

The phase transitions in a rotating hadron resonance gas

Based on:

Eur. Phys. J. C 84, 936 (2024) and arxiv:2507.03708 (2025)



Kshitish Kumar Pradhan

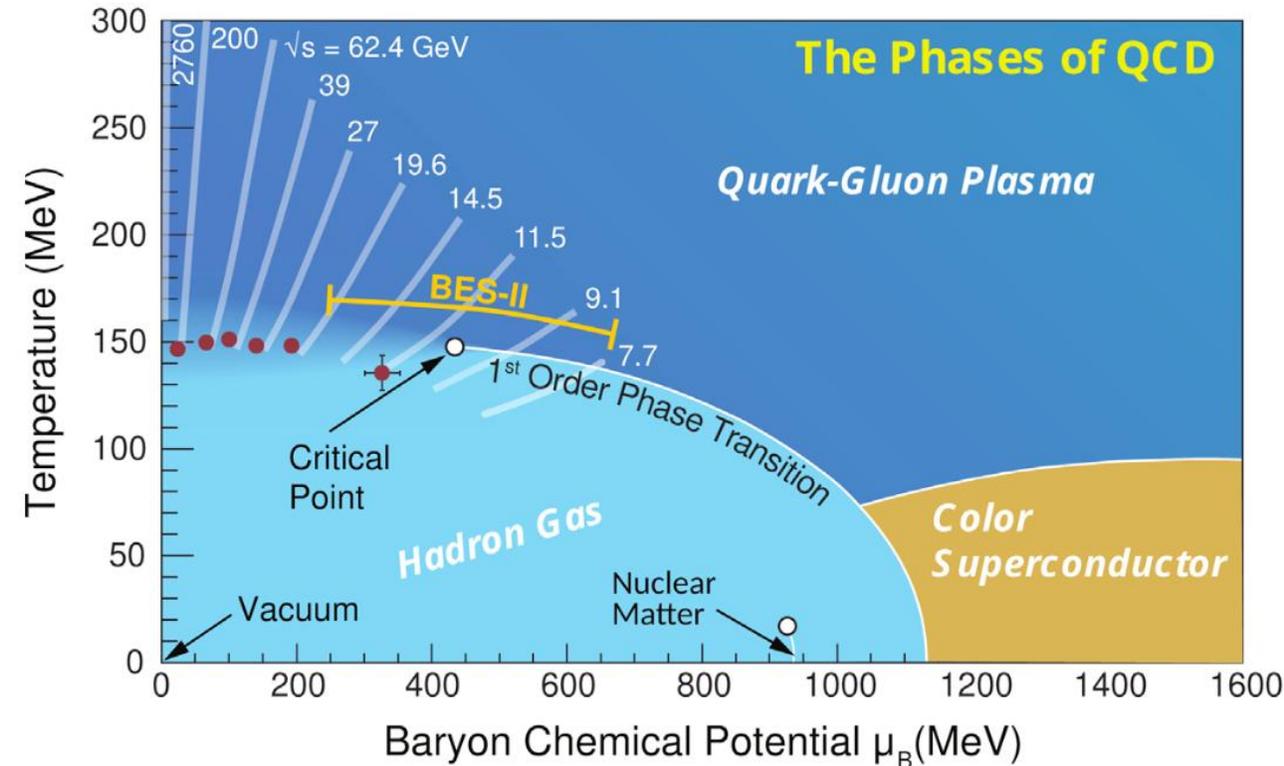
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- Introduction
- Interacting Hadron resonance gas (HRG) model
- Effect of rotation
- Results
- Summary

- 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)

