Dynamics of charmed hadrons in an interacting hadron gas

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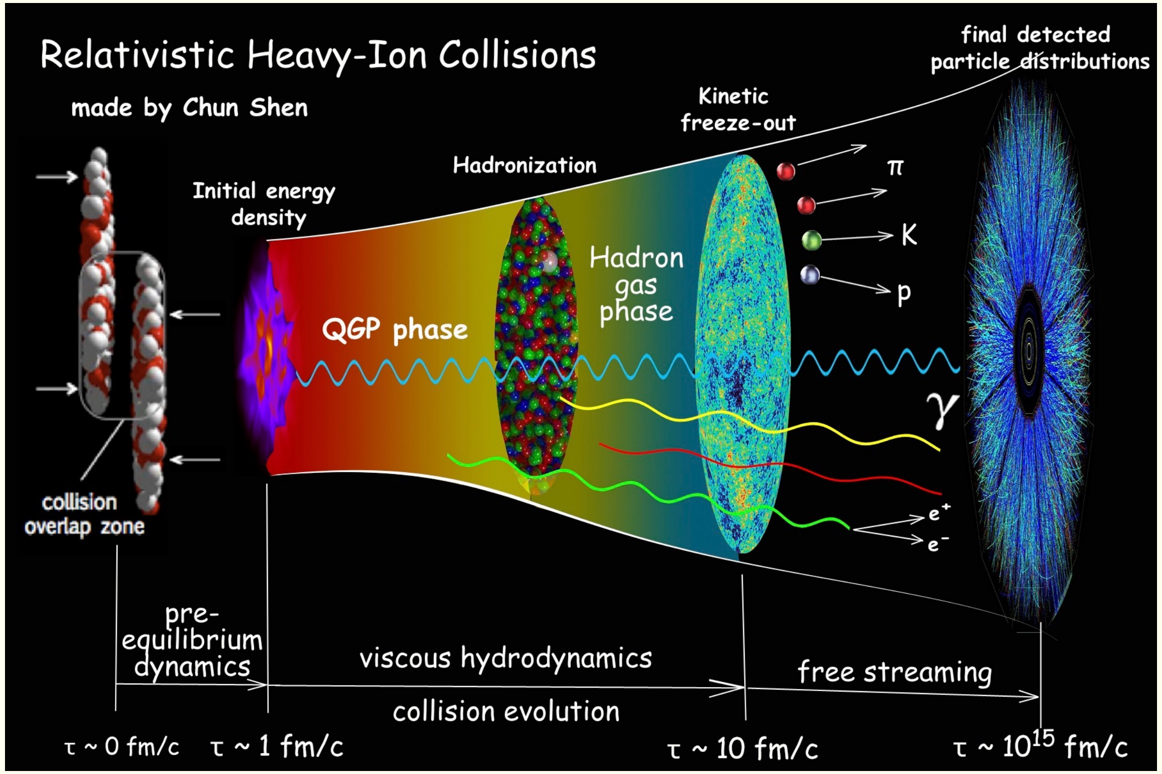
Based on: K. Goswami, K. K. Pradhan, D. Sahu, and R. Sahoo, Phys Rev D **108** 074011 (2023)

67th DAE Symposium on Nuclear Physics
09 – 13 December 2023

Outline

- Introduction
- Motivation
- Van der Waals HRG model
- Diffusion of D^0 meson
- Fluctuation of open charmed hadrons
- Conclusion

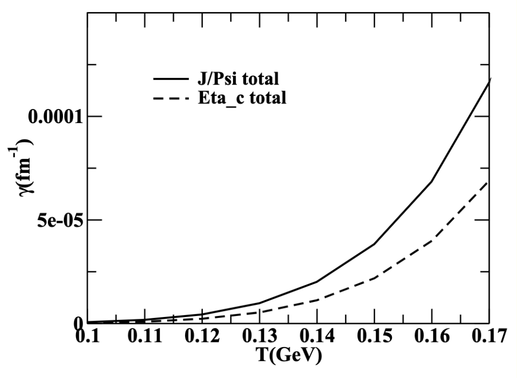
Introduction

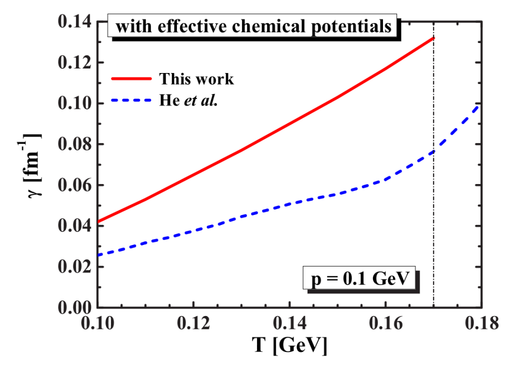


Sketch of relativistic heavy-ion collisions, Chun Shen, Ohio State University

Producing Quark-Gluon Plasma in the laboratory

- ❑ One of the most prominent probes of Quark-Gluon Plasma: Charmonium (J/ψ and higher states)
- ❑ In the hadronic phase, the charmonium states are undiffused.
- ❑ Open charm hadrons like D^0 have relatively larger interaction cross-section in the hadronic medium.
- ❑ Ideal probe to explore the interactions of the hadronic phase.





