Diffusion matrix related to charmed state and a new probe for QCD critical point

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Based on: *Can charm fluctuation be a better probe to study QCD critical point?*

arXiv:2409.13255

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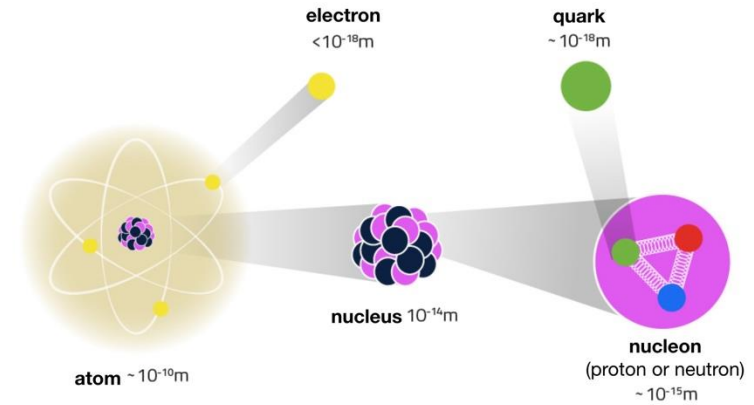
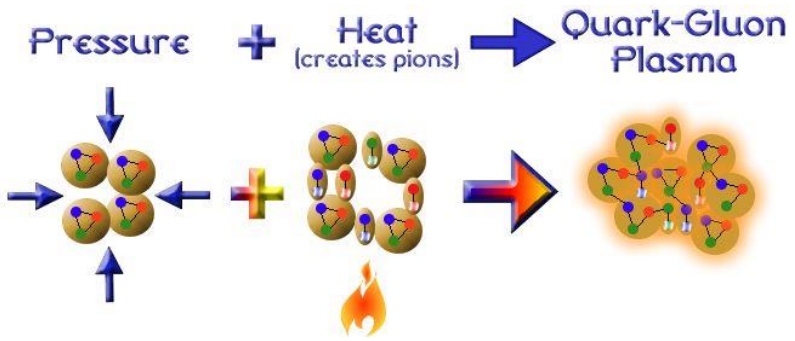
Outline

- Introduction
- Motivation
- Relativistic Fick’s law
- van der Waals HRG Model
- Results
- Summary

