{p_z^2 + p_r^2 + m^2}$$

- **Entropy density**, $s = -\frac{\partial f}{\partial T}$, rises sharply with T, Hagedorn temperature invoked to estimate T_C
- A dip in the squared **speed of sound**, $c_s^2 = \frac{\partial p}{\partial \epsilon} = [\frac{\partial p}{\partial T}]/[\frac{\partial \epsilon}{\partial T}]$, also signals **deconfinement**
- s/T^3 and c_s^2 are used to deduce the **onset of deconfinement** and **map the QCD phases**
- Both methods yield consistent results

Augmented QCD Phase Diagram [T-μ_B-ω-eB]

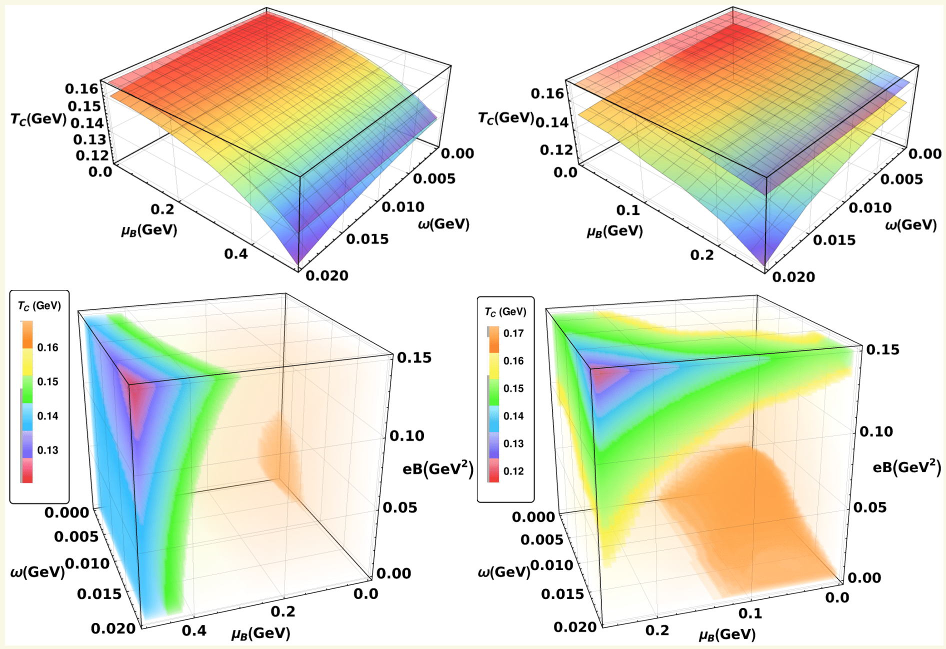

Figure: Top: [3-D plots] Deconfinement transition surfaces showing $T_C(\mu_B,\ \omega)$ for $eB = 0$ (upper surface) and $eB = 0.15$ GeV^2 (lower surface)
Bottom: [4-D plots] Fully augmented phase space showing $T_C(\mu_B,\ \omega,\ eB)$
Left plots obtained from $s/T^3 = 5.5$; Right plots obtained from the minima of c_s^2

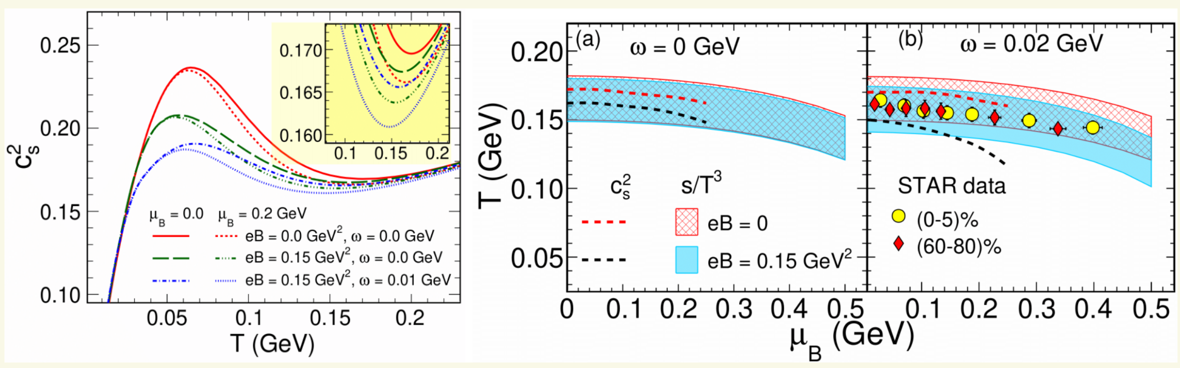

Figure: Left: c_s^2 vs. T, mimima magnified in the inset. Right: 2-D phase diagrams, T vs. μ_B for $eB = 0$ (red) and $eB = 0.15$ GeV^2 (blue) and (a) for $\omega = 0$ GeV and (b) for $\omega = 0.02$ GeV. The bands are constrained by $s/T^3 = 4$ (lower edge) and 7 (upper edge) , and the dashed curves are obtained from the minima of c_s^2 vs. T

References: Fujimoto etal, Phys.Lett.B 816(2021)136184; Chen etal, Phys.Rev.D 93(10)(2016)104052; Liu etal, Phys.Rev.Lett. 120(3)(2018)032001; Chen etal, Phys.Rev.D 96(5)(2017)054032; **This work:** arXiv:2304.12643 (comm.)

Conclusions and Outlook

- T_C strongly **lowered**, drop most pronounced when all 3 quasi-control (via beam energy/centrality) parameters are simultaneously tuned to finite values typically achievable in present/upcoming colliders like RHIC, LHC, FAIR, etc.
- Results may be interpreted as thermo, baryo, anemo, magneto- meter (Reparametrization of freeze-out with ω, eB)
- Further refinements to simulate fireball more realistically: finite size effects, inhomogeneity, anisotropy, shape, etc.

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