DYNAMICS OF OPEN CHARMED HADRONS IN AN INTERACTING HADRONIC MEDIUM

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Dushmanta Sahu
IIT Indore

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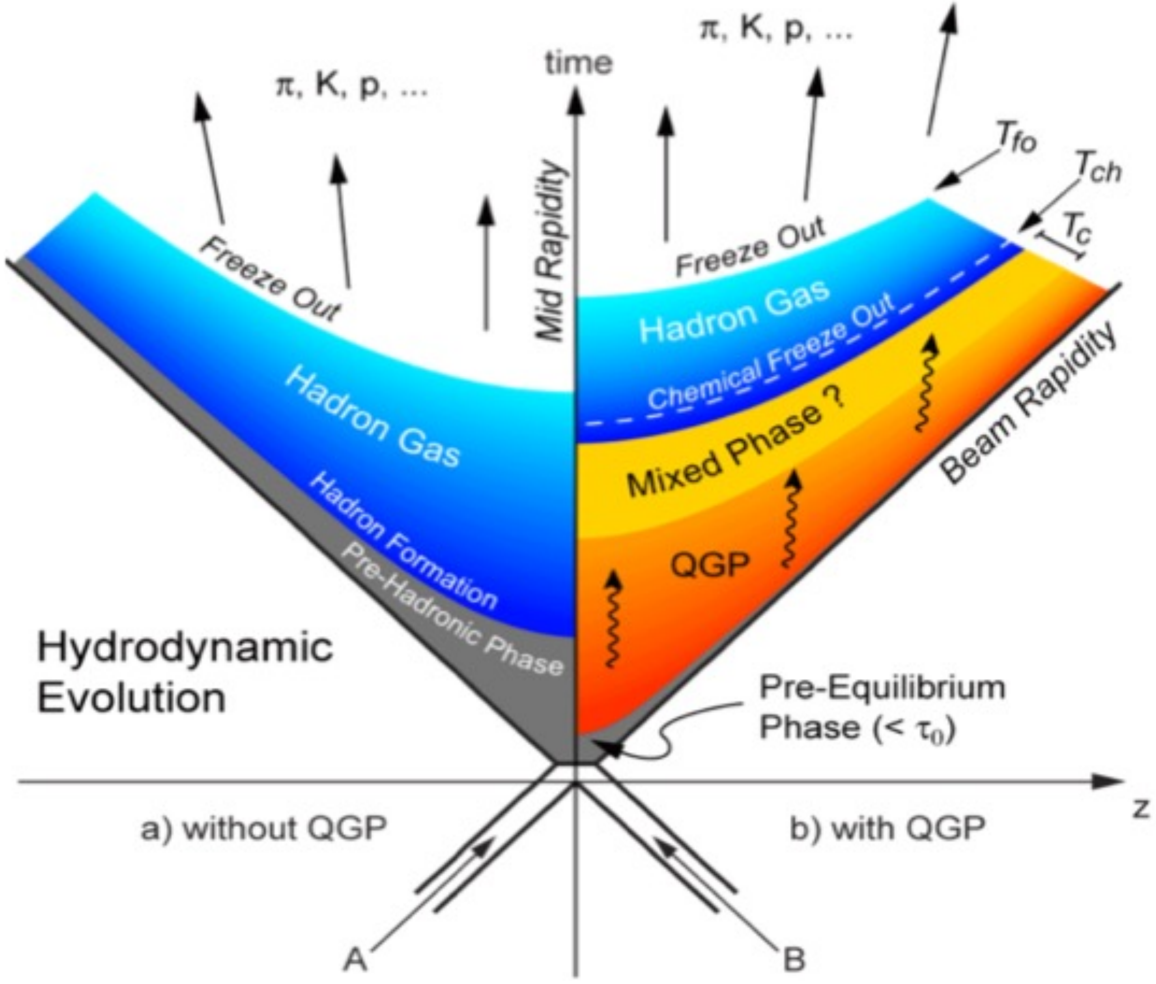
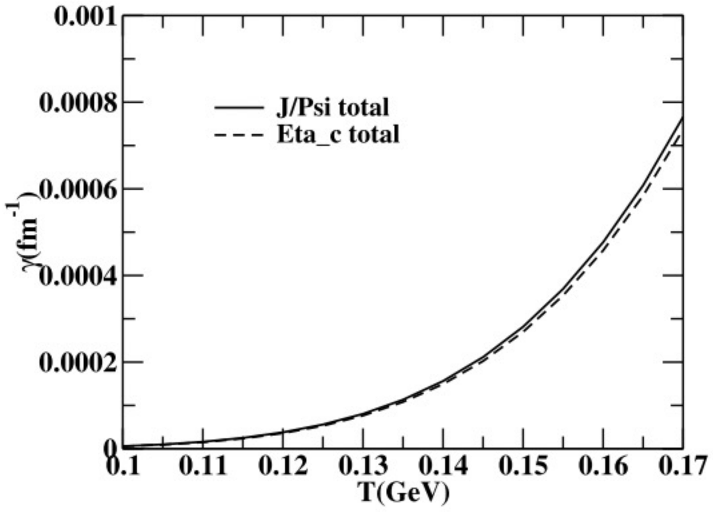
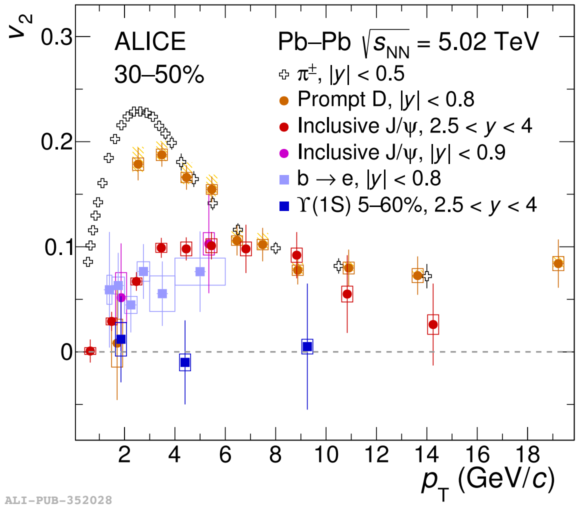
Heavy-Ion Collision



- Quarkonia are produced relatively early in the system
- J/ψ remains largely undiffused in the hadronic phase
- J/ψ is a good probe to study the deconfined phase
- Open charmed hadrons suffer diffusion in the hadronic phase
- D^0 is a good probe to study hadronic phase





Sukanya Mitra et. al, Nucl. Phys. A **951**, 75 (2016)

