Production cross-sections of Heavy Quarkonia in hot magnetized strange hadronic matter

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Outline

- Motivation
- Masses of Heavy Quarkonium states ($\bar{Q}Q$,$Q = c, b$) and Open heavy flavour mesons ($q\bar{Q}$ and $\bar{q}Q$, $q = u, d$) using a chiral effective model
- Decay widths of of Charmonium (Bottomonium) to $D\bar{D}$ ($B\bar{B}$) (a) $^3P_0$ model (b) A Model with composite hadrons
- Production cross-sections of Heavy Quarkonia – due to density, temperature, strangeness, isospin asymmetry and magnetic field!
  Magnetic field effects: Baryonic Dirac sea, pseudoscalar-vector meson (PV) mixing, Landau level contributions.
  Anomalous magnetic moments (AMMs) of baryons considered.
- Summary

Motivation

Strong magnetic fields are produced in peripheral ultra-relativistic heavy ion collisions!

$eB \sim 6 m_\pi^2$ at RHIC, $eB \sim 15 m_\pi^2$ at LHC

Evolution of the magnetic field however is still an open question!

Heavy flavour mesons produced at the early stage when the magnetic field can still be extremely large!

Magnetic field effects can affect the production of heavy quarkonia and open heavy flavour mesons!

Created matter is extremely dilute!

Dominant magnetic field effects:

- Mixing of the pseudoscalar and vector mesons (PV mixing) (leads to significant drop (rise) in mass of pseudoscalar meson (longitudinal component of the vector meson)
- Baryon Dirac sea effects lead to inverse magnetic catalysis (drop in strength of light quark condensates ($\sigma \sim \langle \bar{u}u \rangle + \langle \bar{d}d \rangle$, $\delta \sim \langle \bar{u}u \rangle - \langle \bar{d}d \rangle$, $\zeta \sim \langle \bar{s}s \rangle$) with increase in magnetic field) in magnetized nuclear matter!
- Inclusion of hyperons leads to magnetic catalysis effect
AM, Arvind Kumar, arXiv: 2309.03677 (hep-ph).
- PV mixing is observed as a double peak structure in the production cross-section of Charmonium state ($\psi(3770)$)
AM and Ankit Kumar,arXiv:2308.01482(hep-ph),to be published in Int. Jour. Mod. Phys. E
- PV mixing might show as additional 'anomalous' peak due to the pseudoscalar meson in dilepton spectra!
K. Suzuki and S. H. Lee, Phys. Rev. C **96**, 035203 (2017).

In-medium masses of heavy Quarkonium states

The mass shift of heavy quarkonium state (with Q and $\bar{Q}$ bound by color Coulomb potential) in presence of a gluon field is proportional to the medium change in the scalar gluon condensate

$$\Delta m \sim \Delta \langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \rangle$$

in leading order, assuming the Q-$\bar{Q}$ separation to be small compared to the scale of the gluonic fluctuations.

M.E. Peskin, Nucl. Phys. B156, 365 (1979);
G. Bhanot and M.E. Peskin, Nucl. Phys.B156, 391 (1979);
M.B.Voloshin, Nucl. Phys. B 154 ,365 (1979).

Chiral Effective model:

Hadronic model constructed from symmetries of QCD at low energies:

- Chiral symmetry is spontaneously broken in QCD
  ($\langle\bar{q}q\rangle = \langle(\bar{u}u + \bar{d}d)\rangle \neq 0$ for N_f=2)
  $\rightarrow$ pions are Goldstone modes)

$$m_\pi^2 = -\left(\frac{m_u + m_d}{2}\right)\frac{\langle\bar{q}q\rangle}{f_\pi^2},$$

  Pions get mass from explicit breaking of chiral symmetry by small current quark masses.

- Scale symmetry is also broken. $(\langle G_{\mu\nu}G^{\mu\nu}\rangle \neq 0)$

Impose these constraints to construct effective theory for hadrons–
Generalize to include strange and heavier (charm and bottom) quarks!

Chiral Effective model

Mean field approximation: Meson fields treated as classical fields, independent of space-time.

