

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** [μ_B]
- **Vorticity** [ω], **Magnetic field** [eB]
- Magnetic field, $eB \sim 6m_\pi^2 \sim 0.12 \text{ GeV}^2$
- Angular velocity, $\omega \sim 0.1 \text{ fm}^{-1} \sim 0.02 \text{ GeV}$

Statistical Hadronization or HRG model

- Framework of statistical hadronization or **hadron resonance model** (HRG) model
- 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

- Fast spinning fireball embedded in external magnetic fields, idealized by our model, obeys
- Landau quantization and causality bound: $1/\sqrt{|QB|} \ll R \leq 1/\omega$, 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,

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

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

- **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**, $c_s^2 = \frac{\partial p}{\partial \varepsilon} = \frac{[\partial p]}{[\partial \varepsilon]}$, 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]

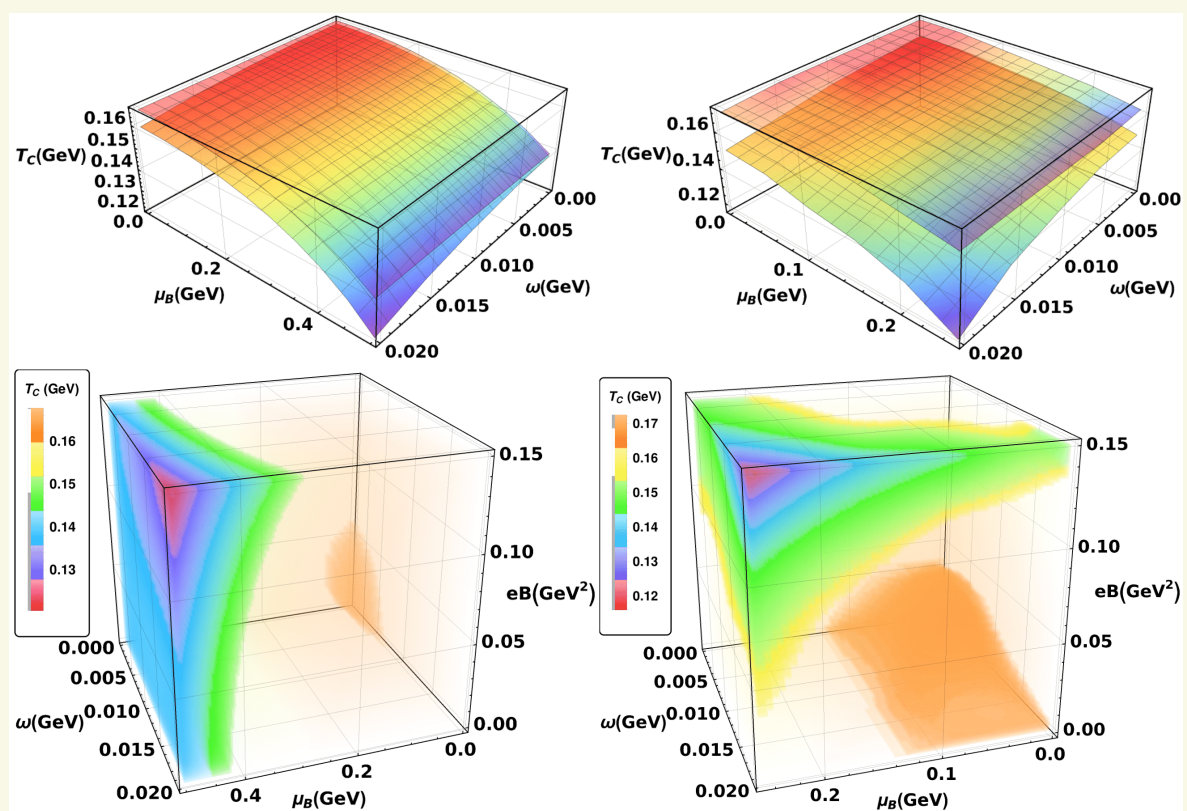


Figure: Top: [3-D plots] Deconfinement transition surfaces showing $T_C(\mu_B, \omega)$ for $eB = 0$ (upper surface) and $eB = 0.15 \text{ GeV}^2$ (lower surface). Bottom: [4-D plots] Fully augmented phase space showing $T_C(\mu_B, \omega, eB)$ as a color-coded density plot with T_C -calibrated legend. Left plots are obtained from $s/T^3 = 5.5$. Right plots are obtained from the minima of c_s^2 . Results may be interpreted as thermo, baryo, anemo, magneto- meter tool.

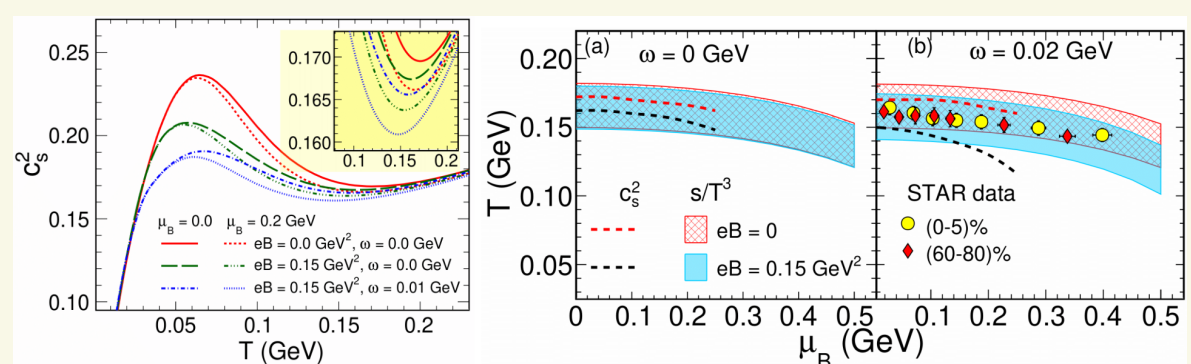


Figure: Left: c_s^2 vs. T , minima magnified in the inset. Right: 2-D phase diagrams, T vs. μ_B for $eB = 0$ (red) and $eB = 0.15 \text{ GeV}^2$ (blue) and (a) for $\omega = 0 \text{ GeV}$ and (b) for $\omega = 0.02 \text{ GeV}$. The bands are constrained by $s/T^3 = 4$ (lower edge) and 7 (upper edge),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

Conclusion

- 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.

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