

Magnetic properties of Hadron Resonance Gas with physical magnetic moment



NATIONAL SCIENCE CENTRE POLAND

Rupam Samanta

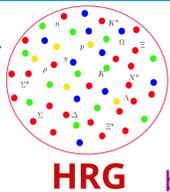
Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Krakow, Poland

2025 XQCD

Based on arXiv: 2505.14484, RS and Wojciech Broniowski

HRG in magnetic field

Lattice QCD : first principle calculation of QCD under extreme condition (in uniform stationary \mathcal{B})

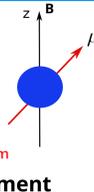


HRG: system of stable and resonance hadrons (Heavy-ion collision below $T_c \sim 155$ MeV)

Charged particle in a uniform magnetic field

$$E = M + \frac{p_z^2}{2M} + \frac{\mathcal{B}|Q|}{2M}(2l+1) - \mu \mathcal{B}$$

Non-relativistic energy l : Landau levels μ : magnetic moment



Relativistic energy $\kappa = 0$

$$E = \sqrt{M^2 + p_z^2 + 2\mathcal{B}|Q| \left(l + \frac{1}{2} - s_z \right)}$$

Susceptibility $\chi_{Q_1 Q_2} = \frac{\partial^2 (P/T^4)}{\partial(\mu_{Q_1}/T) \partial(\mu_{Q_2}/T)} \Big|_T$

Conserved charges $Q_1, Q_2 \equiv \{B, S, Q\}$

$$\chi_{Q_1 Q_2}^{ch} = \frac{Q_1 Q_2 \mathcal{B} |Q|}{2\pi^2 T^3} \sum_{l=0}^{\infty} \sum_{s_z=-s}^s \int_0^{\infty} dp_z f(1-\eta f)$$

charged particles $\chi_{Q_1 Q_2}^{neu} = \frac{Q_1 Q_2}{2\pi^2 T^3} \sum_{s_z=-s}^s \int_0^{\infty} p^2 dp f(1-\eta f)$
neutral particles

Our Goal :
1. To check HRG with lattice data for $\mathcal{B} > 0$
2. To explore the effect of anomalous magnetic moment (κ) of hadrons

$$P = -\eta T(2s+1) \int \frac{d^3 p}{(2\pi)^3} \log[1 - \eta f(E, T, \mu)]$$

Partial pressure

$$f(E, T, \mu) = \frac{1}{\exp(\frac{E-\mu}{T}) + \eta}$$

Distribution function

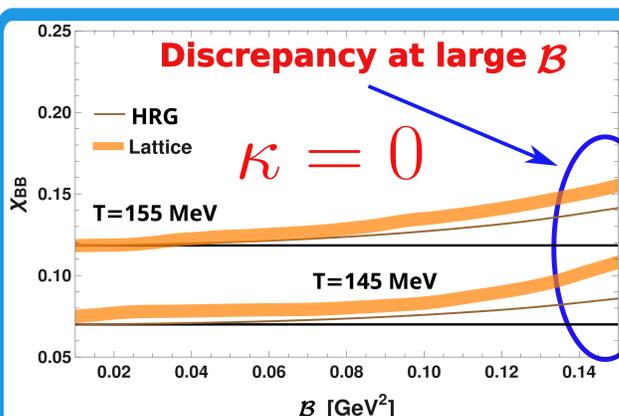
$$\mu = \mu_B B + \mu_S S + \mu_Q Q$$

Chemical potential

$\eta = \pm 1$ (Bosons or fermions)

$$(2s+1) \int \frac{d^3 p}{(2\pi)^3} \rightarrow \frac{\mathcal{B}|Q|}{2\pi^2} \sum_{l, s_z} \int_0^{\infty} dp_z$$

