Exploring the melting of heavy-flavor hadrons and diffusion of charm quarks

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Based on: Phys Rev D **107** 014003 (2023) and Phys Rev D **108** 074011 (2023)

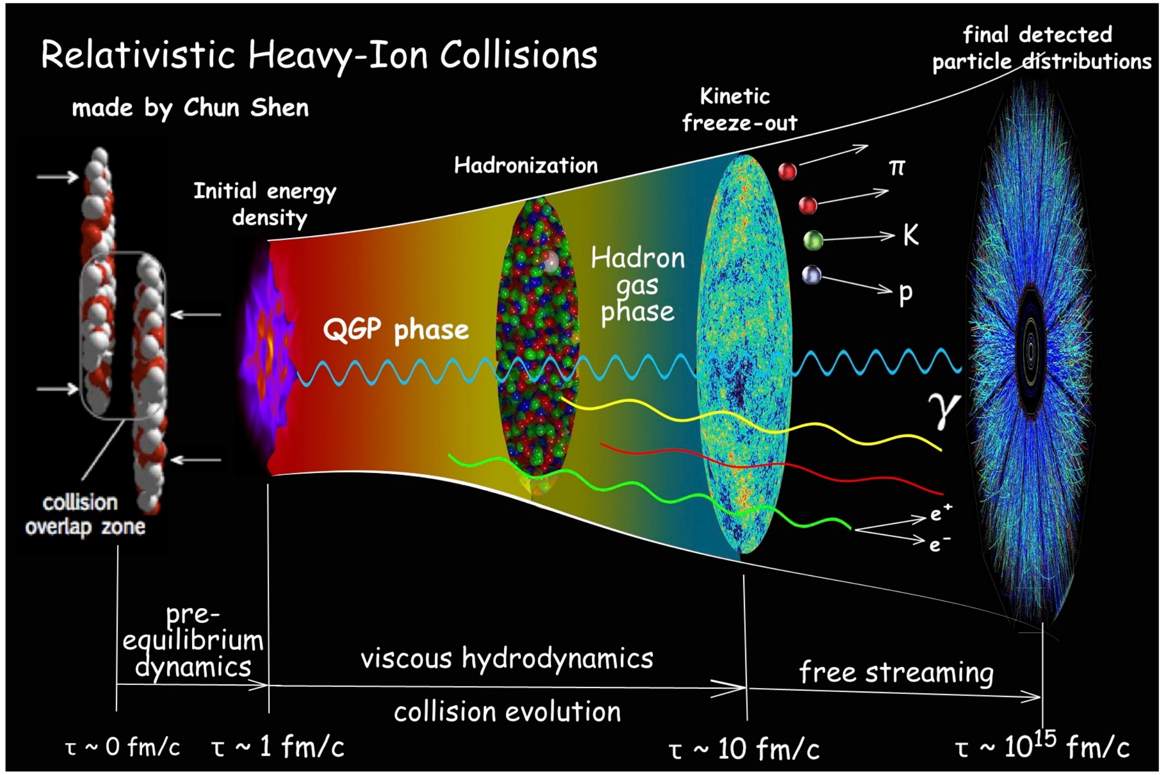
QNP 2024

10th International Conference on Quarks and Nuclear Physics
08 – 12 July 2024

Outline

- Introduction
- Brownian Motion and Fokker-Planck equation
- Phenomenological models
- Results
- Summary

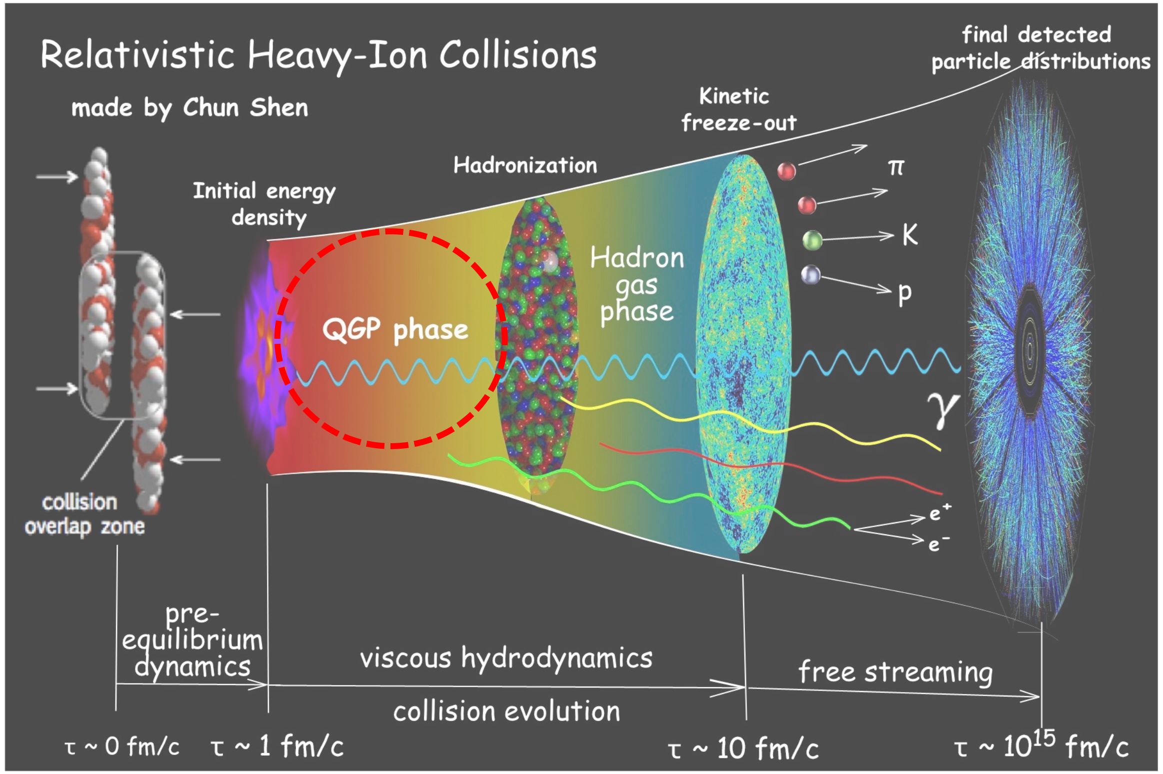
Introduction



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

- To understand the medium formed in an ultra-relativistic heavy ion collision
- Heavy quarks as probe
  - Formed initially in the system
  - Mass >> Temperature of the medium
- Charm quark as a probe to study transport properties of the medium
  - Relaxation time of charm quarks is greater than the lifetime of QGP

