J/ψ mass shift using D meson loop effect

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Outline

- Aim and motivation
- Methodology
- Results
- Summary

Need to study the in medium J/ψ?

- To understand the possible outcomes of future experiments
- J/ψ Suppression
- CBM(Compressed Baryonic Matter)
- PANDA (anti-**P**roton **AN**nihilations at **DA**rmstadt)

Under the FAIR(Facility of Antiproton and Ion Research) project at GSI, Germany.

Phase Diagram

Hadron gas:

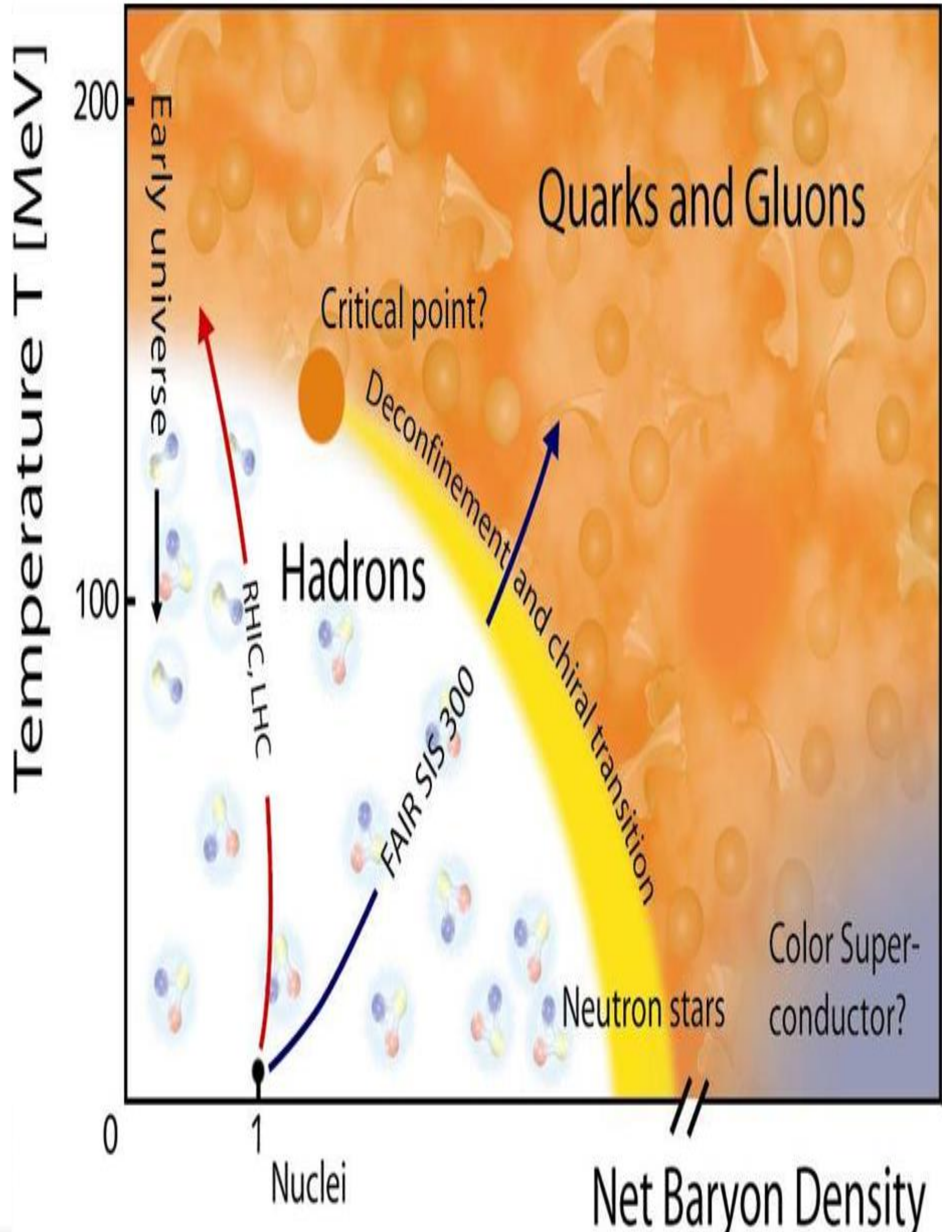
- Moderate temperatures and densities
- Quarks and gluons are confined
- Chiral symmetry is spontaneously broken