S. Mitra et. al, Nucl. Phys. A 951, 75 (2016)
V. Ozvenchuk et. al, Phys Rev C 90 054909 (2014)

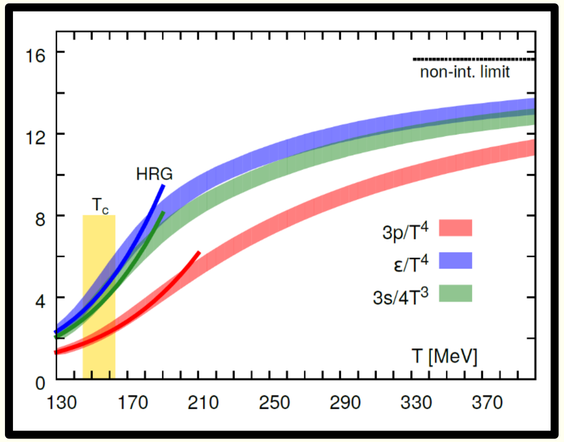
Ideal Hadron Resonance Gas Model

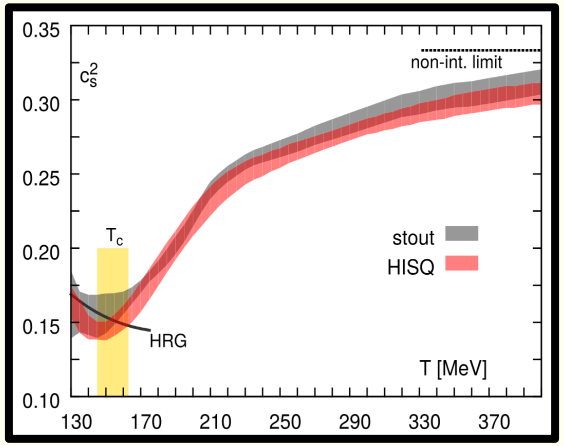
- ❑ Ideal HRG is a non-interacting statistical model consisting of hadrons and resonances.
- ❑ The ideal HRG model successfully reproduces many lattice observables.
- ❑ The agreement between ideal HRG results and the lattice observable in the crossover region deteriorates.
- ❑ This breakdown of the ideal HRG model is much more prominent in the study of higher-order fluctuations.

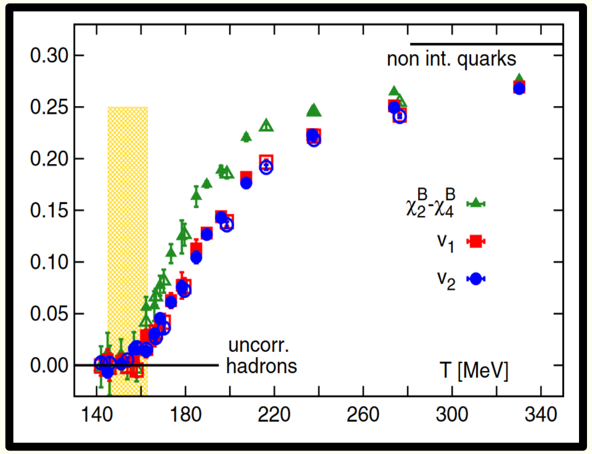
- ❑ Pressure and number density in the ideal HRG model is given as,

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

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



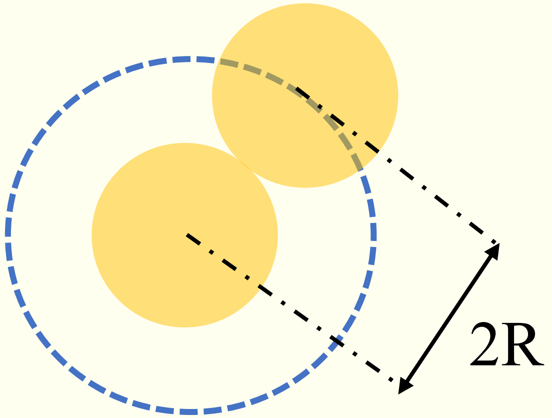


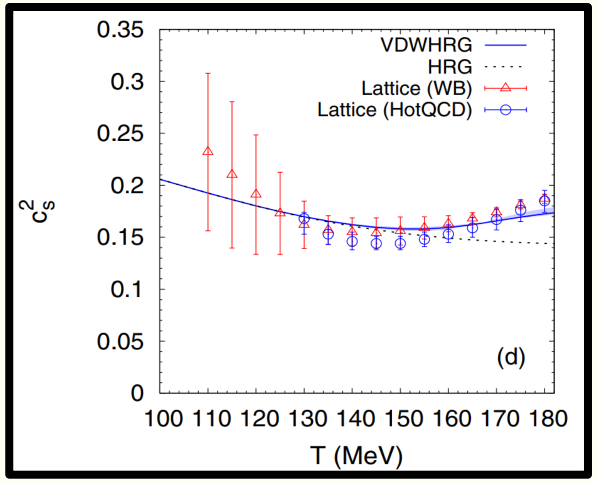


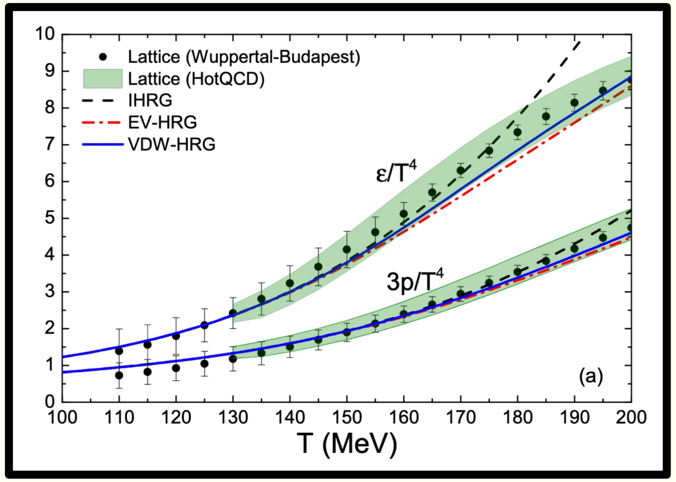
A. Bazavov et al. (Hot QCD collaboration), Phys. Rev. D **90** 094503 (2014)
A. Bazavov et al., Phys. Rev. Lett. **111** 082301 (2013)

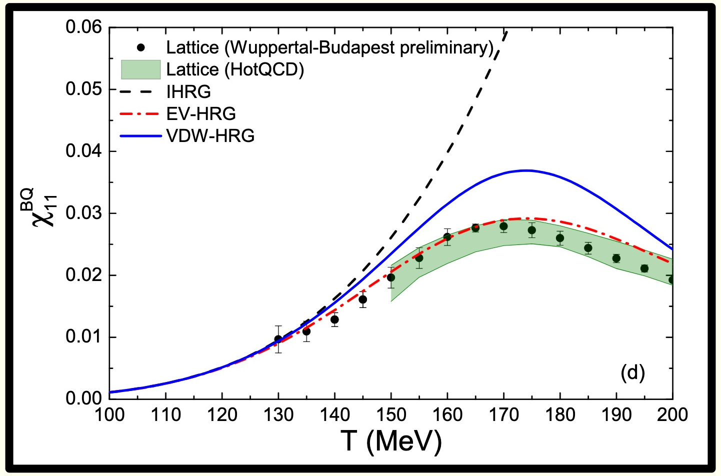
Van der Waals Hadron Resonance Gas Model

- The VDWHRG model introduces attractive and repulsive forces between the hadron species, using two parameters, a and b.