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

$$eB \sim m_\pi^2,$$

$$B \sim 10^{18} \text{ Gauss}$$



$B \sim 0.6 \text{ Gauss}$



$B \sim 100 \text{ Gauss}$

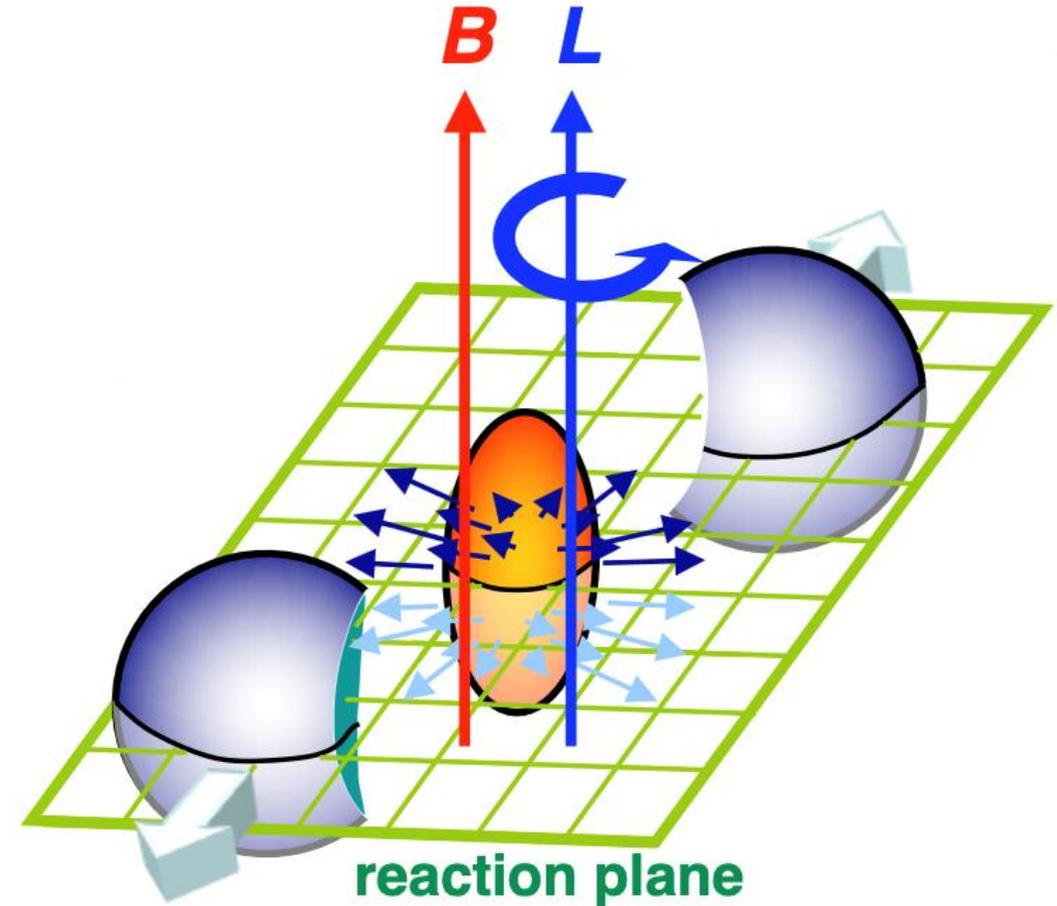
- The peripheral heavy-ion collision also have a large initial orbital angular momentum L , can be written as

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

$$L \sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

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

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



D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A **803**, 227 (2008)
 McLerran and Skokov, Nucl. Phys. A **929**, 184 (2014)
 Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. **94**, 102301 (2005),
 T. Niida, NA61/SHINE Open Seminar 2021

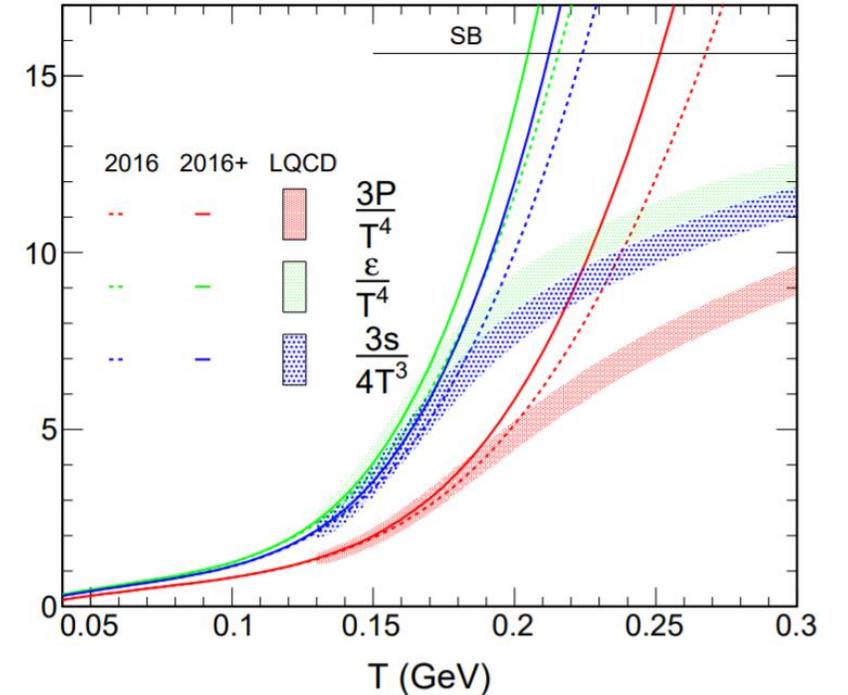
- The ideal HRG model is a non-interacting, multi-component gas of known hadrons and resonances
- HRG model is very successful in describing physical observables from relativistic heavy-ion collisions at RHIC and LHC energies

