# Heavy Quarkonia Decay widths in magnetized matter

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Emergent topics in Relativistic Hydrodynamics
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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 $\bar{q}Q$, $q = u, d$) in a chiral effective model
- Medium modifications of decay widths of Charmonium (Bottomonium) to $D\bar{D}$ $(B\bar{B})$

  – effects of density, isospin asymmetry and magnetic field!

  Magnetic field effects
  – Nucleon Dirac sea
  – Mixing of pseudoscalar meson and vector meson
  – Landau level contributions for charged hadrons
- Summary

# Motivation

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

$eB \sim 6m_\pi^2$ at RHIC, $eB \sim 15m_\pi^2$ 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 be important and affect the production of heavy quarkonia and open heavy flavour mesons in non-central ultra-relativistic heavy ion collision experiments!

Created matter is extremely dilute!

Dominant modifications of the heavy quarkonia in presence of magnetic fields are due to

– Mixing of the pseudoscalar and vector mesons (PV mixing)
(leads to significant drop (rise) in masses of pseudoscalar meson (longitudinal component of the vector meson)

– Nucleon Dirac sea contributions
Dirac sea effects lead to (inverse) magnetic catalysis

Masses of the heavy flavour mesons have appreciable modifications due to Dirac sea effects!

These should have observable consequences on the yields of the open charm (bottom) and charmonium (bottomonium) states in heavy ion collision experiments!

PV Mixing might show 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 shift of 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 gulonic 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 spece-time.

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

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

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

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

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

# Nucleon Dirac sea contributions

Dirac sea contributions to nucleon self-energy are taken into account through summation of tadpole diagrams.
The Dirac sea contribution to the self-energy of the $i$-th baryon (Weak field approximation)

$$\Sigma_i = \sum_{\alpha=\sigma,\zeta,\delta} \frac{{g_{\alpha i}}^2}{4\pi^2 m_\alpha^2} \Big[ \frac{(q_i B)^2}{3 m_i^*} + \{\Delta_i B)^2 m_i^* + (|q_i| B)(\Delta_i B)\} \times \Big\{ \frac{1}{2} + 2\ln\Big(\frac{m_i^*}{m_i}\Big)\Big\}\Big],$$

where, $q_i$ is the charge and $\Delta_i = -\frac{1}{2}\kappa_i \mu_N B$ is related to the anomalous magnetic moment of the baryon $i$.

The scalar fields ($\sigma$, $\zeta$, $\delta$ and $\chi$) are solved from their coupled equations of motion.

For $\rho_B = 0$ the Dirac sea effects lead to magnetic catalysis (MC), i.e., there is enhancement of the quark condensates with increase in the magnetic field.

Magnetic catalysis effect was observed in Walecka model at zero density and zero temperature.

A. Haber, F. Preis, and A.Schmitt, Phys. Rev. D **90**, 125036 (2014); A. Mukherjee, S. Ghosh, M. Mandal, S. Sarkar, and P. Roy, Phys. Rev. D **98**, 056024 (2018).

# Nucleon Dirac sea contributions

For finite densities, with AMMs of nucleons, 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. The inverse magnetic catalysis is identified as a drop in $T_c$ with increase in $B$.

A. Mukherjee, S. Ghosh, M. Mandal, S. Sarkar, and P. Roy, Phys. Rev. D **98**, 056024 (2018).

With inclusion of the Dirac sea effects, at $\rho_B = \rho_0$, the inverse magnetic catalysis is observed, with AMMs of nucleons.

The Dirac sea contributions significantly affect the masses of the Heavy Quarkonia and the open heavy flavour mesons.

S. De and AM, arXiv: 2208:09820 (hep-ph); P. Parui, S. De and AM, arXiv: 2208:10017 (hep-ph); A. Kumar and AM, arXiv: 2208:14962 (hep-ph).

Mass shift of the charmonium (bottomonium) state is

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

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

where, $\langle |\frac{\partial \psi(\mathbf{k})}{\partial \mathbf{k}}|^2\rangle = \frac{1}{4\pi}\int |\frac{\partial \psi(\mathbf{k})}{\partial \mathbf{k}}|^2 d\Omega$. $m_{c(b)}$ is the mass of the charm (bottom) quark, $m_{\Psi(\Upsilon)}$ is the vacuum mass of the $\Psi$ ($\Upsilon$) state and $\epsilon_{\Psi(\Upsilon)} = 2m_{c(b)} - m_{\Psi(\Upsilon)}$ is the binding energy. $\psi(\mathbf{k})$ is the wave function of the heavy quarkonium state.

S.H. Lee and C.M.Ko, Phys. Rev. C 67, 038202 (2003)

Shift in the scalar gluon condensate:

$$\left( \left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \right\rangle - \left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{\mu\nu a} \right\rangle_0 \right)$$
$$= \frac{24}{(33-2n_f)} \Big[ (1-d)\left(\chi^4 - \chi_0^4\right) + m_\pi^2 f_\pi \sigma'$$
$$+ \left( \sqrt{2} m_k^2 f_k - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi \right) \zeta' \Big].$$

where $\sigma'$, $\zeta'$ are the fluctuations in the fields $\sigma$, $\zeta$ from their vaccum values.

