Studying liquid-gas phase transition under the effect of rotation in a hadron resonance gas

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Kshitish Kumar Pradhan

Kshitish.kumar.Pradhan@cern.ch

Collaborators: Bhagyarathi Sahoo, Dushmanta Sahu & Raghunath Sahoo

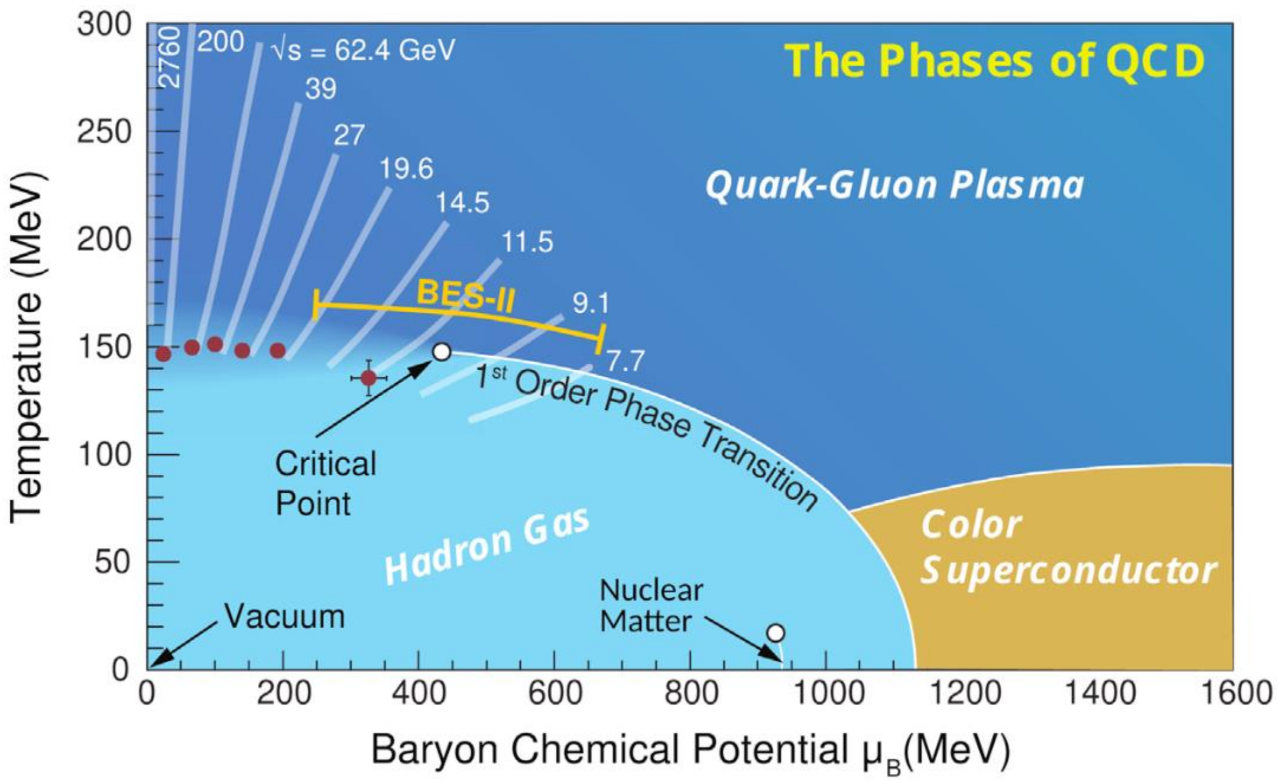
Indian Institute of Technology Indore, India

Outline

- Introduction
- Interacting Hadron resonance gas (HRG) model
- Effect of rotation
- Results
- Summary

Quark Gluon Plasma & Hadron Gas

- Quantum Chromodynamics is the theory of strong interaction between quarks mediated by gluons
- Two basic properties of strong interaction:
  - Color confinement
  - Asymptotic freedom
- LQCD calculations indicate a smooth cross-over transition from hadronic to a QGP phase at vanishing baryon chemical potential (μ_B) and finite temperature (T)
- A first-order phase transition line at high μ_B and low T ends at the critical point