Introduction

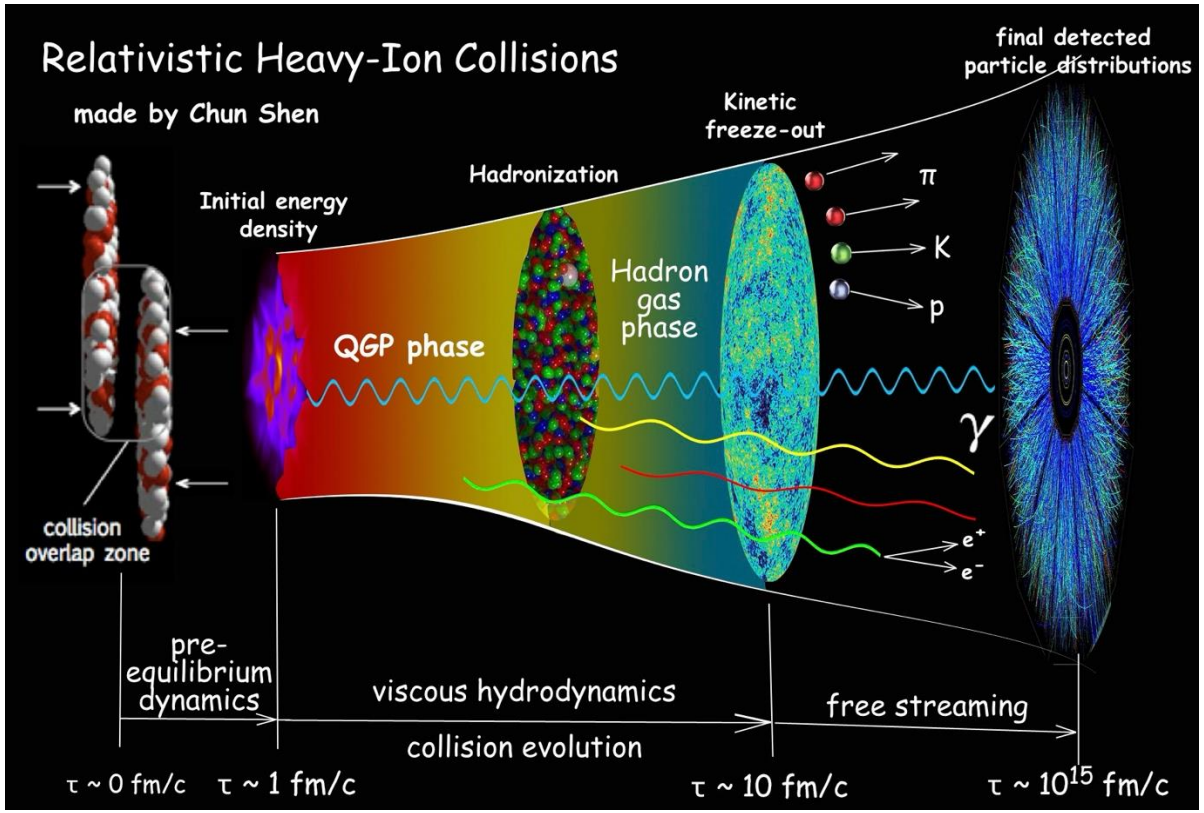




Under high temperature and high baryon density, a deconfined medium of thermalized quarks and gluons is predicted. It is termed as **Quark-Gluon Plasma (QGP)**

Source: Quark Matter 2018, http://scienzapertutti.infn.it , Quark Gluon Plasma, http://hep.itp.tuwien.ac.at/~ipp/qgp.html,

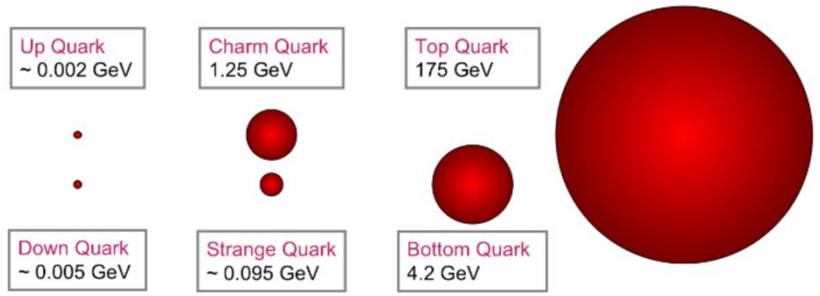
Producing Quark-Gluon Plasma in laboratory



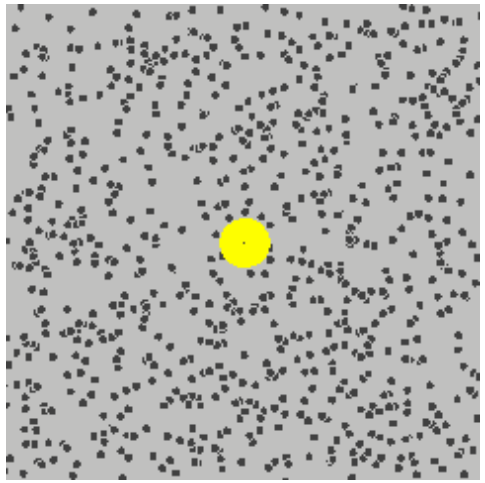
Sketch of relativistic heavy-ion collisions, Chun Shen, Ohio State University

Motivation

- 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
- Brownian Motion:
  - Charm quarks are much heavier than the constituent of the QGP medium, i.e. u, d, and s quarks
  - D Meson are relatively heavier than the major constituent of the hadronic medium, i.e. pion, kaon, and proton
- Can give us information about the medium through its study of the diffusion of heavy quarks and heavy-flavor hadrons
- This information can't be observed directly in experiments
- However, in principle this should affect experimental observables such as, elliptic flow (v_2) and nuclear modification factor (R_{AA})



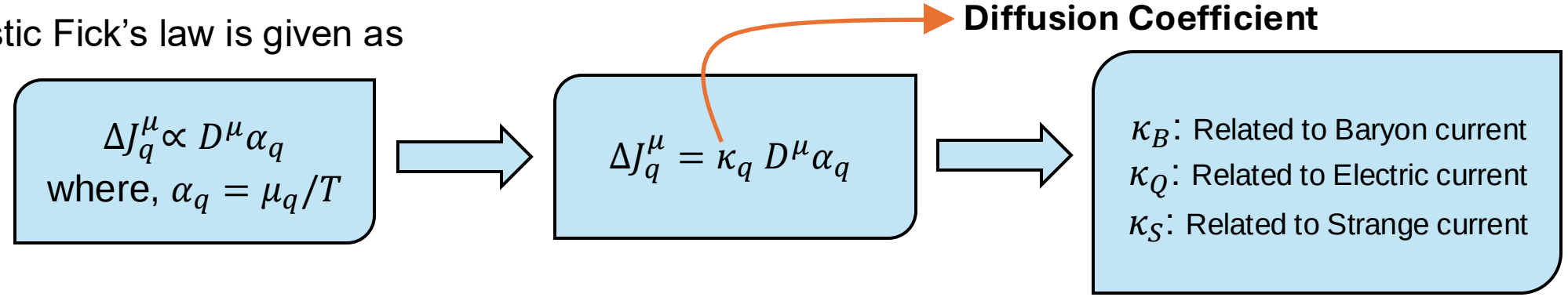
D. Kazakov, Phys. Usp. 57, 930 (2014)