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

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

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

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



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

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

- 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 :

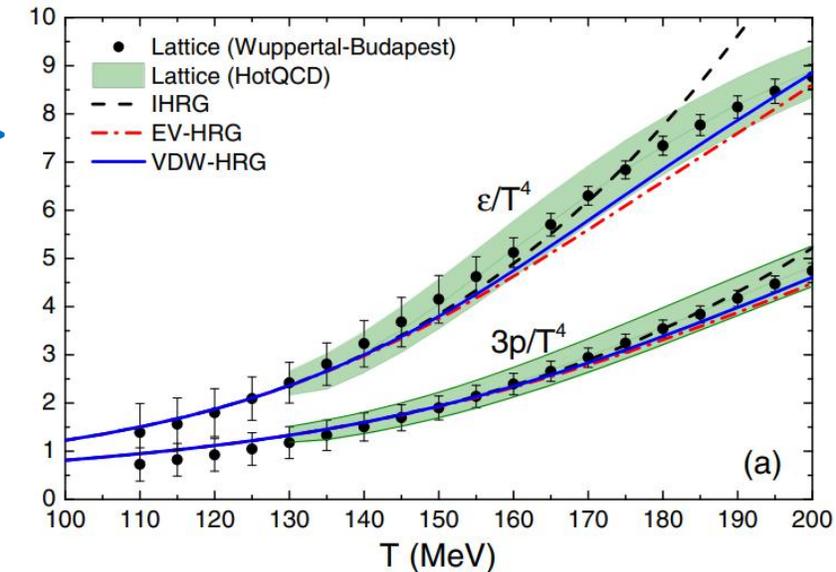
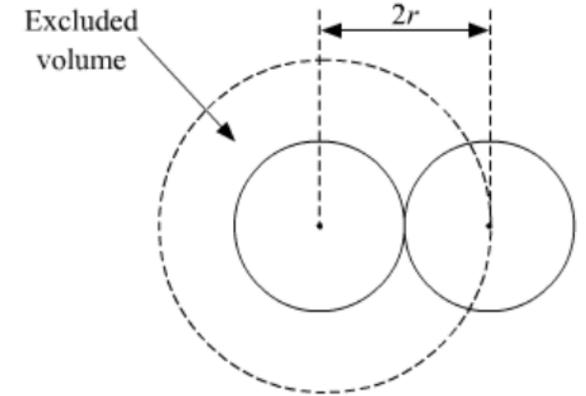
$$P(V, T, N) = \frac{NT}{V - bN} - a \frac{N^2}{V^2}$$