Equating the explicit chiral symmetry breaking terms in chiral effective model and QCD yields

$$m_u\langle\bar{u}u\rangle = \frac{1}{2}m_\pi^2 f_\pi(\sigma+\delta), \quad m_d\langle\bar{d}d\rangle = \frac{1}{2}m_\pi^2 f_\pi(\sigma-\delta),$$

$$m_s\langle\bar{s}s\rangle = \Big(\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\Big)\zeta.$$

Broken scale invariance introduced through a scalar dilaton field, χ as a logarithmic term in the Lagrangian.

Equating trace of Energy momentum tensor in QCD and in the hadronic model relates the scalar field, χ to the scalar gluon condensate.

Baryon Dirac sea contributions

Dirac sea contributions to baryon self-energy are taken into account through summation of tadpole diagrams.

Scalar fields (σ, ζ, δ and χ) and vector fields (ω, ρ and ϕ), solved for given magnetic field (B), baryon density (ρ_B), temperature (T), asymmetry parameter (η), strangeness fraction (f_s).

$\eta = -\frac{\sum_i I_{3i}\rho_i}{\rho_B}$ and $f_s = \frac{\sum_i s_i \rho_i}{\rho_B}$,

ρ_i, I_{3i} and s_i are the number density, the third component of isospin and the number of strange quarks of baryon i.

For $\rho_B = 0$ (with and without AMMs) and $\rho_B = \rho_0$ (without AMMs), the Dirac sea effects lead to magnetic catalysis (MC) (enhancement of the light quark condensates with increase in B.)

Baryon Dirac sea contributions

Magnetic Catalysis observed in Walecka model for $\rho_B = 0$, $T = 0$.

A. Haber et al, Phys. Rev. D 90, 125036 (2014); A. Mukherjee et al, Phys. Rev. D 98, 056024 (2018).

In magnetized nuclear matter, there is drop in nucleon mass with increase in B, for zero as well as finite temperatures upto T_c, when there is a sudden drop in nucleon mass. Inverse magnetic catalysis identified as a drop in T_c as B is raised.

A. Mukherjee et al,Phys. Rev. D 98, 056024 (2018).

Within chiral effective model, the Dirac sea effects lead to inverse magnetic catalysis in nuclear matter for $\rho_B = \rho_0$.

S. De, P. Parui and AM, Phys. Rev. C 107, 065204 (2023)

Inclusion of hyperons leads to magnetic catalysis.

AM, Arvind Kumar, arXiv: 2309.03677 (hep-ph).

In-medium Masses of Heavy Quarkonia

Mass shift of the charmonium (bottomonium) state is

$$\Delta m_{\Psi(\Upsilon)} = \frac{1}{18} \int d|\mathbf{k}|^2 \langle | \frac{\partial \psi(\mathbf{k})}{\partial \mathbf{k}} |^2 \rangle \frac{|\mathbf{k}|}{|\mathbf{k}|^2/m_{c(b)} + \epsilon_{\Psi(\Upsilon)}}$$

$$\times \left(\left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \right\rangle - \left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \right\rangle_0 \right),$$

$\langle | \frac{\partial \psi(\mathbf{k})}{\partial \mathbf{k}} |^2 \rangle = \frac{1}{4\pi} \int |\frac{\partial \psi(\mathbf{k})}{\partial \mathbf{k}}|^2 d\Omega$, $m_{c(b)}$ is the mass of charm (bottom) quark, $m_{\Psi(\Upsilon)}$ and $\epsilon_{\Psi(\Upsilon)}$ are mass and binding energy of the $\Psi(\Upsilon)$.
S.H. Lee and C.M.Ko, Phys. Rev. C 67, 038202 (2003)

$\left(\left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \right\rangle - \left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \right\rangle_0 \right) = \frac{24}{(33-2n_f)} (1-d) \left(\chi^4 - \chi_0^4 \right)$

A.Kumar and AM, Eur. Phys. Jour. A 47, 164 (2011);
AM and D. Pathak, Phys. Rev. C 90, 025201 (2014).

