Holographic spin alignment of J/ψ in anisotropic plasma

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Content

Introduction

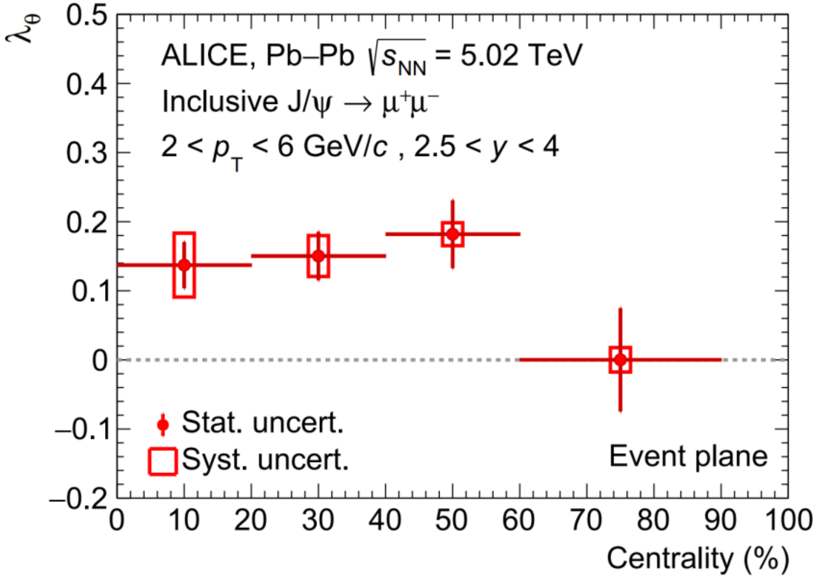
- Spin alignment for a vector meson is 00-element ρ_{00} of its normalized density matrix.

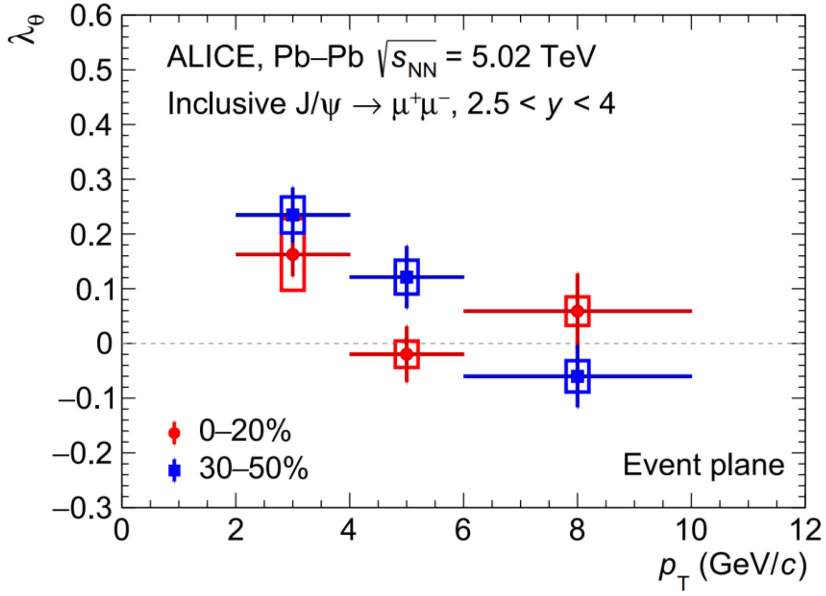
$$\rho_{rs}^{S=1} = \begin{pmatrix} \rho_{+1,+1} & \rho_{+1,0} & \rho_{+1,-1} \\ \rho_{0,+1} & \rho_{00} & \rho_{0,-1} \\ \rho_{-1,+1} & \rho_{-1,0} & \rho_{-1,-1} \end{pmatrix}$$

- Spin alignment is measured through polar angle distribution of decay products ($J/\psi \to \mu^+ + \mu^-$)

$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right),$$

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$





[ALICE, Collaboration. arXiv:2204.10171]