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

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

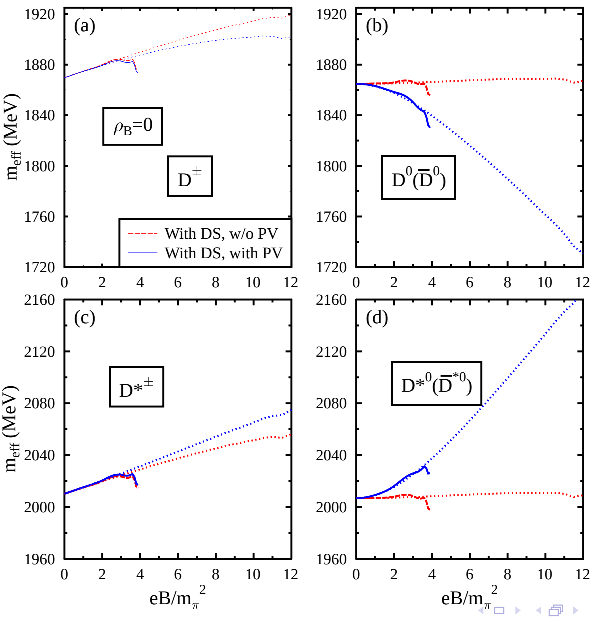
Significant drop (rise) in the mass of $P(V^{||})$ for $\eta_c - J/\psi$ mixing.
S. Cho, K. Hattori, S. H. Lee, K. Morita and S. Ozaki, Phys. Rev. D 91 (2015) 045025

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).

# Open charm mesons (PV mixing)



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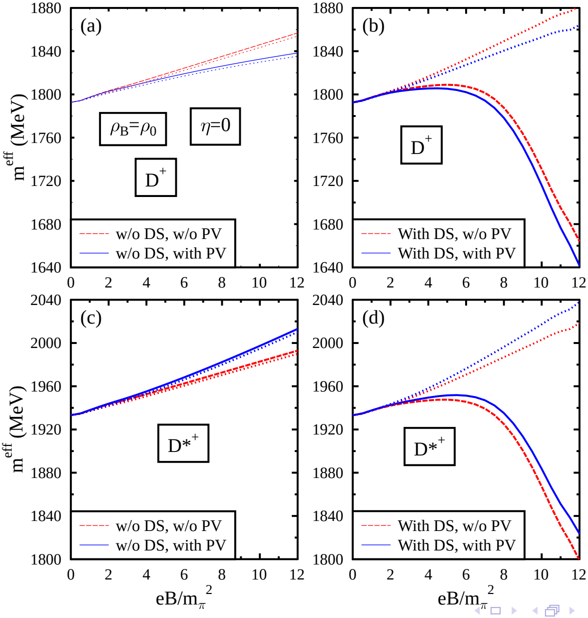

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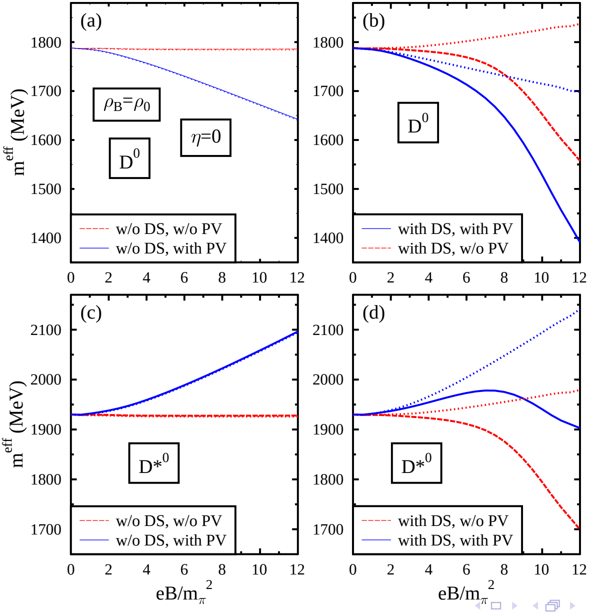

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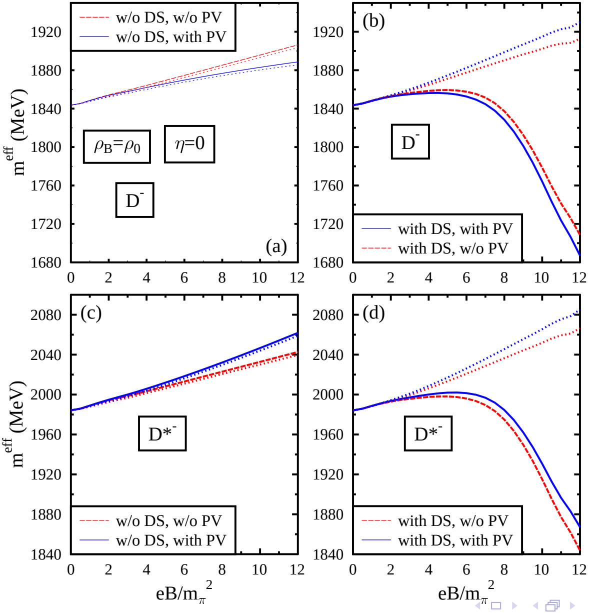