Hadron resonance gas model

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

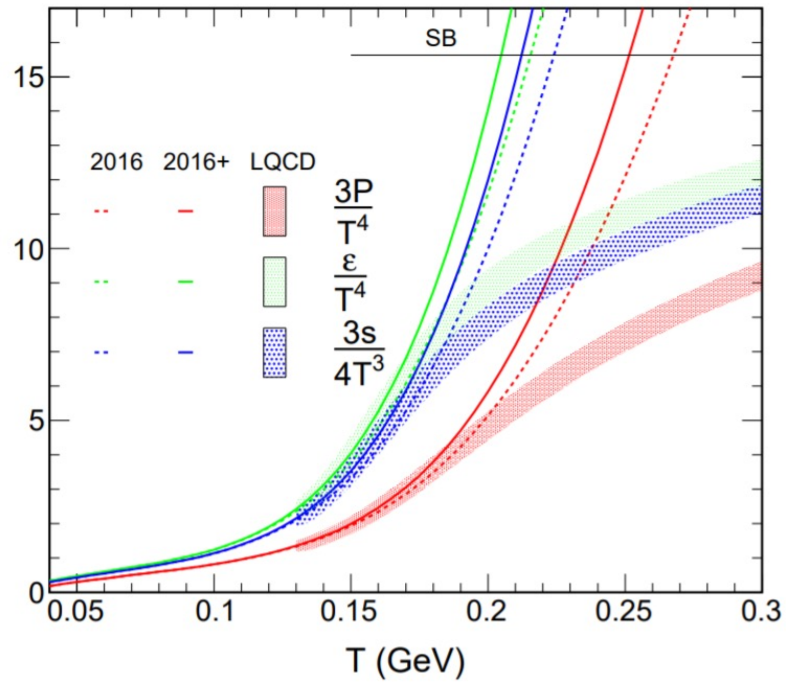
$$\ln Z_i^{id} = \pm \frac{V g_i}{2\pi^2} \int_0^\infty p^2\, dp \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

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

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

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

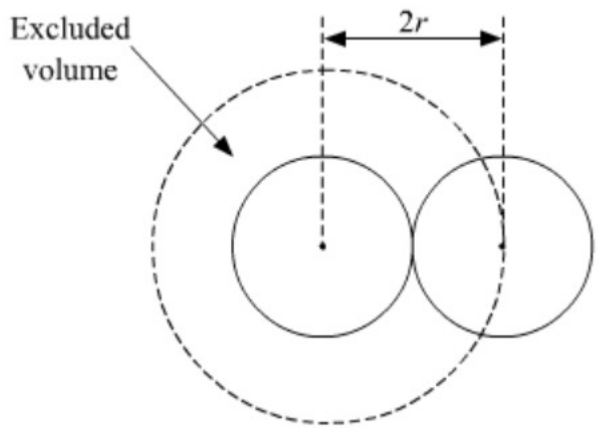
- Successful in reproducing zero chemical potential lQCD data at low-temperature T < 150 MeV
- Disagreement between lQCD data and HRG model at high temperature



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

van der Waals HRG

- Interaction with both attractive and repulsive parts has been introduced in the HRG model
- 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

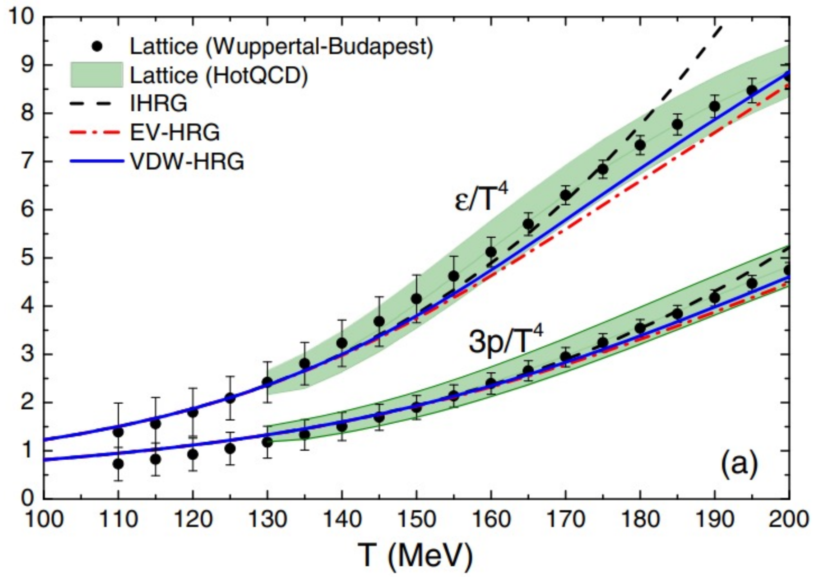


$$P(V,T,N) = \frac{NT}{V-bN} - a\frac{N^2}{V^2}$$

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

$$n \equiv n(T,\mu) \equiv \left(\frac{\partial p}{\partial \mu}\right)_T = \frac{n^{id}(T,\mu^*)}{1+bn^{id}(T,\mu^*)} \qquad = \mu - b\frac{n(T,\mu)T}{1-bn_(T,\mu)} + 2an$$

$$\varepsilon(T,\mu) = \frac{\varepsilon^{id}(T,\mu^*)}{1+bn^{id}(T,\mu^*)} - an^2$$

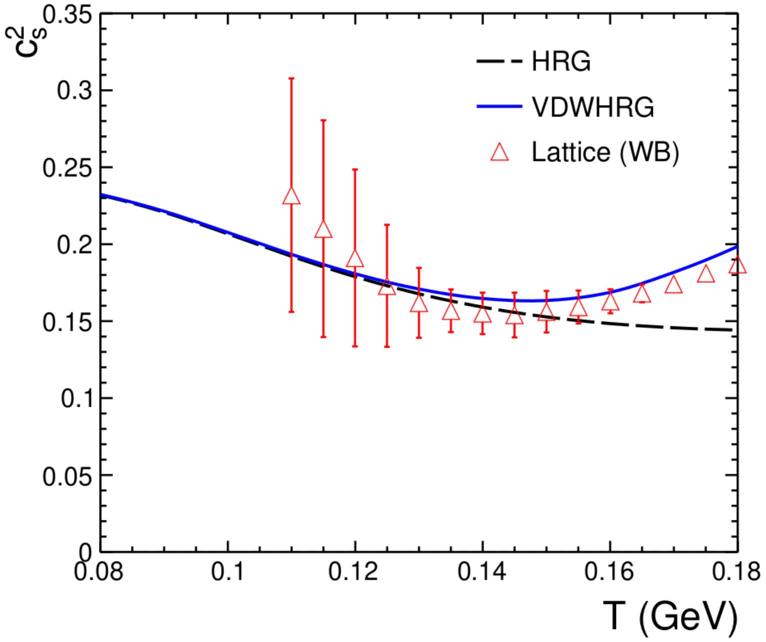


Volodymyr Vovchenko et. al, Phys. Rev. Lett. **118**, 182301 (2017)

van der Waals HRG

- We also consider the repulsive interaction among mesons by considering a hardcore radius and attractive interaction through resonances