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

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

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

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



Volodymyr Vovchenko, Phys. Rev. Lett. **118**, 182301

Effect of Rotation on Hadron gas

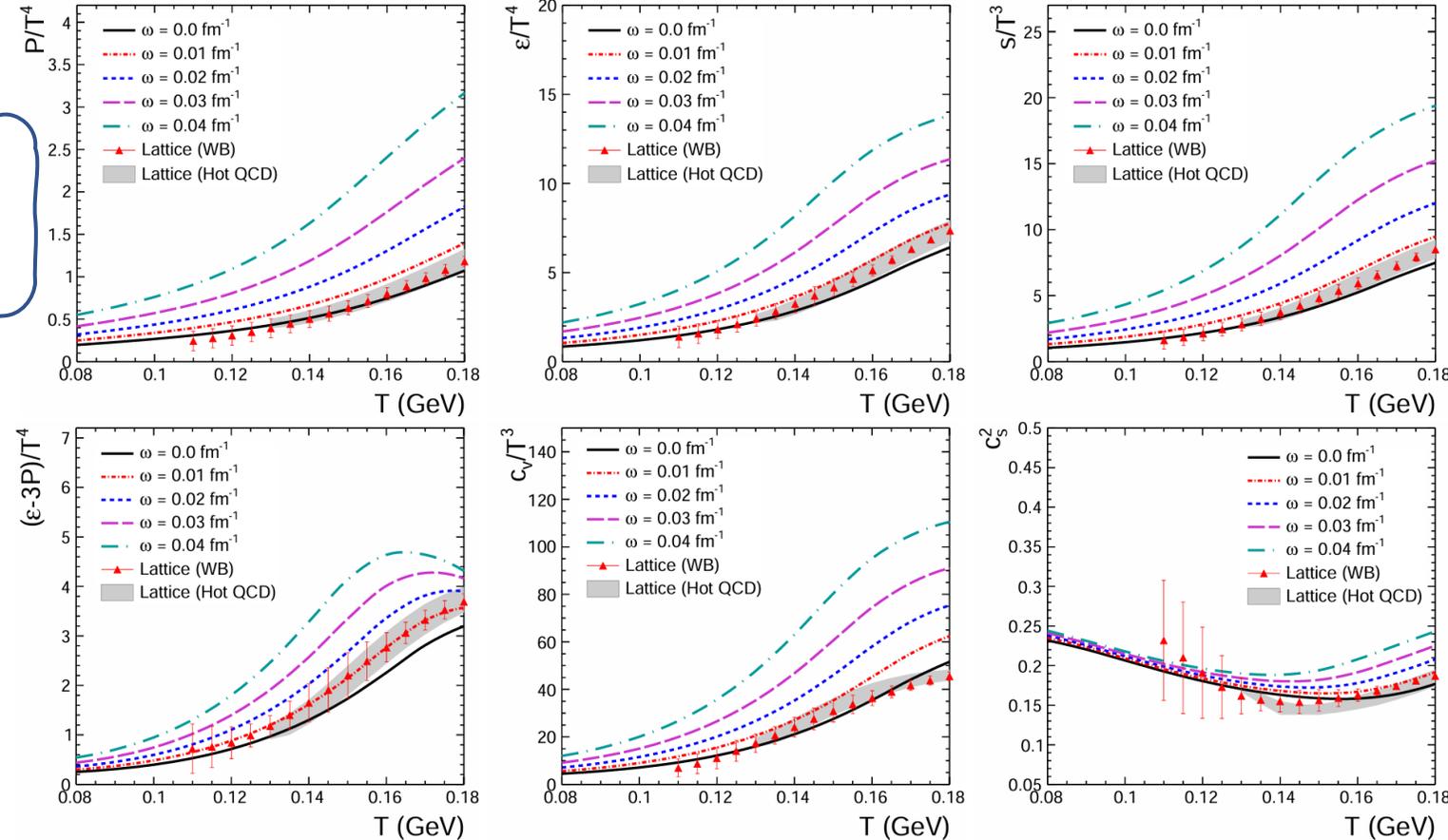
- The fundamental Euler's thermodynamic equation gets modified in presence of finite rotation adding a new Rotational Chemical Potential
- The pressure for the rotational grand canonical ensemble is obtained as