Holographic model

- **Soft wall model:**

The action: $S = S_{bulk} + S_{bndy} + S_f,$

$$S_{bulk} = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left(R - F^{MN}F_{MN} + \frac{12}{L^2}\right),$$

$$S_{bndy} = \frac{1}{8\pi G_5}\int d^4x\sqrt{-\gamma}\left(K - \frac{3}{L} - \frac{L}{2}F^{\mu\nu}F_{\mu\nu}\left(ln\frac{\zeta}{L}\right)\right)|_{\zeta=\delta},$$

$$S_f = \frac{N_c}{16\pi^2}\int d^4x\int_0^{\zeta_h} d\zeta e^{-\phi}\sqrt{-g}Tr\left(|DX|^2 - m_5^2|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2)\right),$$

- **The D'Hoker-Kraus solution** $(X = 0, F_L = F_R \sim B)$**:**

$$ds^2 = \frac{L^2}{\zeta^2}\left(-f(\zeta)dt^2 + h(\zeta)\left(dx^2 + dy^2\right) + q(\zeta)dz^2 + \frac{d\zeta^2}{f(\zeta)}\right).$$

$$f(\zeta) = 1 - \frac{\zeta^4}{\zeta_h^4} + \frac{2}{3}\frac{e^2\mathfrak{B}^2}{1.6^2}\zeta^4 ln\frac{\zeta}{\zeta_h} + \mathcal{O}(e^4\mathfrak{B}^4);$$

$$h(\zeta) = 1 - \frac{4}{3}\frac{e^2\mathfrak{B}^2}{1.6^2}\zeta_h^4\int_0^{\frac{\zeta}{\zeta_h}}\frac{y^3 lny}{1-y^4}dy + \mathcal{O}(e^4\mathfrak{B}^4);$$

$$q(\zeta) = 1 + \frac{8}{3}\frac{e^2\mathfrak{B}^2}{1.6^2}\zeta_h^4\int_0^{\frac{\zeta}{\zeta_h}}\frac{y^3 lny}{1-y^4}dy + \mathcal{O}(e^4\mathfrak{B}^4);$$

4D physical magnetic field

[1] D. Dudal, D. R. Granado, and T. G. Mertens, Phys.Rev.D 93 (2016) 12, 125004 [arXiv:1511.04042].
[2] E. D'Hoker and P. Kraus, JHEP 0910 (2009) 088 [arXiv:0908.3875].
[3] E. D'Hoker and P. Kraus, JHEP 1003 (2010) 095 [arXiv:0911.4518].

Two point correlation function

- Maxwell action for a bulk gauge field $A_M(x^\mu, \zeta)$:

$$S_M = -\int d^5x Q(\zeta) F^{MN} F_{MN}.$$

- Equation of motion:

$$\partial_M [Q(\zeta) F^{MN}] = 0.$$

- Taking radial gauge $A_\zeta = 0$ and Fourier transform

$$A_\mu(x, \zeta) = \int \frac{d^4p}{(2\pi)^4} e^{ip_\nu x^\nu} A_\nu(p, \zeta),$$

- Action expressed by boundary values:

$$S = -2\int \frac{d^4p}{(2\pi)^4} \{\mathrm{Q}(\zeta)\mathrm{g}^{\zeta\zeta}\mathrm{g}^{\mu\nu}\mathrm{A}_\mu(-\mathrm{p}, \zeta)\partial_\zeta A_\nu(p, \zeta)\}|_0^{\zeta_h}.$$

Two point correlation function

- **Action expressed by electric field**

$$S = -2\int \frac{d^4p}{(2\pi)^4}\left\{\frac{Q(\zeta)}{p_t} g^{\zeta\zeta} g^{ik} G^j_k E_i(-p,\zeta)\partial_\zeta E_j(p,\zeta)\right\}\Big|_0^{\zeta_h}. \qquad \pm E_j(\pm p,\zeta) = -p_t A_j(\pm p,\zeta) + p_j A_t(\pm p,\zeta)$$

- **Separating ζ dependence** $\pm E_j(\pm p,\zeta) = \pm \mathcal{E}^k_j(\zeta) E^0_k(\pm p) = \mathcal{E}_j(\zeta)\left(-p_t A^0_j(\pm p) + p_j A^0_t(\pm p)\right).$