- The VDW-HRG consists of three subsystems: excluded volume mesons, VDW baryons, and VDW anti-baryons



$$P_M(T,\mu) = \sum_{j\in M} p_j^{\rm id}(T,\mu_j),$$

$$P_B(T,\mu) = \sum_{j\in B} p_j^{\rm id}(T,\mu_j^{B*}) - an_B^2$$

$$P_{\bar{B}}(T,\mu) = \sum_{j\in \bar{B}} p_j^{\rm id}(T,\mu_j^{\bar{B}*}) - an_{\bar{B}}^2$$

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

For (anti)baryons

$$\mu^* = \mu - bp(T,\mu)$$

For Mesons

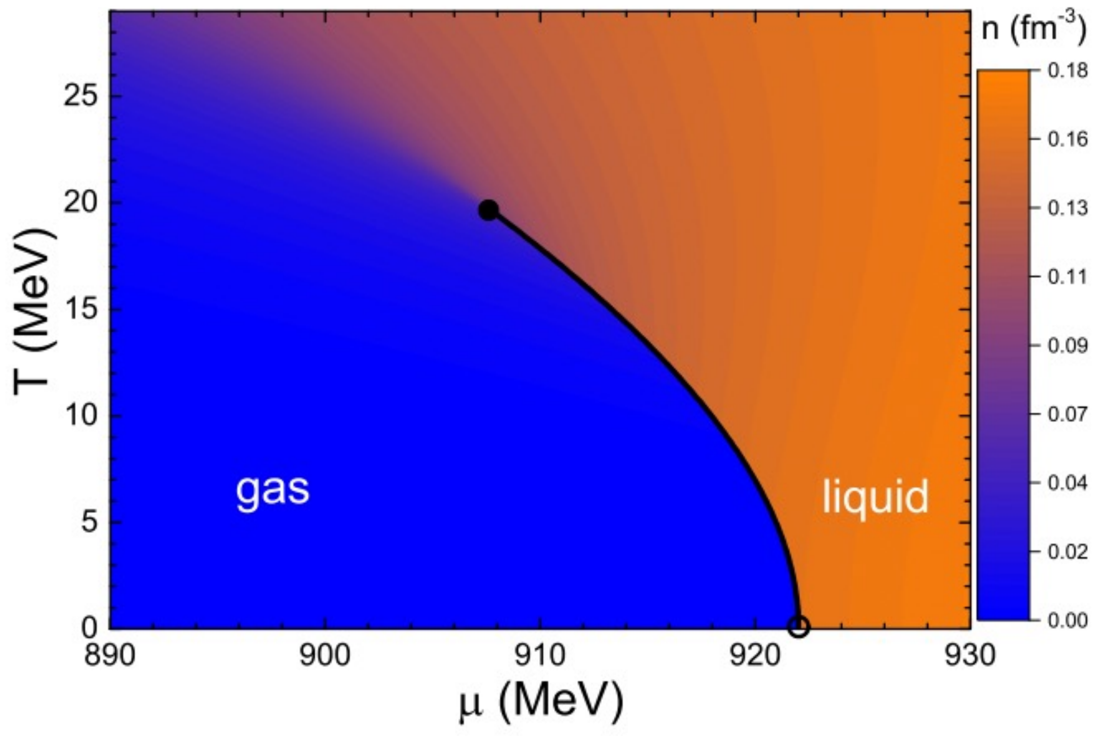
The VDW parameters: a = 0.926 GeV fm^3

b = $\frac{16}{3}\pi r^3$ fm^3

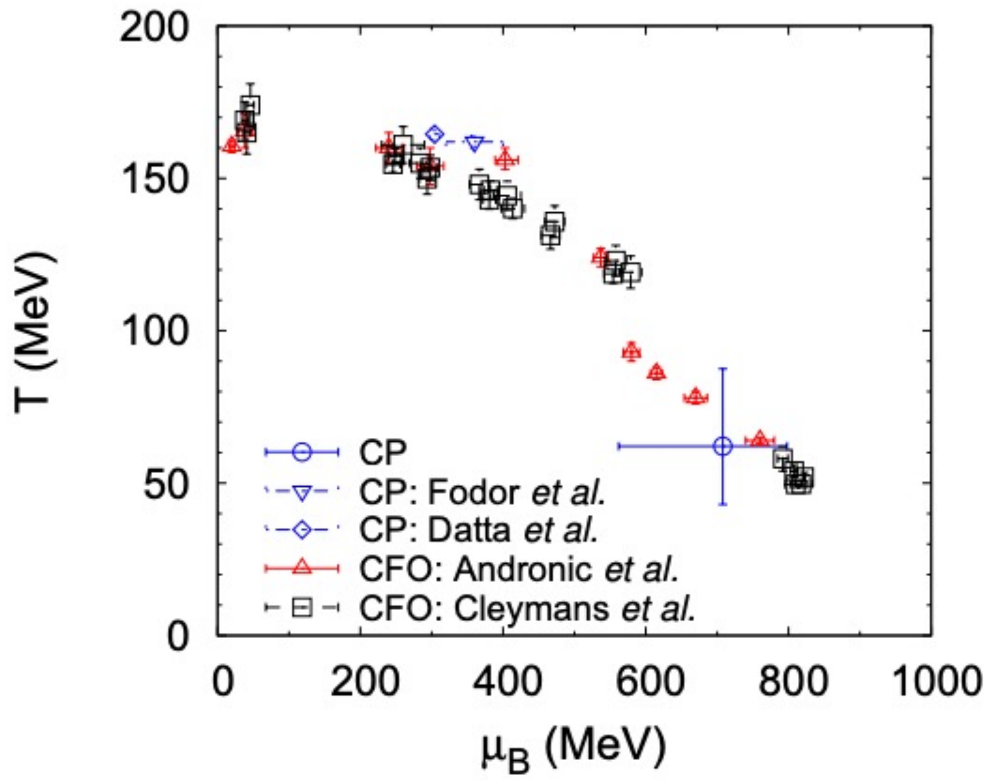
where r_m = 0.2 fm and r_b = 0.62 fm

N. Sarkar and P. Ghosh, Phys. Rev. C 98, 014907 (2018)

Liquid-Gas phase transition



Volodymyr Vovchenko et. al, Phys. Rev. Lett. **118**, 182301 (2017)



