

# Impact of $D$ meson loop on $J/\psi$ mass shift in nuclear medium

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# Outline

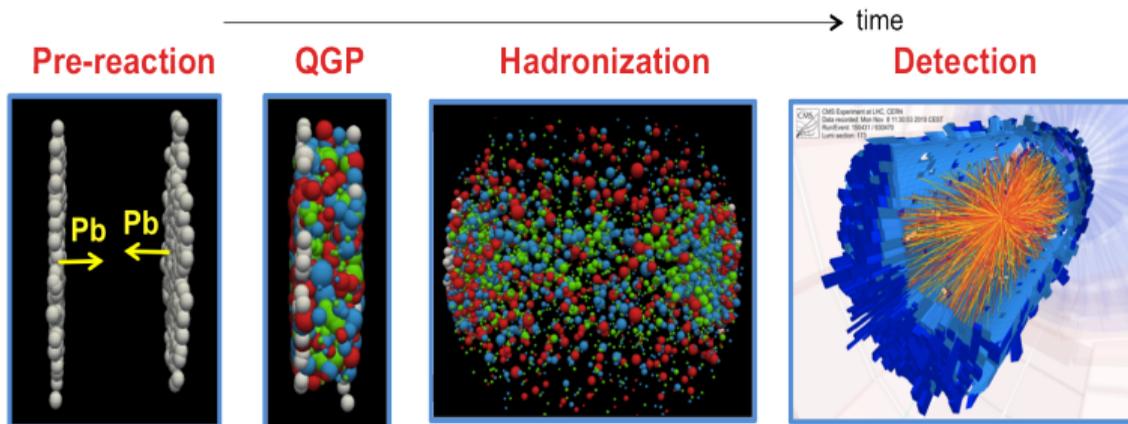
## 1 Introduction

- ▶ Introduction
- ▶ In-medium mass of  $J/\psi$
- ▶ Effective Model
- ▶ Results for  $m_{J/\psi}^*$
- ▶ Summary



# Heavy Ion Collisions

## 1 Introduction



Relativistic heavy-ion collisions are a unique tool to create and study hot QCD matter and its phase transition under controlled conditions.



# Why Study In-Medium $J/\psi$ ?

## 1 Introduction

- **Historical Motivation:** Matsui and Satz proposed that quarkonium suppression could serve as a signature of deconfinement [T. Matsui, H. Satz, Phys. Lett. B 178 \(1986\) 416](#).
- **Probe of QGP Formation:** Significant parts of experimental heavy-ion programs focus on quarkonium yields to search for QGP signatures.
- **Charmonium Stability:**  $J/\psi$  survives up to high  $T$ , making it a clean and sensitive probe.
- **Experimental Relevance:** Direct implications for RHIC, LHC, FAIR, and NICA measurements.



# Outline

## 2 In-medium mass of $J/\psi$

▶ Introduction

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# Flow of the Work

## 2 In-medium mass of $J/\psi$

The chiral SU(3) hadronic mean field model  
Medium-modified condensates

Condensates as Input

$\langle \bar{q}q \rangle, \langle G^2 \rangle$

QCD Sum Rules

In-medium  $m_D, m_{D^*}$

Effective Lagrangian approach

$m_D, m_{D^*}$  as input

$J/\psi$  Mass Shift



# Interaction Lagrangian framework

## 2 In-medium mass of $J/\psi$

- For the computation of the charmonium self-energy, we employ an effective Lagrangian framework, which is formulated as an SU(4)-flavor extension of the chiral-symmetric Lagrangians for light pseudoscalar and vector mesons [G. N. Zeminian et.al, Eur. Phys. J. A **57** (2021) 259.].

$$\begin{aligned}\mathcal{L}_{\psi DD} &= ig_{\psi DD} \psi^\mu [\bar{D}(\partial_\mu D) - (\partial_\mu \bar{D})D], \\ \mathcal{L}_{\psi DD^*} &= \frac{g_{\psi DD^*}}{m_\psi} \epsilon_{\alpha\beta\mu\nu} (\partial^\alpha \psi^\beta) [(\partial^\mu \bar{D}^{*\nu})D + \bar{D}(\partial^\mu D^{*\nu})], \\ \mathcal{L}_{\psi D^* D^*} &= ig_{\psi D^* D^*} \left\{ \psi^\mu [(\partial_\mu \bar{D}^{*\nu})D_\nu^* - \bar{D}^{*\nu}(\partial_\mu D_\nu^*)] \right. \\ &\quad + [(\partial_\mu \psi^\nu)\bar{D}_\nu^* - \psi^\nu(\partial_\mu \bar{D}_\nu^*)] D^{*\mu} \\ &\quad \left. + \bar{D}^{*\mu} [\psi^\nu(\partial_\mu D_\nu^*) - (\partial_\mu \psi^\nu)D_\nu^*] \right\}.\end{aligned}$$