Introduction



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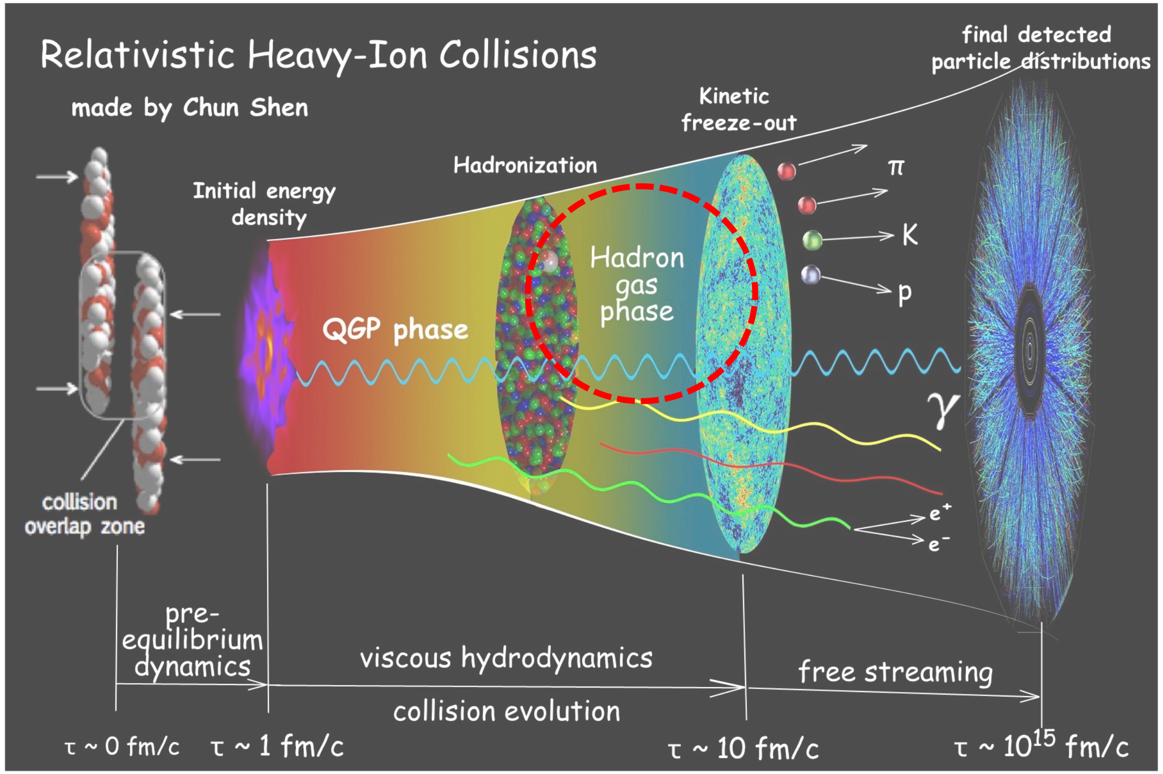
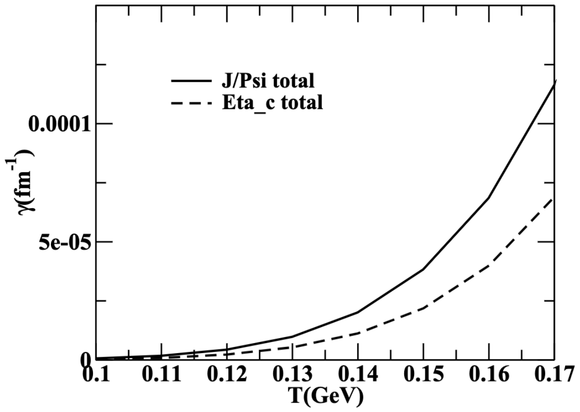
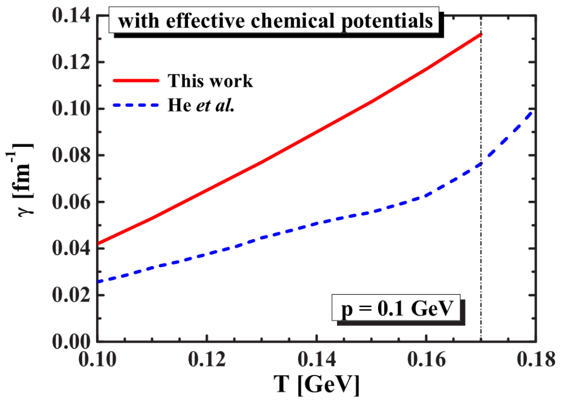


Sketch of relativistic heavy-ion collisions, Chun Shen, Ohio State University

- One of the most prominent probes of Quark-Gluon Plasma: Charmonia ($c\bar{c}$)
  - In the hadronic phase, the charmonia states are relatively undiffused.
- Open charm hadrons like $D^0(c\bar{u})$ have relatively larger interaction cross-section in the hadronic medium.
  - Ideal probe to explore the interactions of the