Source: Brownian motion, Wikipedia

Diffusion matrix related to charm sector

The relativistic Fick's law is given as



M. Greif, et al., Phys. Rev. Lett. **120**, 242301 (2018).
Das et. al. Phys Rev D **106** 014013 (2022)

Diffusion matrix related to charm sector

The relativistic Fick's law is given as

$\Delta J_q^\mu \propto D^\mu \alpha_q$
where, $\alpha_q = \mu_q / T$

$\Delta J_q^\mu = \kappa_q \, D^\mu \alpha_q$

Diffusion Coefficient

κ_B: Related to Baryon current
κ_Q: Related to Electric current
κ_S: Related to Strange current

Contribution due to cross terms (κ_{BS}, κ_{BQ} etc.) can't be neglected.

$$\begin{pmatrix} \Delta J_B^i \\ \Delta J_Q^i \\ \Delta J_S^i \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \begin{pmatrix} D^i \alpha_B \\ D^i \alpha_Q \\ D^i \alpha_S \end{pmatrix}$$

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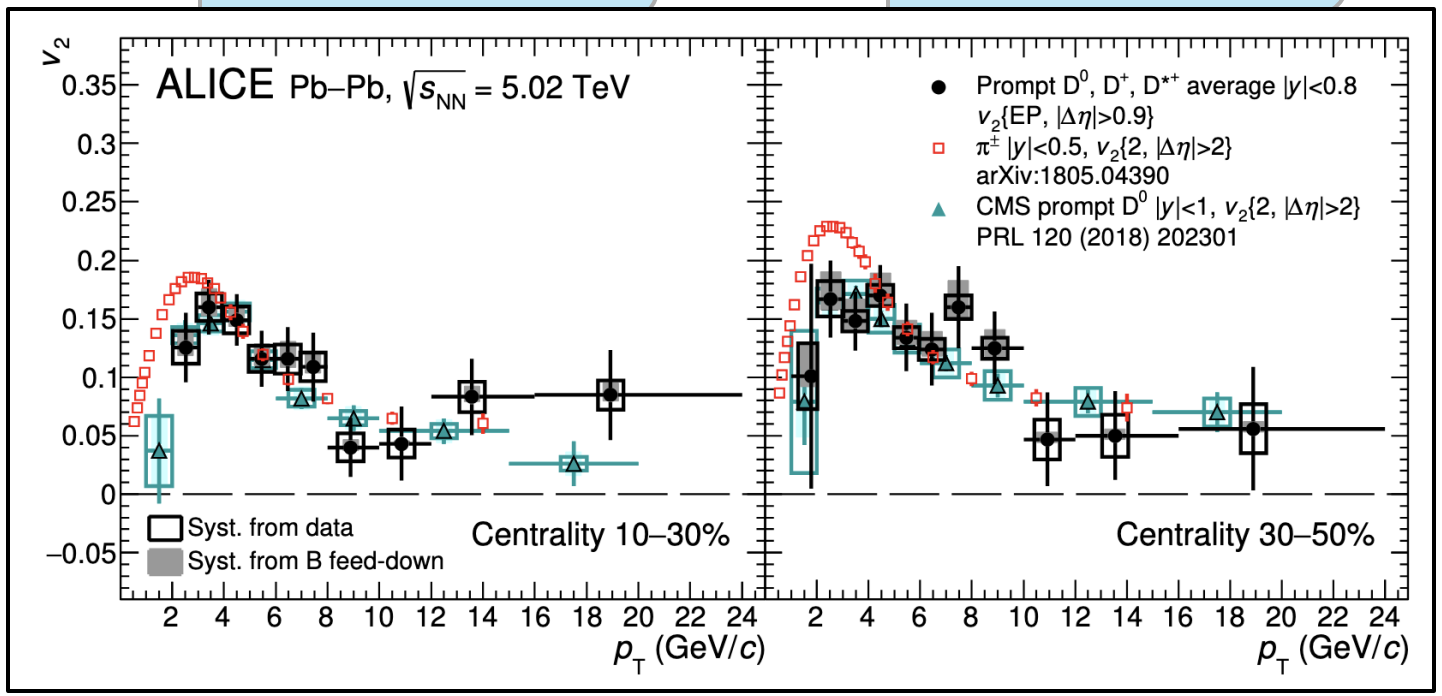
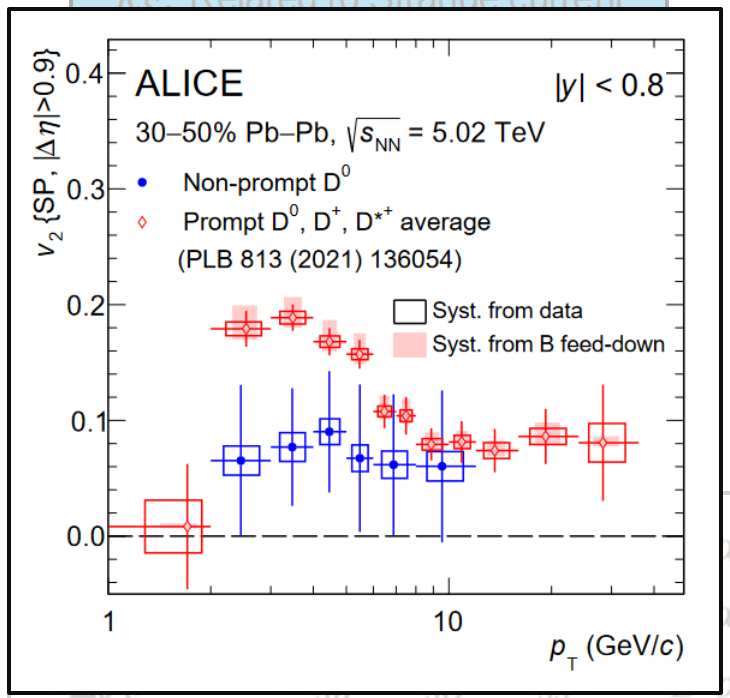