# Self-Energy

## 2 In-medium mass of $J/\psi$

The  $J/\psi$  self-energy due to the  $D$ - $D^*$  meson loop contributions

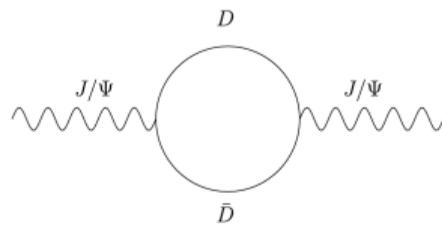
$$\Sigma_l(m_\psi^2) = -\frac{g_\psi^2}{3\pi^2} \int_0^\infty dq q^2 F_l(q^2) K_l(q^2),$$

$$K_{DD}(q^2) = \frac{q^2}{\omega_D} \left( \frac{1}{\omega_D^2 - m_\psi^2/4} \right),$$

$$K_{DD^*}(q^2) = \frac{q^2 \bar{\omega}_D}{\omega_D \omega_{D^*}} \frac{1}{\bar{\omega}_D^2 - m_\psi^2/4},$$

$$K_{D^*D^*}(q^2) = \frac{1}{4m_\psi \omega_D} \left[ \frac{\mathcal{A}(q^0 = \omega_{D^*})}{\omega_{D^*} - m_\psi/2} - \frac{\mathcal{A}(q^0 = \omega_{D^*} + m_\psi)}{\omega_{D^*} + m_\psi/2} \right].$$

### Loop Diagram





## Self-Energy

### 2 In-medium mass of $J/\psi$

Form factor:

$$F_{D,D^*}(q^2) = u^2(q^2) = \left( \frac{\Lambda_{D,D^*}^2 + m_{J/\psi}^2}{\Lambda_{D,D^*}^2 + 4\omega_{D,D^*}^2(q)} \right)^4$$

with cuto parameter  $\Lambda_D$ .

where

$$\omega_D = \sqrt{q^2 + m_D^2}, \quad \omega_{D^*} = \sqrt{q^2 + m_{D^*}^2}, \quad \bar{\omega}_D = \frac{1}{2}(\omega_D + \omega_{D^*}).$$

and we present results for  $\Lambda_D$  in the interval 1000-3000 MeV



# In-medium mass of $J/\psi$

## 2 In-medium mass of $J/\psi$

- We are interested in the difference between the in-medium mass of the  $J/\psi$ ,  $m_{J/\psi}^*$ , and its vacuum value,  $m_{J/\psi}$ ,

$$\Delta m_{J/\psi} = m_{J/\psi}^* - m_{J/\psi},$$

- The masses are obtained from

$$m_{J/\psi}^2 = (m_{J/\psi}^0)^2 + \Sigma_{J/\psi}(k^2 = m_{J/\psi}^2),$$

where  $m_{J/\psi}^0$  is the bare  $J/\psi$  mass

- $m_D$  and  $m_{D^*}$  are evaluated within the chiral hadronic SU(3) mean field model plus QCD sum-rule approach.



# Outline

## 3 Effective Model

- ▶ Introduction
- ▶ In-medium mass of  $J/\psi$
- ▶ **Effective Model**
- ▶ Results for  $m_{J/\psi}^*$
- ▶ Summary



# QCD Non-Perturbative Regime

## 3 Effective Model

- Non-Perturbative Regime cannot be studied by QCD alone.
- Hadron properties at finite Density and Temperature.
- Different Effective Theoretical Models:
  - Walecka Model.
  - Nambu–Jona-Lasinio (NJL) Model.
  - The chiral  $SU(3)$  hadronic mean field model.
  - QCD Sum Rules.
  - Quark Meson Coupling (QMC) Model.