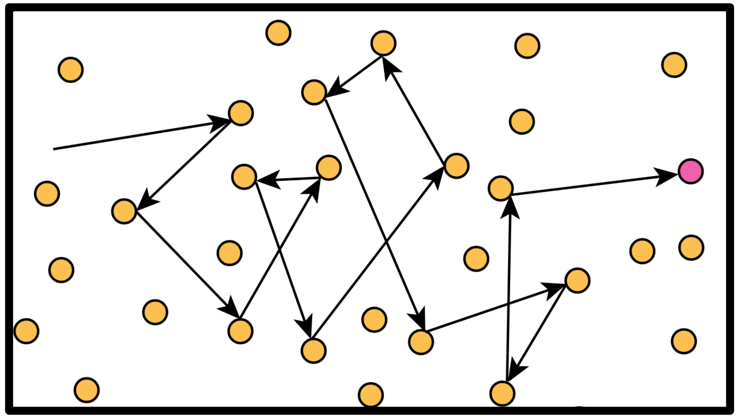


S. Mitra et. al, Nucl. Phys. A 951, 75 (2016)
V. Ozvenchuk et. al, Phys Rev C 90 054909 (2014)

Brownian Motion and Fokker-Planck equation

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

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

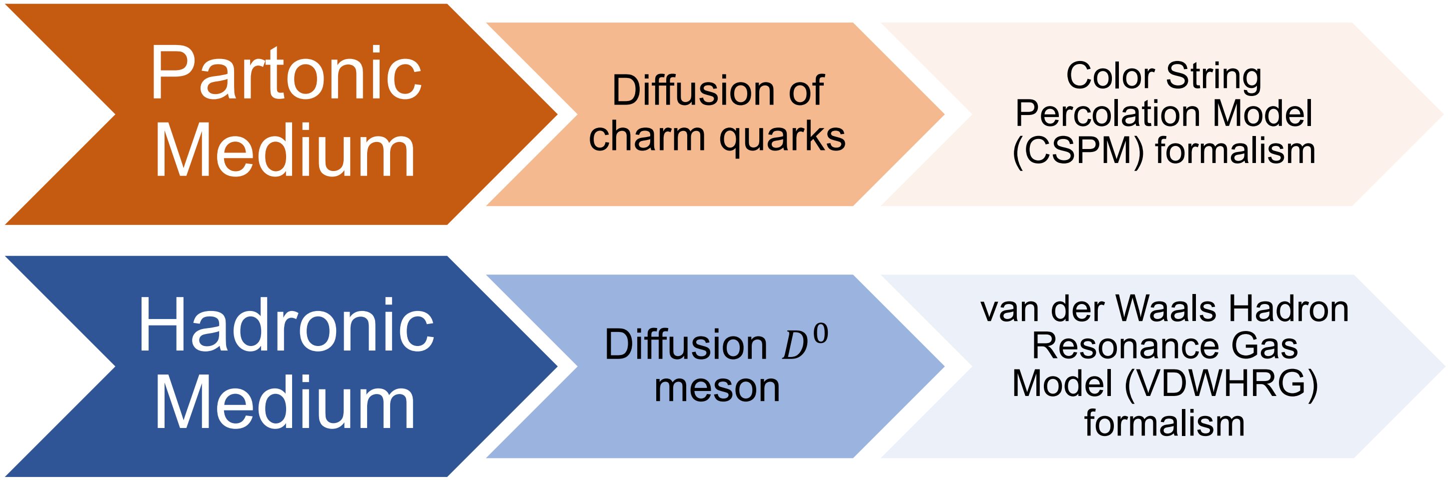


- The drag, A^i, and diffusion, B^{ij}, coefficient in the low momenta limit, $p \to 0$ by,

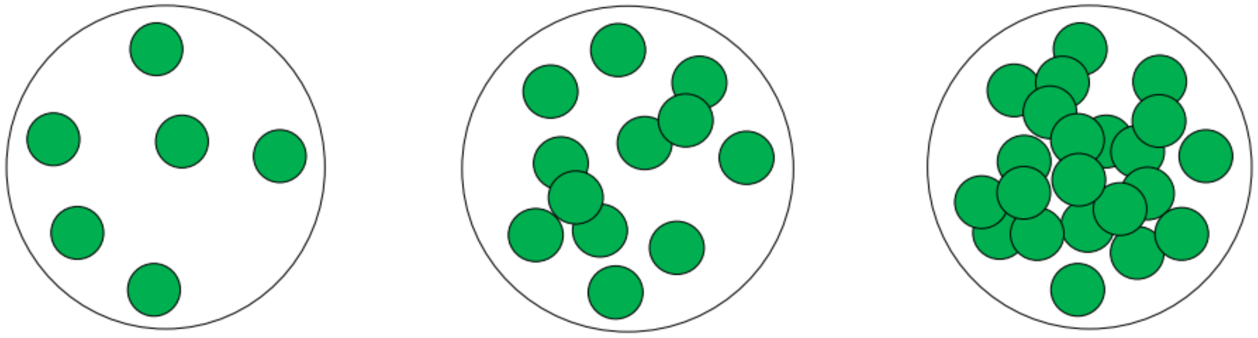
$$A^i = \gamma p^i$$

$$B^{ij} = B_0 P_{\perp}^{ij} + B_1 P_{\parallel}^{ij}$$

- We estimate the relaxation time for the partonic medium using Color String Percolation Model (CSPM) formalism and for the hadronic phase the VDWHRG model has been incorporated



Color String Percolation Model (CSPM)