In-medium masses of open charm (bottom) mesons

In-medium masses for D, $\bar{D}$, B and $\bar{B}$ mesons
are calculated from the dispersion relations obtained from the Fourier transformation of their equations of motion:

$$-\omega^2 + \vec{k}^2 + m_i^2 - \Pi_i\left(\omega, |\vec{k}|\right) = 0, \quad i = D, \bar{D}, B, \bar{B}$$

for $|\vec{k}| = 0$, i.e., $m_i^* = \omega(|\vec{k}| = 0)$.

In the presence of a magnetic field, $m_i^{eff} = \sqrt{m_i^{*2} + |eB|}$
for charged open charm (bottom) mesons
(contribution from lowest Landau level).

S. Reddy P, A. Jahan CS, N. Dhale, AM, J. Schaffner-Bielich, Phys. Rev. C97, 065208 (2018); N. Dhale, S. Reddy P, A. Jahan CS, AM, Phys. Rev. C 98, 015202 (2018).

Pseudoscalar meson-Vector meson (PV) mixing

A phenomenological interaction $\mathcal{L}_{PV\gamma} = \frac{g_{PV}}{m_{\rm av}} e\tilde{F}_{\mu\nu}(\partial^\mu P)V^\nu$
g_{PV} fitted to the observed decay width of $V \rightarrow P\gamma$.

Significant drop (rise) in the mass of $P(V^{||})$ for $\eta_c - J/\psi$ mixing.
S. Cho, K. Hattori, S. H. Lee, K. Morita and S. Ozaki, Phys. Rev. D 91 (2015) 045025

Dominant modifications to the masses due to PV mixing in charmonium states ($J/\psi - \eta_c$, $\psi' - \eta'_c$ and $\psi(3770) - \eta'_c$) as well as for the open charm mesons ($D(\bar{D}) - D^*(\bar{D}^*)$).
AM and S.P.Misra, Int. Jour. Mod. Phys. E **30** 2150064 (2021); AM and S.P.Misra, Phys. Rev. C 102, 045204 (2020).

Dirac sea effects on the heavy quarkonia masses significant.

Ankit Kumar and AM, arXiv: 2208:14962 (hep-ph).

Charmonium to $D\bar{D}$ Decay widths in $^3P_0$ model

Decay widths of charmonium state to $D\bar{D}$ studied using a light quark-antiquark ($q\bar{q}$) pair creation model.

$\Psi(c\bar{c}) + q\bar{q} \rightarrow D(c\bar{q}) + \bar{D}(\bar{c}q)$

$^3P_0$ model: $q\bar{q}$ created in the $^3P_0$ state.

A. Le Yaouanc, L. Oliver, O. Pene and J.-C. Raynal, Phys. Rev. D8 2223, (1973); ibid, Phys. Rev. D 9, 1415 (1974); ibid, Phys. Rev. D **11**, 1272 (1975); E.S.Ackleh, T. Barnes and E. S. Swanson, Phys. Rev. D54, 6811, 1996; T. Barnes, F. E. Close, P. R. Page and E. S. Swanson, Phys. Rev. D55, 4157 (1997).

The $^3P_0$ model explains the experimental observation of the strong suppression of the decay of $\psi(4040)$ to $D\bar{D}$ as well as $(D\bar{D}^* + \bar{D}D^*)$, as compared to $D^*\bar{D}^*$.

A. Le Yaouanc, L. Oliver, O. Pene and J.-C. Raynal, Phys. Lett. B **71** 397 (1977).

Charmonium to $D\bar{D}$ Decay widths in ${}^3P_0$ model

$$\Psi(c(\mathbf{p_D}-\mathbf{p_q})\bar{c}(-\mathbf{p_D}+\mathbf{p_q}))+q(\mathbf{p_q})\bar{q}(-\mathbf{p_q})(\text{in } {}^3P_0 \text{ state})$$

$$\rightarrow D(\mathbf{p_D})+\bar{D}(-\mathbf{p_D})$$

Matrix element for the decay:

$$M_{\Psi\rightarrow D\bar{D}}\sim\int d^3p_q\phi_\Psi(2\mathbf{p_q}-2\mathbf{p_D})\phi_D(2\mathbf{p_q}-\mathbf{p_D})$$

$$\times\phi_{\bar{D}}(-2\mathbf{p_q}+\mathbf{p_D})[\bar{u}_{\mathbf{p_q},s}v_{-\mathbf{p_q},s}]^{{}^3P_0},$$

where ϕ_i, $i=\Psi, D, \bar{D}$ represents the wave function of the i-th meson, and $[\bar{u}_{\mathbf{p_q},s}v_{-\mathbf{p_q},s}]^{{}^3P_0}\sim p_qY_1^m(\mathbf{p_q})$ is the wave function of the light quark-antiquark pair created.

B. Friman,S. H. Lee and T. Song, Phys. Lett. B 548, 153 (2002);
A. Kumar and AM, Eur. Phys. Jour. A47, 164 (2011),

Charmonium to $D\bar{D}$ Decay widths in a field theoretic Model of composite hadrons

Charmonium (Ψ) to $D\bar{D}$ decay width calculated **using the light quark-antiquark pair creation of the free Dirac Hamiltonian** and explicit constructions of the Ψ, D and $\bar{D}$ states.

AM, S.P.Misra, W.Greiner, Int. Jour. Mod. Phys. E 24 (2015) 1550053.

Decay width of charmonium state, Ψ to $D\bar{D}$ has the form:

$$\Gamma(\Psi \rightarrow D(\mathbf{p})\bar{D}(-\mathbf{p})) = \gamma_\Psi^2 \frac{p^0_D(|\mathbf{p}|)p^0_{\bar{D}}(|\mathbf{p}|)}{m_\Psi} \exp[-C|\mathbf{p}|^2] P^\Psi(|\mathbf{p}|)$$

$p^0_{D(\bar{D})}(|\mathbf{p}|) = \left(m^2_{D(\bar{D})} + |\mathbf{p}|^2\right)^{1/2}$, **$C$ is given in terms of R_D and R_Ψ, $P^\Psi(|\mathbf{p}|)$ is a polynomial in $|\mathrm{p}|$, the magnitude of the momentum of the outgoing $D(\bar{D})$ meson, $\mathrm{p}|$.**

γ_Ψ is determined from the observed $\Gamma(\psi(3770) \rightarrow D\bar{D})$.

Charmonium to $D\bar{D}$ Decay widths

$$|\mathbf{p}| = \left(\frac{{M_\psi}^2}{4} - \frac{{m_D}^2 + {m_{\bar{D}}}^2}{2} + \frac{({m_D}^2 - {m_{\bar{D}}}^2)^2}{4{M_\psi}^2} \right)^{1/2}.$$

Decay width calculated using (a) $^3P_0$ model, and (b) the model of composite hadrons depend on $|\mathrm{p}|$ through a polynomial term multiplied by a Gaussian part.

In $^3P_0$ model, due to the vanishing of the polynomial part of the decay width, the in-medium decay width was observed to even vanish (nodes). B. Friman et al, Phys. Lett. B 548, 153 (2002)

In presence of PV mixing:

$$\Gamma^{PV}(\Psi \to D(\mathbf{p})\bar{D}(-\mathbf{p})) = \frac{2}{3}\Gamma^T(|\mathbf{p}|) + \frac{2}{3}\Gamma^L(|\mathbf{p}|)|_{m_\psi \to m_\psi^{PV}}$$

The first (second) term corresponds to the transverse (longitudinal) polarizations for the charmonium state, Ψ, whose mass remains unaffected (modified) due to PV mixing.

Production Cross-sections of Heavy Quarkonia

Relativistic Breit Wigner spectral function

$$A_V(M) = C \cdot \frac{2}{\pi} \frac{M^2 \Gamma_V^*}{(M^2 - {m_V^*}^2)^2 + (M \Gamma_V^*)^2}$$

Production corss-section of the vector meson V

$$\sigma(M) = \frac{6\pi^2 \Gamma_V^* A_V(M)}{q(m_V^*, m_a^*, m_b^*)^2}$$

M is the invariant mass,

m_V^*, m_a^* and m_b^* are in-medium masses of V, a and b,

Γ_V^* is in-medium decay width of V,

$q(m_V^*, m_a^*, m_b^*)$ is the momentum of the scattering particle a(b) in the center of mass frame of the vector meson, V.