# The chiral SU(3) hadronic mean field model

## 3 Effective Model

Lagrangian density [ P. Papazoglou, et al., Phys. Rev. C 59 (1999) 411]

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{BW} + \mathcal{L}_0 + \mathcal{L}_{vec} + \mathcal{L}_{SB}.$$

- $\mathcal{L}_{kin}$  is kinetic energy term.
- $\mathcal{L}_{BW}$  baryon-mesons interaction.
- $\mathcal{L}_0$  scalar meson self-interaction term ( $\sigma$ ,  $\zeta$ ,  $\delta$  and  $\chi$  fields).
- $\mathcal{L}_{vec}$  vector meson self-interaction term ( $\omega$ ,  $\rho$  and  $\phi$  fields).
- $\mathcal{L}_{SB}$  explicit symmetry breaking terms.



# Quark and Gluon Condensates

## 3 Effective Model

In the chiral model, the scalar light quark condensates can be related to symmetry breaking via the relation:

$$\sum_i m_i \langle \bar{q}_i q_i \rangle_{\rho N} = -\mathcal{L}_{\text{ESB}}.$$

The quark condensates are expressed as:

$$\langle \bar{u}u \rangle_{\rho N} = \frac{1}{m_u} \left( \frac{\chi}{\chi_0} \right)^2 \left[ \frac{1}{2} m_\pi^2 f_\pi (\sigma + \delta) \right],$$

$$\langle \bar{d}d \rangle_{\rho N} = \frac{1}{m_d} \left( \frac{\chi}{\chi_0} \right)^2 \left[ \frac{1}{2} m_\pi^2 f_\pi (\sigma - \delta) \right].$$

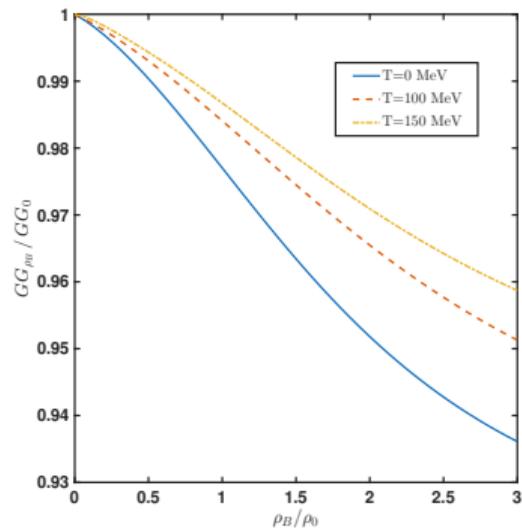
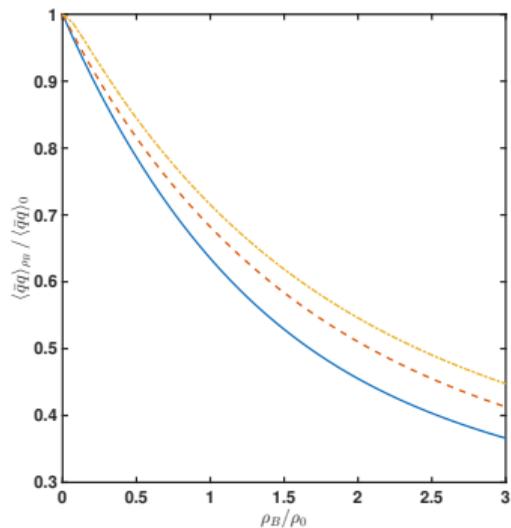
The gluon condensate is given by:

$$\left\langle \frac{\alpha_s}{\pi} G_{\mu\nu}^a G^{a\mu\nu} \right\rangle_{\rho N} = \frac{8}{9} \left\{ (1-d)\chi^4 + \left( \frac{\chi}{\chi_0} \right)^2 \left[ m_\pi^2 f_\pi \sigma + (\sqrt{2} m_K^2 f_K - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi) \zeta \right] \right\}.$$



# Quark and Gluon Condensates

Results for Condensates





## QCD sum rules

### 3 Effective Model

We start with the two-point current correlation function  $\Pi(q)$ , which represents the Fourier transformation of the time-ordered product of the isospin-averaged meson current,  $J'(x)$ , and can be written as [E. G. Drukarev et.al. Part. Nucl. Phys. **27**, (1991) 77. and A. Hayashigaki, Phys. Lett. B **487**, (2000) 96.]

$$\Pi(q) = i \int d^4x e^{iq \cdot x} \langle \mathcal{T} \{ J'(x) J'^{\dagger}(0) \} \rangle$$