A. Andronic, Int. J. Mod. Phys. A **29**, 1430047 (2014)

Magnetic field and rotation in heavy-ion collision

- The non-central heavy-ion collision leads to production of strong transient magnetic field due to the motion of spectator protons

$eB \sim m_\pi^2$, $B \sim 10^{18}$ Gauss

$B \sim 0.6$ Gauss

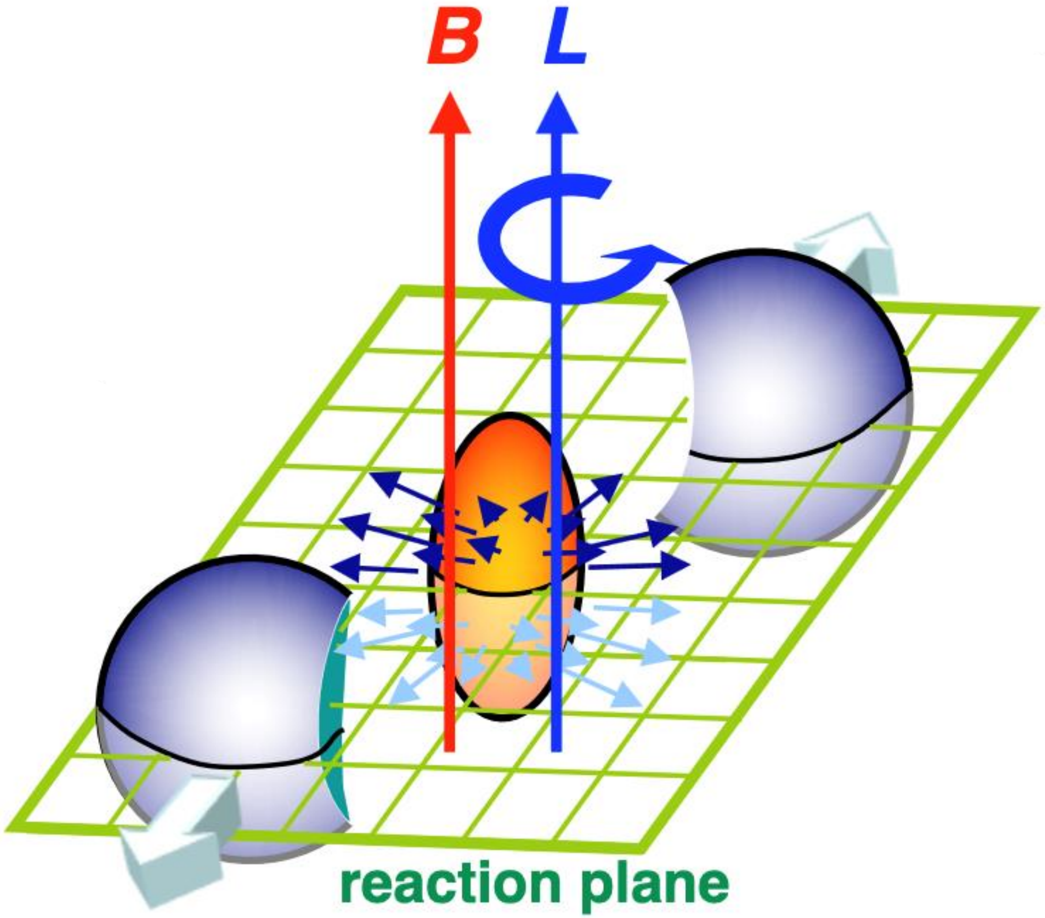
$B \sim 100$ Gauss

- The peripheral heavy-ion collision also have a large initial orbital angular momentum L, can be written as

$\mathbf{L} = \mathbf{r} \times \mathbf{p}$ $\mathbf{L} \sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$

This leads to an angular velocity of $\omega \sim 10^{21} s^{-1}$

- The magnitude of magnetic field and rotation decays with the expansion of the medium



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McLerran and Skokov, Nucl. Phys. A **929**, 184 (2014)
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T. Niida, NA61/SHINE Open Seminar 2021