Quark-gluon plasma:

- Very high temperatures and densities
- Deconfined quarks and gluons
- Chiral symmetry is restored

Color superconductor:

- T < 100 MeV and very high densities
- quarks form bosonic pairs in analogy to BCS theory



Methodology

$$\mathcal{L}_{\psi DD} = i g_{\psi DD} \psi^{\mu} \left[\bar{D}(\partial_{\mu} D) - (\partial_{\mu} \bar{D}) D \right],$$

SU(4) extension of light-flavor chiral-symmetric Lagrangians of pseudoscalar meson that is extended to the charm sector.

SU(4) flavor symmetry is strongly broken in nature, and in order to stay as close as possible to phenomenology, we use experimental values for the charmed mesons masses and use the empirically known meson coupling constants.

We are interested in the difference of the in-medium mass and the vacuum mass.

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

With the bare mass m_{ψ}^{0} calculated as,

$$m_{\psi}^{2} = \left(m_{\psi}^{0}\right)^{2} + \Sigma\left(k^{2} = m_{\psi}^{2}\right).$$

Where $\Sigma(k^2)$ is the total J/Ψ self-energy obtained from the sum of the contributions from the DD pairs.

We take the averaged, equal masses for the neutral and charged D mesons, i.e. $m_{D^0} = m_{D^\pm}$. Averaging over the three polarizations of J/Ψ, one can calculate the $D\bar{D}$-loop contribution to the J/Ψ self-energy $\Sigma_{D\bar{D}}$ as

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

where $F_l(\mathbf{q}^2)$ is the product of vertex form-factors

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

where $\omega_D = (\vec{q}^{\,2} + m_D^2)^{1/2}, \xi = 0$

$$u_D(\vec{q}^{\,2}) = \left(\frac{\Lambda_D^2 + m_\psi^2}{\Lambda_D^2 + 4\omega_D^2(\vec{q}\,)}\right)^2, \qquad F_{D\bar{D}}(\vec{q}^{\,2}) = u_D^2(\vec{q}^{\,2}),$$

where Λ_D is a cutoff mass.

Chiral SU(3) Model

- Chiral symmetry

  Limit of massless quarks i.e $m_u = m_d = m_s = 0$

  Invariance of QCD Lagrangian under $SU(3)_L \times SU(3)_R$ transformation.

- Broken scale invariance, which leads to non zero trace of energy momentum tensor

$$\boxed{\theta_\mu^\mu = \langle \frac{\beta_{QCD}}{2g} G^a_{\mu\nu} G_a^{\mu\nu} \rangle}$$

- Mean-field approximation

Lagrangian Density is given as

Explicit symmetry breaking

Kinetic term

Interaction of Vector mesons

$$\mathcal{L} = \mathcal{L}_{kin} + \sum_{W=X,Y,V,A,u} \mathcal{L}_{BW} + \mathcal{L}_{vec} + \mathcal{L}_0 + \mathcal{L}_{SB}$$

Baryon meson interactions

Meson-meson interactions

Coupled equations of motion of scalar fields derived from effective Lagrangian using mean field approximation :

For sigma field:

$$k_0\chi^2\sigma - 4k_1(\sigma^2+\zeta^2)\sigma - 2k_2(\sigma^3) - 2k_3\chi\sigma\zeta$$
$$-\frac{d}{3}\chi^4\left(\frac{2}{\sigma}\right) + \left(\frac{\chi}{\chi_0}\right)^2 m_\pi^2 f_\pi - \sum g_{\sigma i}\rho_i^s = 0$$

For zeta field:

$$k_0\chi^2\zeta - 4k_1(\sigma^2+\zeta^2)\zeta - 4k_2(\zeta^3) - k_3\chi\sigma^2 - \frac{d}{3}\frac{\chi^4}{\zeta}$$
$$-\left(\frac{\chi}{\chi}\right)^2\left[\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right] - \sum g_{\zeta i}\rho_i^s = 0$$