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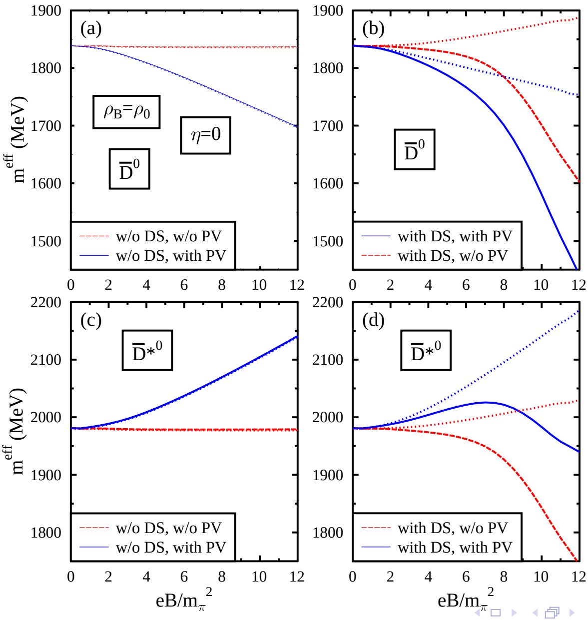
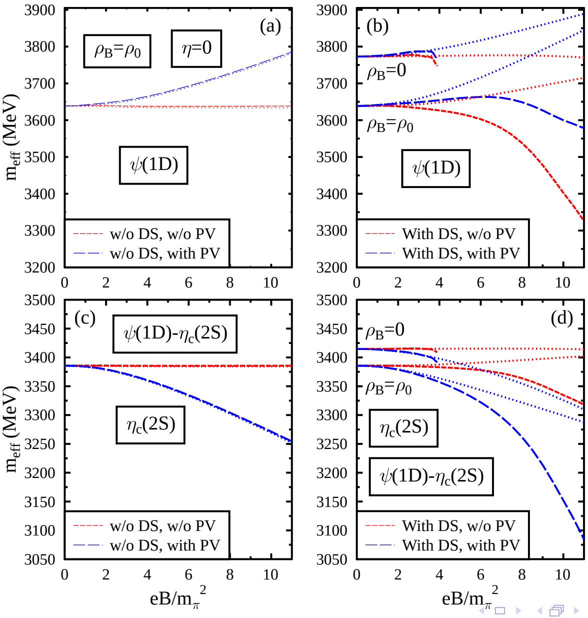


# $\psi(1D) - \eta_c'$ mixing effects



# In-medium charmonium decay widths – a field theoretic model with composite hadrons

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

Charmonium state, $\Psi$ with spin projection m at rest
$|\Psi_m(\mathbf{0})\rangle = \int d\mathbf{k} {c_r}^i(\mathbf{k})^\dagger u_r a_m(\Psi, \mathbf{k}) \tilde{c_s}^i(-\mathbf{k}) v_s |vac\rangle$,

where, $i$ is the color index of the charm quark/antiquark operators, $u_r$ and $v_s$ are the two component spinors for the quark and antiquark and $a_m(\Psi, \mathbf{k})$ is given in terms of the wave functions (assumed to be harmonic oscillator type).

# In-medium charmonium decay widths – a field theoretic model with composite hadrons

$$
\begin{aligned}
|D(\mathbf{p})\rangle &= \frac{1}{\sqrt{6}}\Big(\frac{R_D^2}{\pi}\Big)^{3/4}\int d\mathbf{k}\exp\Big(-\frac{R_D^2\mathbf{k}^2}{2}\Big) \\
&\quad {c_r}^i(\mathbf{k}+\lambda_2\mathbf{p})^\dagger u_r^\dagger {\tilde{q}_s}^i(-\mathbf{k}+\lambda_1\mathbf{p})v_s d\mathbf{k}, \\
|\bar{D}(\mathbf{p}')\rangle &= \frac{1}{\sqrt{6}}\Big(\frac{R_D^2}{\pi}\Big)^{3/4}\int d\mathbf{k}\exp\Big(-\frac{{R_D}^2\mathbf{k}^2}{2}\Big) \\
&\quad {q_r}^i(\mathbf{k}+\lambda_1\mathbf{p}')^\dagger u_r^\dagger {\tilde{c}_s}^i(-\mathbf{k}+\lambda_2\mathbf{p}')v_s d\mathbf{k},
\end{aligned}
$$

where, $q=(d,u)$ for $(D^+,D^-)$ and $(D^0,\bar{D}^0)$ respectively.