Hadron Resonance Gas (HRG) Model

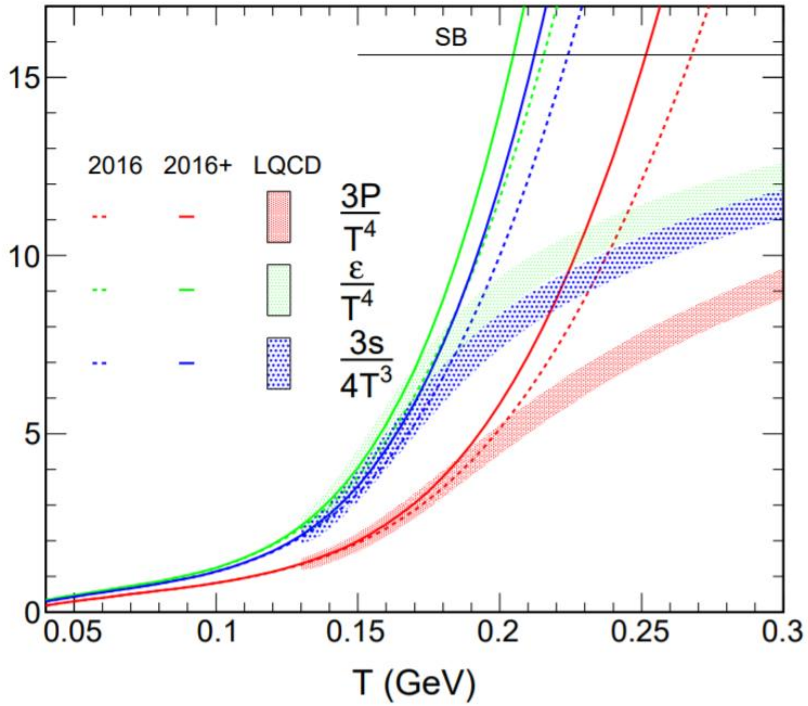
- The ideal HRG model is a non-interacting, multi-component gas of known hadrons and resonances
- HRG model is very successful in describing physical observables from relativistic heavy-ion collisions at RHIC and LHC energies

$$\ln Z_i^{id} = \pm \frac{V g_i}{2\pi^2} \int_0^\infty p^2\, dp \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$$p^{id} = \sum_i (\pm) \frac{g_i T}{2\pi^2} \int_0^\infty p^2\, dp \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$$\varepsilon^{id} = \sum_i \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2\, dp}{\exp[(E_i - \mu_i)/T] \pm 1} E_i$$

$$n^{id} = \sum_i \frac{g_i}{2\pi^2} \int_o^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T \pm 1}$$



S. Samanta et al, J. Phys. G **46** 065106 (2019)

- Successful in reproducing zero chemical potential lQCD data at low-temperature, T < 150 MeV.
- Disagreement between lQCD data and HRG model at high temperature.

Van der Waals HRG Model

- Interaction with both attractive and repulsive parts has been introduced in the HRG model
- Based on the following assumptions:
  - VDW interactions are assumed to exist between all pairs of baryons and between all pairs of antibaryons
  - The baryon-antibaryon, meson-meson, and meson-(anti)baryon VDW interactions are neglected
- The equation of state with both repulsive (b > 0) & attractive (a > 0) terms as suggested by van der Waals is :

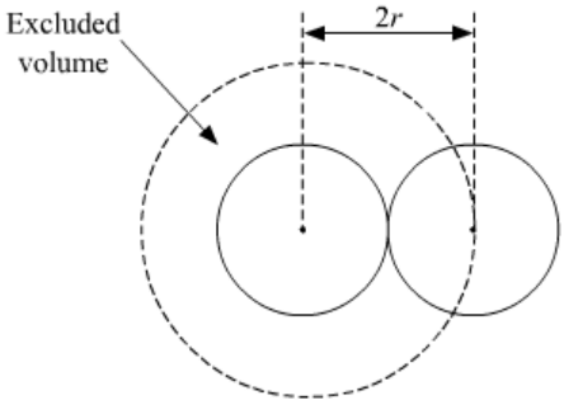
$$P(V,T,N) = \frac{NT}{V-bN} - a\frac{N^2}{V^2}$$