S. Samanta et al. Phys. Rev. C **97** 015201 (2018)
V. Vovchenko et. al, Phys. Rev. Lett. 118, 182301 (2017)

Van der Waals Hadron Resonance Gas Model

- Interaction between baryons, anti-baryons, and mesons are incorporated by introducing two parameters, a and b. Modifying its equation of state as,

$$\left(P + \left(\frac{N}{V}\right)^2 a\right)(V - Nb) = NT$$

- The equation of state in the GCE can be expressed as,

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

- Number density and modified chemical potential are given as,

$$n(T,\mu) = \frac{\sum_i n_i^{id}(T,\mu^*)}{1 + b\sum_i n_i^{id}(T,\mu^*)}$$

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

- P^{id} and n^{id} are pressure and number density in ideal HRG model.

Brownian Motion and Fokker-Planck equation

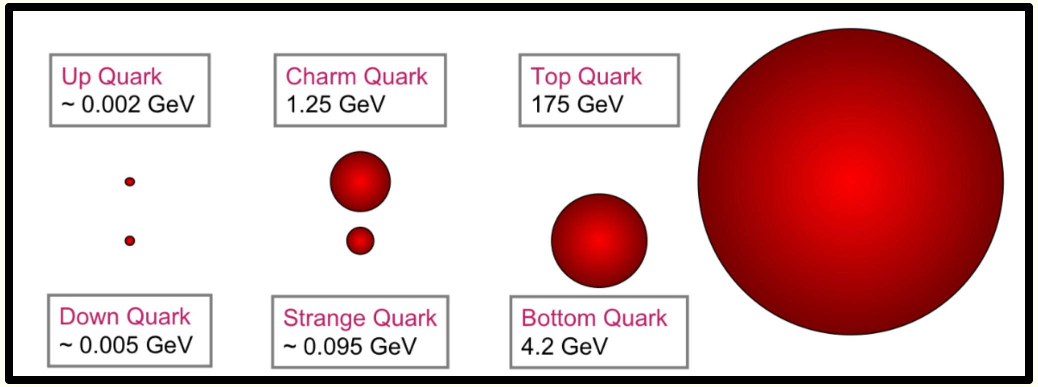
Hadron gas consists mainly of pions, kaons, and protons.

Pions are the lightest mesons.
Mass: 0.135-0.139 GeV

Kaons are the lightest strange mesons.
Mass: 0.493-0.497 GeV

Proton is the lightest baryon.
Mass: 0.938 GeV

Lightest charmed meson: $D^0(c\bar{u})$
Mass: 1.869 GeV



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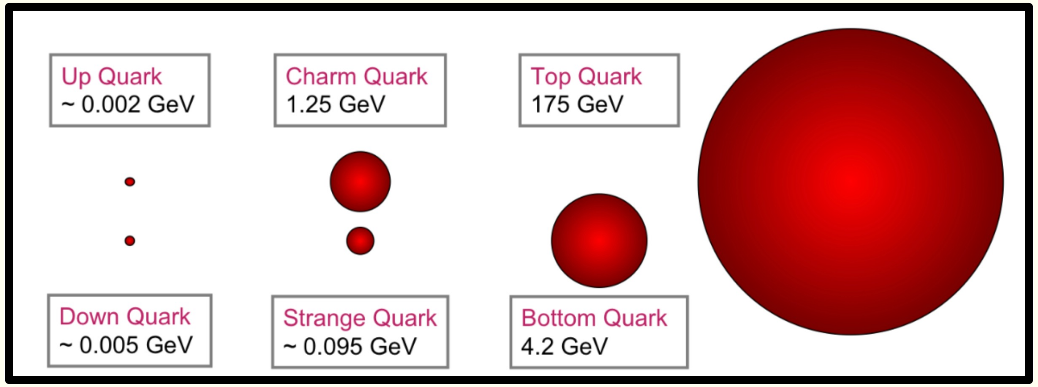
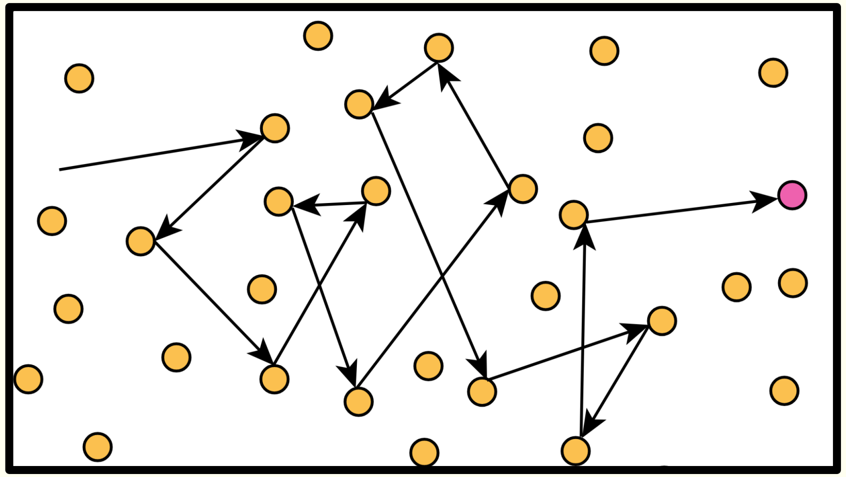




Brownian Motion and Fokker-Planck equation

We use the Fokker-Planck equation to study the diffusion of D^0 meson in a thermal bath of lighter hadron species

$$\boxed{\frac{\partial f(t,p)}{\partial t} = \frac{\partial}{\partial p^i}\left(A^i f(t,p) + \frac{\partial}{\partial p^j}\left(B^{ij} f(t,p)\right)\right)}$$

where, $f(t,p)$ is the distribution function of the heavier hadron in a medium characterized by drag, A^i, and diffusion, B^{ij}, coefficient given by,

$$\boxed{A^i = \int dk\, \omega(p,k) k^i} \qquad \boxed{B^{ij} = \frac{1}{2}\int dk\, \omega(p,k) k^i k^j}$$

where, $\omega(p,k)$ is the collision rate of the heavy quark

In the low momenta limit, $p \to 0$, we can reduce A^i and B^{ij} as,

$$\boxed{A^i = \gamma p^i} \qquad \boxed{B^{ij} = B_0 P_\perp^{ij} + B_1 P_\parallel^{ij}}$$

where, γ is the drag coefficient and B_0 and B_1 are the transverse and longitudinal momentum diffusion coefficient. $P_\perp^{ij}$ and $P_\parallel^{ij}$ are transverse and longitudinal projection operators respectively.