In the presence of a magnetic field



Hadrons have internal structures : non-zero anomalous magnetic moment

$$\chi_{BB} \sim a + b [g^2 s(s+1) - Q^2] \mathcal{B}^2$$

$$g = \frac{\mu_{exp} M}{s \mu_N m_p}$$

$\mu_{exp}^p = 2.793 \mu_N$ $g^p = 5.586$
 $\mu_{exp}^n = -1.913 \mu_N$ $g^n = -3.831$
 $\mu_{exp}^{\Sigma^+} = 2.458 \mu_N$ $g^{\Sigma^+} = 6.232$

$$g = 2Q + 2\kappa$$

Model : Need for κ

Spin-0 ($\mu = 0$)

$$E_{ch} = \sqrt{M^2 + p_z^2 + \mathcal{B}|Q|(2l+1)}$$

$$E_{neu} = \sqrt{M^2 + p^2}$$

Spin-1 and 3/2 [Good approximation]

$$E_{ch} = \sqrt{M^2 + p_z^2 + \mathcal{B}|Q|(2l+1) - 2Q\mathcal{B}s_z - \mu_M \mathcal{B} 2\kappa s_z}$$

$$E_{neu} = \sqrt{M^2 + p^2 - \mu_M \mathcal{B} 2\kappa s_z}$$

Spin-1/2 [Exact, Tsai-Yildiz]

$$E_{ch} = \sqrt{\left(\sqrt{M^2 + \mathcal{B}|Q|(2l+1) - 2Q\mathcal{B}s_z} - \mu_M \mathcal{B} 2\kappa s_z \right)^2 + p_z^2}$$

$$E_{neu} = \sqrt{\left(\sqrt{M^2 + p^2 - p_z^2} - \mu_M \mathcal{B} 2\kappa s_z \right)^2 + p_z^2}$$

