

## Partial pressure of charmed hadrons in an interacting hadronic medium

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### Introduction

Ultra-relativistic heavy-ion collisions at RHIC and the LHC provide a unique opportunity to investigate the deconfined medium of quarks and gluons, the quark-gluon plasma (QGP). Heavy quarks, produced predominantly in the very early stages of the collision through hard partonic scatterings, act as excellent probes of this medium. Due to their large masses, they traverse the entire space-time evolution of the system and hadronize near the phase boundary into open-charm and bottom hadrons, as well as quarkonium states. The study of such heavy-flavor hadrons thus offers direct insight into the properties of the medium formed in these collisions. Experimental measurements of their production yields, polarization, and anisotropic flow coefficients provide valuable constraints on the microscopic dynamics of the QGP and the hadronization process. Furthermore, a recent study suggests that charm fluctuations may serve as a particularly sensitive probe of the QCD phase boundary and the possible location of the critical point [1].

In this study, we look into the partial pressure of the charmed baryons and mesons, quantified through charm susceptibility. We study the partial pressure of strange charm hadrons as a function of temperature. In this work, we employ the VDWHRG framework to study the partial pressure of the charm sector and explore the effect of attractive and re-

pulsive interactions among the hadrons on the partial pressure.

### Formulation

The generalized susceptibilities are obtained from derivatives of the pressure with respect to the reduced chemical potentials, which in turn allow the separation of partial pressures of charmed mesons and baryons, given as

$$\chi_{klmn}^{BQSC} = \frac{\partial^{k+l+m+n} [P(\mu_B, \mu_Q, \mu_S, \mu_C)/T^4]}{\partial \hat{\mu}_B^k \partial \hat{\mu}_Q^l \partial \hat{\mu}_S^m \partial \hat{\mu}_C^n} \Big|_{\mu=0}, \quad (1)$$

where  $k$ ,  $l$ ,  $m$ , and  $n$  denote the order of the derivatives,  $P$  is the pressure evaluated within the VDWHRG model, and  $\mu_i$  represent the chemical potentials associated with baryon number ( $B$ ), electric charge ( $Q$ ), strangeness ( $S$ ), and charm ( $C$ ). In particular, the partial pressure of charmed baryons ( $P_C^B$ ) can be expressed in terms of charm susceptibilities as

$$P_C^B = \frac{1}{2} (3\chi_{22}^{BC} - \chi_{13}^{BC}) \quad (2)$$

For the charm-strangeness sector, the partial pressures are given by

$$P_{C,S=1}^M = \chi_{13}^{SC} - \chi_{112}^{BSC}, \quad (3)$$

A detailed formulation can be found in [2].

### Results

In Fig. 1, we present the partial pressure of charmed baryons as a function of temperature at  $\mu_B = 0$ . While the ideal HRG tend to overestimate the lattice QCD results above

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$T \gtrsim 160$  MeV, the VDWHRG framework provides a significantly improved description up to  $T \sim 180$  MeV. This highlights the importance of including both attractive and repulsive interactions in order to capture the thermodynamics of charmed baryons near the crossover region.

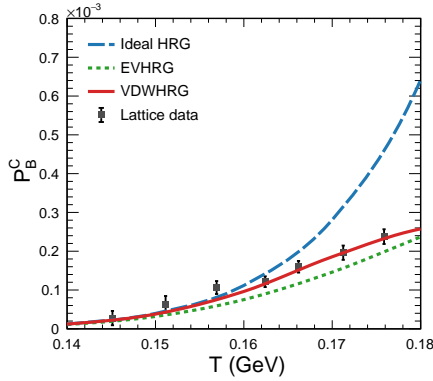


FIG. 1: Partial pressure of charmed baryons in VDWHRG compared to HRG, EVHRG and lQCD estimations [2].

Figure 2 shows the partial pressure of charmed baryons with strangeness  $S = 1$ . All three HRG models describe the lattice QCD data within uncertainties. However, EVHRG seems to work reasonably well at higher temperatures.

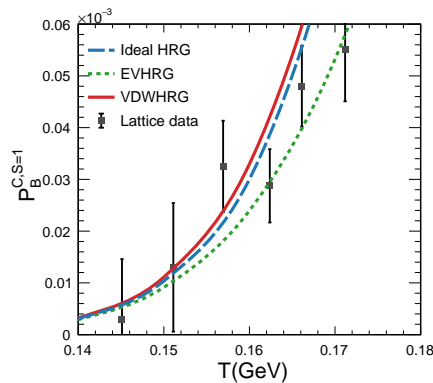


FIG. 2: Partial pressure of charmed baryons with strangeness  $S = 1$  in VDWHRG [2].

Finally, Fig. 3 presents the ratio of the partial pressure of strange-charmed baryons ( $S = 1$ ) to the total charm pressure. The HRG models follow the lattice QCD trend up to  $T \sim 160$  MeV, but begin to deviate at higher temperatures, where missing charm-quark contributions become relevant.

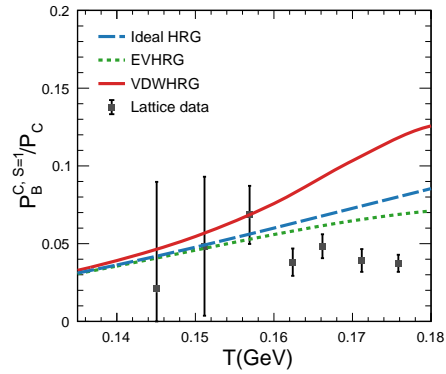


FIG. 3: Ratio of partial pressure of charmed baryons with  $S = 1$  to the total charm pressure in VDWHRG, compared with lQCD [2].

## Summary

We explored the partial pressure of the charm sector using the VDWHRG model, which accounts for both attractive and repulsive hadronic interactions. The model provides improved agreement with lattice QCD results for partial pressures of charmed mesons and baryons, including strange-charm states, up to  $T \sim 180$  MeV. While the framework captures the main trends below  $T \sim 160$  MeV, deviations at higher temperatures suggest the onset of deconfined charm degrees of freedom, underscoring the limits of hadronic descriptions near the crossover.

## References

- [1] K. Goswami, K. K. Pradhan, D. Sahu, J. Dey and R. Sahoo, Phys. Rev. D **111**, 014029 (2025).
- [2] K. Goswami, K. K. Pradhan, D. Sahu and R. Sahoo, arXiv:2508.07716.