Diffusion of D^0 meson

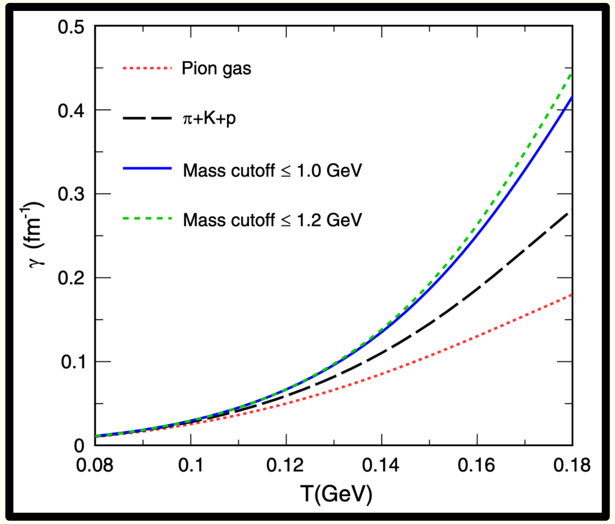
❑The inverse of relaxation time can be expressed as,

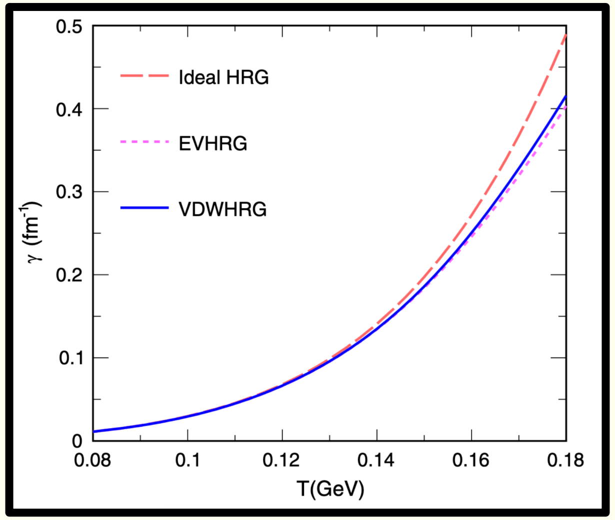
$$\tau^{-1} = \sum_j n_j \langle \sigma_{jD} v_{jD} \rangle$$

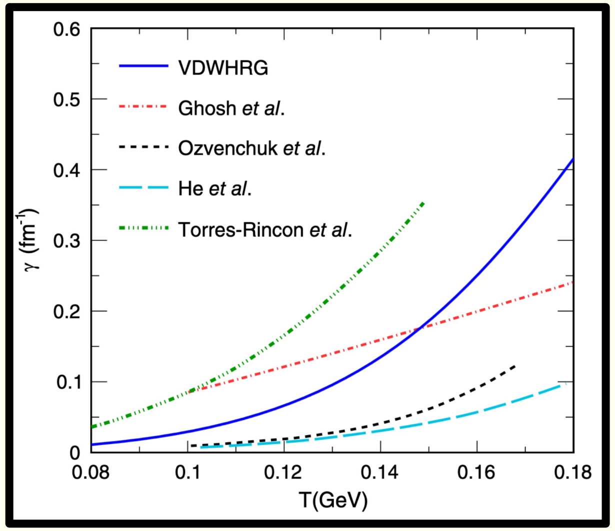
σ_{jD} and v_{jD} is the scattering cross-section and relative velocity of j^{th} hadronic species with D-meson

❑Using the relaxation time, we can compute

$$\gamma = \frac{1}{\tau}$$







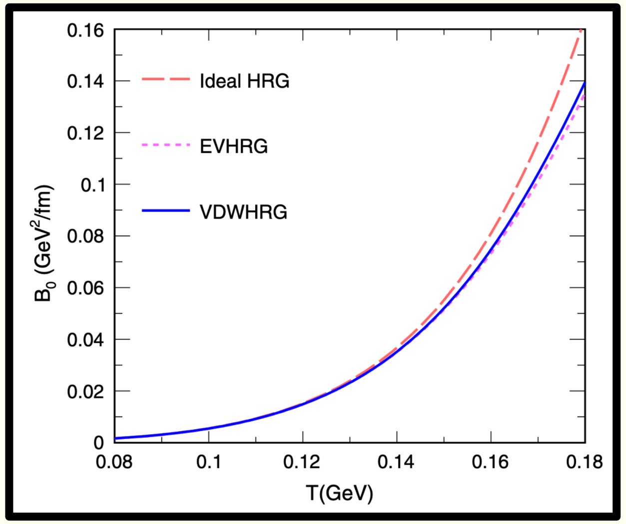
K. Goswami, K. K. Pradhan, D. Sahu, and R. Sahoo, Phys Rev D **108** 074011 (2023)