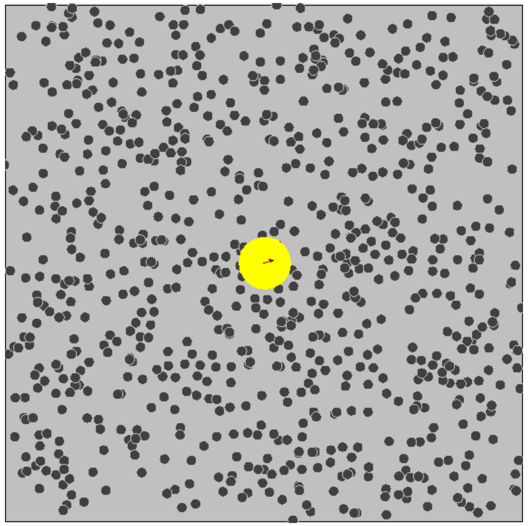
Subhasis Samanta et. al, Phys. Rev. C **97**, 015201 (2018)

- VDW parameters extracted by reproducing the ground state nuclear matter

- VDW parameters extracted by fitting the lQCD data at vanishing baryochemical potential

Diffusion of D^0 meson

Fokker-Planck equation: $$\frac{\partial f(t,p)}{\partial t} = \frac{\partial}{\partial p_i}\left\{A_i(p)f(t,p) + \frac{\partial}{\partial p_j}[B_{ij}f(t,p)]\right\}$$



Here, $f(t,p)$ is the time evolution phase-space distribution function of D^0 meson

$$A_i = \int dk\ \omega(p,k)k_i \qquad B_{ij} = \int dk\ \omega(p,k)k_ik_j$$

where, $\omega(p,k)$ is the collision rate the of D^0 meson, with initial momenta p and final momenta $(p-k)$

$i,j = 1,2,3$ are the spatial indices

In the low transverse momentum limit, $(p \to 0)$, $A_i = \gamma p_i$ and $B_{ij} = B\delta_{ij}$

where, γ is the drag coefficient and B is the momentum diffusion coefficient

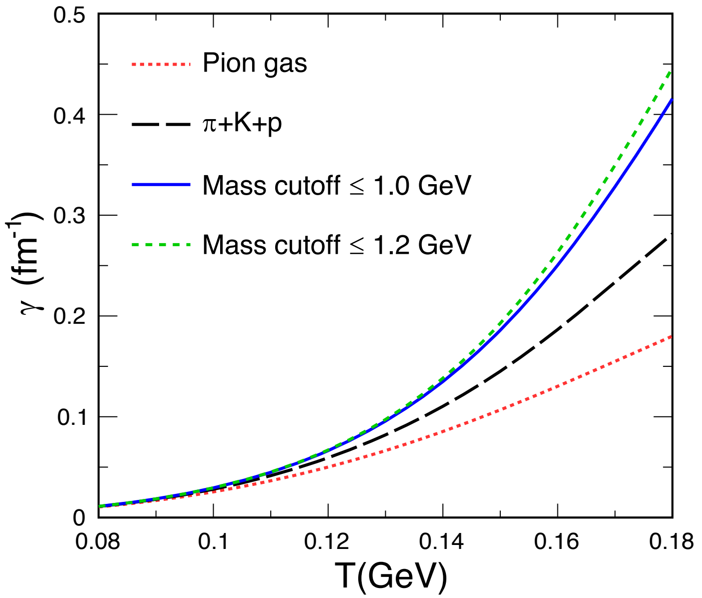
Drag coefficient

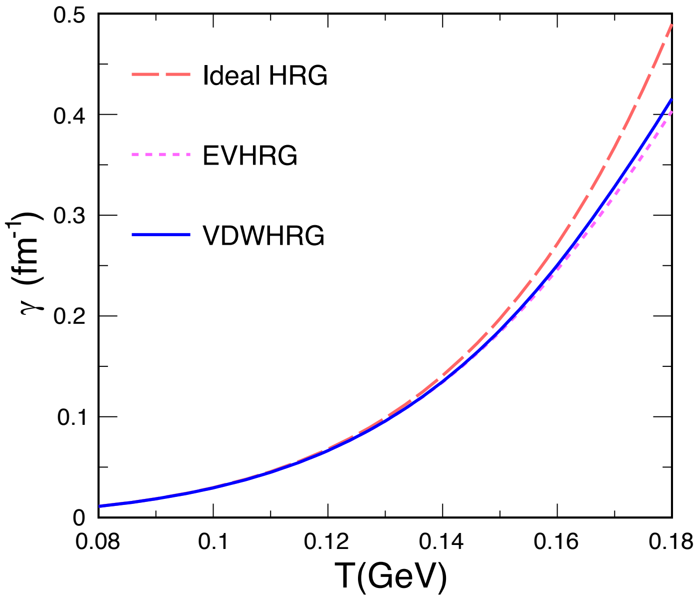
- Inverse of relaxation time can be expressed as, $\tau^{-1} = \sum_j n_j \langle \sigma_{jD} v_{jD} \rangle$
- σ_{jD} and v_{jD} is the scattering cross-section and relative velocity of j[th] hadronic species with D-meson

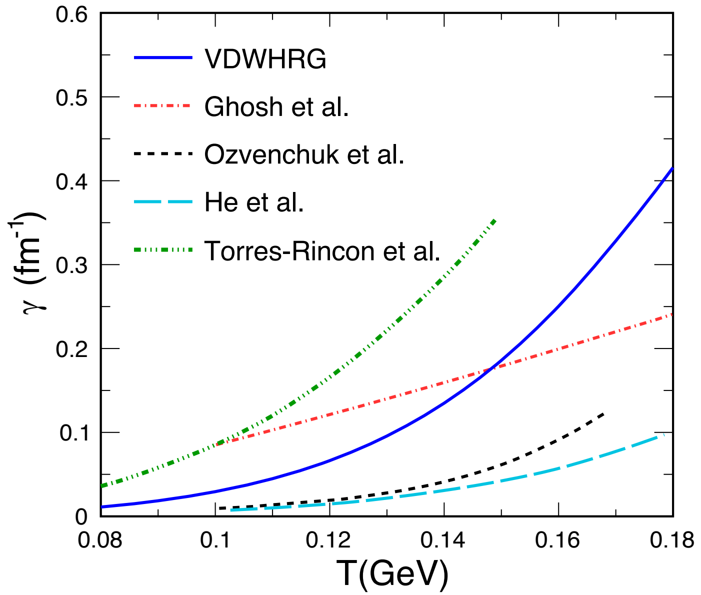
$$\langle \sigma_j v_j \rangle = \frac{\sigma_{Dj}}{8T m_D^2 m_j^2 K_2(\frac{m_D}{T}) K_2(\frac{m_j}{T})} \int_{(m_D+m_j)^2}^{\infty} ds \frac{s-(m_D-mj)^2}{\sqrt{s}} (s-(m_D+m_j)^2) K_1(\frac{\sqrt{s}}{T})$$