The constant C in spectral function obtained from $\int_0^\infty A_V(M) dM = 1$.

Production Cross-sections of Heavy Quarkonia

$$\sigma(M) = 6\pi^2 \sum_i \frac{{\Gamma_V^i}^*}{q(m_V^*, m_{a_i}^*, m_{b_i}^*)^2} A_V(M)$$

accounting for all the channels (i) for production of V.

In presence of PV mixing:

$$\sigma(M) = 6\pi^2 \Big(\frac{1}{3} \sum_i \frac{{\Gamma_V^{*i}}^L}{q({m_V^*}^L, m_{a_i}^*, m_{b_i}^*)^2} A_V^L(M)$$
$$+ \frac{2}{3} \sum_i \frac{{\Gamma_V^{*i}}^T}{q({m_V^*}^T, m_{a_i}^*, m_{b_i}^*)^2} A_V^T(M) \Big),$$

${m_V^*}^{T(L)}$ and ${\Gamma_V^{*i}}^{T(L)}$ are the mass and decay width (in channel i) of the transverse (longitudinal) component of the vector meson.

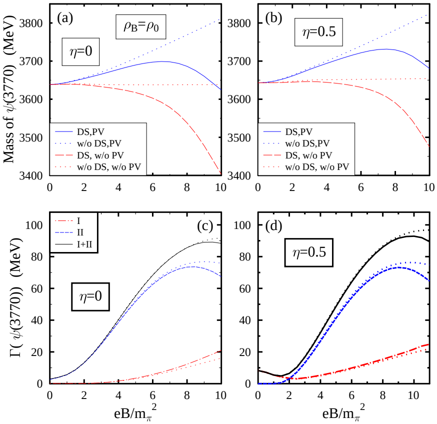
$$A_V^{T(L)}(M) = C \cdot \frac{2}{\pi} \frac{M^2 \Gamma_V^{*T(L)}}{\left(M^2 - {m_V^{*T(L)}}^2\right)^2 + \left(M \Gamma_V^{*T(L)}\right)^2},$$

$\int_0^\infty \left(\frac{1}{3} A_V^L(M) + \frac{2}{3} A_V^T(M) \right) dM = 1$ determines constant C.

AM and Ankit Kumar, arXiv:2308.01482 (hep-ph),

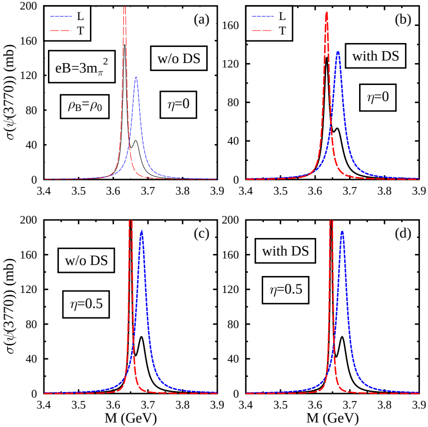
to be published in Int. Jour. Mod. Phys. E

Mass and Decay width of $\psi(3770)$ in magnetized nuclear matter



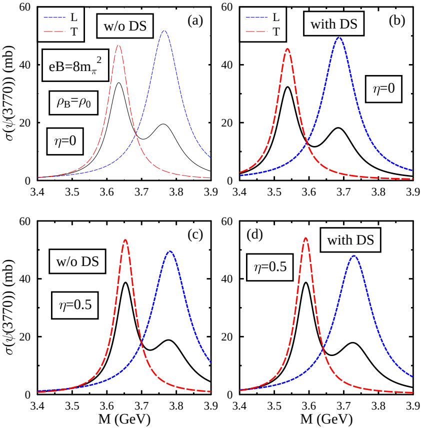
AM and S.P.Misra, Phys. Rev. D 107, 074003 (2023).