K. Goswami, D. Sahu and R. Sahoo, Phys. Rev. D **107,** 014003, (2023)

- Color strings formed between the partons of the colliding nuclei are viewed as discs in the transverse plane
- A macroscopic cluster appears at a certain critical string density (ξ_c), that marks the percolation phase transition.
- Here, ξ is the percolation density parameter given as $\xi = \rho S_1 = \frac{N_s S_1}{S}$
- The color suppression factor is given as,

$$F(\xi) = \sqrt{\frac{1 - e^{-\xi}}{\xi}}$$

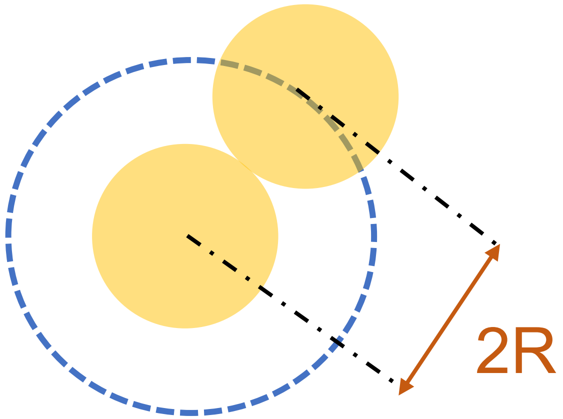
- The initial temperature of the percolation cluster can be expressed in terms of F(ξ) as,

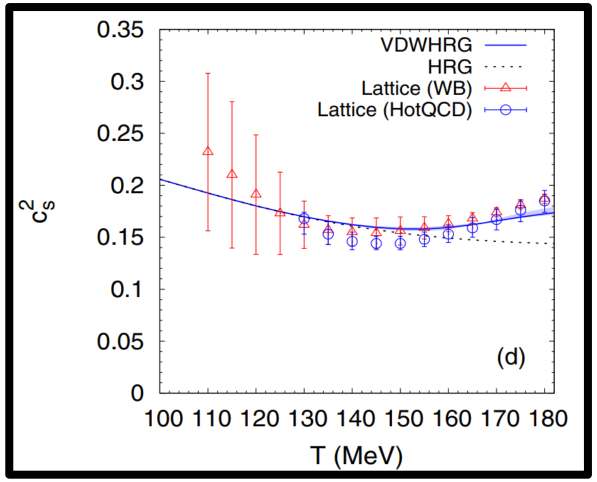
$$T(\xi) = \sqrt{\frac{\langle p_T^2 \rangle_1}{2F(\xi)}}$$

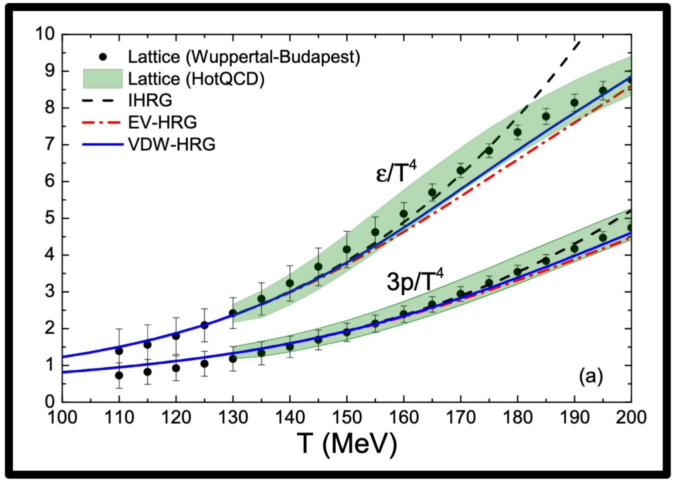
- where, $\langle p_T^2 \rangle_1$ is the average transverse momentum squared of a single string.
- With the information of temperature and percolation density parameter, we can estimate further observables.

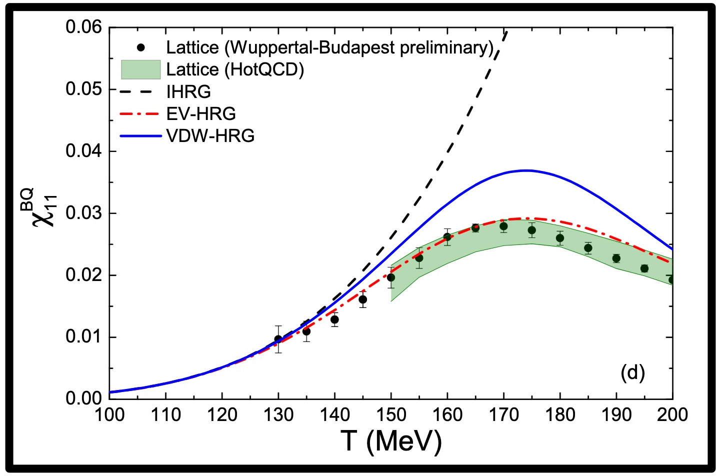
Van der Waals Hadron Resonance Gas Model

- Ideal HRG is a non-interacting statistical model consisting of hadrons and resonances.
- The VDWHRG model introduces attractive and repulsive forces between the hadron species, using two parameters, a and b.
- The interactive parameters are determined by fitting the thermodynamical quantities to lattice QCD calculation









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.