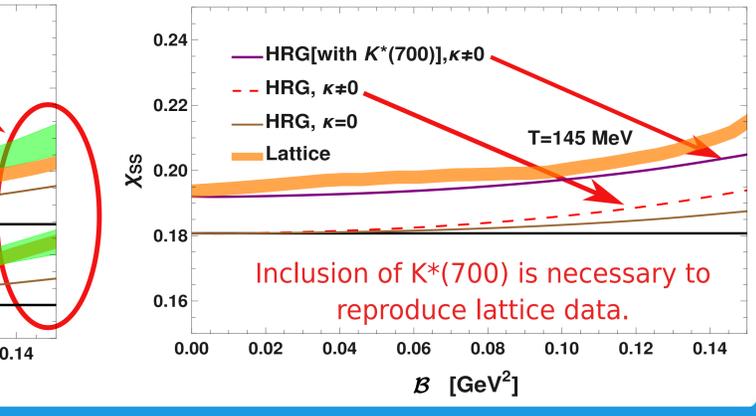
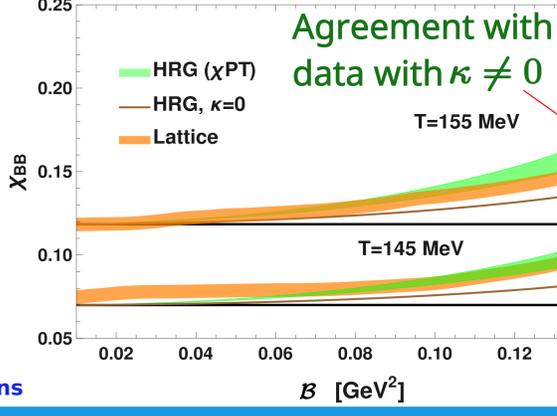
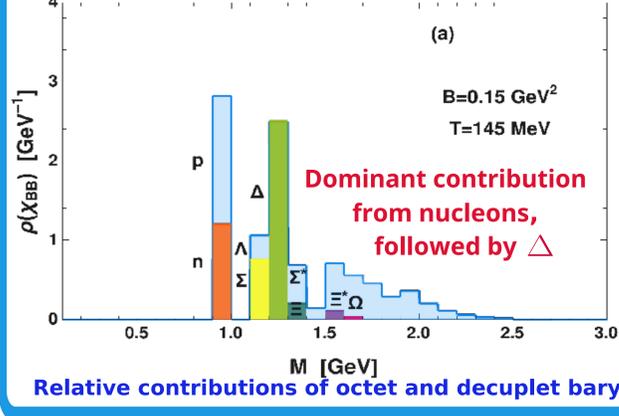
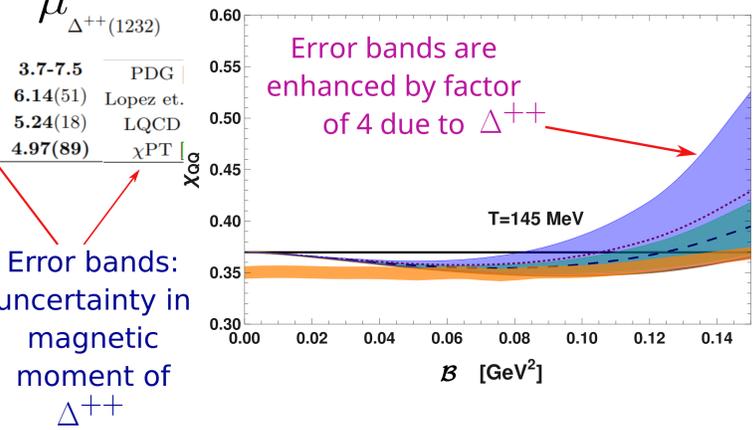
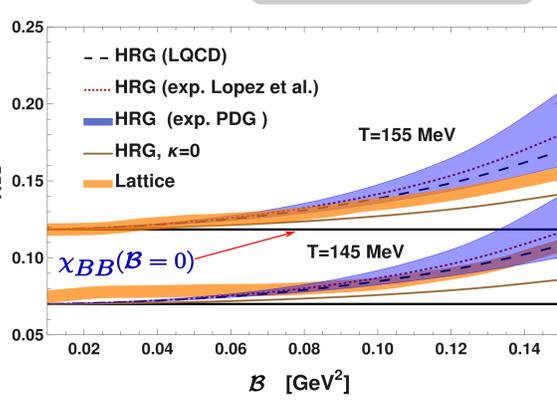
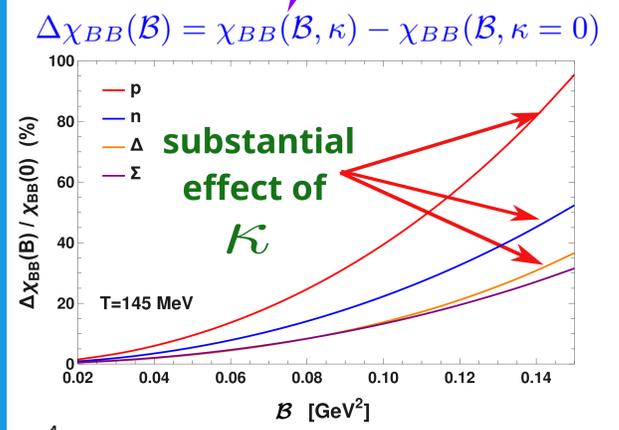
Spin > 3/2 [Approximation]

$$E_{ch} = \sqrt{M^2 + p_z^2 + \mathcal{B}|Q|(2l+1) - \mu_M \mathcal{B} g s_z}$$

$$E_{neu} = \sqrt{M^2 + p^2 - \mu_M \mathcal{B} g s_z}$$

1. We use spectra that is analytic function of κ
2. For low-mass hadrons, κ is large and for high mass hadrons, κ is small (perturbative approach)

Results



Conclusion

With proper inclusion of anomalous magnetic moment, HRG model works for susceptibilities in magnetic field !

Acknowledgments

RS acknowledges the support from Polish National Science Centre (NCN) grant: 2023/51/B/ST2/01625 for the participation in the conference. The authors thank the XQCD2025 organizers for successfully organizing this conference and giving them the opportunity to present their results.

References

1. Marczenko, et al., "Magnetic effects in the hadron resonance gas", Phys. Rev. C110, 065203 (2024).
2. Vovchenko, "Magnetic field effect on hadron yield ratios and fluctuations in a hadron resonance gas", Phys. Rev. C 110, 034914 (2024).
3. Ding et al., "Second order fluctuations of conserved charges in external magnetic fields", arXiv: 2503.18467
4. Friman et al., "Strangeness fluctuations from K - π interactions", Phys.Rev.D 92 (2015) 7, 074003