The shifts in the masses of the  $D$  and  $D^*$  mesons can be written as:

$$\Delta m_D^* = 2\pi \frac{m_N + m_D}{m_N m_D} \rho_B a_D,$$

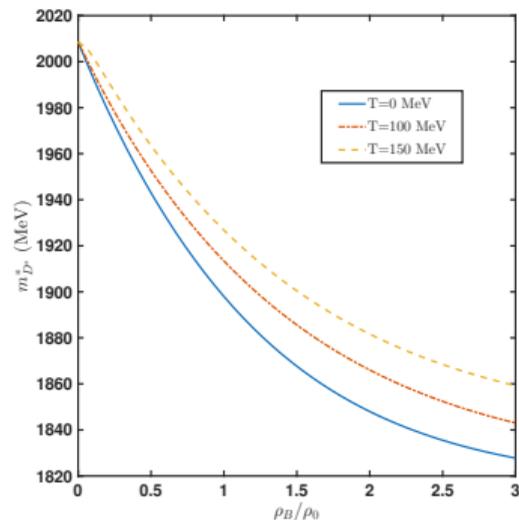
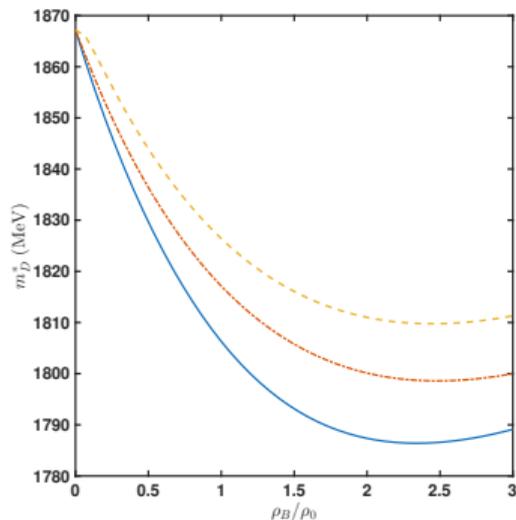
and

$$\Delta m_{D^*}^* = 2\pi \frac{(m_N + m_{D^*}) a \rho_N}{m_N m_{D^*} f_{D^*}^2 m_{D^*}^2 (-8\pi(m_N + m_{D^*}))}.$$



# In medium masses of $D$ and $D^*$ mesons at different temperatures

Results for  $m_D$  and  $m_{D^*}$





# Outline

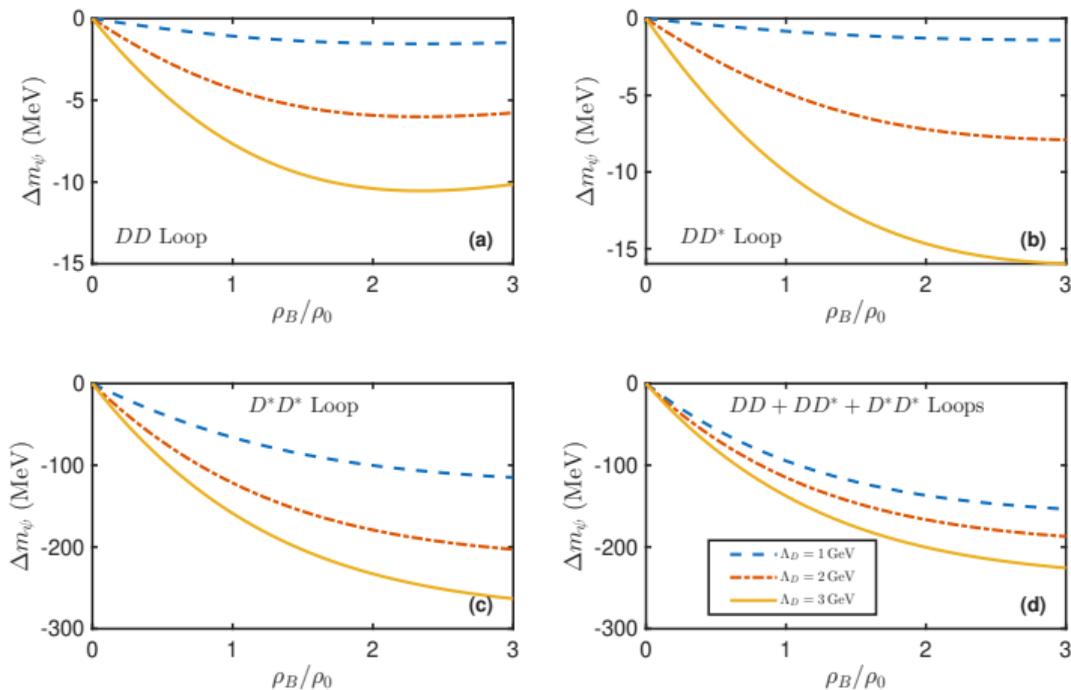
## 4 Results for $m_{J/\psi}^*$

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# Contribution of Different Loops to $m_{J/\psi}^*$ at $T = 0$