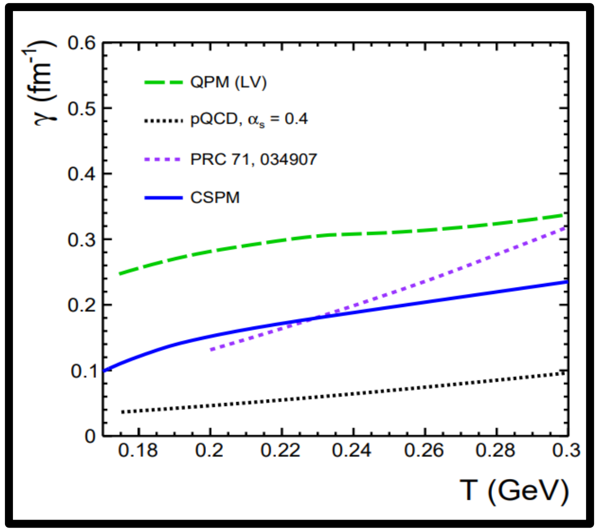
Drag coefficient - γ

- We estimate the drag coefficient by using the relation

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

- For the partonic medium, in the CSPM formalism, we use

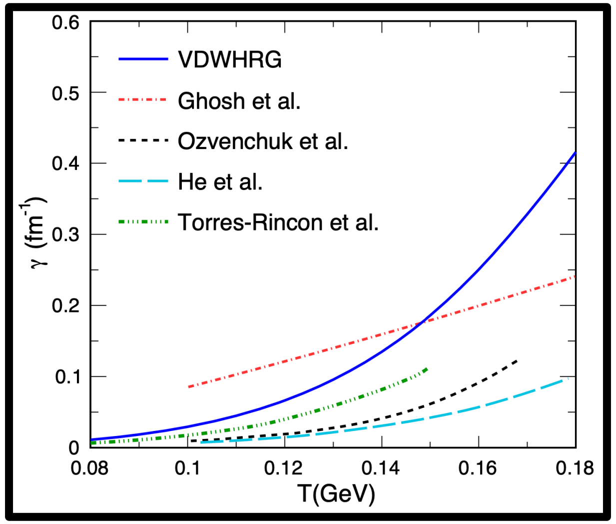
$$\tau = \frac{m_c}{T}\lambda = \frac{m_c}{T}\frac{L}{1 - e^{-\xi}}$$

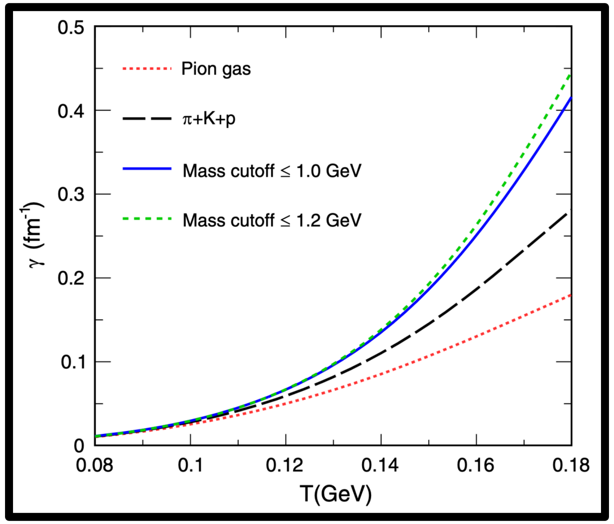


- The inverse of relaxation time can be expressed as,

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

σ_{jD} and v_{jD} is the scattering cross-section and relative velocity of j[th] hadronic species with D^0 meson