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

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

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

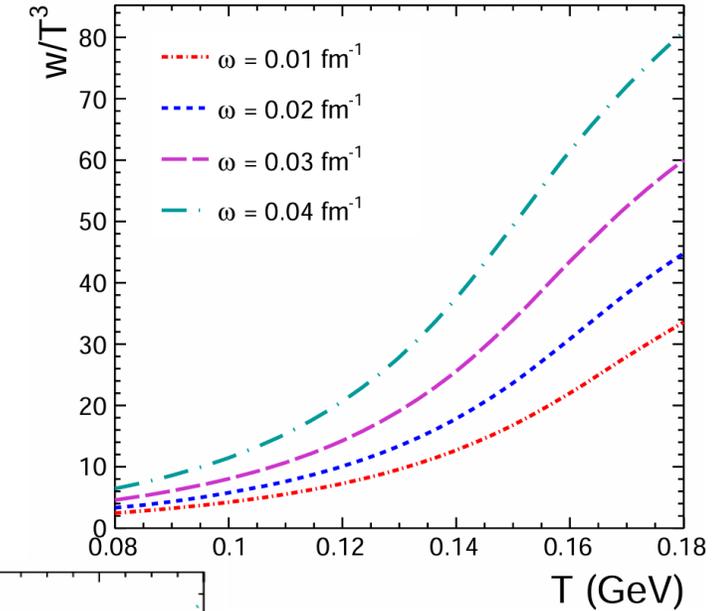
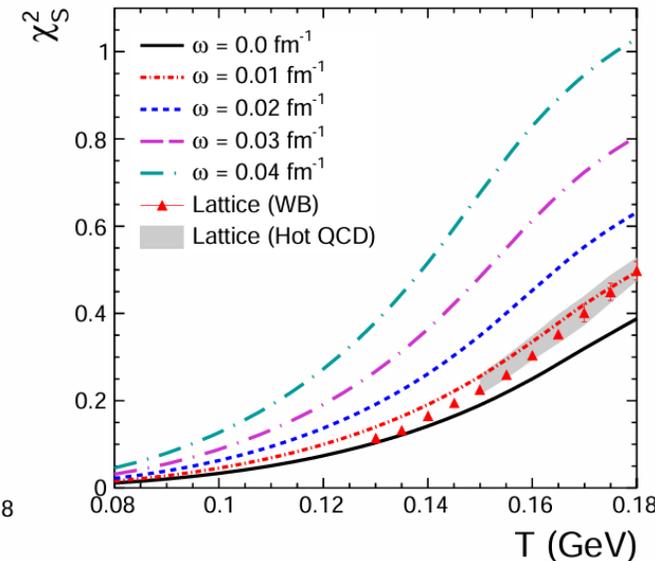
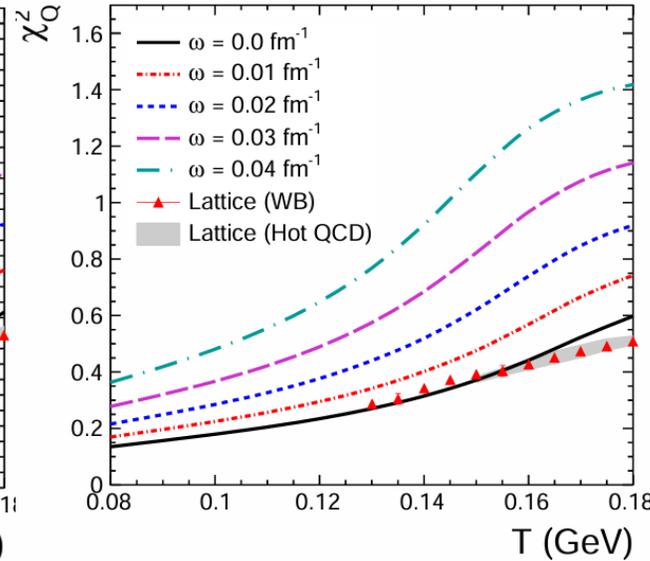
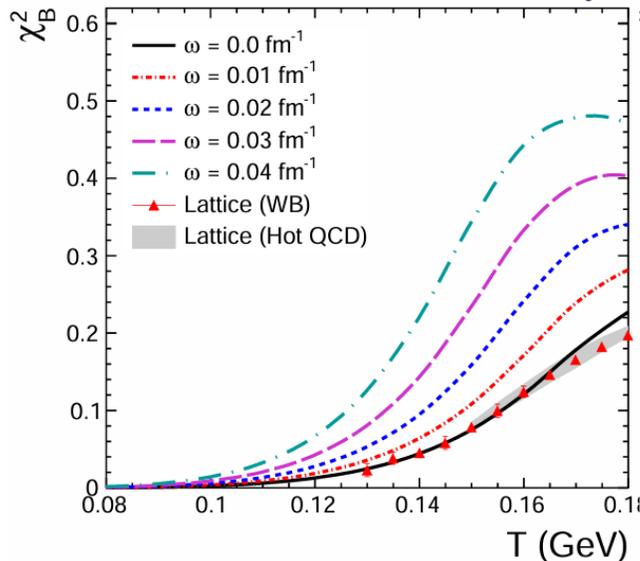


K. K. Pradhan, B. Sahoo, D. Sahu, and R. Sahoo, Eur. Phys. J. C 84, 936 (2024)

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 charges varies with ω in a similar manner as it used to vary with μ_B