ALICE Collaboration, JHEP **02**, 150 (2019)



ALICE Collaboration, EPJC **83** 1123 (2023)

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$$\begin{pmatrix} J_{\mathrm{B}}^\nu \\ J_{\mathrm{Q}}^\nu \\ J_{\mathrm{S}}^\nu \\ J_{\mathrm{C}}^\nu \end{pmatrix} = \begin{pmatrix} \kappa_{\mathrm{BB}} & \kappa_{\mathrm{BQ}} & \kappa_{\mathrm{BS}} & \kappa_{\mathrm{BC}} \\ \kappa_{\mathrm{QB}} & \kappa_{\mathrm{QQ}} & \kappa_{\mathrm{QS}} & \kappa_{\mathrm{QC}} \\ \kappa_{\mathrm{SB}} & \kappa_{\mathrm{SQ}} & \kappa_{\mathrm{SS}} & \kappa_{\mathrm{SC}} \\ \kappa_{\mathrm{CB}} & \kappa_{\mathrm{CQ}} & \kappa_{\mathrm{CS}} & \kappa_{\mathrm{CC}} \end{pmatrix} \cdot \begin{pmatrix} \Delta^\nu \alpha_{\mathrm{B}} \\ \Delta^\nu \alpha_{\mathrm{Q}} \\ \Delta^\nu \alpha_{\mathrm{S}} \\ \Delta^\nu \alpha_{\mathrm{C}} \end{pmatrix}$$

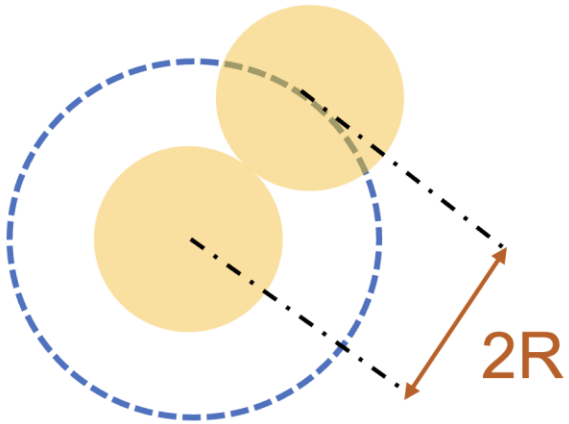
M. Greif, et al., Phys. Rev. Lett. **120**, 242301 (2018).
Das et. al. Phys Rev D **106** 014013 (2022)