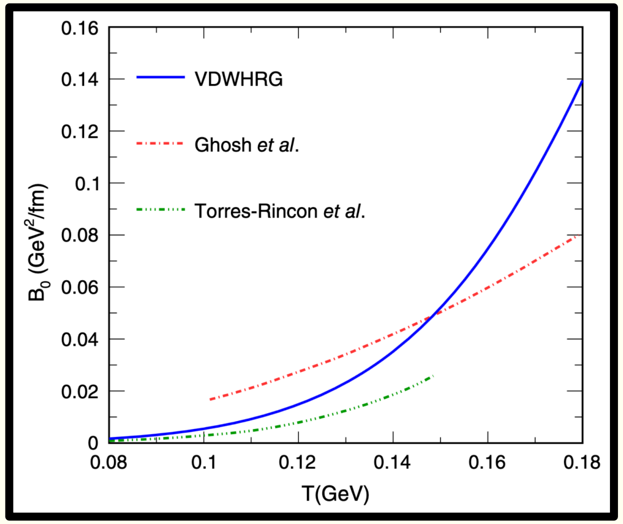
Diffusion of D^0 meson

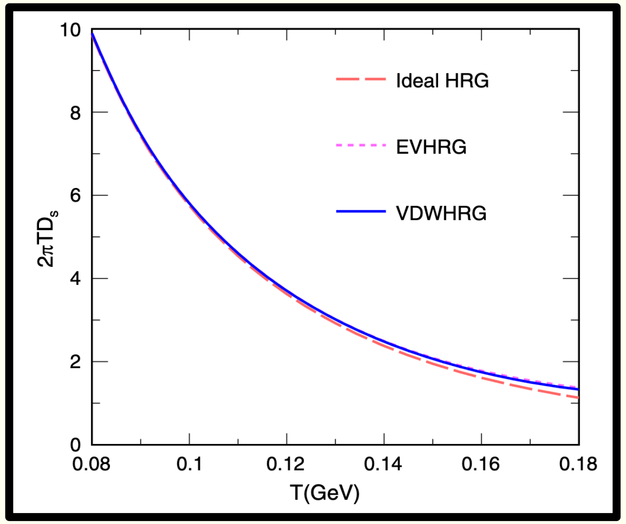
- The momentum and spatial diffusion coefficient is related to drag coefficient as,

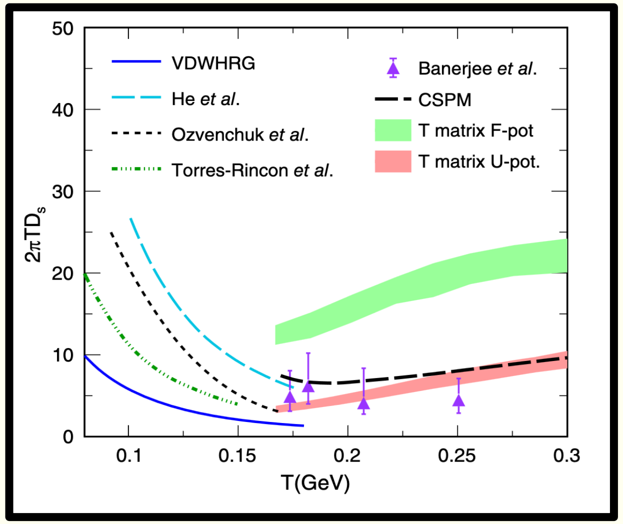
$$B_0 = \gamma m_D T \qquad D_s = \frac{T}{m_D \gamma}$$

- The momentum diffusion coefficient describes the broadening of momentum spectra of the final state hadrons.
- The spatial diffusion coefficient can be understood as the speed of diffusion in space.









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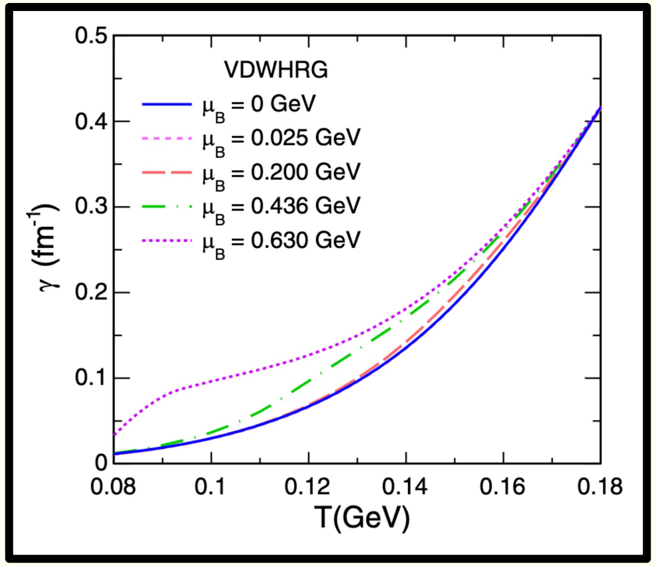
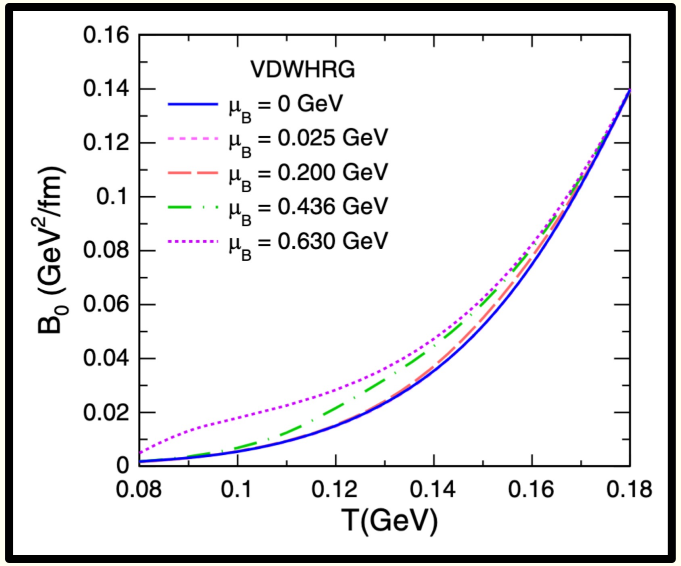
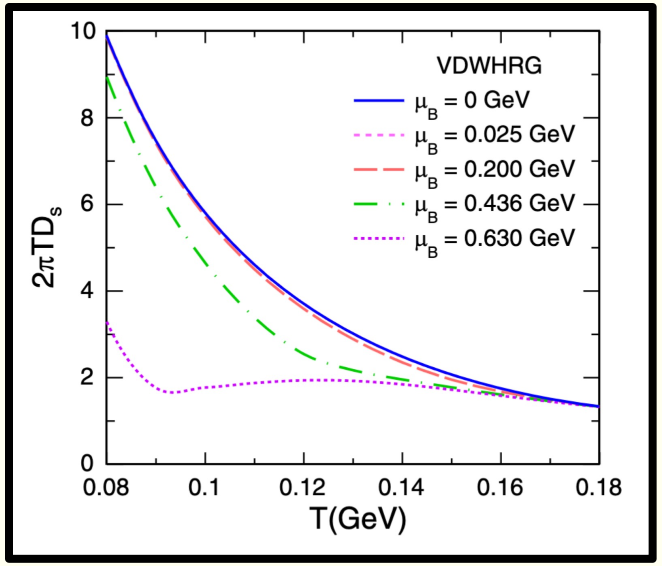






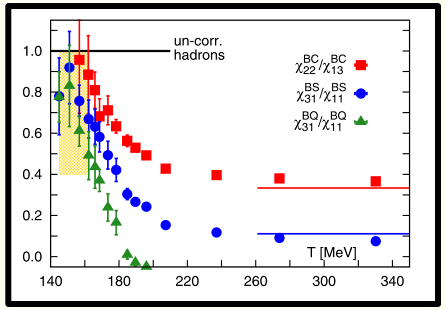
- ❑ We study the drag and diffusion coefficients at finite chemical potential.
- ❑ With the increase in chemical potential, a sharp change can be observed at low temperatures.