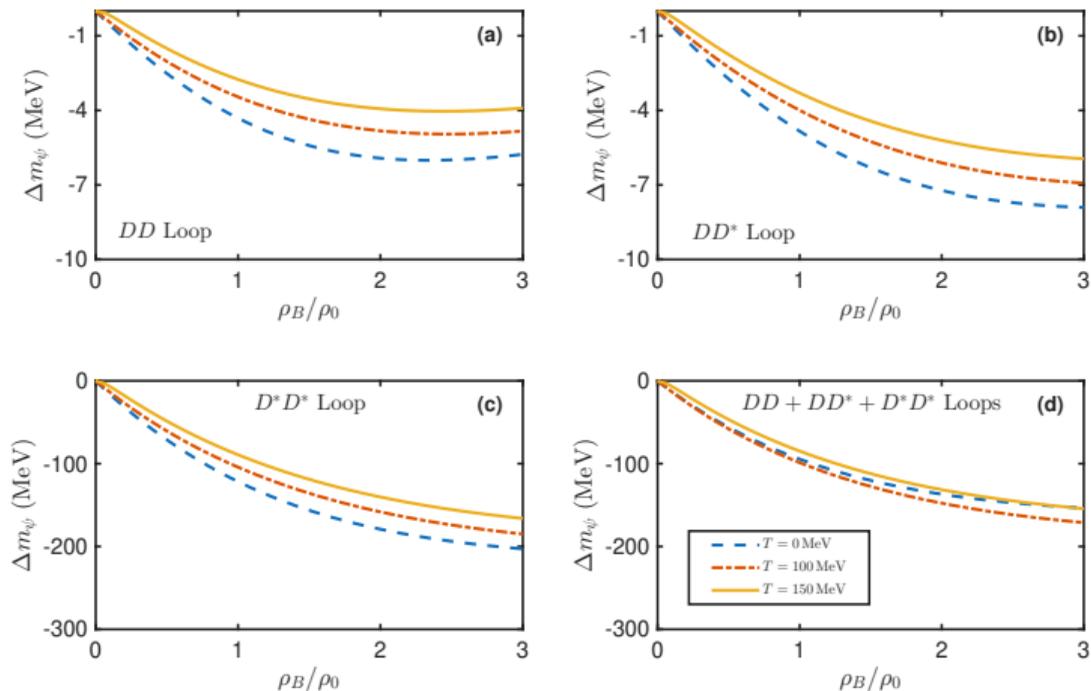
## 4 Results for $m_{J/\psi}^*$





# Contribution of Different Loops to $m_{J/\psi}^*$ at $\Lambda_D = 2 \text{ GeV}$

## 4 Results for $m_{J/\psi}^*$





# Outline

## 5 Summary

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# Results Overview

## 5 Summary

- We investigate the **in-medium mass shift of  $J/\psi$ ,  $\Delta m_{J/\psi}$** , in isospin symmetric nuclear matter.
- A **negative mass shift** ( $\Delta m_{J/\psi} < 0$ )  $\Rightarrow$  the nuclear medium provides an effective **attractive potential** for  $J/\psi$ .
- **Total loop contribution:**  $DD + DD^* + D^*D^*$ 
  - **Quark meson coupling model:**  $\Delta m_{J/\psi} \sim -61$  to  $-164$  MeV [G. N. Zeminiani et.al, Eur. Phys. J. A **57** (2021) 259].
  - **QCD sum rules:**  $\Delta m_{J/\psi} \sim -70$  to  $-140$  MeV (At nuclear saturation density and depending on  $\Lambda_D$ ).
  - **Our results:** in close agreement with QMC model.
- **Implication:** These findings may contribute to a deeper understanding of heavy quark dynamics in heavy-ion collisions.



# Impact of $D$ meson loop on $J/\psi$ mass shift in nuclear medium

*Thank you for listening!*