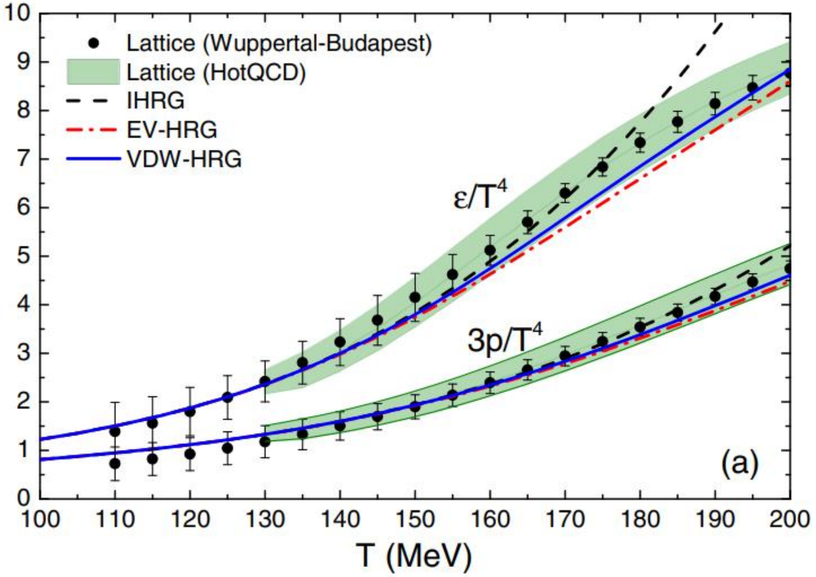
$$p(T,\mu) = p^{id}(T,\mu^*) - an^2$$

$$n \equiv n(T,\mu) \equiv \left(\frac{\partial p}{\partial \mu}\right)_T = \frac{n^{id}(T,\mu^*)}{1+bn^{id}(T,\mu^*)}$$

$$\mu^* = \mu - bp(T,\mu) - abn^2 + 2an$$

$$= \mu - b\frac{n(T,\mu)T}{1-bn(T,\mu)} + 2an$$





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Effect of Rotation on Hadron gas

- The fundamental Euler's thermodynamic equation gets modified in presence of finite rotation adding a new Rotational Chemical Potential