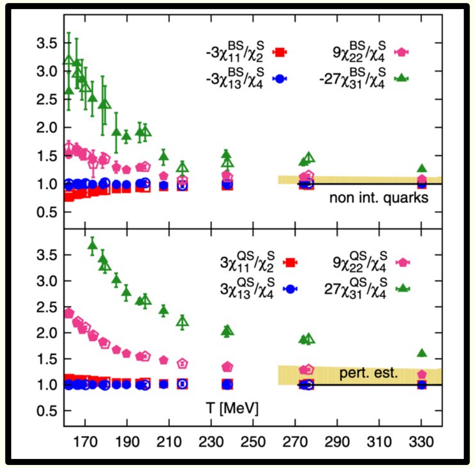
K. Goswami, K. K. Pradhan, D. Sahu, and R. Sahoo, Phys Rev D **108** 074011 (2023)

Susceptibility of charmed hadrons

- The fluctuation of one charged particle in or out of the considered sub-volume produces a different fluctuation of the net conserved charge in hadronic medium as compared to a deconfined medium.
- We can estimate susceptibilities of conserved charges as,

$$\chi_{ijkl}^{BSQC} = \frac{\partial^{i+j+k+l}\left(\frac{P}{T^4}\right)}{\partial\left(\frac{\mu_B}{T}\right)^i\left(\frac{\mu_S}{T}\right)^j\left(\frac{\mu_Q}{T}\right)^k\left(\frac{\mu_C}{T}\right)^l}$$





A. Bazavov et al., Physics Letters B 737 (2014)
A. Bazavov et al., Phys. Rev. Lett. **111** 082301 (2013)

- We estimate the net charm fluctuation and its correlation with the fluctuation of other conserved charges in the VDWHRG model.

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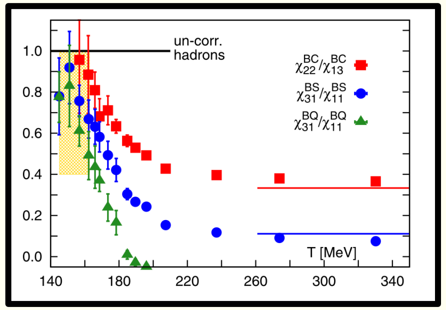

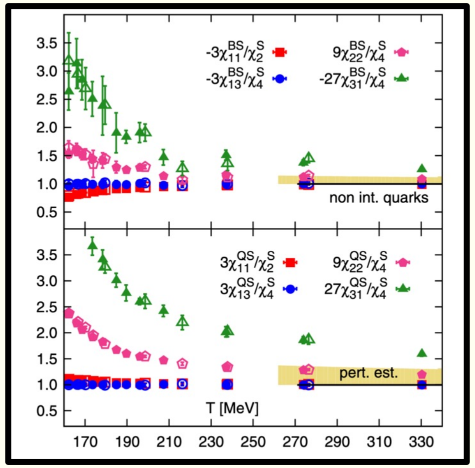

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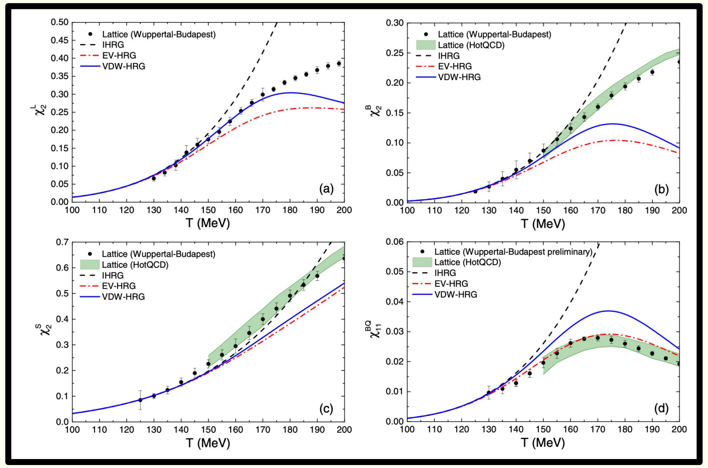
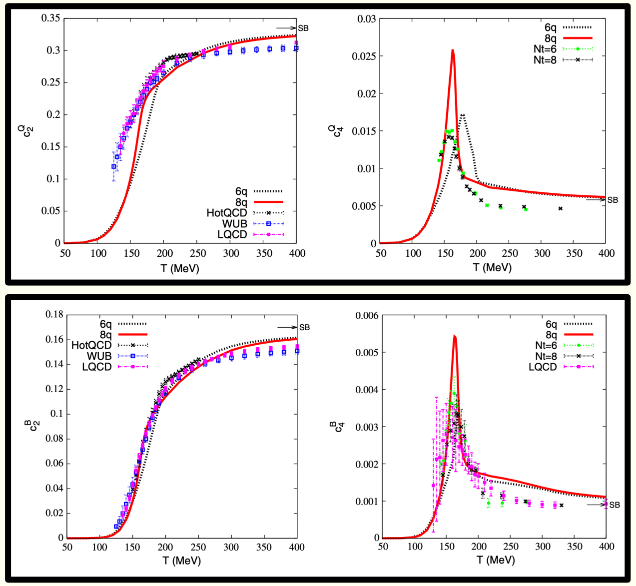