- Using the relaxation time, $\gamma = \frac{1}{\tau}$

Goswami et. al, Phys. Rev. D **108**, 074011 (2023)





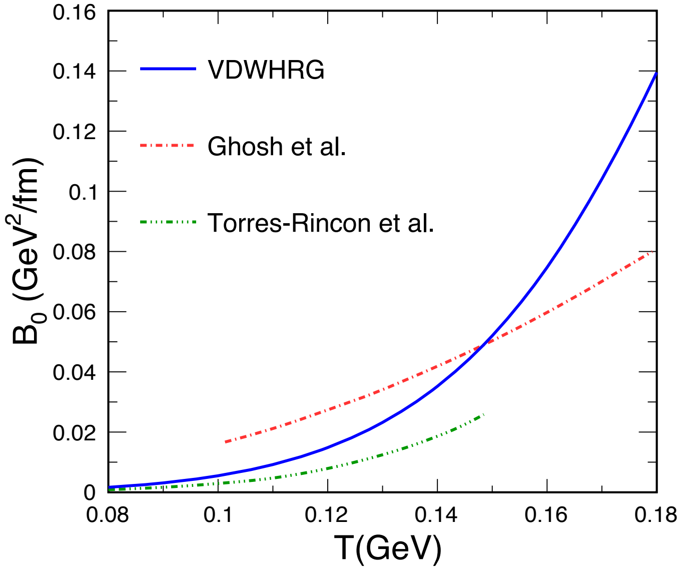


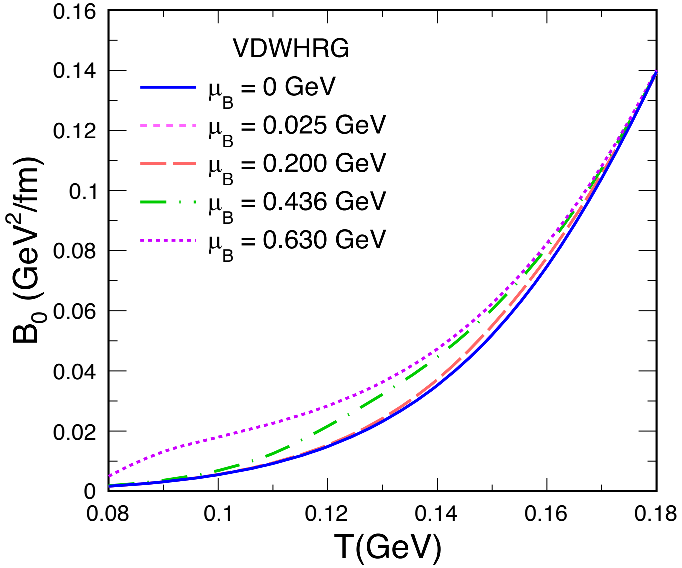
Momentum diffusion coefficient

$$B_0 = \gamma m_D T$$

- Momentum diffusion coefficient describes the momentum broadening of final state particles
- Our results compatible with other estimations

- Ghosh et. al : Effective field theory
- Torres-Rincon et. al : Kadanoff-Baym approach to derive the off-shell Fokker-Planck equation
- He et. al : calculated using empirical elastic scattering amplitudes
- Ozvenchuk et. al : in a hadron gas using cross-section of D meson with hadrons



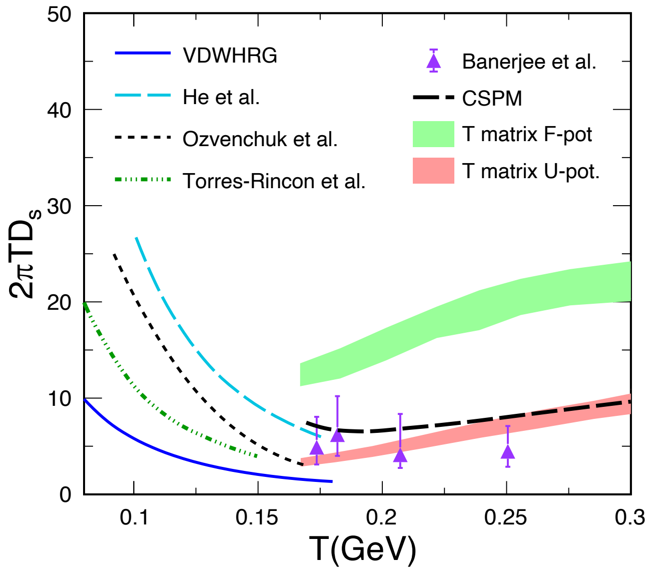


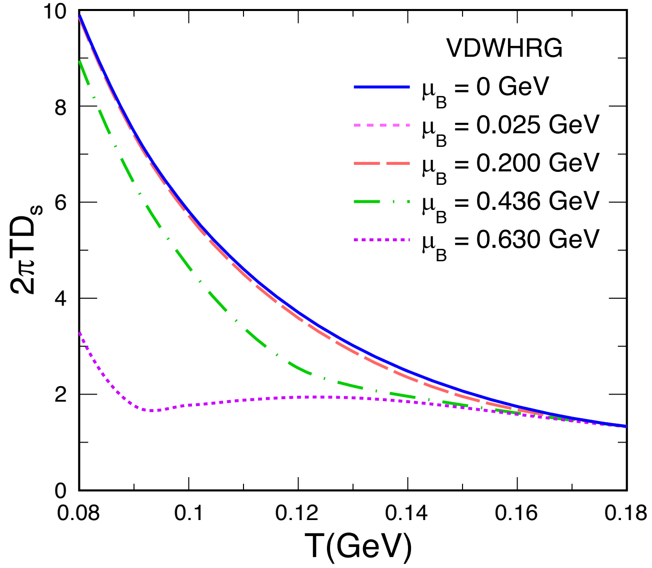
Goswami et. al, Phys. Rev. D **108**, 074011 (2023)