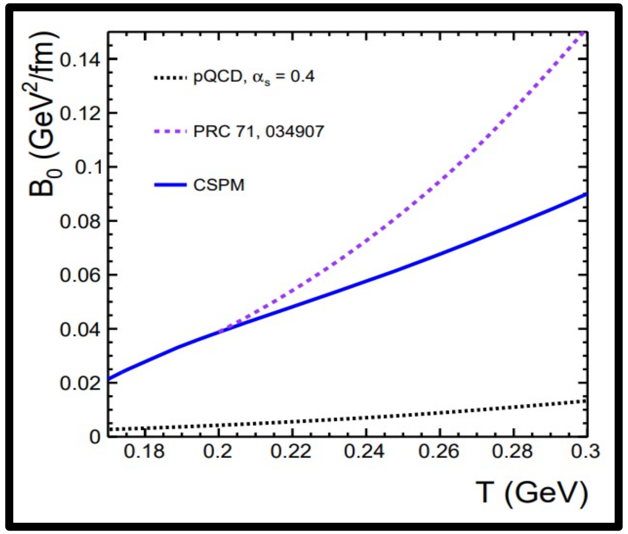


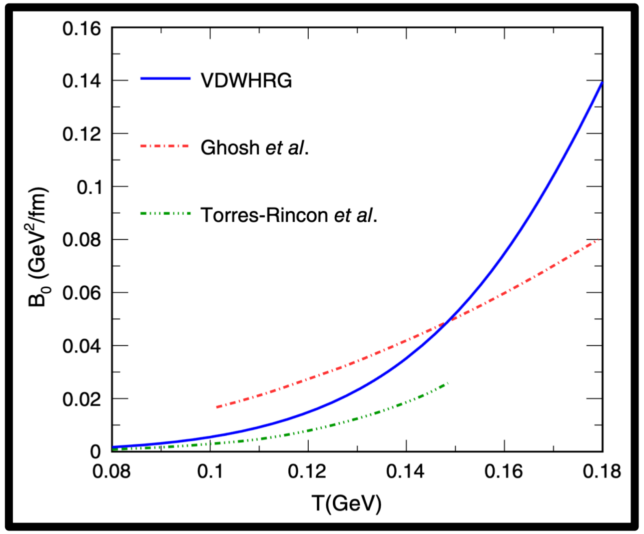


Diffusion coefficient - B_0 and D_s

- The momentum coefficient is related to drag coefficient as,

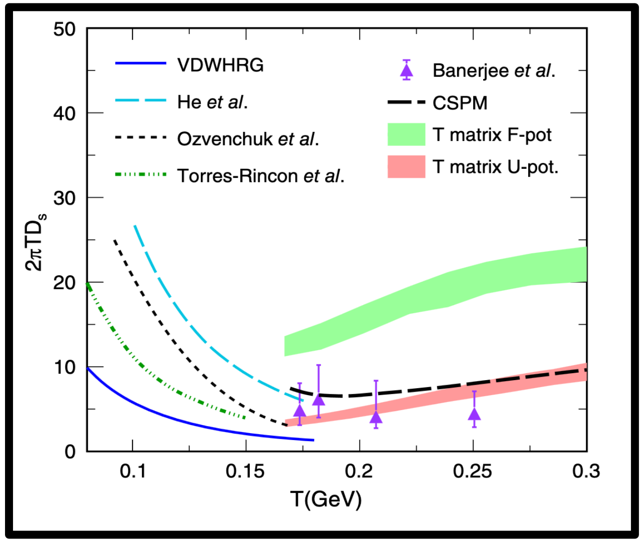
$$B_0 = \gamma m T$$

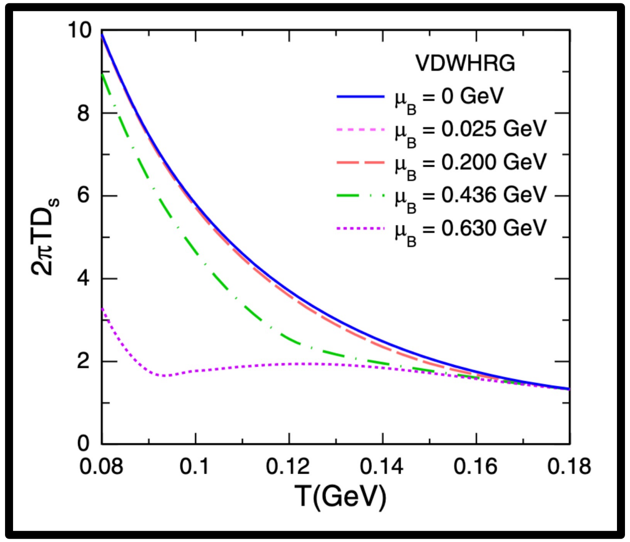




- The spatial diffusion coefficient is given in terms of drag coefficient as,

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

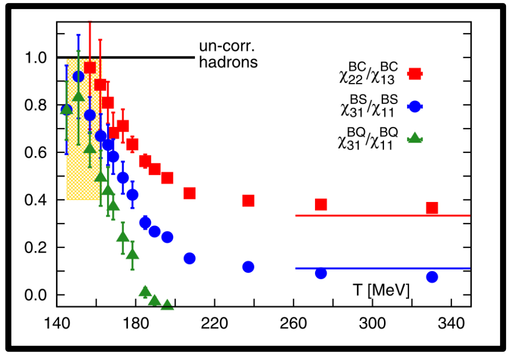


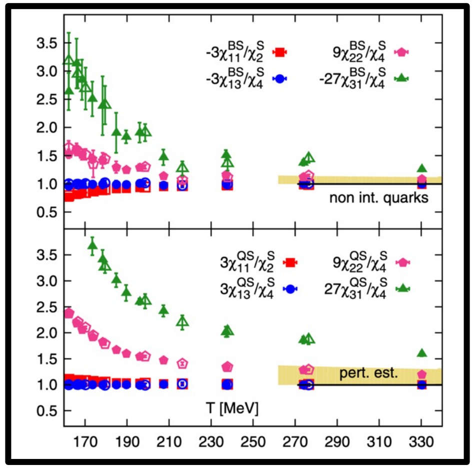


Melting of open charmed hadrons

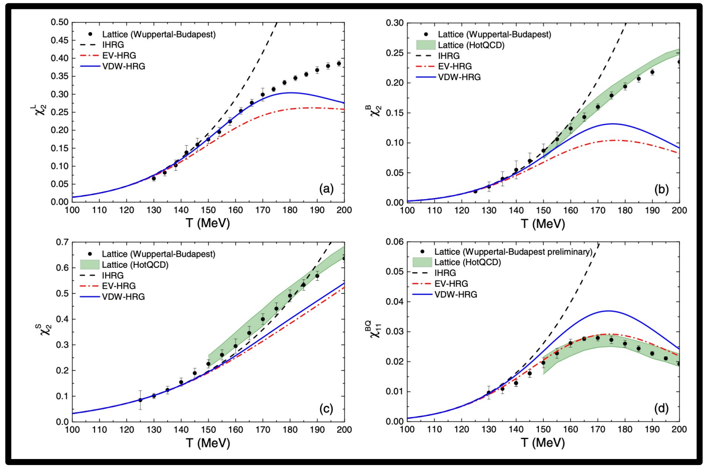
- The fluctuation of one charged particle in or out of the considered sub-volume produces a different fluctuation of the net conserved charge in hadronic medium as compared to a deconfined medium.
- We can estimate susceptibilities of conserved charges as,

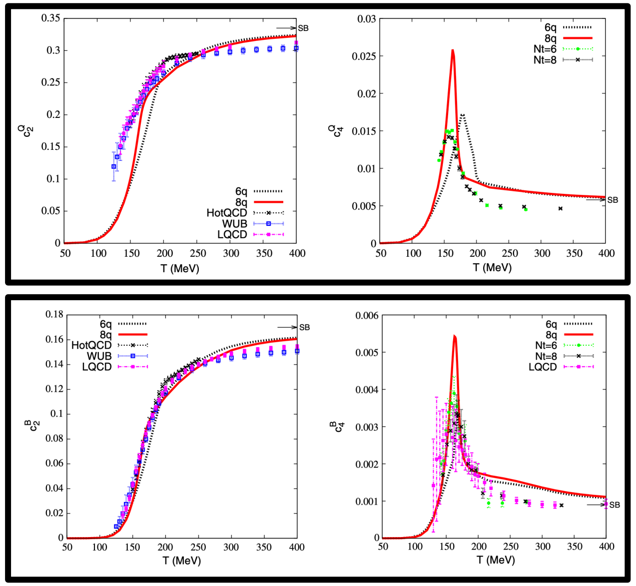
$$\chi_{ijkl}^{BSQC} = \frac{\partial^{i+j+k+l}\left(\frac{P}{T^4}\right)}{\partial\left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_S}{T}\right)^j \left(\frac{\mu_Q}{T}\right)^k \left(\frac{\mu_C}{T}\right)^l}$$