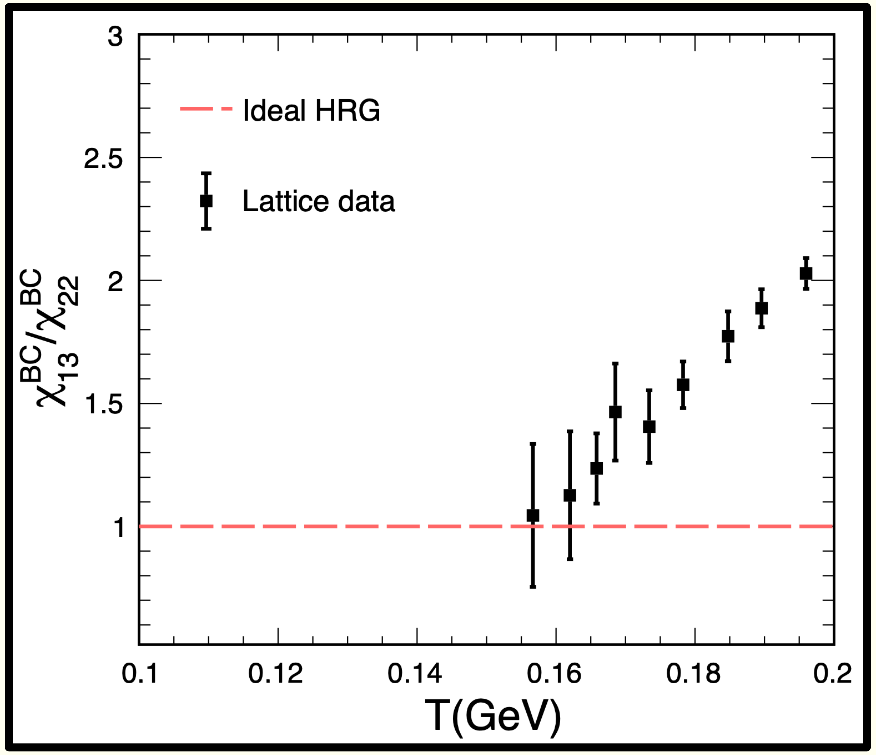


Volodymyr Vovchenko et. al, Phys. Rev. Lett. 118, 182301 (2017)
Abhijit Bhattacharyya, Phys. Rev. D 95, 054005 (2017)

- We estimate the net charm fluctuation and its correlation with the fluctuation of other conserved charges in the VDWHRG model.

Susceptibility of charmed hadrons

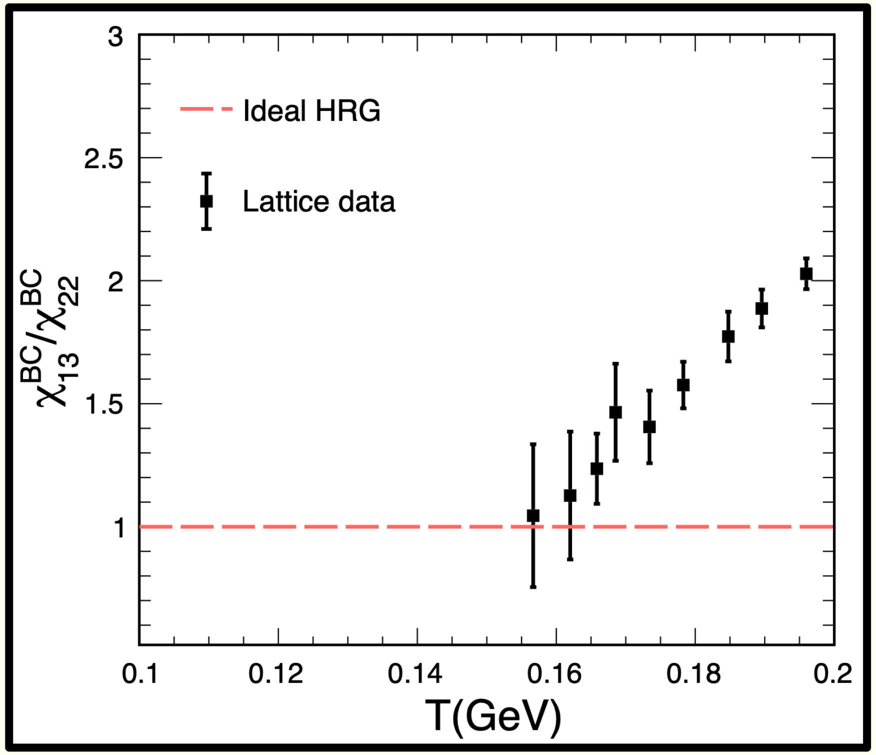
- Comparison between the HRG models and existing lattice data.

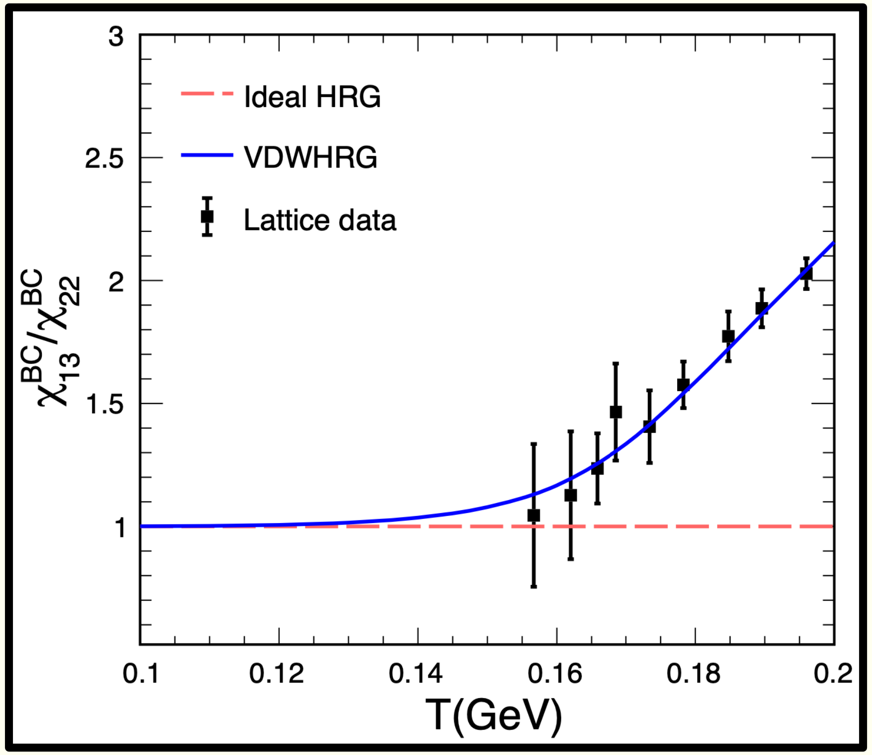


- The ratio is the charm to baryon number, which is 1 in hadronic medium and 3 in QGP medium.
- A slow rise indicates towards a mixed phase at vanishing chemical potential.