Spatial diffusion coefficient

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

- The spatial diffusion coefficient can be understood as the speed of diffusion in space
- Shows a minima near the critical temperature
- AdS/CFT estimation gives $2\pi T D_s \simeq 1$
- With an increase in chemical potential, a sharp change can be observed at low temperature





Goswami et. al, Phys. Rev. D **108**, 074011 (2023)

Fluctuations of open charmed hadrons

Physics Letters B 737 (2014) 210–215

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The melting and abundance of open charm hadrons

A. Bazavov [a], H.-T. Ding [b], P. Hegde [b], O. Kaczmarek [c], F. Karsch [c,d], E. Laermann [c], Y. Maezawa [c], Swagato Mukherjee [d], H. Ohno [d,e], P. Petreczky [d], C. Schmidt [c], S. Sharma [c,*], W. Soeldner [f], M. Wagner [g]

[a] Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52240, USA
[b] Key Laboratory of Quark & Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan, 430079, China
[c] Fakultät für Physik, Universität Bielefeld, D-33615 Bielefeld, Germany
[d] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[e] Center for Computational Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan
[f] Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany
[g] Physics Department, Indiana University, Bloomington, IN 47405, USA

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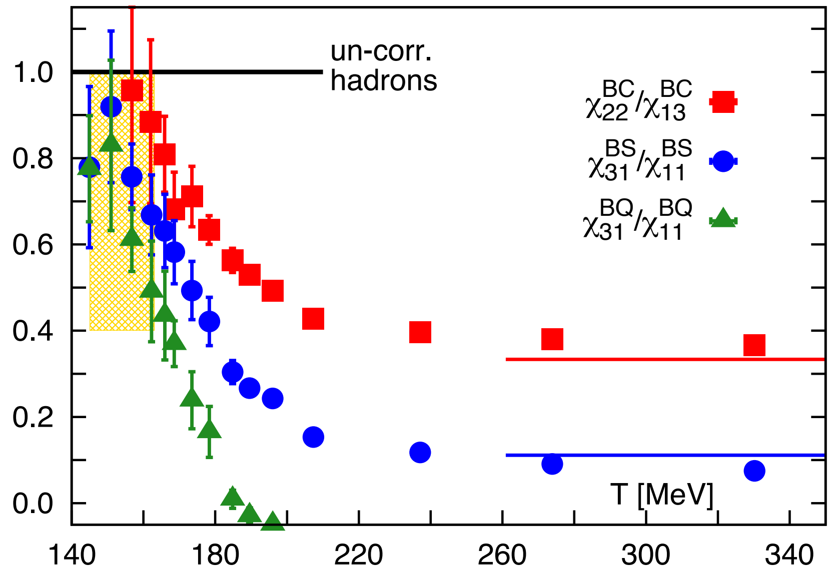
ABSTRACT

Ratios of cumulants of conserved net charge fluctuations are sensitive to the degrees of freedom that are carriers of the corresponding quantum numbers in different phases of strong interaction matter. Using lattice QCD with 2 + 1 dynamical flavors and quenched charm quarks we calculate second and fourth order cumulants of net charm fluctuations and their correlations with other conserved charges such as net baryon number, electric charge and strangeness. Analyzing appropriate ratios of these cumulants we probe the nature of charmed degrees of freedom in the vicinity of the QCD chiral crossover region. We show that for temperatures above the chiral crossover transition temperature, charmed degrees of freedom can no longer be described by an uncorrelated gas of hadrons. This suggests that the dissociation of open charm hadrons and the emergence of deconfined charm states sets in just near the chiral crossover transition. Till the crossover region we compare these lattice QCD results with two hadron resonance gas models—including only the experimentally established charmed resonances and also including additional states predicted by quark model and lattice QCD calculations. This comparison provides evidence for so far unobserved charmed hadrons that contribute to the thermodynamics in the crossover region.

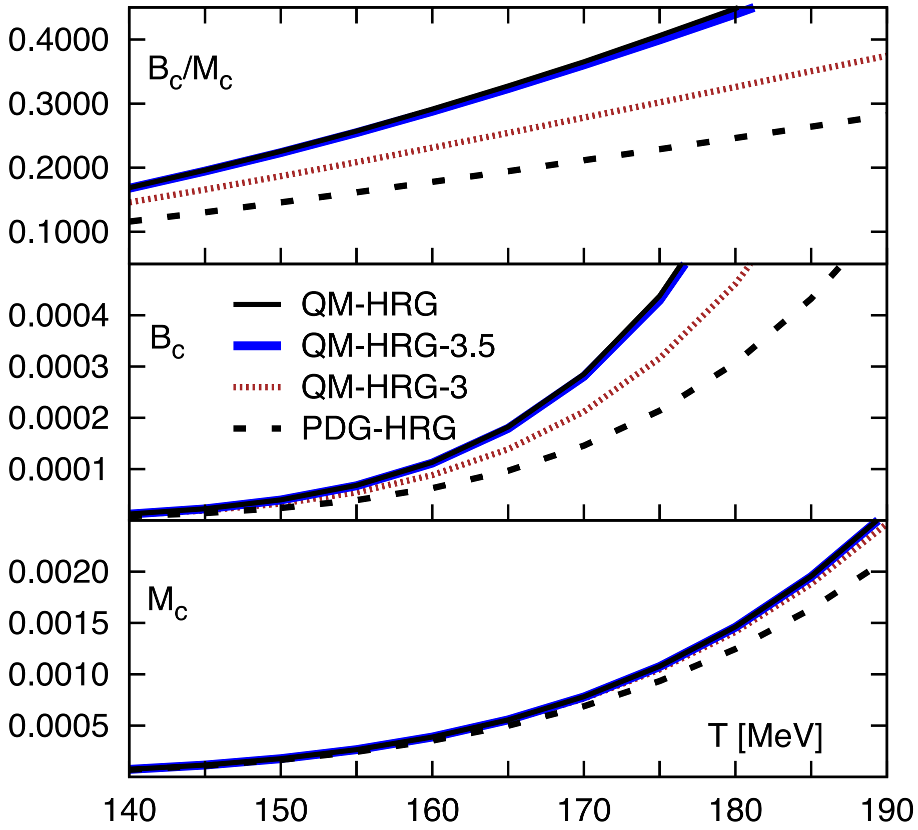
- Fluctuations of conserved quantities are sensitive to the QCD phase transition and QCD critical point
- The susceptibilities of conserved charges are given by