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

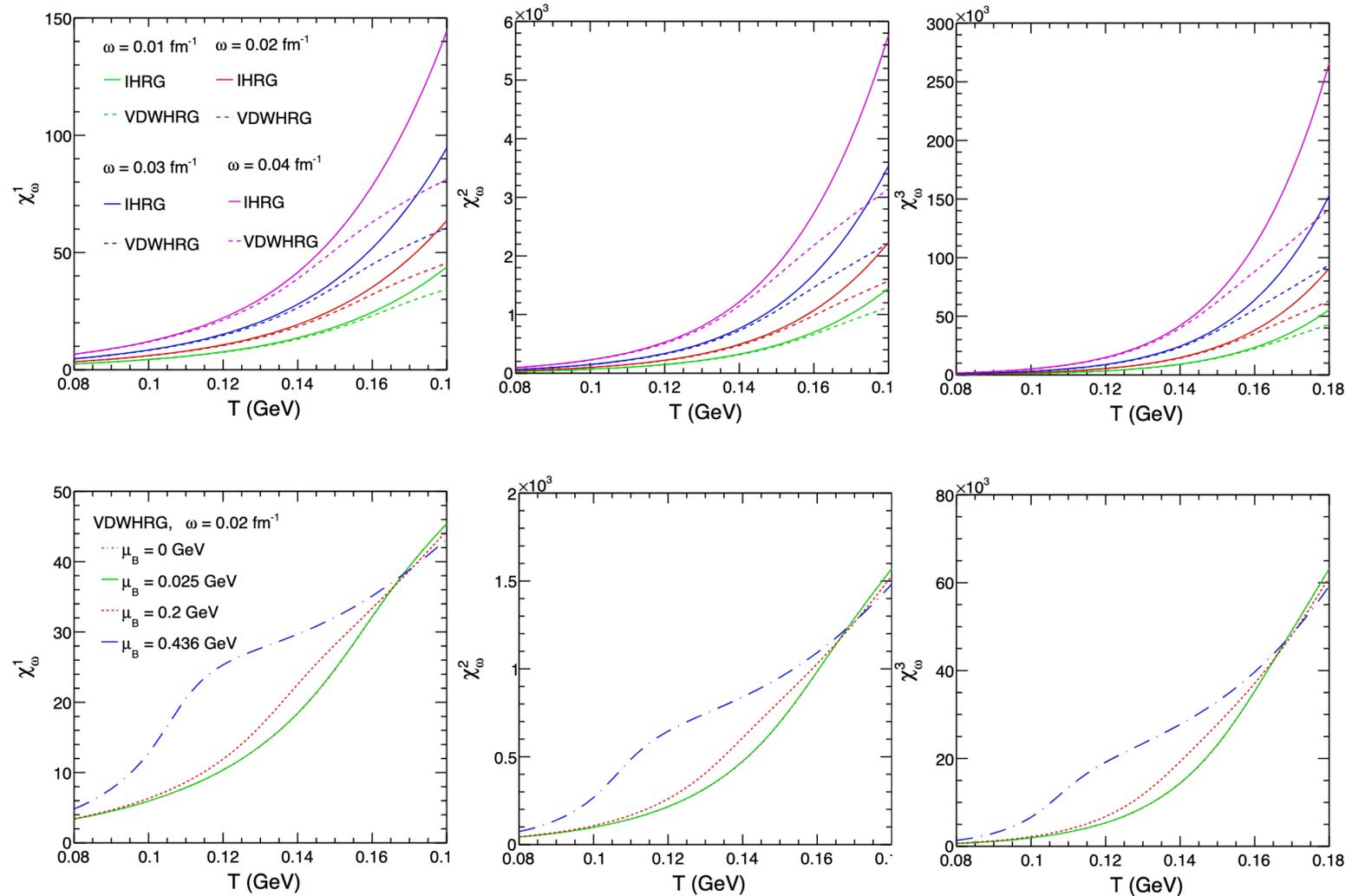


K. K. Pradhan, B. Sahoo, D. Sahu, and R. Sahoo, Eur. Phys. J. C 84, 936 (2024)

- Rotational susceptibility is defined as

$$\chi_i^n = \left. \frac{\partial^n P}{\partial \omega^n} \right|_{\mu_B}$$

- It reflects the system's intrinsic tendency to respond to weak external fields through thermodynamic fluctuations