**$\lambda_1$ and $\lambda_2$ are the fractions of the mass (energy) of the $D(\bar{D})$ meson at rest (in motion), carried by the constituent light $\bar{q}$ ($q$) and the constituent $c$ ($\bar{c}$), with $\lambda_1+\lambda_2=1$.**

# In-medium charmonium decay widths – a field theoretic model with composite hadrons

Decay width calculated from the matrix element

$\langle D(\mathbf{p})|\langle \bar{D}(\mathbf{p}')|\int \mathcal{H}_{q^\dagger \tilde{q}}(\mathbf{x},t=0)d\mathbf{x}|\Psi_m(\vec{0})\rangle = \delta(\mathbf{p}+\mathbf{p}')A^\Psi(|\mathbf{p}|)p_m,$

$A^\Psi(|\mathbf{p}|) = 6c_\Psi e^{(a_\Psi {b_\Psi}^2 - R_D^2\lambda_2^2)\mathbf{p}^2} \cdot \left(\frac{\pi}{a_\Psi}\right)^{\frac{3}{2}} \left[F_0^\Psi + F_1^\Psi \frac{3}{2a_\Psi} + F_2^\Psi \frac{15}{4a_\Psi^2}\right],$

$a_\Psi$, $b_\Psi$ and $c_\Psi$ are given in terms of $R_D$ and $R_\Psi$, $F_i^\Psi (i=0,1,2)$ are polynomials in $|\mathbf{p}|$, the magnitude of the momentum of the outgoing $D(\bar{D})$ meson, $\mathbf{p}|$.

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

# In-medium charmonium decay widths – a field theoretic model with composite hadrons

Decay width of the charmonium state, $\Psi$ to $D\bar{D}$,

$$
\begin{aligned}
& \Gamma(\Psi \rightarrow D(\mathbf{p})\bar{D}(-\mathbf{p})) \\
= \quad & \gamma_\Psi^2 \frac{8\pi^2}{3} |\mathbf{p}|^3 \frac{p_D^0(|\mathbf{p}|) p_{\bar{D}}^0(|\mathbf{p}|)}{m_\Psi} A^\Psi(|\mathbf{p}|)^2,
\end{aligned}
$$

with $p^0_{D(\bar{D})}(|\mathbf{p}|) = \left(m^2_{D(\bar{D})} + |\mathbf{p}|^2\right)^{1/2}$, and $\gamma_\Psi$ is a parameter determined from the observed $\Gamma(\psi(3770) \rightarrow D\bar{D})$ in vaccum.
**The decay width depends on $|\mathrm{p}|$ through a polynomial and a Gaussian part. Due to the vanishing of the polynomial term, the decay width can even vanish at certain densities (nodes).**
B. Friman,S. H. Lee and T. Song, Phys. Lett. B 548, 153 (2002);
Arvind Kumar and AM, Eur. Phys. Jour. A 47, 164 (2011).

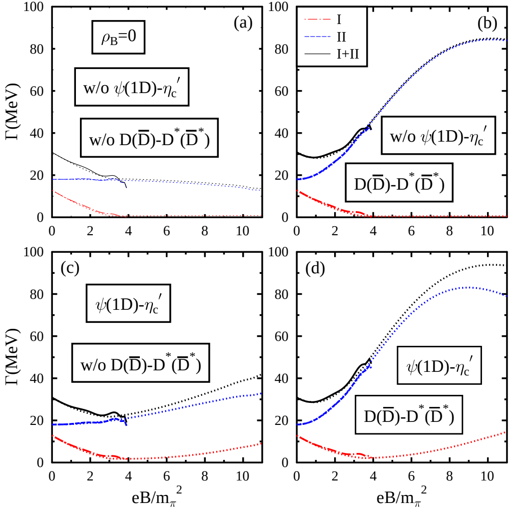
# Decay width of $\Psi \to D\bar{D}$ with PV mixing

$$\Gamma^{PV}(\Psi \to D(\mathbf{p})\bar{D}(-\mathbf{p})) = \gamma_\Psi^2 \frac{8\pi^2}{3} \Bigg[ \left( \frac{2}{3}|\mathbf{p}|^3 \frac{p_D^0(|\mathbf{p}|) p_{\bar{D}}^0(|\mathbf{p}|)}{m_\Psi} A^\Psi(|\mathbf{p}|)^2 \right)$$

$$+ \left( \frac{1}{3}|\mathbf{p}|^3 \frac{p_D^0(|\mathbf{p}|) p_{\bar{D}}^0(|\mathbf{p}|)}{m_\Psi^{PV}} A^\Psi(|\mathbf{p}|)^2 \right) \left( |\mathbf{p}| \to |\mathbf{p}|(m_\Psi = m_\Psi^{PV}) \right) \Bigg].$$

The first (second) term corresponds to the transverse (longitudinal) polarizations for the charmonium state, $\Psi$, whose masses remain unaffected (modified) due to mixing with the pseudoscalar meson in the presence of the magnetic field.