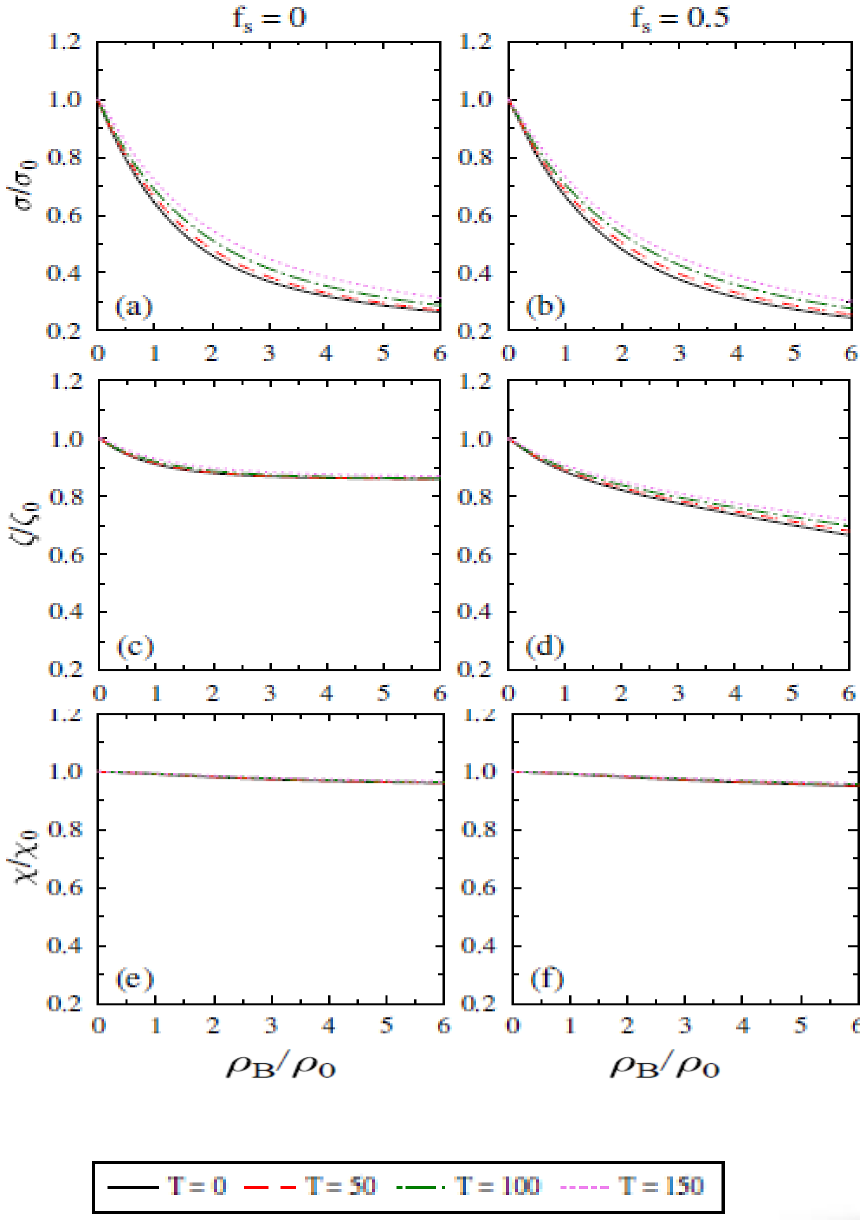
For dilaton field:

$$k_0\chi(\sigma^2+\zeta^2) - k_3\sigma^2\zeta + \chi^3\left[1+\ln\left(\frac{\chi^4}{\chi_0^4}\right)\right]$$
$$+(4k_4-d)\chi^3 - \frac{4}{3}d\chi^3 ln\left\{\left[\frac{(\sigma^2\zeta)}{\sigma_0^2\zeta_0}\right]\left(\frac{\chi\hat{}4}{\chi_0^4}\right)\right\}$$
$$+2\frac{\chi}{\chi_0}\left[m_\pi^2 f_\pi\sigma + \left(\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta\right] = 0$$