Production Cross-section of $\psi(3770)$ $(eB = 3m_\pi^2)$



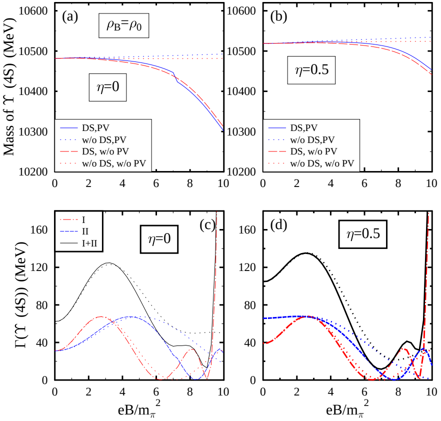
AM and Ankit Kumar, arXiv: 2308.01482 (hep-ph), to be published in Int. Jour. Mod. Phys. E

Production Cross-section of $\psi(3770)$ ($eB = 8m_\pi^2$)



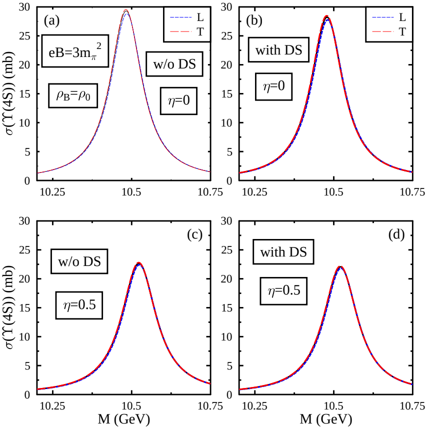
AM and Ankit Kumar, arXiv: 2308.01482 (hep-ph), to be published in Int. Jour. Mod. Phys. E

Mass and Decay width of $\Upsilon(4S)$



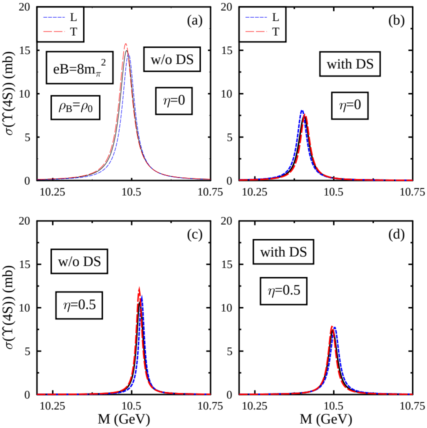
AM and S.P.Misra, Phys. Rev. D 107, 074003 (2023).

Production Cross-section of $\Upsilon(4S)$ $(eB = 3m_\pi^2)$



AM and Ankit Kumar, arXiv: 2308.01482 (hep-ph), to be published in Int. Jour. Mod. Phys. E

Production Cross-section of $\Upsilon(4S)$ ($eB = 8m_\pi^2$)



AM and Ankit Kumar, arXiv: 2308.01482 (hep-ph), to be published in Int. Jour. Mod. Phys. E

Heavy Quarkonia Production Cross-sections in magnetized nuclear matter

- Masses of Heavy Quarkonia ($\psi(3770)$ and $\Upsilon(4S)$) have significant contributions from **Dirac sea** and **PV mixing**.
- The PV mixing of the open charm (bottom) mesons are also accounted for the computation of the decay width of $\Psi(3770)$ ($\Upsilon(4S)$) to $D\bar{D}(B\bar{B})$.
- Decay widths computed using the model of composite hadrons with explicit constructions of initial and final states.
- The isospin asymmetry dependence of the masses and decay widths are observed to be marginal.