# Charmonium ($\psi(3770)$ decay widths to $D\bar{D}$



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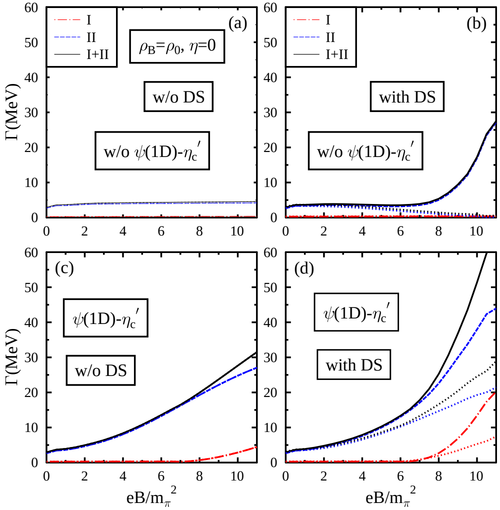

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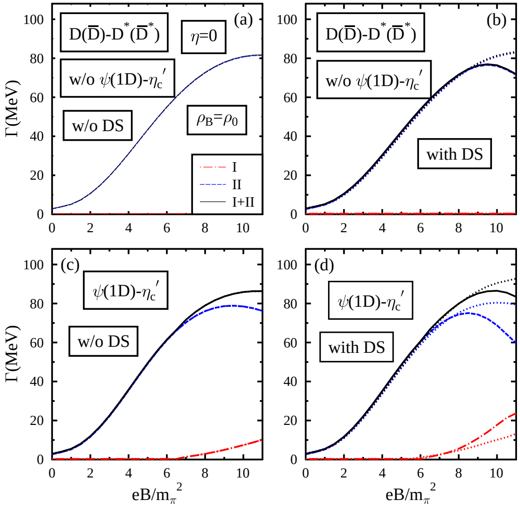

# Bottomonium masses in magnetized matter

S. Iwasaki, M. Oka, K. Suzuki, Eur. Phys. Jour. A **57** (2021) 222; Ankit Kumar and AM, arXiv:2208.14962 (hep-ph).

$$H_{\rm spin-mixing} = -\sum_{i=1}^{2} \boldsymbol{\mu}_i \cdot \mathbf{B},$$

which decribes the interaction of the magnetic moments of the quark (antiquark) with the external magnetic field. In the above, $\boldsymbol{\mu}_i = g|e|q_i\mathbf{S_i}/(2m_i)$ is the magnetic moment of the $i$-th particle, $g$ is the Lande g-factor (taken to be $2$ $(-2)$ for the quark (antiquark)), $q_i$, $\mathbf{S_i}$, $m_i$ are the electric charge (in units of the magnitude of the electronic charge, $|e|$), spin and mass of the $i$-th particle.

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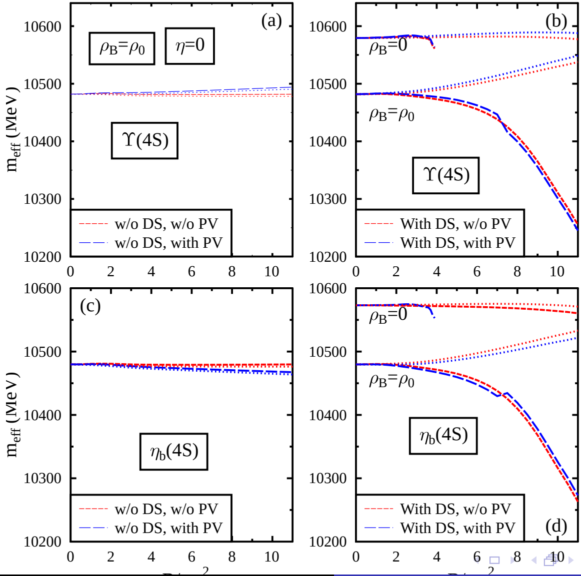
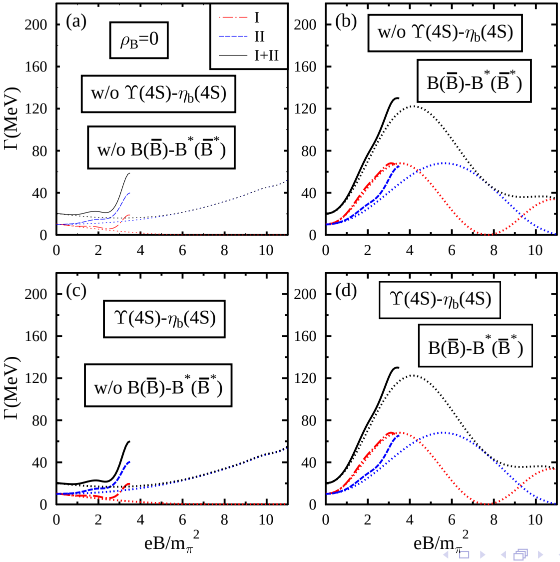