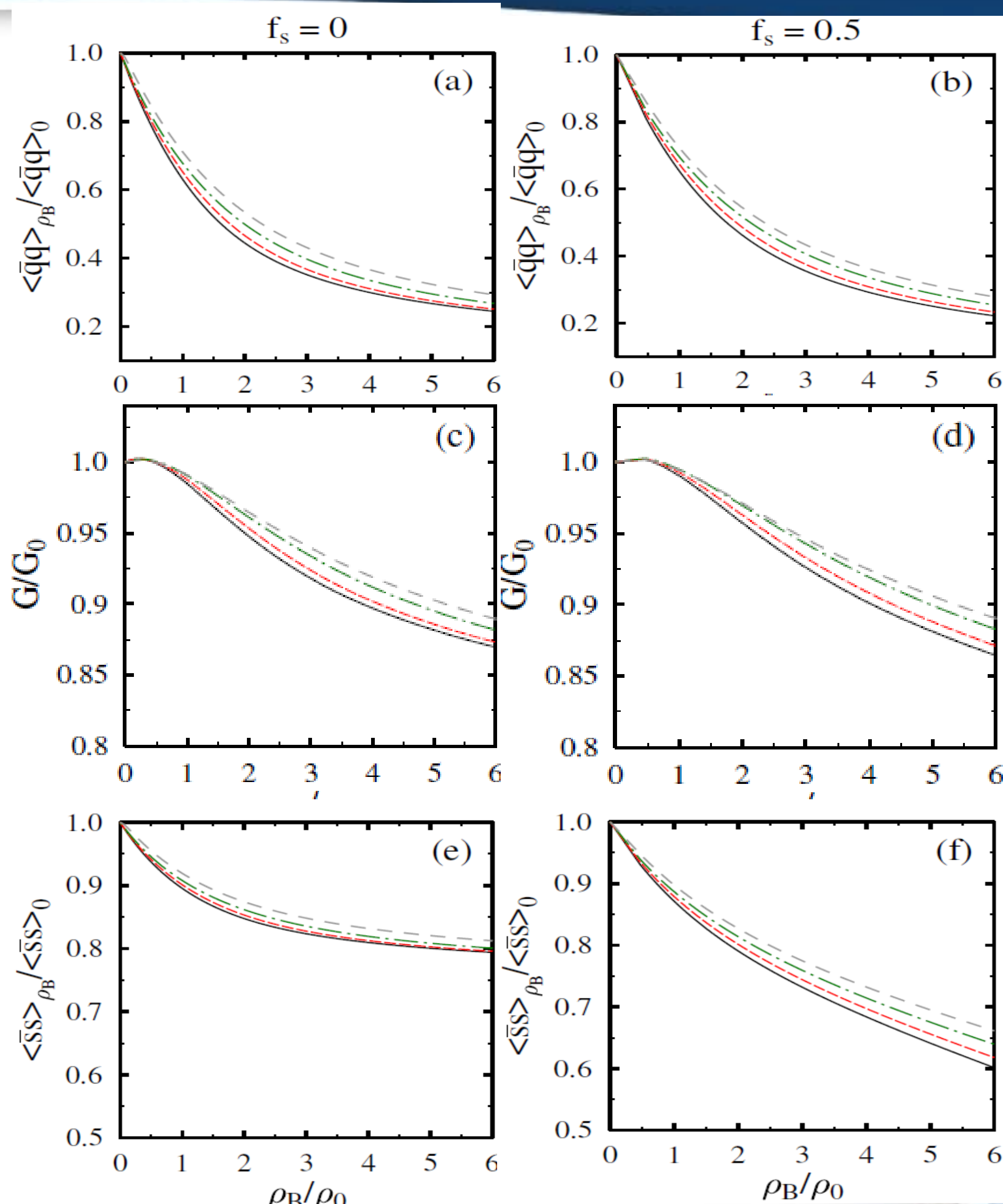
On solving these coupled equations we can calculate the density and temperature dependence of scalar fields σ, ς and dilaton field χ.

Strangeness fraction is defined as $f_s = \frac{\sum_i |s_i|\rho_i}{\rho_B}$.