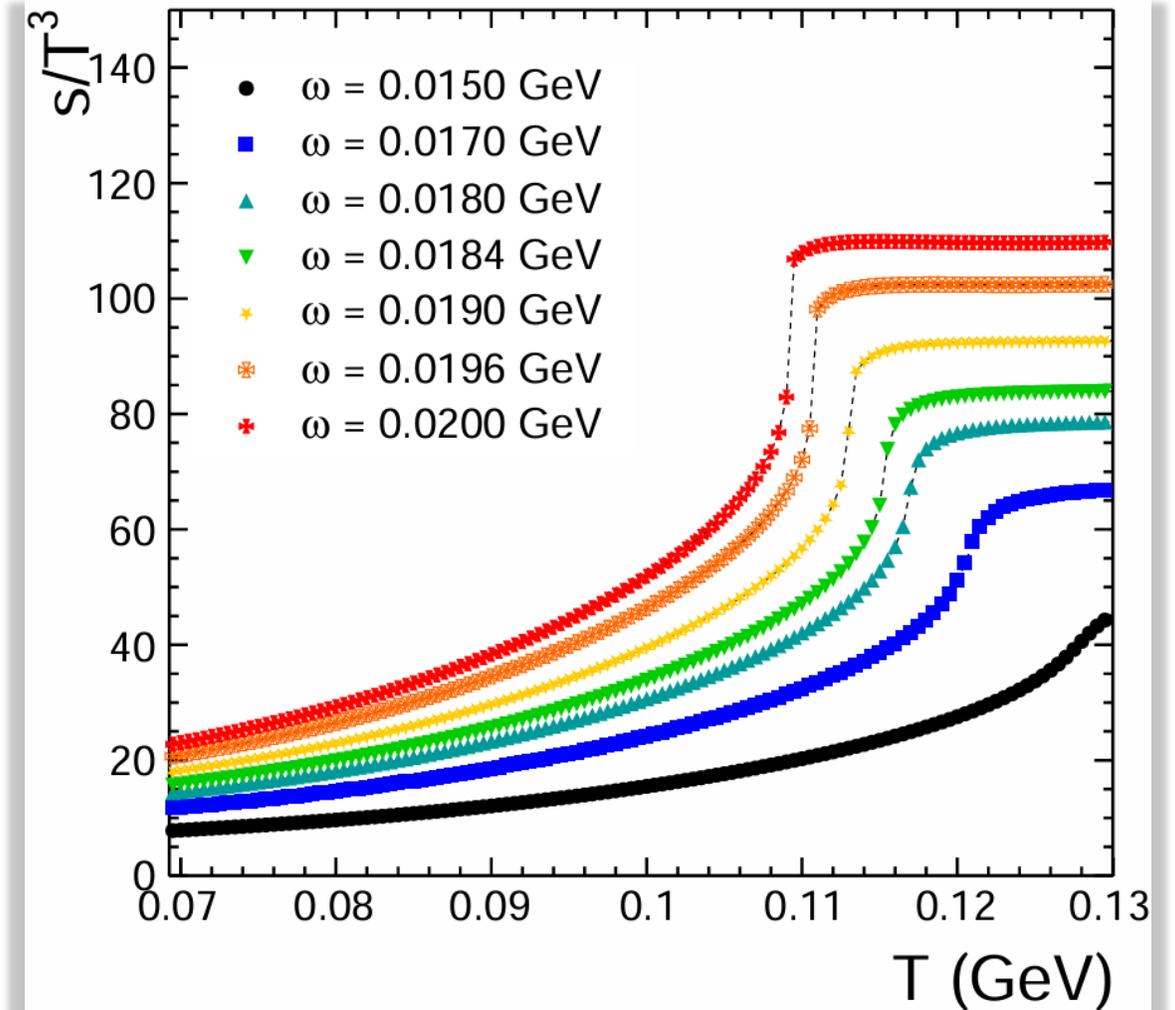


B. Sahoo, K. K. Pradhan, D. Sahu, and R. Sahoo, arxiv: 2507.03708 (2025)

- 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

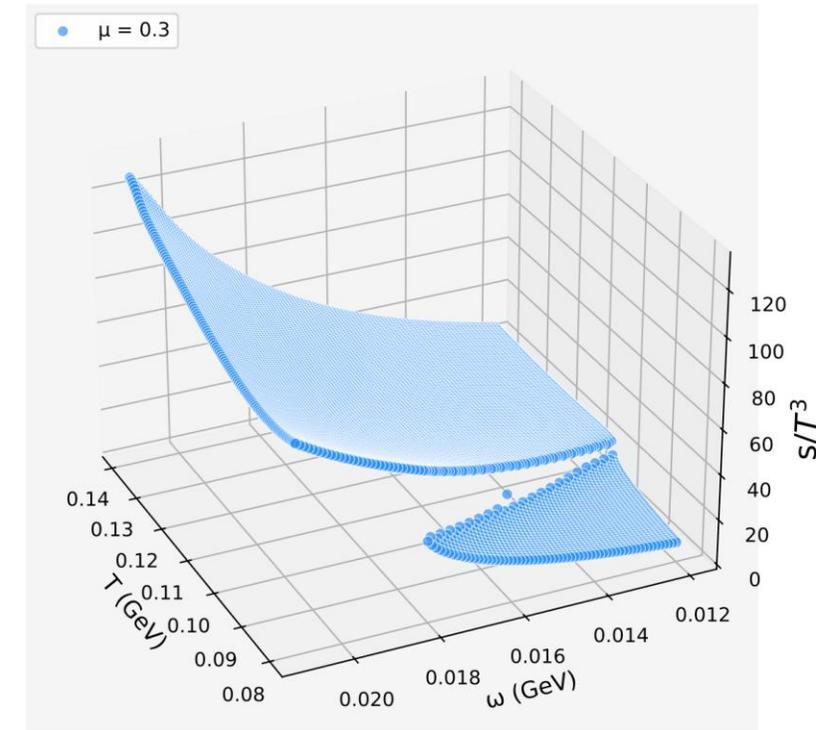
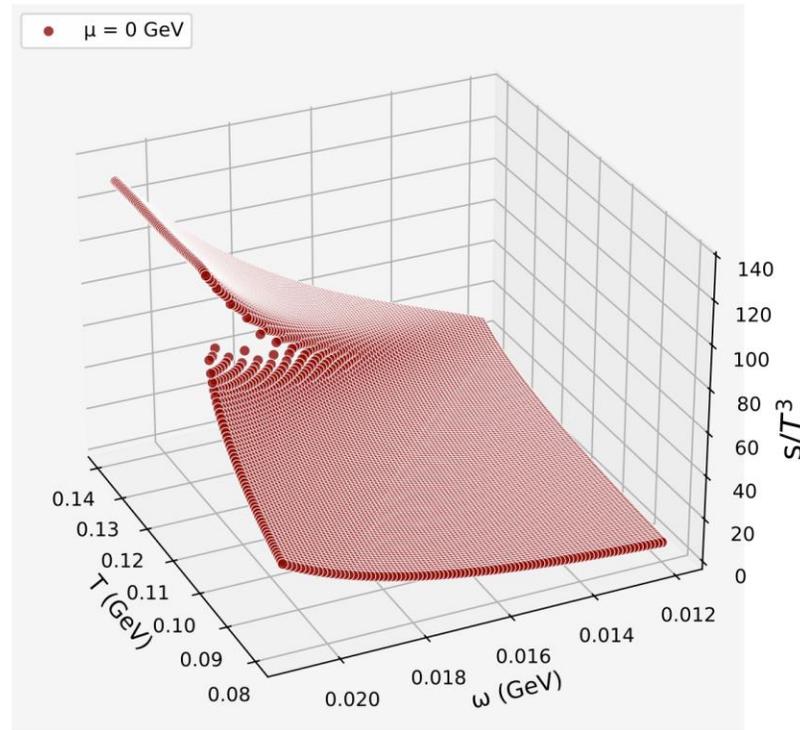
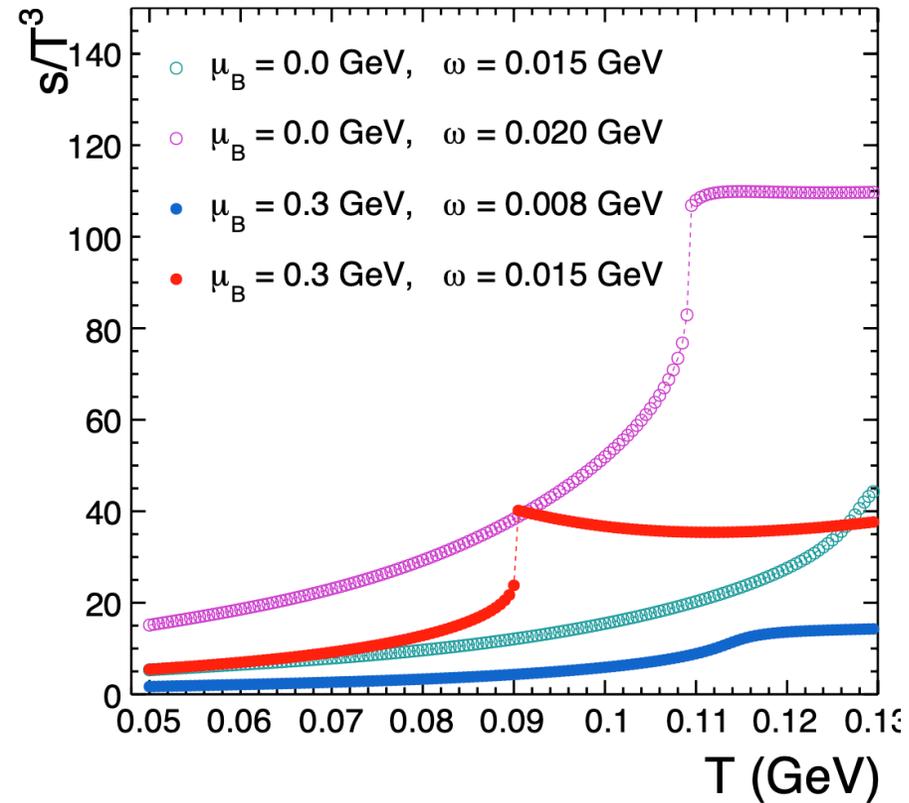
$\omega = 0.0 \text{ GeV}$	$\mu_B = 0.0 \text{ GeV}$
$T_c = 0.065 \text{ GeV}$	$T_c = 0.113 \text{ GeV}$
$\mu_{B_c} = 0.716 \text{ GeV}$	$\omega_c = 0.019 \text{ GeV}$

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



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

- At finite baryochemical potential the phase transition occurs at even low ω and T



K. K. Pradhan, B. Sahoo, D. Sahu, and R. Sahoo, J. Subatomic Part. Cosmol. 4, 100134 (2025)

- 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 **$T - \mu_B - \omega$** plane

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

B. Sahoo , K. K. Pradhan, D. Sahu, and R. Sahoo, arxiv: 2507.03708 (2025)

THANK YOU