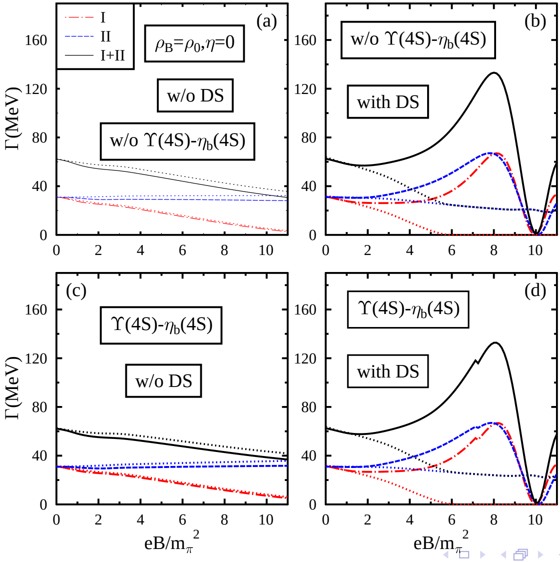
# $\Gamma(\Upsilon(4S) \to B\bar{B})$ in magntized matter

AM and S.P. Misra, arXiv:2210.09192 (hep-ph).



# $\Gamma(\Upsilon(4S) \to B\bar{B})$ in magnetized nuclear matter

AM and S.P. Misra, arXiv:2210.09192 (hep-ph).



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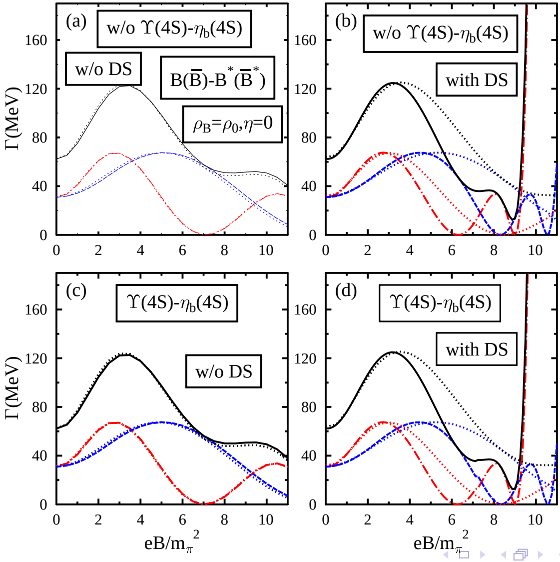

# Summary

- In-medium masses of Open heavy flavour mesons and heavy quarkonia and charmonium (bottomonium) to $D\bar{D}$ ($B\bar{B}$) decay widths studied!

– **effects from density, isospin asymmetry, magnetic field!**

- The pseudoscalar-vector meson mixing effects observed to have significant modifications to the masses of the charmonium (bottomonium) states as well as open charm and open bottom mesons for large magnetic fields.

Amruta Mishra and S.P.Misra, Int. Jour. Mod. Phys. E **31** 22500600 (2022); Amruta Mishra and S.P.Misra, Int. Jour. Mod. Phys. E **30** 2150064 (2021); Amruta Mishra and S.P.Misra, Phys. Rev. C 102, 045204 (2020).

- The decay width of $\psi(3770) \to D\bar{D}$ as well as $\Upsilon(4S) \to B\bar{B}$ in magnetized matter observed to be modified significantly due to Nucleon Dirac sea and $PV$ mixing effects. Should have observable consequences on the production of these particles at RHIC, LHC!

THANK YOU FOR YOUR ATTENTION!

# Chiral Effective model

$$\mathcal{L}_{scalebreak} = -\frac{1}{4}\chi^4 \ln\frac{\chi^4}{\chi_0^4} + \frac{d}{3}\chi^4 \ln\left(\frac{\left(\sigma^2 - \delta^2\right)\zeta}{\sigma_0^2\zeta_0}\left(\frac{\chi}{\chi_0}\right)^3\right).$$

Equating trace of Energy momentum tensor in QCD and in the hadronic model yields

$$\theta_\mu^\mu = \langle \frac{\beta_{QCD}}{2g} G_{\mu\nu}^a G^{\mu\nu a} \rangle + \sum_{q_i} m_{q_i} \bar{q}_i q_i \equiv -(1-d)\chi^4,$$

with $\beta_{QCD} = -\frac{g^3}{48\pi^2}(33 - 2n_f)$ at one loop order.

The energies of the light antiquark (quark) and heavy charm quark (antiquark), $\omega_i = \lambda_i m_D (i = 1, 2)$, are assumed to be

$$\omega_1 = M_q + \frac{\mu}{M_q} \times BE, \;\; \omega_2 = M_c + \frac{\mu}{M_c} \times BE,$$

where $BE = (m_D - M_c - M_q)$ is the binding energy of $D(\bar{D})$ meson, with $M_c$ and $M_q$ as the masses of the constitutent $\bar{c}$ $(c)$ and light $q$ $(\bar{q})$, and, $\mu$ is the reduced mass of the $D(\bar{D})$ meson, defined by $1/\mu = 1/M_q + 1/M_c$.