Where s_i is the number of strange quarks and ρ_i is the Number density of ith baryon.



Variation of quark, gluon and strange condensates with temperature and strangeness fraction.



QCD Sum Rule

In QCD Sum rule approach we start with the two point correlation function.

$$\Pi_{\mu\nu}(q) = i \int d^4x \, e^{iq\cdot x} \left\langle T\left\{J_\mu(x) J_\nu^\dagger(0)\right\}\right\rangle_{\rho_B, T}.$$

Where $J_\mu(x)$ denotes the isospin averaged current $x = x^\mu = (x^0, \mathbf{x})$ Is the four coordinate and $q = q^\mu = (q^0, \mathbf{q})$s the four momentum, and T denotes the time ordered operation on the product of quantities in the brackets.

Vector meson isospin averaged average currents are given by the expression

$$J_\mu(x) = J_\mu^\dagger(x) = \frac{\bar{c}(x)\gamma_\mu q(x) + \bar{q}(x)\gamma_\mu c(x)}{2},$$

Here q denotes light quark and c denotes heavy charm quark.

The two point correlation function can be decomposed into the vacuum part, static one-nucleon part and pion bath contribution.

$$\Pi_{\mu\nu}(q) = \Pi^0_{\mu\nu}(q) + \frac{\rho_B}{2M_N} T^N_{\mu\nu}(q) + \Pi^{P.B.}_{\mu\nu}(q),$$

Where,

$$T^N_{\mu\nu}(\omega, \boldsymbol{q}) = i \int d^4x e^{iq\cdot x} \langle N(p)| T \left\{ J_\mu(x) J^\dagger_\nu(0) \right\} |N(p)\rangle .$$

Here $|N(p)\rangle$ denotes the isospin and spin averaged static nucleon part With the four momentum $p = (M_N, 0)$. Third term in the equation denotes the contribution from pion bath at finite temperature.
In our present work we take the effect of finite temperature on the vector D and B meson through the temperature dependence of fields σ, ς and χ.

Shift in mass can be defined by the relation

$$\delta M_{D^*} = \sqrt{m^2_{D^*} + \Delta m^2_{D^*}} - m_{D^*}$$

Borel transformation equation can be written as

$$
\begin{aligned}
& a\left\{\frac{1}{M^2}e^{-\frac{M_{D^*}^2}{M^2}}-\frac{s_0}{M_{D^*}^4}e^{-\frac{s_0}{M^2}}\right\}+b\left\{e^{-\frac{M_{D^*}^2}{M^2}}-\frac{s_0}{M_{D^*}^2}e^{-\frac{s_0}{M^2}}\right\} \\
+ & \; B\left[\frac{1}{(M_H+M_N)^2-M_{D^*}^2}-\frac{1}{M^2}\right]e^{-\frac{M_{D^*}^2}{M^2}}-\frac{B}{(M_H+M_N)^2-M_{D^*}^2}e^{-\frac{(M_H+M_N)^2}{M^2}} \\
= & \left\{-\frac{m_c\langle\bar{q}q\rangle_N}{2}-\frac{2\langle q^\dagger iD_0 q\rangle_N}{3}+\frac{m_c^2\langle q^\dagger iD_0 q\rangle_N}{M^2}\right\}e^{-\frac{m_c^2}{M^2}}+\frac{m_c\langle\bar{q}g_s\sigma Gq\rangle_N}{3M^2}e^{-\frac{m_c^2}{M^2}} \\
+ & \left\{\frac{8m_c\langle\bar{q}iD_0iD_0q\rangle_N}{3M^2}-\frac{m_c^3\langle\bar{q}iD_0iD_0q\rangle_N}{M^4}\right\}e^{-\frac{m_c^2}{M^2}} \\
& -\frac{1}{24}\langle\frac{\alpha_s GG}{\pi}\rangle_N\int_0^1 dx\left(1+\frac{\widetilde{m}_c^2}{2M^2}\right)e^{-\frac{\widetilde{m}_c^2}{M^2}} \\
+ & \;\frac{1}{48M^2}\langle\frac{\alpha_s GG}{\pi}\rangle_N\int_0^1 dx\frac{1-x}{x}\left(\widetilde{m}_c^2-\frac{\widetilde{m}_c^4}{M^2}\right)e^{-\frac{\widetilde{m}_c^2}{M^2}}\,.
\end{aligned}
$$

Where $B=\frac{2f_{D^*}^2M_{D^*}^2M_N(M_H+M_N)g_{D^*NH}^2}{(M_H+M_N)^2-M_{D^*}^2}$.