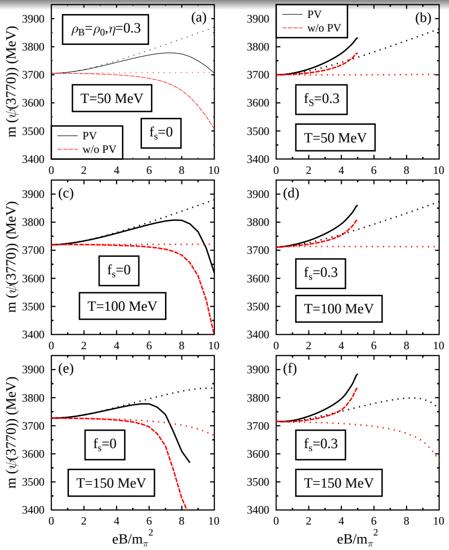
Heavy Quarkonia Production Cross-sections in magnetized nuclear matter

- The production cross-section of $\psi(3770)$ is observed to have a double peak structure due to different contributions from the longitudinal and transverse components (due to PV mixing).
- PV mixing leads to drop (increase) in the mass of the pseudoscalar (longitudinal component of vector) meson, more pronounced at higher values of B.

– reflected in the production cross-section of $\psi(3770)$

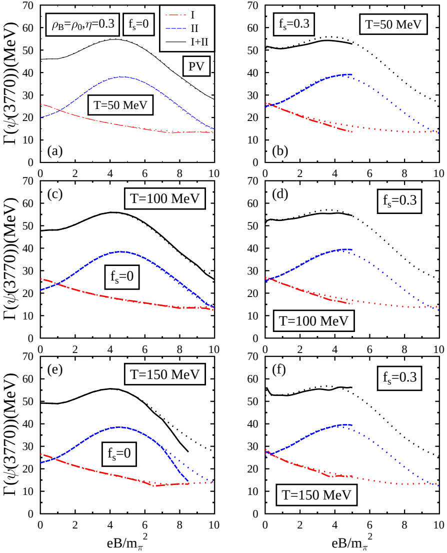
- Appreciable drop in the production cross-section for large B.
- For higher value of B, Dirac sea effect dominates over the PV mixing for the production cross-section of $\Upsilon(4S)$.

In-medium mass of $\psi(3770)$

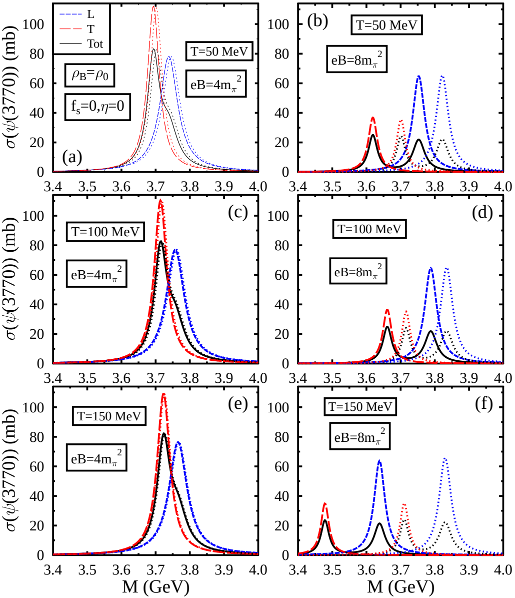


AM, Arvind Kumar, arXiv: 2309.03677 (hep-ph).

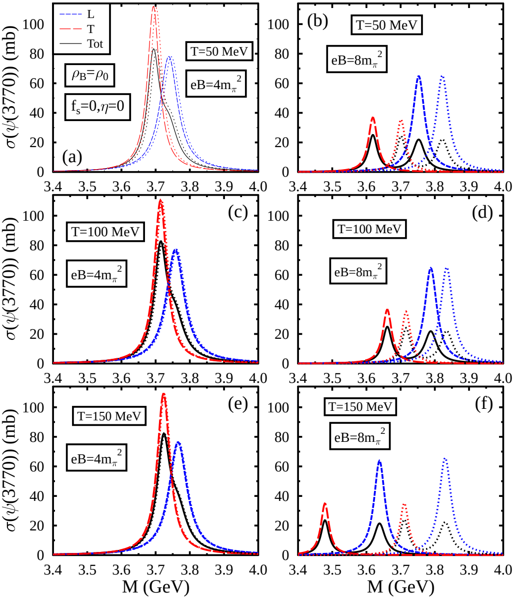
Decay width of $\psi(3770) \to D\bar{D}$