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$$|\bar{D}(\mathbf{p}')\rangle = \frac{1}{\sqrt{6}}\Big(\frac{R_D^2}{\pi}\Big)^{3/4}\int d\mathbf{k}\exp\Big(-\frac{{R_D}^2\mathbf{k}^2}{2}\Big) q_r{}^i(\mathbf{k}+\lambda_1\mathbf{p}')^\dagger u_r^\dagger \tilde{c_s}{}^i(-\mathbf{k}+\lambda_2\mathbf{p}')v_s d\mathbf{k},$$

where, $q=(d,u)$ for $(D^+, D^-)$ and $(D^0, \bar{D^0})$ respectively.

**$\lambda_1$ and $\lambda_2$ are the fractions of the mass (energy) of the $D(\bar{D})$ meson at rest (in motion), carried by the constituent light $\bar{q}$ ($q$) and the constituent $c$ ($\bar{c}$), with $\lambda_1+\lambda_2=1$.**

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The energies of the light antiquark (quark) and heavy charm quark (antiquark), $\omega_i = \lambda_i m_D (i = 1, 2)$, are assumed to be

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where $BE = (m_D - M_c - M_q)$ is the binding energy of $D(\bar{D})$ meson, with $M_c$ and $M_q$ as the masses of the constitutent $\bar{c}$ $(c)$ and light $q$ $(\bar{q})$, and, $\mu$ is the reduced mass of the $D(\bar{D})$ meson, defined by $1/\mu = 1/M_q + 1/M_c$.

Decay width calculated from the matrix element

$\langle D(\mathbf{p})|\langle \bar{D}(\mathbf{p}')| \int \mathcal{H}_{q^\dagger \tilde{q}}(\mathbf{x}, t = 0) d\mathbf{x} |\Psi_m(\vec{0})\rangle = \delta(\mathbf{p} + \mathbf{p}') A^\Psi(|\mathbf{p}|) p_m,$

# In-medium charmonium decay widths – a field theoretic model with composite hadrons

$$A^{\Psi}(|\mathbf{p}|) = 6c_{\Psi}e^{(a_{\Psi}{b_{\Psi}}^2 - R_D^2\lambda_2^2)\mathbf{p}^2} \cdot \left(\frac{\pi}{a_{\Psi}}\right)^{\frac{3}{2}} \left[F_0^{\Psi} + F_1^{\Psi}\frac{3}{2a_{\Psi}} + F_2^{\Psi}\frac{15}{4a_{\Psi}^2}\right],$$

$a_{\Psi}$, $b_{\Psi}$ and $c_{\Psi}$ are given in terms of $R_D$ and $R_{\Psi}$, $F_i^{\Psi}(i = 0, 1, 2)$ are polynomials in $|\mathbf{p}|$, the magnitude of the momentum of the outgoing $D(\bar{D})$ meson, $\mathbf{p}|$.

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

$\langle f|S|i\rangle = \delta_4(P_f - P_i)M_{fi}$ implies $M_{fi} = 2\pi(-iA^{\Psi}(|\mathbf{p}|)p_m$.

# In-medium charmonium decay widths – a field theoretic model with composite hadrons

Decay width of the charmonium state, $\Psi$ to $D\bar{D}$,

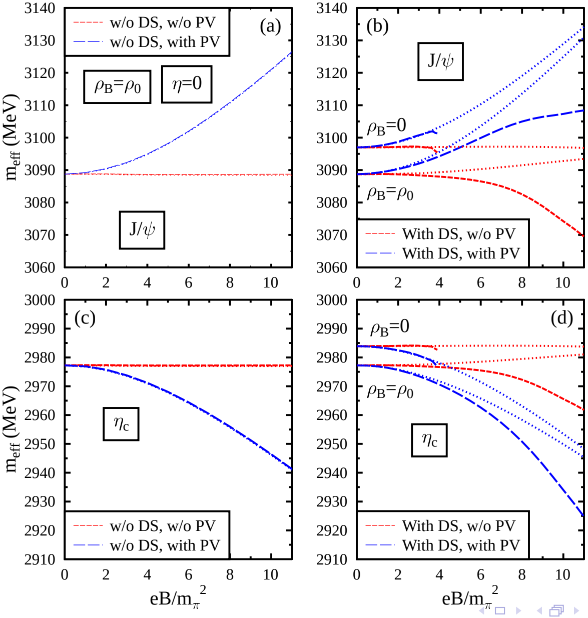
$$
\begin{aligned}
& \Gamma(\Psi \to D(\mathbf{p})\bar{D}(-\mathbf{p})) \\
= \;& \gamma_\Psi^2 \frac{1}{2\pi} \int \delta(m_\Psi - p_D^0 - p_{\bar{D}}^0) |M_{fi}|^2_{\text{av}} \cdot 4\pi |\mathbf{p}_D|^2 d|\mathbf{p}_D| \\
= \;& \gamma_\Psi^2 \frac{8\pi^2}{3} |\mathbf{p}|^3 \frac{p_D^0(|\mathbf{p}|) p_{\bar{D}}^0(|\mathbf{p}|)}{m_\Psi} A^\Psi(|\mathbf{p}|)^2,
\end{aligned}
$$

with $p^0_{D(\bar{D})}(|\mathbf{p}|) = \left(m^2_{D(\bar{D})} + |\mathbf{p}|^2\right)^{1/2}$, and $\gamma_\Psi$ is a parameter determined from the observed $\Gamma(\psi(3770) \to D\bar{D})$ in vaccum.