This eqn. has two unknowns a and . b

To solve this we differentiate this eqn w.r.t $\frac{1}{M^2}$

To get two equations with two unknowns.

Solving these two coupled equations we can calculate a and b .

Zhi-Gang Wang, Int. J. Mod Phys. A 28, 1350049 (2013)

Within Chiral SU(3) model we can calculate the values of $\mathcal{O}_{\rho_B}$ at finite density of the nuclear medium, hence can find the $\mathcal{O}_N$

$$\mathcal{O}_N = [\mathcal{O}_{\rho_B} - \mathcal{O}_{vacuum}] \frac{2M_N}{\rho_B}.$$

Here $\mathcal{O}_N$ is nucleon expectation value of the operator at finite baryonic density, $\mathcal{O}_{vacuum}$ is vacuum expectation value of operator, $\mathcal{O}_{\rho_B}$ is the expectation value of operator at finite baryonic density.

In our present investigation of hadrons properties, we are interested in light quark condesates $\bar{u}u$ and $\bar{d}d,$ which are proportional to the non-strange scalar field σ, within chiral SU(3) model. Considering equal mass of light quakrs, u = d = 0.006 GeV. We write,

$$\langle \bar{q}q \rangle_{\rho_B} = \frac{1}{2m_q} \left(\frac{\chi}{\chi_0} \right)^2 \left[m_\pi^2 f_\pi \sigma \right].$$

Quark condensate, $\langle \bar{q}q \rangle_{\rho_B}$ is calculated from the chiral SU(3) model

$\langle \bar{q}q \rangle_{\rho_B}$ Can be used to calculate the other condensates, which are

$$\langle \bar{q} g_s \sigma G q \rangle_{\rho_B} = \lambda^2 \langle \bar{q}q \rangle_{\rho_B} + 3.0 GeV^2 \rho_B.$$

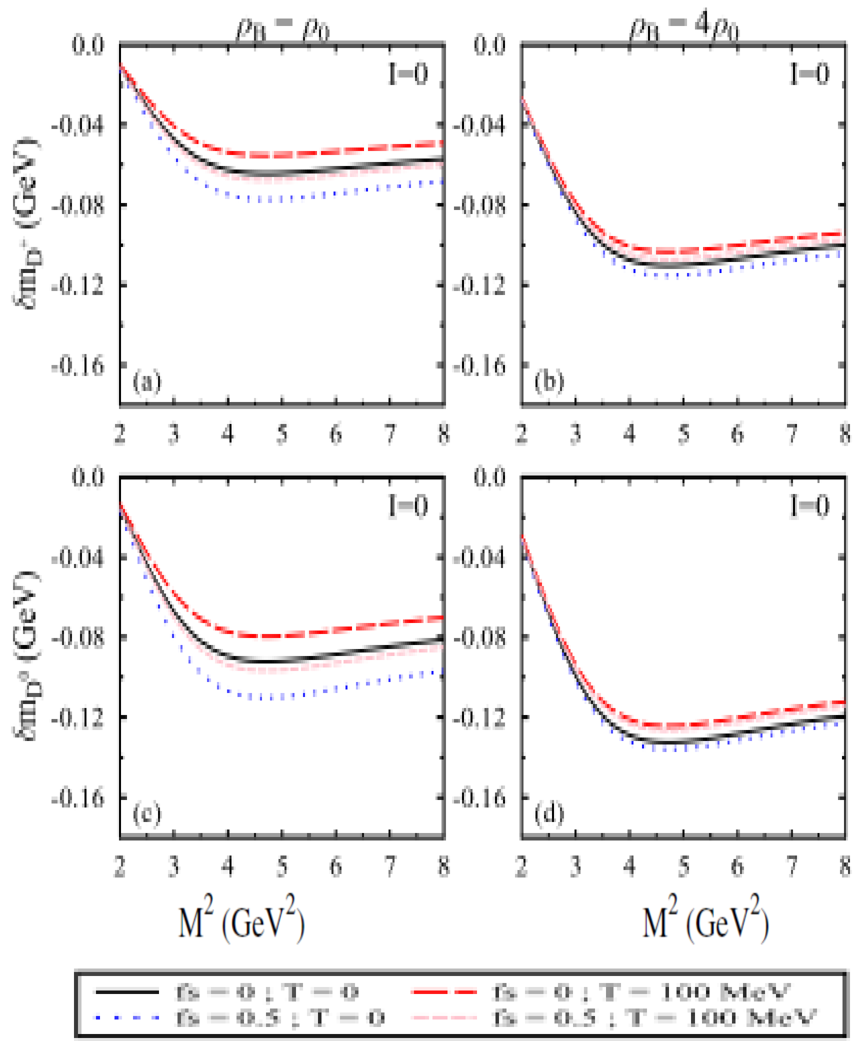
$$\langle \bar{q} i D_0 i D_0 q \rangle_{\rho_B} + \frac{1}{8} \langle \bar{q} g_s \sigma G q \rangle_{\rho_B} = 0.3 GeV^2 \rho_B.$$