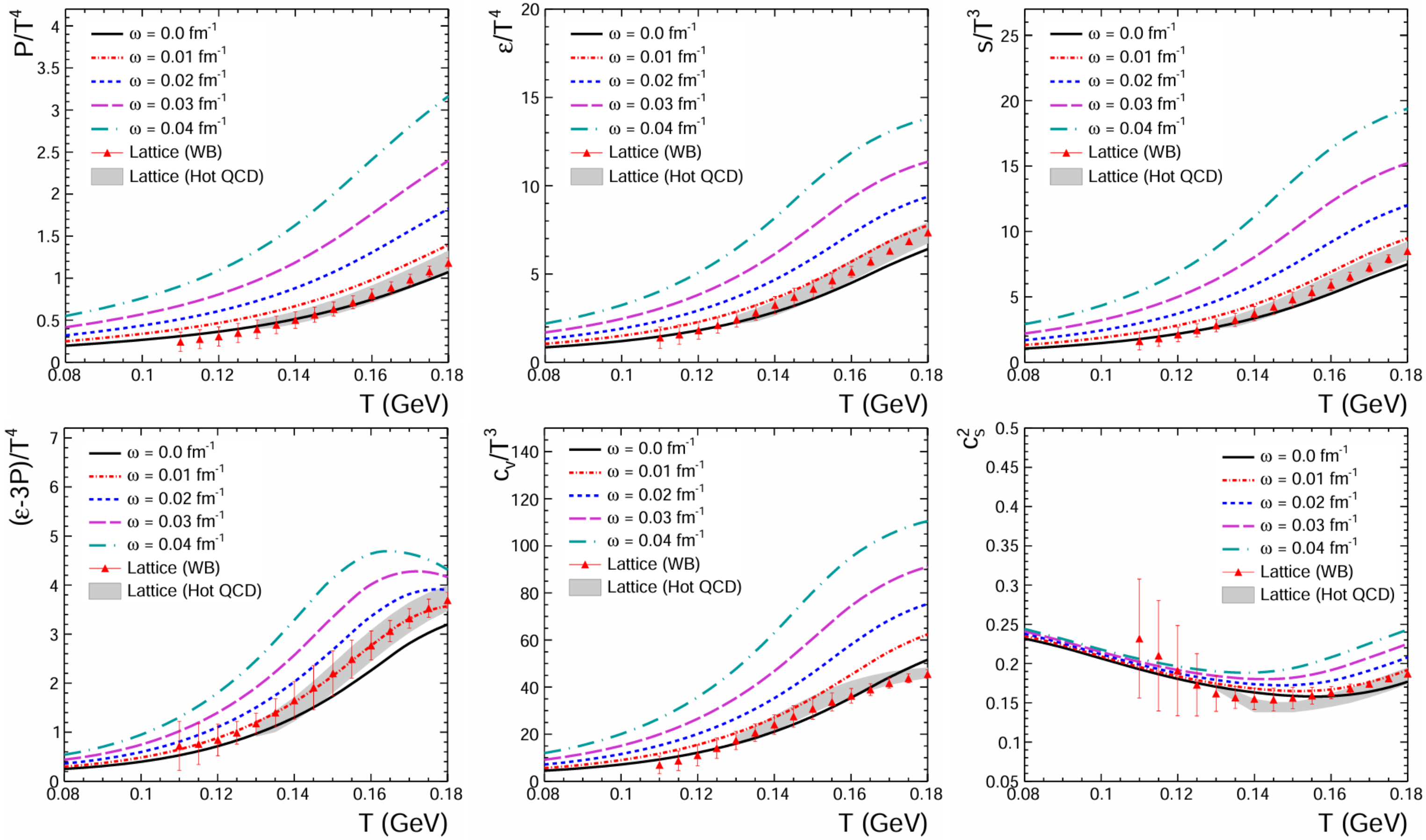
$$\varepsilon + P = sT + n\mu + W\omega$$

- The pressure for the rotational grand canonical ensemble is obtained as

$$P_i^{id}(T,\mu_i,\omega) = \frac{g_i}{2\pi^2}\int p^2 dp \frac{p^2}{3E_i}\frac{e^{\frac{p.v}{T}}}{\exp\left[\frac{E_i-\mu_i}{T}\right]\pm 1}\chi\left(\frac{\omega}{T}\right)$$

Where $\chi\left(\frac{\omega}{T}\right) = \frac{\sinh\left(S+\frac{1}{2}\right)\frac{\omega}{T}}{\sinh\left(\frac{\omega}{2T}\right)}$

- Every thermodynamic quantities increases with increase in magnitude of rotation
- The effect of ω on thermodynamic variables is similar to that of baryochemical potential μ_B