- **The action can be simplified as**

$$S = \int \frac{d^4p}{(2\pi)^4}\{E^0_l(-p) H^{ls} E^0_s(p)\}\Big|_0^{\zeta_h} \qquad H^{ls} = -\frac{2Q(\zeta)g^{\zeta\zeta}}{p_t} g^{ik} G^j_k \mathcal{E}^l_i(\zeta)\partial_\zeta \mathcal{E}^s_j(\zeta)$$

with $G^{ij} = \frac{1}{p_t}(-\delta^{ij} + \frac{p^i p^j}{p^2}),\ \ \delta^{ij} = g^{ik}\delta^j_k.$

- **Two point Green function** $E^0_l(\pm p) = \pm C^\mu_l A^0_\mu(\pm p).$ $C^\mu_l = \begin{pmatrix} p_x & -p_t & 0 & 0 \\ p_y & 0 & -p_t & 0 \\ p_z & 0 & 0 & -p_t \end{pmatrix};$

$$\boxed{G^R_{\alpha\beta} = \frac{\delta^2 S}{\delta A^0_\alpha(-p)\delta A^0_\beta(p)} = -2\eta_{\alpha\mu}\eta_{\beta\nu}\lim_{\zeta\to 0}\mathcal{F}^{\mu\nu} = 2\lim_{\zeta\to 0^+}\eta_{\alpha\mu}\eta_{\beta\nu}\mathcal{F}^{\mu\nu} = 2\lim_{\zeta\to 0^+}\eta_{\alpha\mu}\eta_{\beta\nu}\left[-C^\mu_l H^{ls} C^\nu_s\right].}$$

[4] D. T. Son, A.O. Starinets, JHEP 09 (2002) 042 arXiv: hep-th/0205051.

Two point correlation function

- **Green function projected onto different spin states:**

$$G_{\lambda\lambda'}(p) = n^*_\mu(\lambda,p)G_R^{\mu\nu}(p)n_\nu(\lambda',p),$$

polarization vectors

$$n_\mu(\lambda,p) \equiv (-\frac{\vec{p}\cdot\epsilon_\lambda}{m}, \epsilon_\lambda + \frac{\vec{p}\cdot\epsilon_\lambda}{m(\omega+m)}\vec{p})$$

ϵ_λ **is spin direction in vector field's rest frame, which is normalized as:**

$$\epsilon^*_\lambda \cdot \epsilon_{\lambda'} = \delta_{\lambda\lambda'}, \qquad \eta^{\mu\nu}n_\mu(\lambda,q)n^*_\nu(\lambda',q) = \delta_{\lambda\lambda'}.$$

- **Spectral function for spin state $\boldsymbol{\lambda}$,**

$$\rho_\lambda(p) = -\mathrm{Im}G_{\lambda\lambda}(p).$$

- **Dilepton pair production rate from contribution of $\boldsymbol{J/\psi}$ resonance state with spin $\boldsymbol{\lambda}$:**

$$\frac{dN_{\mu^+\mu^-}}{d^4xd^4p}(\lambda) = -\frac{2e^4Q^2}{3(2\pi)^5p^2}\left(1+\frac{2m_\mu^2}{p^2}\right)\sqrt{1-\frac{4m_\mu^2}{p^2}}\,n_B(\omega)\mathrm{Im}G_{\lambda\lambda}(p).$$

- **Spin alignment for $\boldsymbol{J/\psi}$ mesons with momentum $\vec{\boldsymbol{p}}$:**

$$\boxed{\rho_{00}(\vec{p}) = \frac{\int d^4xd\omega\, \frac{dN_{\mu^+\mu^-}}{d^4xd^4p}(\lambda=0)}{\sum_{\lambda=-1}^{1}\int d^4xd\omega\, \frac{dN_{\mu^+\mu^-}}{d^4xd^4p}(\lambda)}.}$$