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

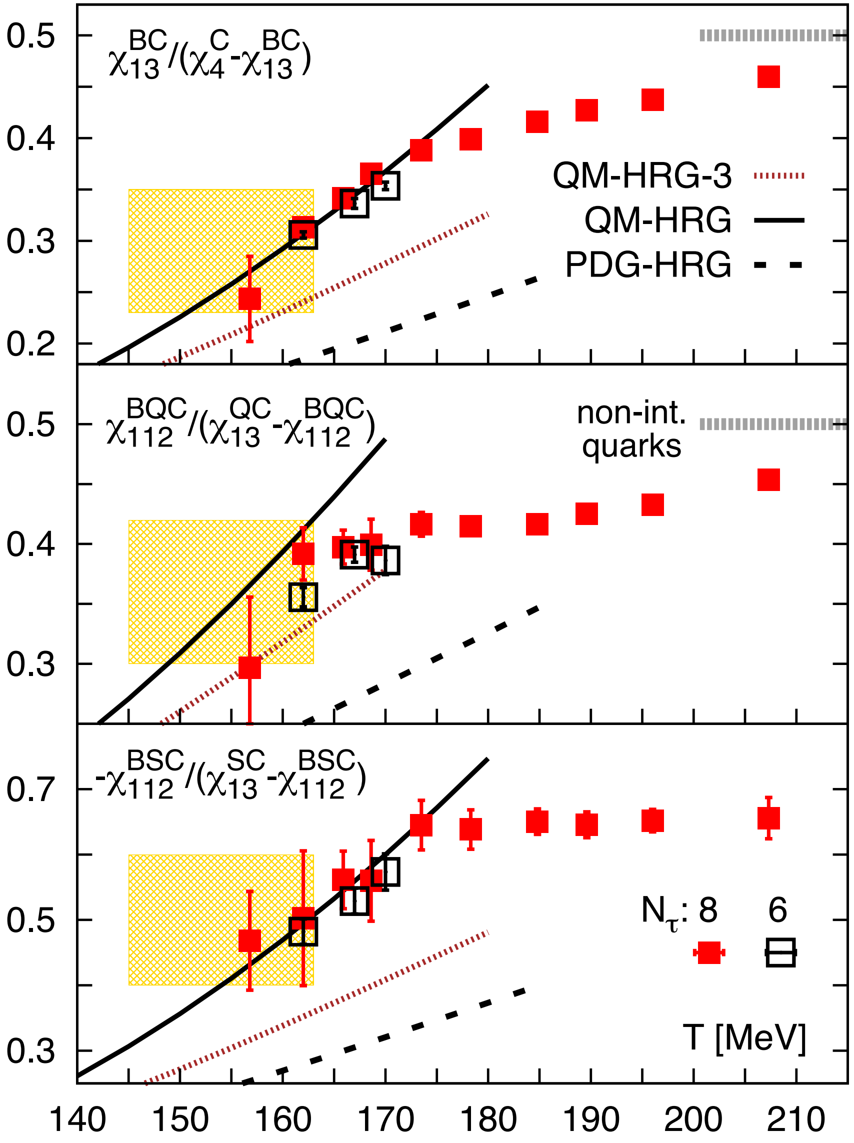


A. Bazavov et. al, Phys. Lett. B **737**, 210 (2014)

Fluctuations of open charmed hadrons



A. Bazavov et. al, Phys. Lett. B **737**, 210 (2014)

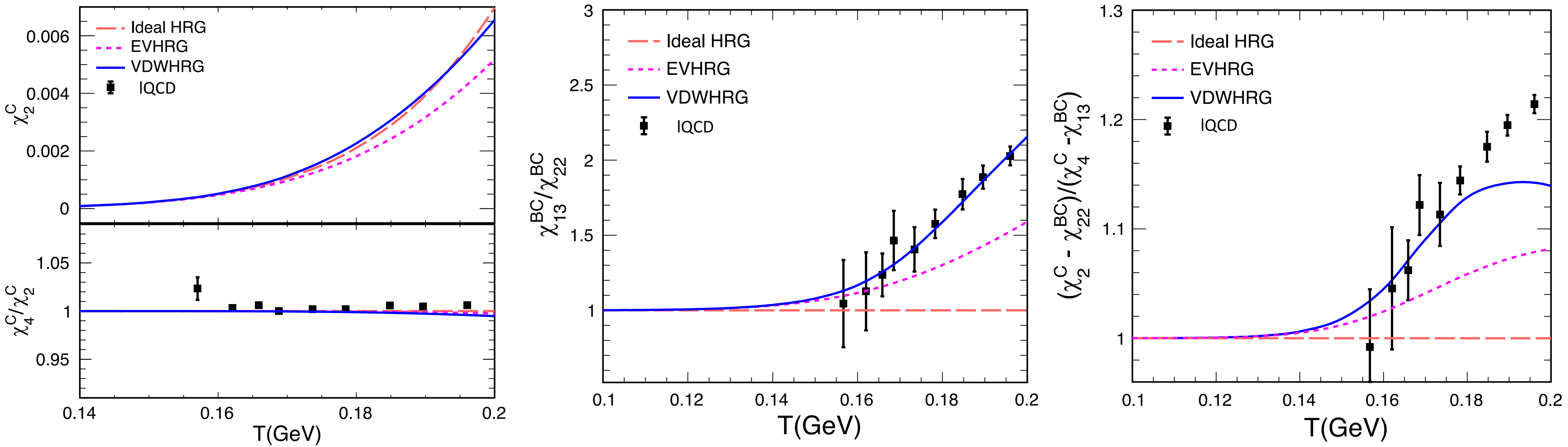


- Some charmed states are still missing from the PDG
- Quark model predictions compensates for the same

Eur. Phys. J. C **66**, 197 (2010)

Phys. Rev. D **84**, 014025 (2011)