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



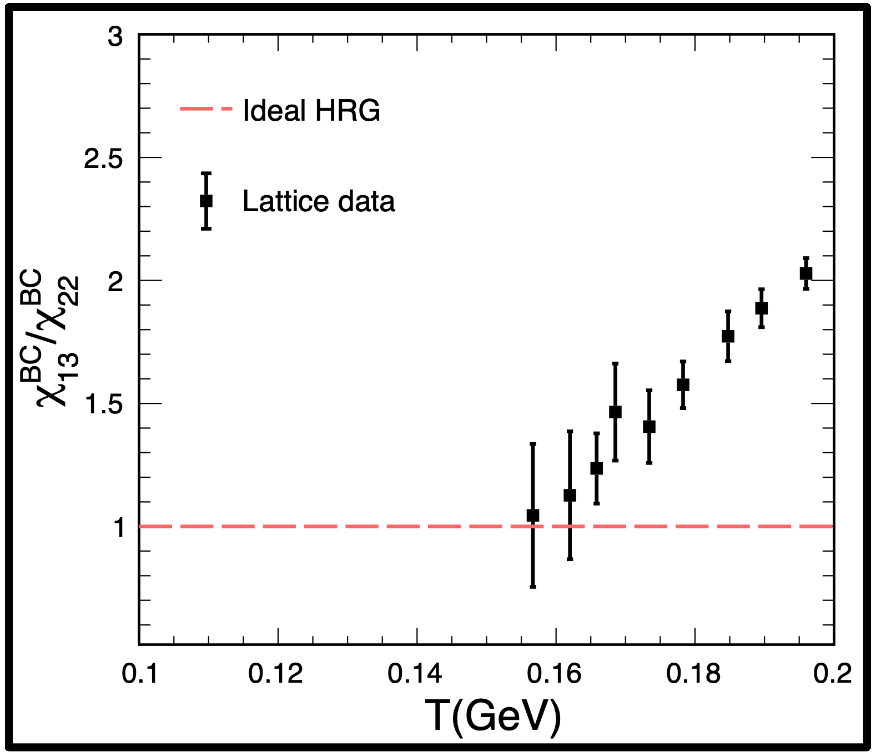


Volodymyr Vovchenko et. al, Phys. Rev. Lett. 118, 182301 (2017)
Abhijit Bhattacharyya, Phys. Rev. D 95, 054005 (2017)

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

Melting of open 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.

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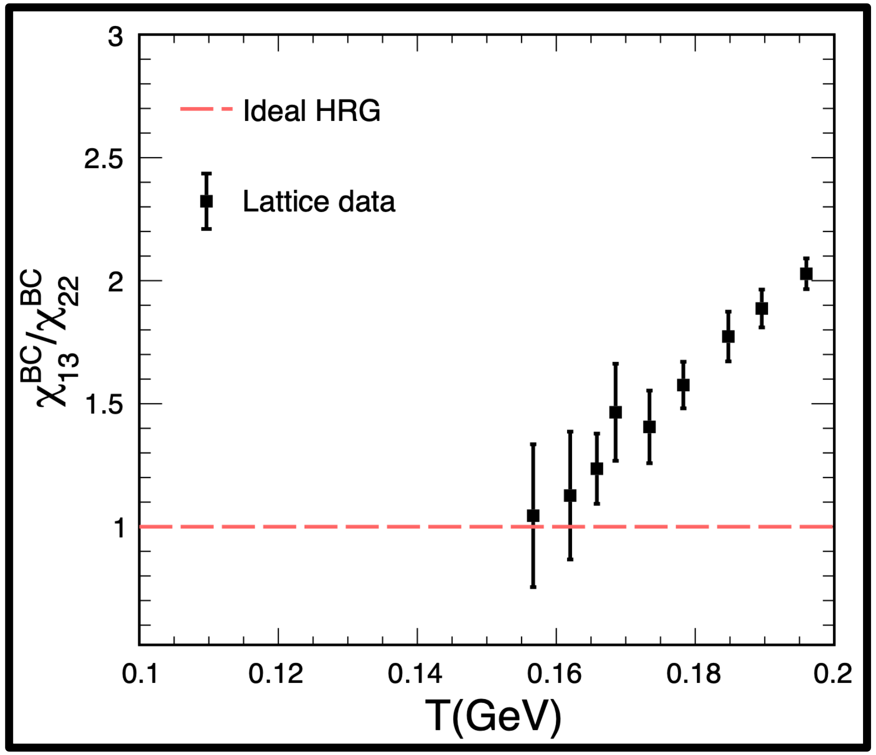