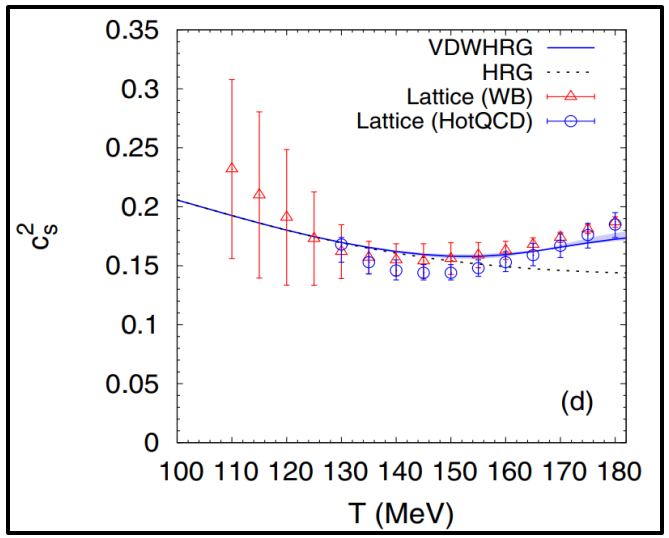
van der Waals Hadron Resonance Gas Model (VDWHRG)

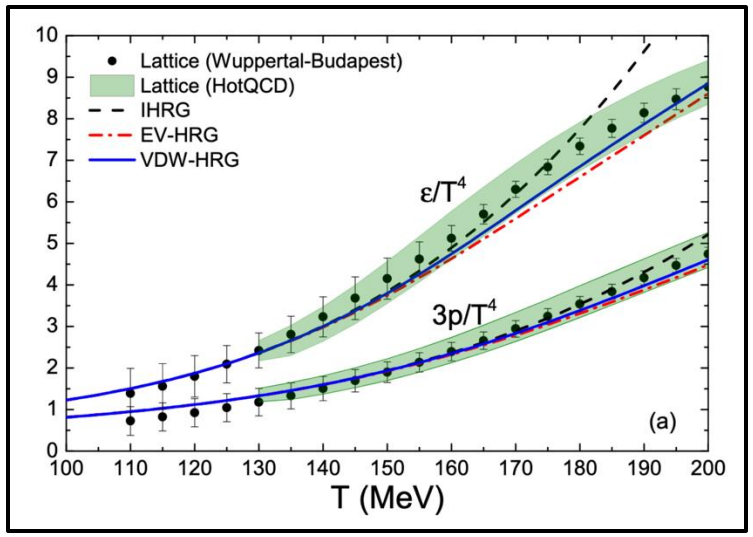
V. Vovchenko et al., Phys. Rev. Lett. 118, 182301 (2017)

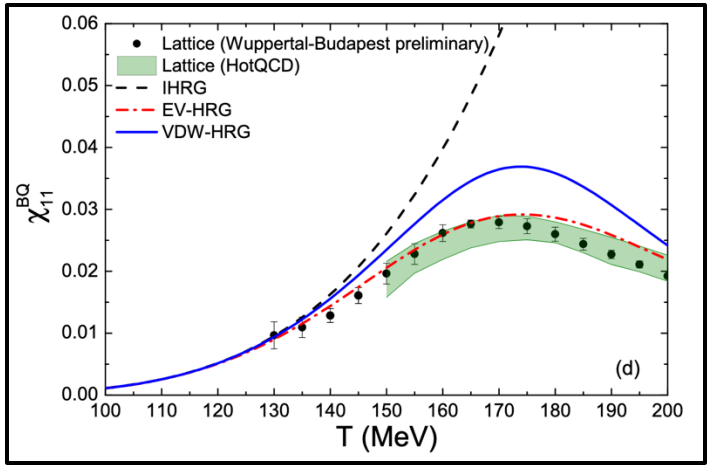
- Ideal HRG is a non-interacting statistical model consisting of hadrons and resonances

- 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 (VDWHRG)

- 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 pressure of the system can be expressed as,