Susceptibility of charmed hadrons

- ❑ Comparison between the HRG models and existing lattice data.





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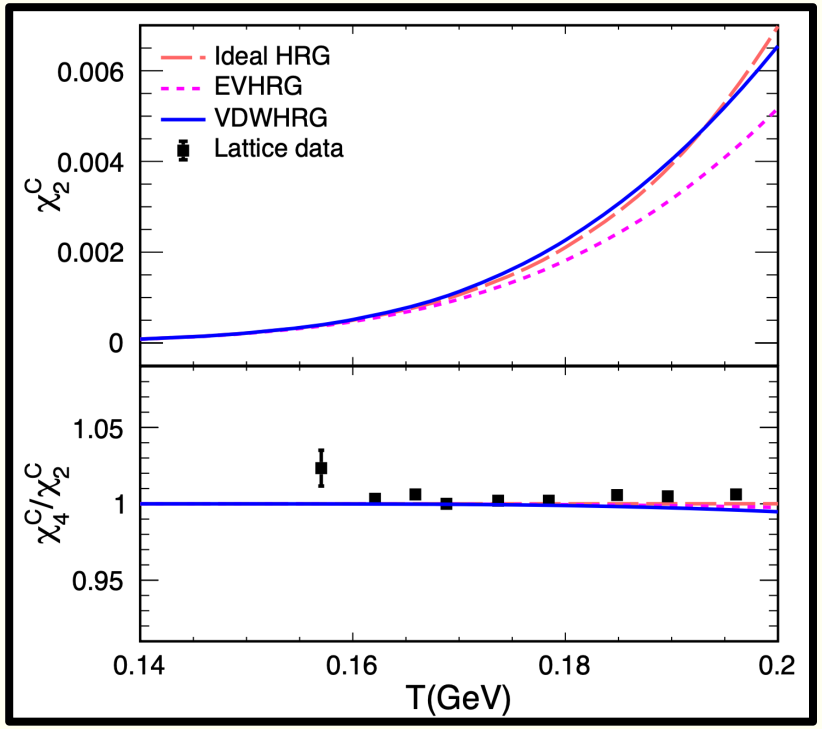
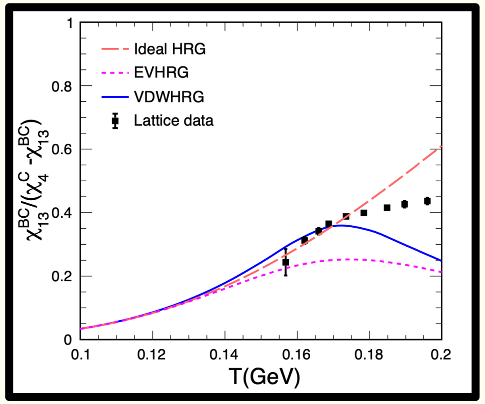
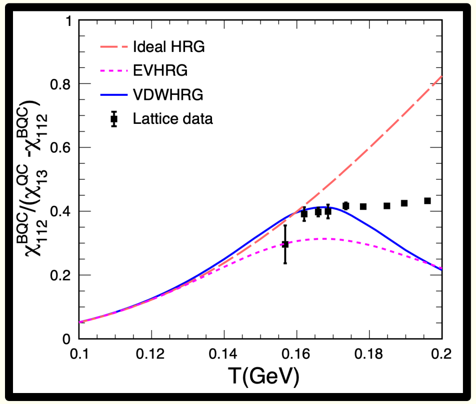
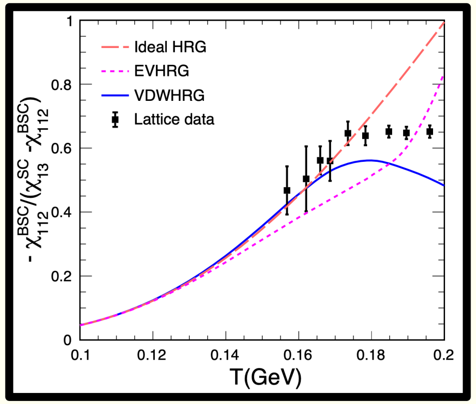
Susceptibility of charmed hadrons

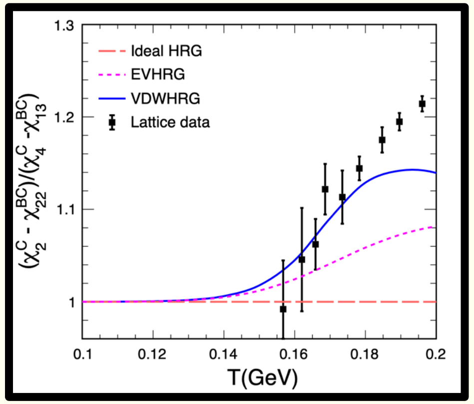
- ❑ Comparison between Van der Waals HRG model and existing lattice data.











- ❑ Including VDW interactions improves the model prediction and reproduces the trend in lQCD data.

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Summary

- Estimated the diffusion of D^0 meson in a hadronic medium with VDW interactions.
- Compared our results with other phenomenological studies.
- Approximated the melting of charmed hadrons with the help of charm fluctuations.
- Incorporating the VDW interactions allows us to reproduce the lQCD data accurately.

Thank you

Backup Slides

Backup

- Thermal average of scattering cross-section and relative velocity.

$$\langle \sigma_j v_j \rangle = \frac{\sigma_{Dj}}{8 T m_D^2 m_j^2 K_2(\frac{m_D}{T}) K_2(\frac{m_j}{T})} \int_{(m_D+m_j)^2}^{\infty} \times ds \frac{s-(m_D-mj)^2}{\sqrt{s}} (s-(m_D+m_j)^2) K_1\left(\frac{\sqrt{s}}{T}\right)$$