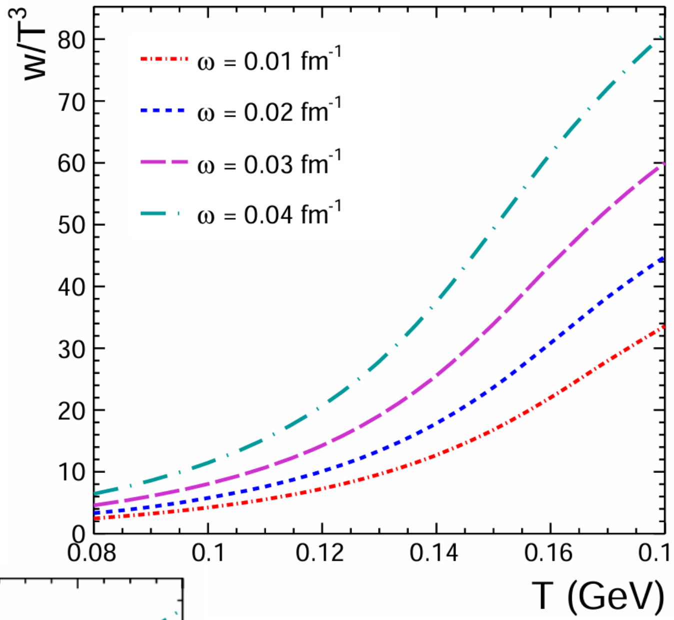


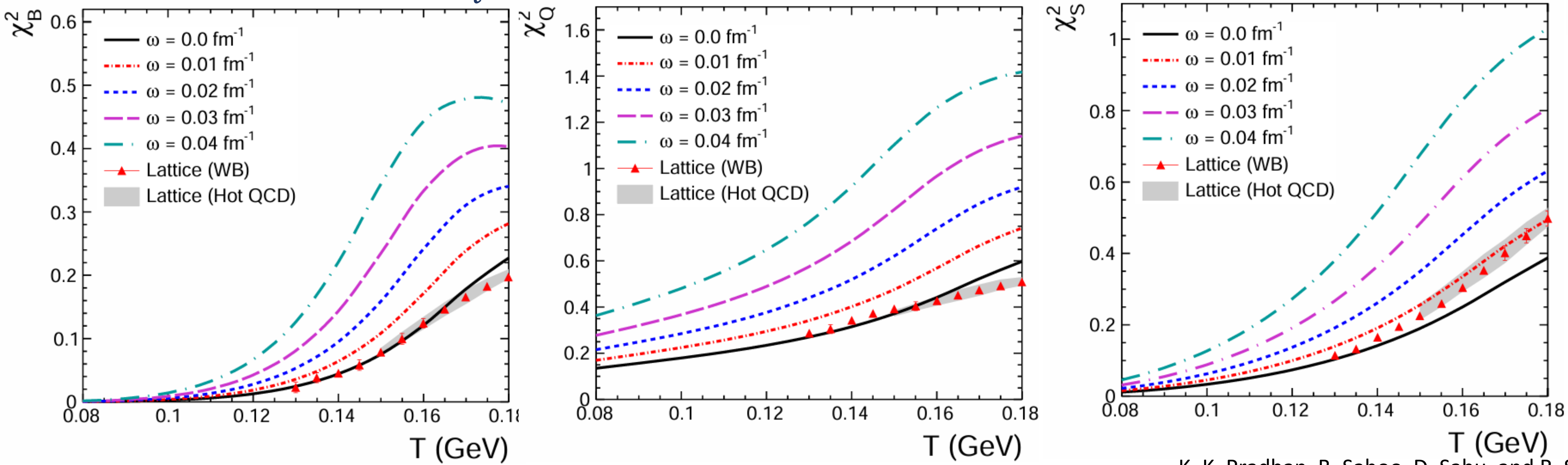
K. K. Pradhan, B. Sahoo, D. Sahu, and R. Sahoo, Eur. Phys. J. C 84, 936 (2024)

Effect of Rotation on Hadron gas

- Similar to number density, spin density is defined as the change in pressure with rotational chemical potential $W = \frac{\partial P}{\partial \omega}$
- W increases slowly with temperature but increases rapidly with ω
- The susceptibilities of conserved varies with ω in a similar manner as it used to vary with μ_B