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

- Number density and modified chemical potential are given as,

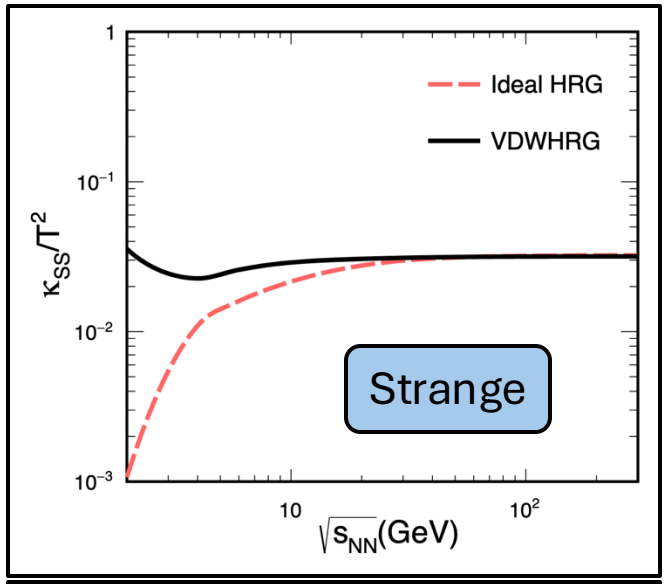
$$n(T,\mu) = \frac{\sum_i n_i^{id}(T,\mu^*)}{1 + b\sum_i n_i^{id}(T,\mu^*)}$$

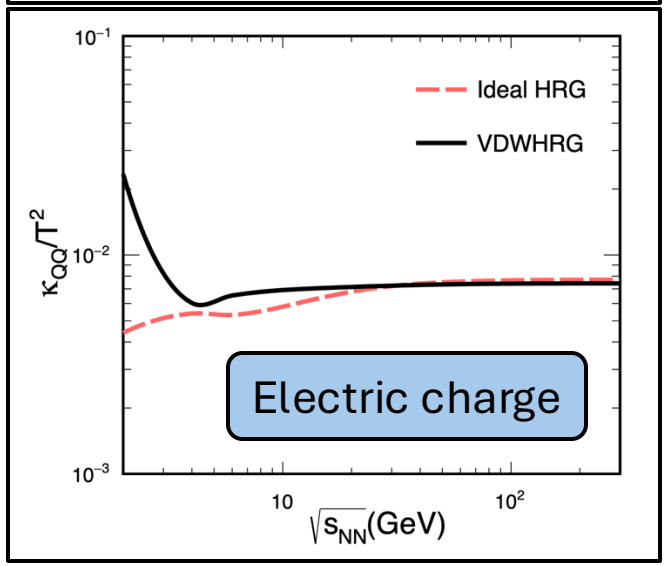
$$\mu^* = \mu - bP(T,\mu) - abn^2(T,\mu) + 2an(T,\mu)$$

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

V. Vovchenko et al., Phys. Rev. C **91**, 064314 (2015).
N. Sarkar and P. Ghosh, Phys. Rev. C **98**, 014907 (2018).

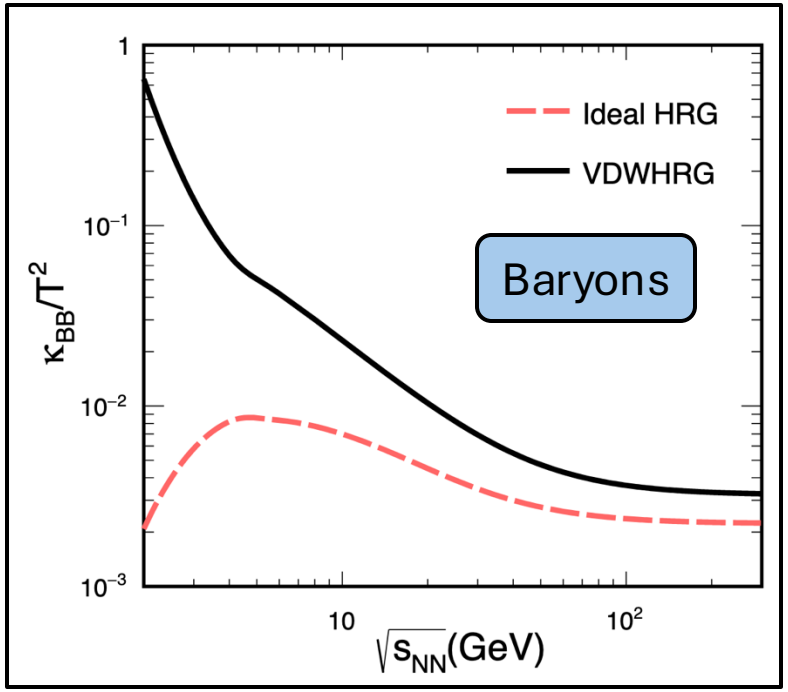
Results: as a function of center-of-mass energy