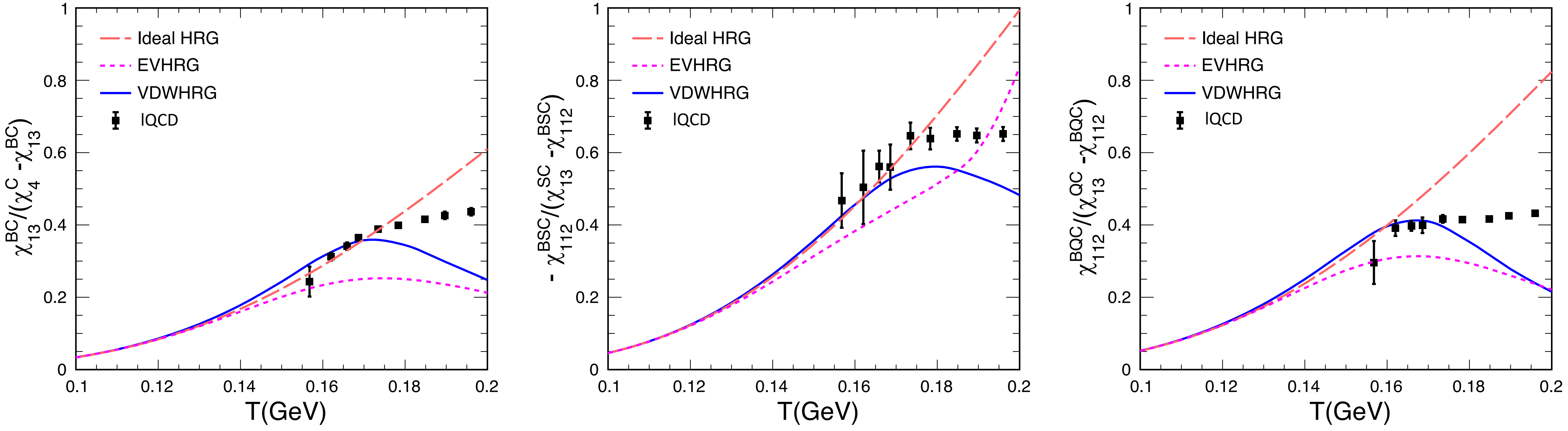
Fluctuations of open charmed hadrons



Goswami et. al, Phys. Rev. D **108**, 074011 (2023)

- IHRG model fails to explain the trend for some of the ratios, while the VDWHRG agrees well with lQCD data
- The rise from unity towards 3 hints at the melting of charmed hadrons to charm quark degree of freedom
- Open charm hadrons start to dissolve already close to the chiral crossover

Fluctuations of open charmed hadrons



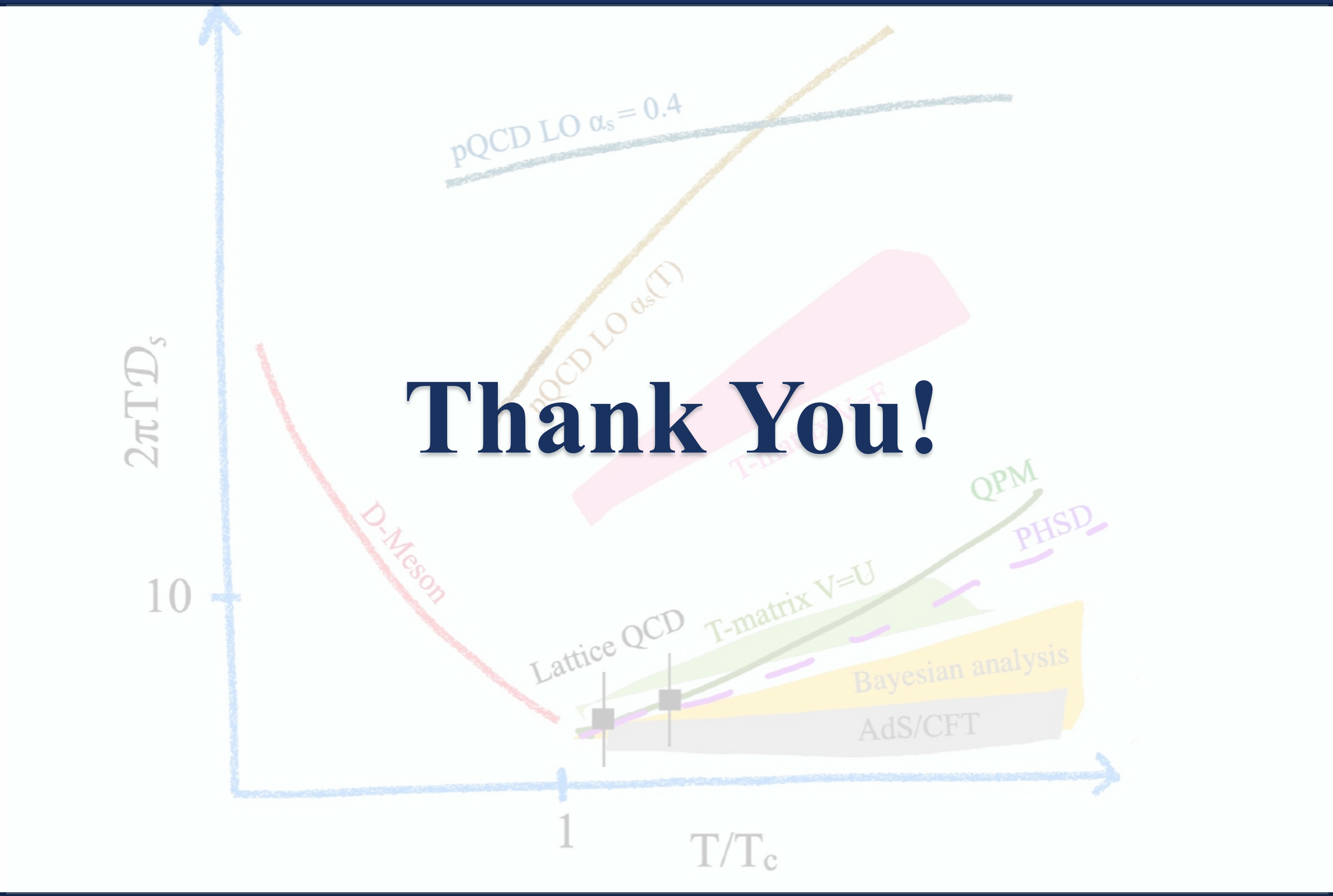
Goswami et. al, Phys. Rev. D **108**, 074011 (2023)

- A large number of experimentally not measured open charm hadrons will contribute to bulk thermodynamics close to the melting temperature
- This should be taken into account when analyzing the hadronization of charmed hadrons in heavy ion collision experiments

Summary

- Estimated D^0 meson diffusion in an interacting hadron resonance gas
- Results are compatible with other phenomenological models
- Estimated the charm fluctuations in the interacting hadronic medium
- VDWHRG explains the lQCD data very well up to 170-180 MeV temperature
- Alternative method to study higher-order fluctuations in a hadronic medium

Thank You!


pQCD LO $\alpha_s = 0.4$
pQCD LO $\alpha_s(T)$
$2\pi T \mathcal{D}_s$
10
D-Meson
QPM
PHSD
T-matrix V=U
Lattice QCD
Bayesian analysis
AdS/CFT
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T/T_c