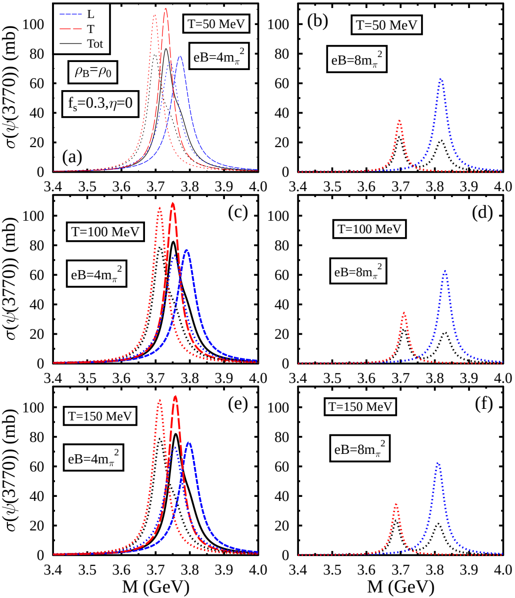
Production cross-section of $\psi(3770)$ (η=0, f_s=0)



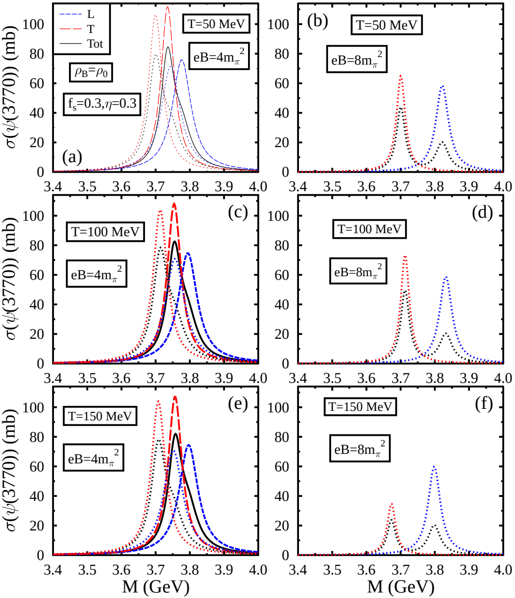
Production cross-section of $\psi(3770)$ (η=0.3, f_s=0)



Production cross-section of $\psi(3770)$ (η=0, f_s=0.3)



Production cross-section of $\psi(3770)$ (η=0.3, f_s=0.3)



Summary

- In-medium masses of Open heavy flavour mesons and heavy quarkonia and charmonium (bottomonium) to $D\bar{D}$ ($B\bar{B}$) decay widths in hot magnetized asymmetric strange matter studied including the effects from Baryonic Dirac sea and PV mixing.!

Anomalous magnetic moments (AMMs) of baryons are considered.

Inverse magnetic catalysis (IMC) observed for nuclear matter!

Inclusion of hyperons observed to lead to magnetic catalysis!

- Effects of strangeness, temperature and magnetic field are observed to be appreciable .

AM, Arvind Kumar, arXiv: 2309.03677 (hep-ph).

- The pseudoscalar-vector meson (PV) mixing effects observed to modify the masses of the (open and hidden) heavy flavour mesons significantly for large magnetic fields.
- Production cross-section of $\psi(3770)$ in magnetized matter observed as a double peak structure (due to PV mixing).

AM and Ankit Kumar,arXiv:2308.01482(hep-ph),to be published in Int. Jour. Mod. Phys. E; AM, Arvind Kumar, arXiv: 2309.03677 (hep-ph).

• PV mixing might show as additional 'anomalous' peak due to the pseudoscalar meson in dilepton spectra!
K. Suzuki and S. H. Lee, Phys. Rev. C **96**, 035203 (2017).

Should have observable consequences on the production of the heavy flavour mesons at RHIC, LHC!

THANK YOU FOR YOUR ATTENTION!