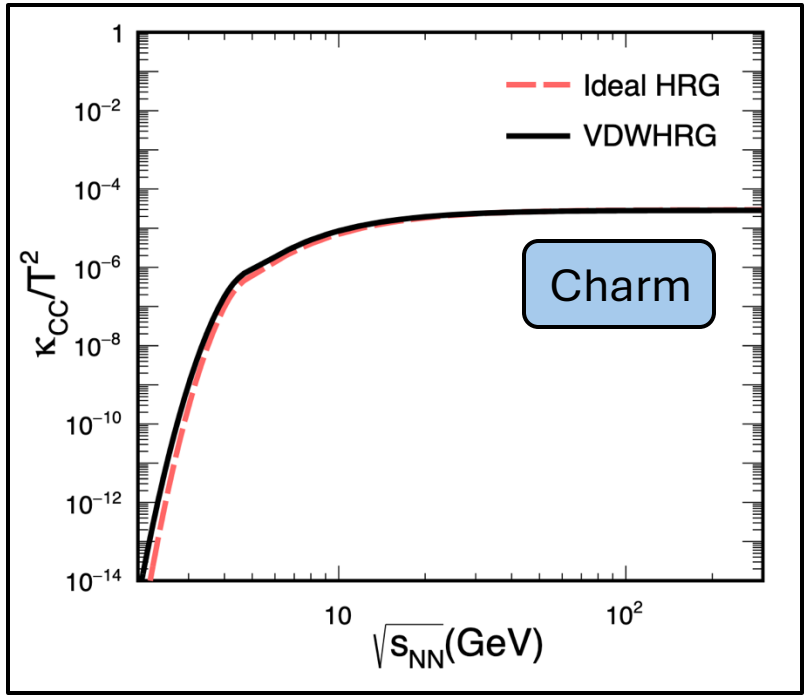




K. Goswami et al., arXiv :2409.13255

- We study the diffusion matrix coefficient related to all the conserved charges: baryon, electric charge, strange and charm, as a function of center-of-mass energies
- We observe that, $\kappa_{CC} \ll \kappa_{BB}$, specifically at lower center of mass energy
  - The charm hadrons are relatively less diffused as compared to baryons





$$\kappa_{qq'} = \sum_i \int \frac{d^3p_i}{(2\pi)^3} \frac{p_i^2}{3E_i} \left(q_i - \frac{n_q E_i}{\omega}\right) \frac{\tau_i}{E_i} \left(q_i' - \frac{n_q' E_i}{\omega}\right) f_i^0$$