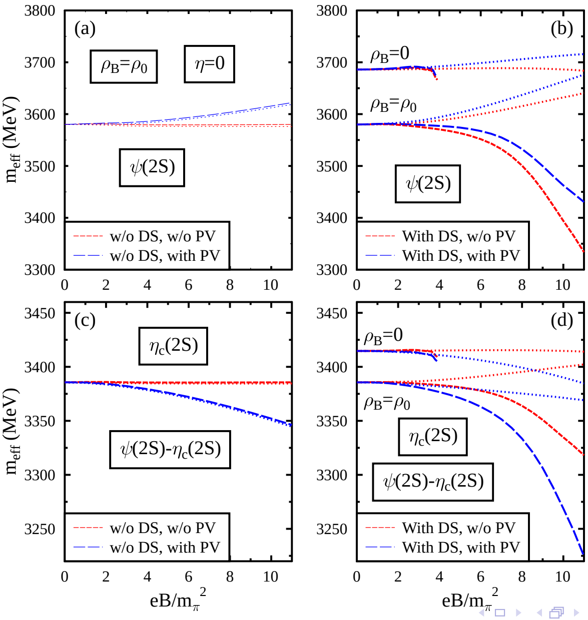
**The decay width depends on $|\mathrm{p}|$ through a polynomial and a Gaussian part. Due to the vanishing of the polynomial term, the decay width can even vanish at certain densities (nodes).**

B. Friman,S. H. Lee and T. Song, Phys. Lett. B 548, 153 (2002);
Arvind Kumar and AM, Eur. Phys. Jour. A 47, 164 (2011).

# $J/\psi - \eta_c$ mixing effects



# $\psi' - \eta_c'$ mixing effects



# Masses and Decay widths of Bottomonium states

In-medium masses of the Bottomonium states ($\Upsilon(1S)$,$\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$) due to interaction with the gluon condensates in the magnetized medium.

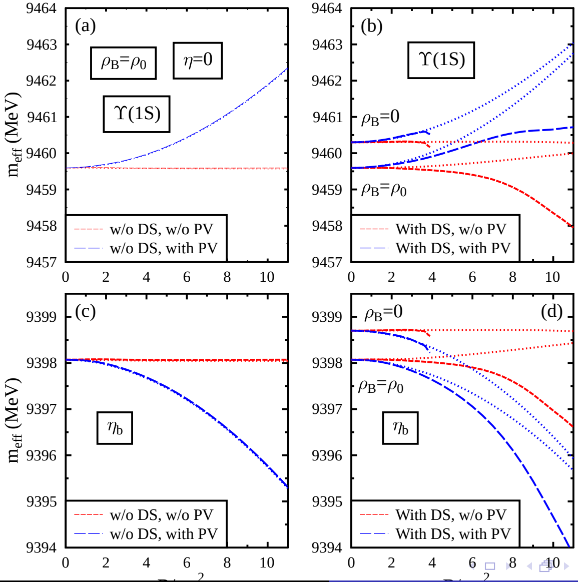
Ankit Kumar and AM, arXiv:2208.14962 (hep-ph).

In medium Decay widths of Bottomonium state ($\Upsilon(4S)$ decaying to $B\bar{B}$ are studied in a field theoretic model for composite hadrons.

AM and S.P.Misra, arXiv:2210.09192 (hep-ph).

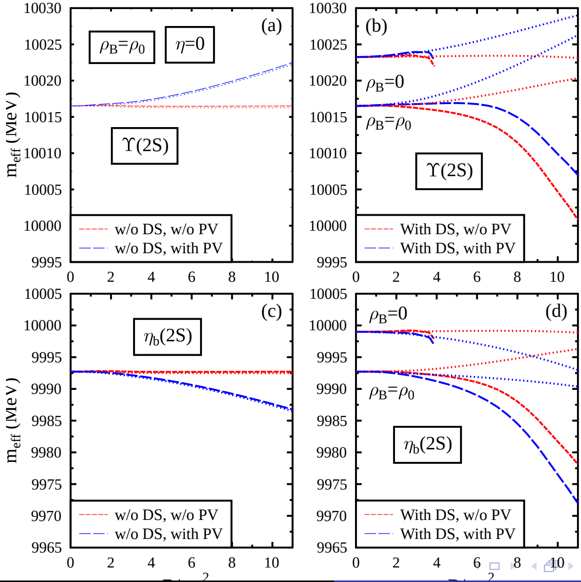
# Bottomonium masses in magnetized matter

Ankit Kumar and AM, arXiv:2208.14962 (hep-ph).



# Bottomonium masses in magnetized matter

Ankit Kumar and AM, arXiv:2208.14962 (hep-ph).



# Bottomonium masses in magnetized matter

Ankit Kumar and AM, arXiv:2208.14962 (hep-ph).