Value of the condensate $\langle q^\dagger i D_0 q \rangle$ is not calculated from the chiral SU(3) model. It's value is approximated as $0.18 GeV^2 \rho_B$
.

R. Thomas, T. Hilger, B. Kampher, Nucl. Phys. A 795, 19 (2007).

Qualitative Results and Discussion

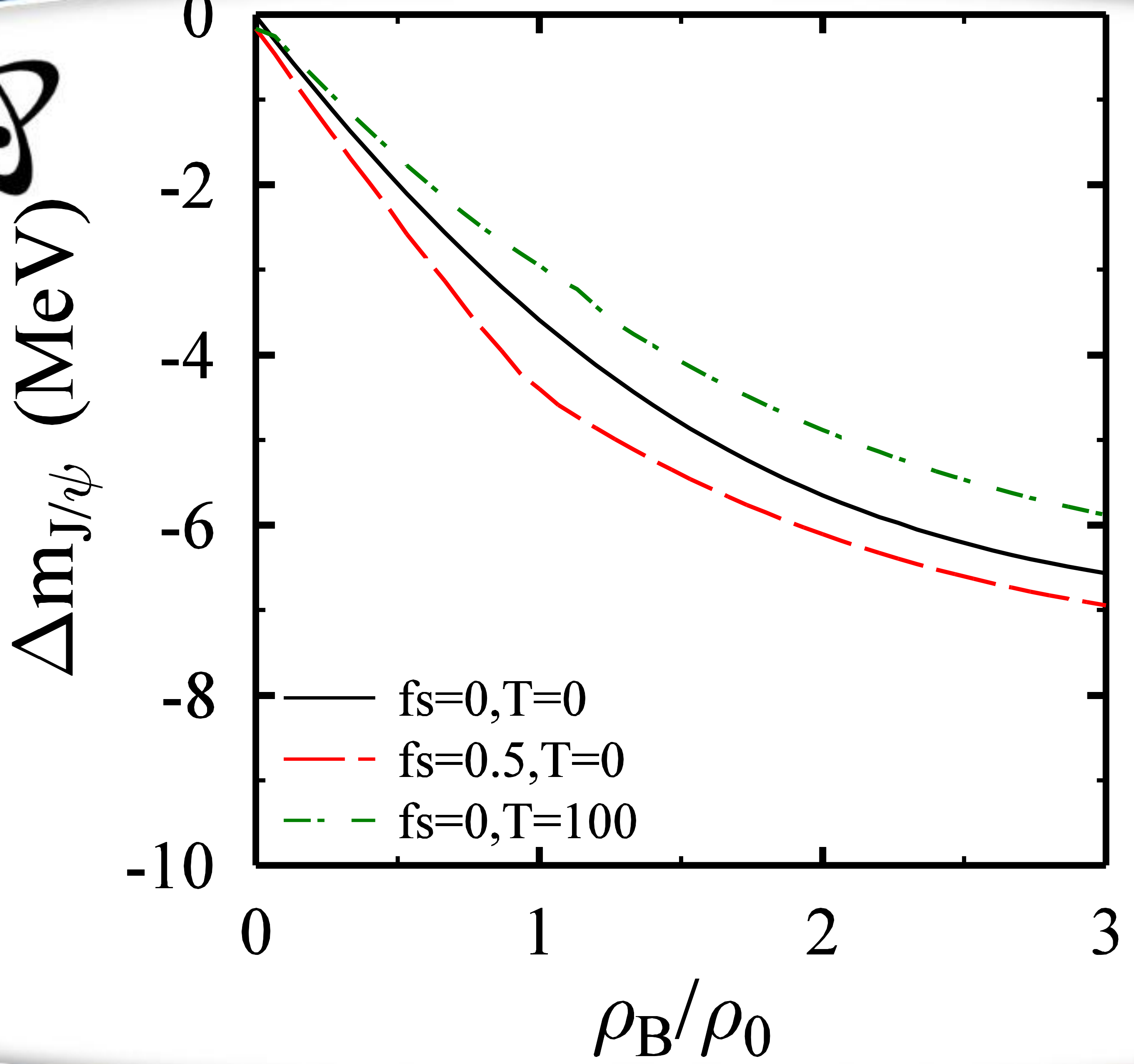
D Meson Mass Shift :