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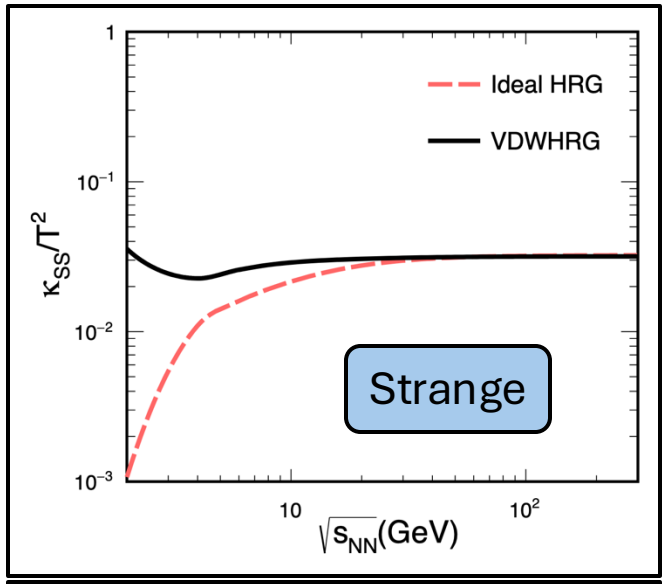
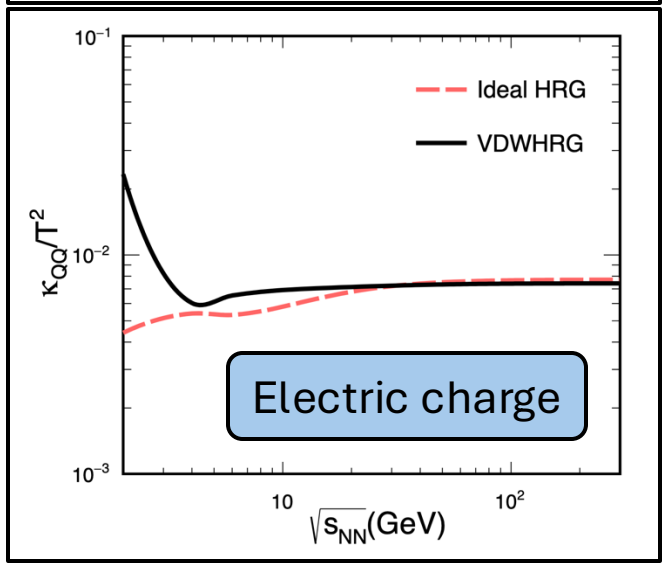
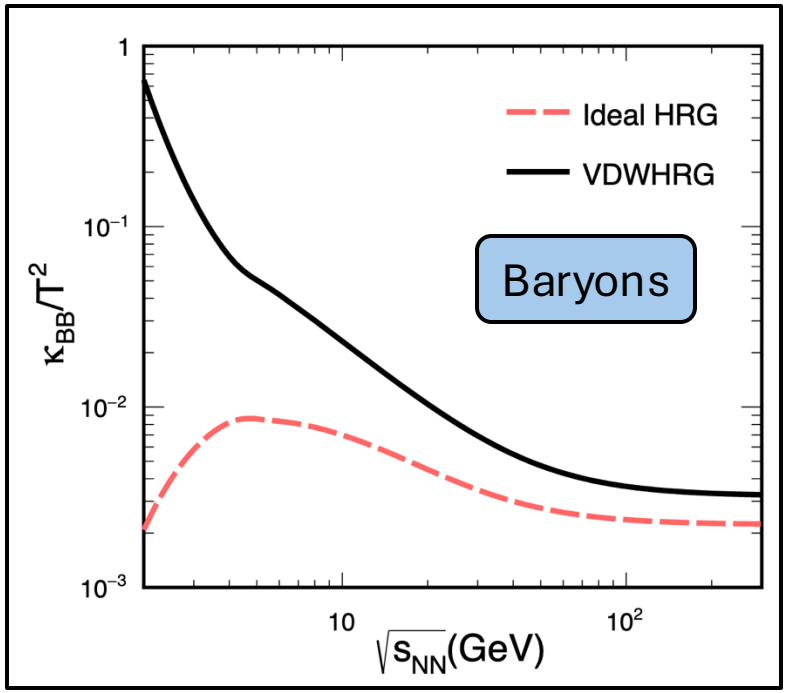
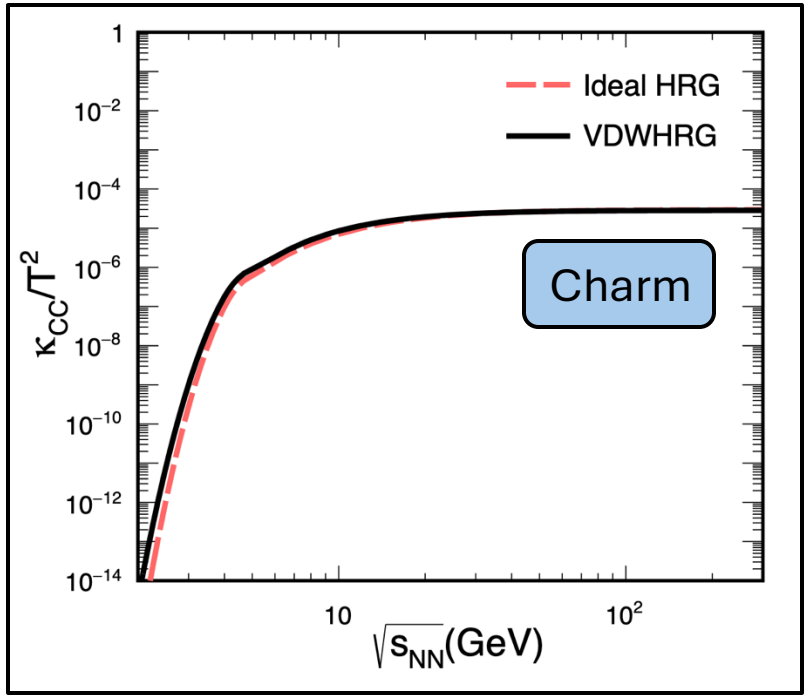




K. Goswami et al., arXiv :2409.13255

A possibility to explore the QCD critical point with the net charm fluctuations instead of net proton fluctuations!





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Summary

- We expand the 3X3 diffusion matrix to a 4X4 matrix by considering the contribution coming from charm sector
- We assume attractive and repulsive interactions among the hadrons
- We estimate the diagonal component of the diffusion coefficient as a function of center-of-mass energy
- A very small diffusion of the charm sector hints towards that they might be an effective probe to study the QCD critical point


THANK YOU
Quarks
Higgs boson
Forces
Leptons
ACCELERATING SCIENCE