$$\chi_i^2 = \frac{\partial^2 P}{\partial \mu_i^2}|_\omega$$





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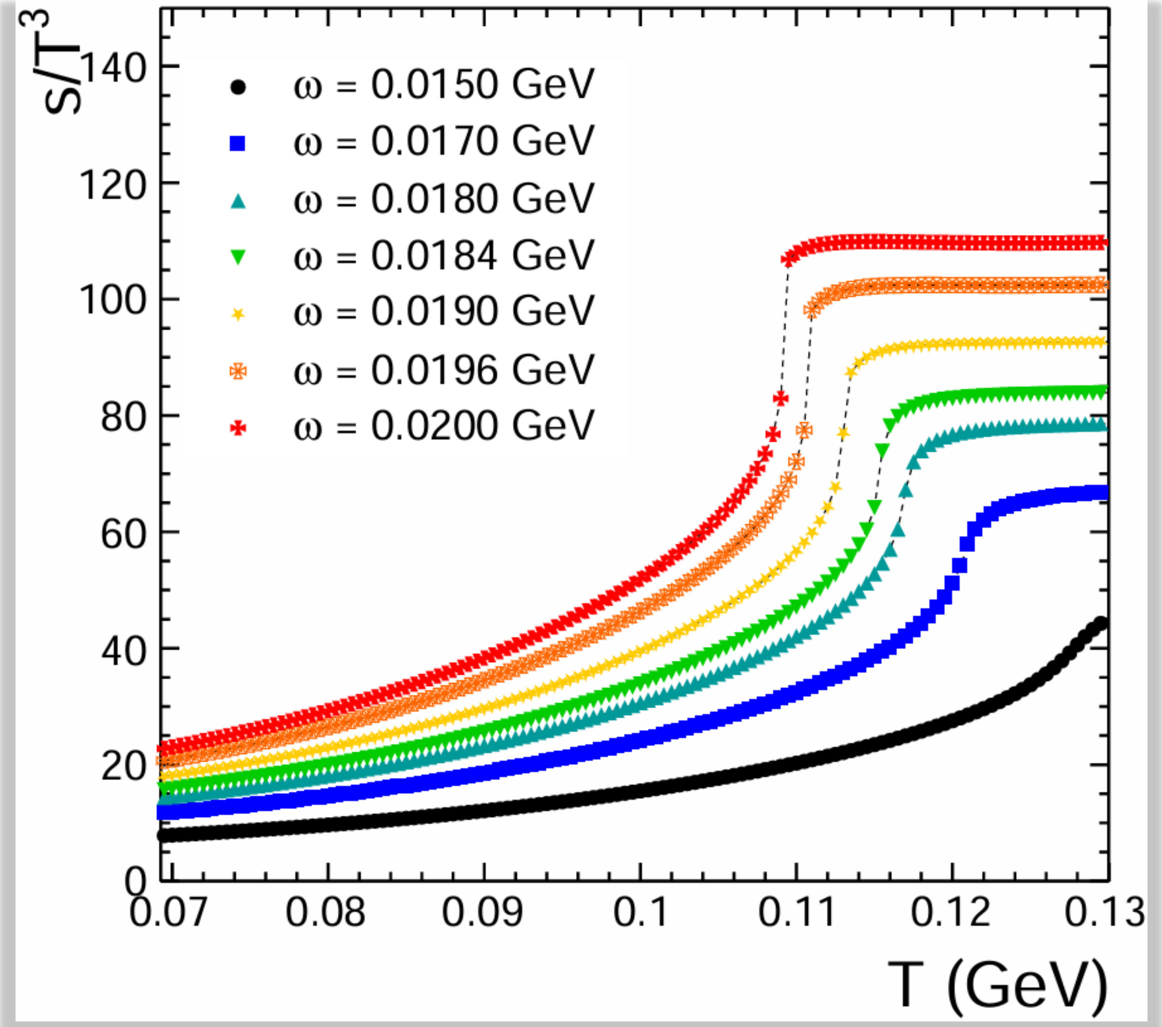
Effect of Rotation on Hadron gas

- The addition of an extra chemical potential affects the liquid-gas critical point
- Similar to magnetic field, the rotation also alters the position of the critical point
- The begin of the discontinuity in the curve of s/T^3 shows the liquid gas critical point

$\omega = 0.0\ GeV$	$\mu_B = 0.0\ GeV$
$T_c = 0.065\ GeV$ $\mu_{B_c} = 0.716\ GeV$	$T_c = 0.113\ GeV$ $\omega_c = 0.019\ GeV$

- Therefore, the rotation helps the gas to liquefy earlier than the baryochemical potential



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Summary

- The effect of rotation on the thermodynamic properties of hadron gas is studied
- It is observed that the rotation has a similar effect on the thermodynamic properties as the baryochemical potential
- The rotation in a system also leads to the liquid-gas phase transition even at zero baryochemical potential
- These results allows us to reinvestigate at the QCD matter properties under the effect of rotation and study the phase diagram in the $\boldsymbol{T - \mu_B - \omega}$ plane

K. K. Pradhan, B. Sahoo, D. Sahu, and R. Sahoo, Eur. Phys. J. C 84, 936 (2024)

THANK YOU