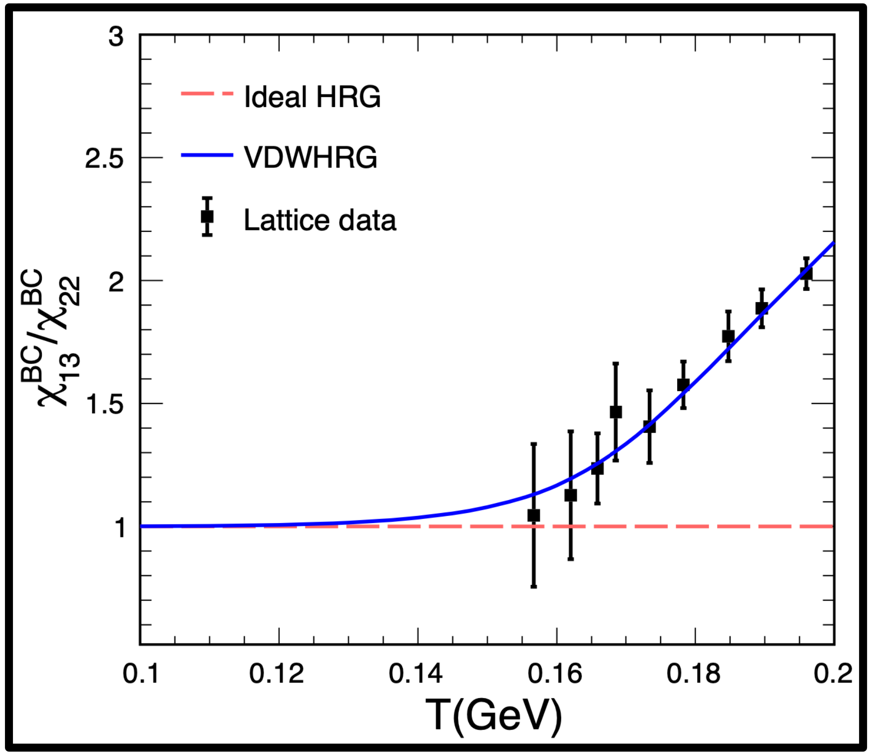

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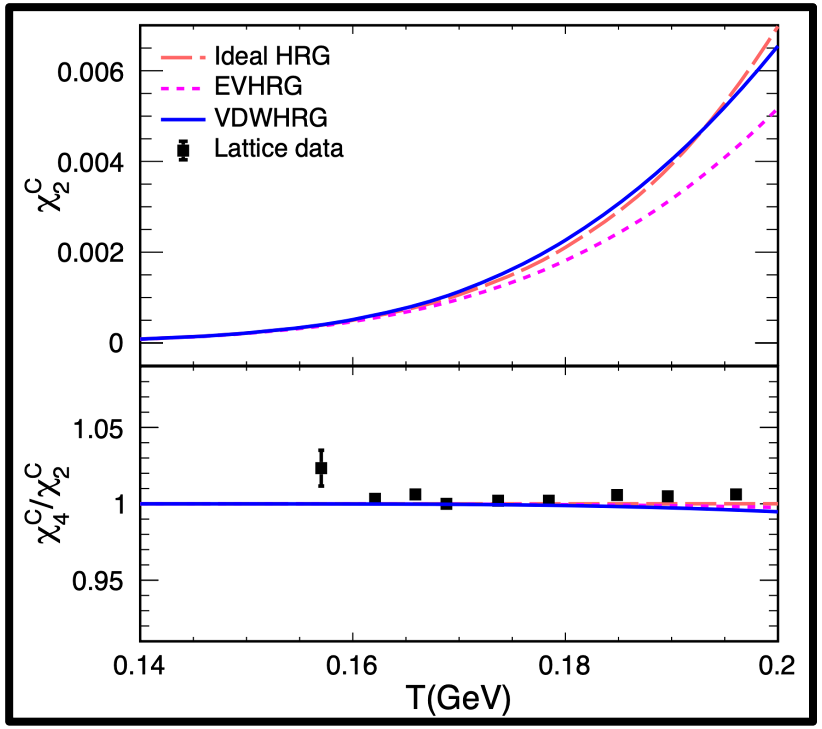
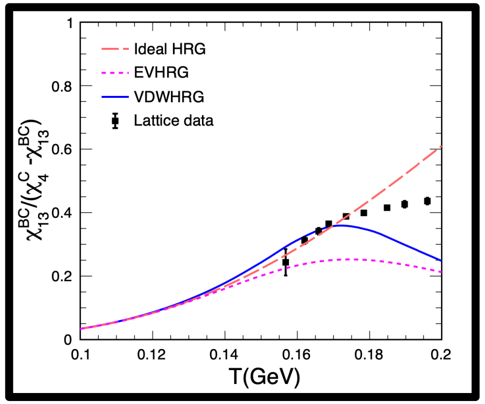
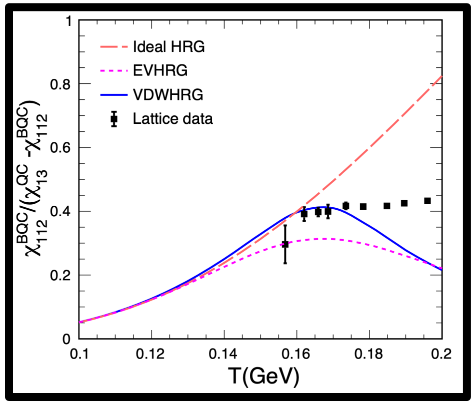
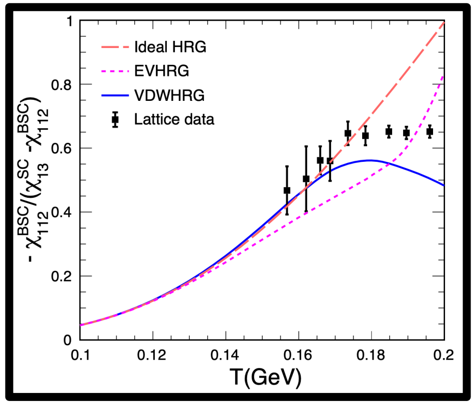
Melting of open charmed hadrons

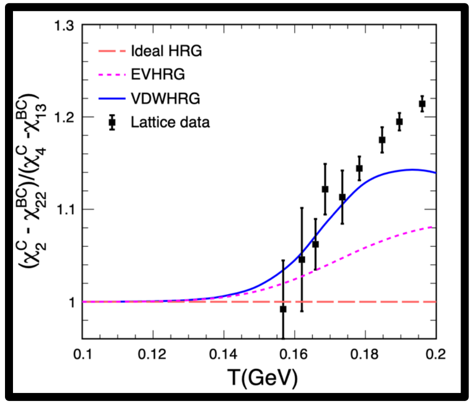
- Comparison between Van der Waals HRG model and existing lattice data.











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

Summary

- Explored drag and diffusion of charm quarks using CSMP formalism in a partonic medium
- 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 lattice-QCD data to a great extent

THANK YOU

Backup Slides

Backup

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

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

Backup

- Solution of 1-dimensional Fokker-Planck equation, where one can observe that 1/F, works as an intrinsic time for the relaxation process.

$$f(t,p) = \sqrt{\frac{F}{2\pi\Gamma(1-e^{-2Ft})}} \exp\left[-\frac{F(p-p_0e^{-Ft})^2}{2\Gamma\,(1-e^{-2Ft})}\right]$$

Torres-Rincon et. al. J. Phys. Conf. Ser. **503** 012020 (2014)

- Thus, we proceed with $\tau_R = 1/F$.