Temperature : decreases the magnitude of shift in mass

Strange medium f_s : Increases the magnitude of mass shift.

Density ρ_B : Increases the magnitude of mass shift.



0
-2
-4
-6
-8
-10
0
1
2
3
$\Delta m_{J/\psi}$ (MeV)
ρ_B/ρ_0
fs=0,T=0
fs=0.5,T=0
fs=0,T=100

COMPARISON

- Shift in mass of J/psi meson by using DD loop effect, but mass of D meson was calculated through QMC model.

- Only in nuclear matter, and observed shift 3 MeV,

- In our work, 3-4 MeV.

- Temperature of the medium causes a drop in the shift.

- Presence of strange hadrons (along with nucleons) cause enhancement in the magnitude of the shift.

Summary

- We have used effective Lagrangian approach to calculate in mass of J/\psi meson in hot and dense symmetric hadronic medium, by considering pseudoscalar D meson loop effect.

- In medium mass of D meson was calculated through chiral model and QCD sum rule approach to observe the effect of strange medium, temperature and baryonic density on the shift in masses and decay constants of D meson.

- Strange medium cause a drop in the mass of J/psi meson.

- Finite temperature causes an increase in the mass.

- With increase in density of the medium increases the magnitude of the shift.

Thank you

Parameters used

Nuclear saturation density used in the present investigation is 0.15 fm^{-3} . Coupling constant used in this case is $g_{D^*N\Lambda_c} \approx g_{D^*N\Sigma_c} \approx g_{B^*N\Lambda_b} \approx g_{B^*N\Sigma_b} \approx$ 3.86. The masses of mesons m_{D^*} , m_{B^*} , $m_{D_s^*}$ and $m_{B_s^*}$ are 2.01, 5.325,2.112 and 5.415 MeV respectively. Values of decay constants of f_{D^*}, f_{B^*}, $f_{D_s^*}$ and $f_{B_s^*}$ are 0.270, 0.195,1.16*f_{D^*} and 1.16*f_{B^*} respectively. Masses of quarks namely (up)u , (down)d, strange(s), (charm)c and (bottom)b are taken as 0.006, 0.006, 0.095, 1.35and 4.7 GeV respectively. Values of threshold parameter s_0 used in the present investigations for D^* ,B^* ,D_S^* and B_S^* mesons are 6.5, 35, 7.5 and 38GeV^2 respectively. To represent the exact mass and decay shift we chose a suitable Borel window within which there is almost no variation in the mass and decay constant the detailed information regarding Borel window chosen and parameters used can be found from the paper []