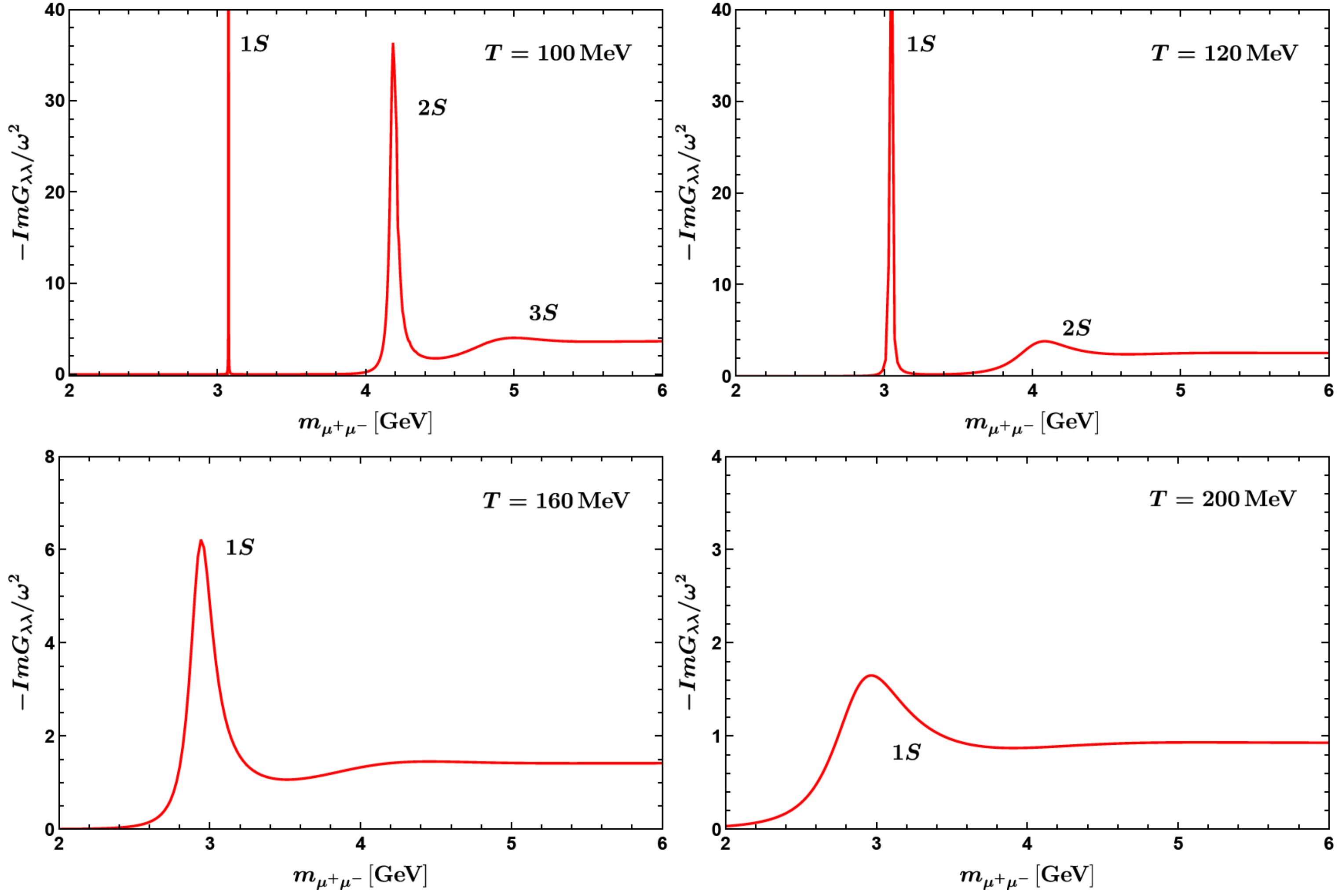
[5] Y. Burnier, M. Laine, M. Vepsalainen. JHEP 02 (2009) 008 arXiv: 0812.2105.
[6] C. Gale, J. I. Kapusta. Nucl.Phys.B 357 (1991) 65-89
[7] H.A. Weldon. Phys.Rev.D 42 (1990) 2384-2387
[8] L. D. McLerran, T. Toimela. Phys.Rev.D 31 (1985) 545

Result @ Spectral function

Temperature dependence:

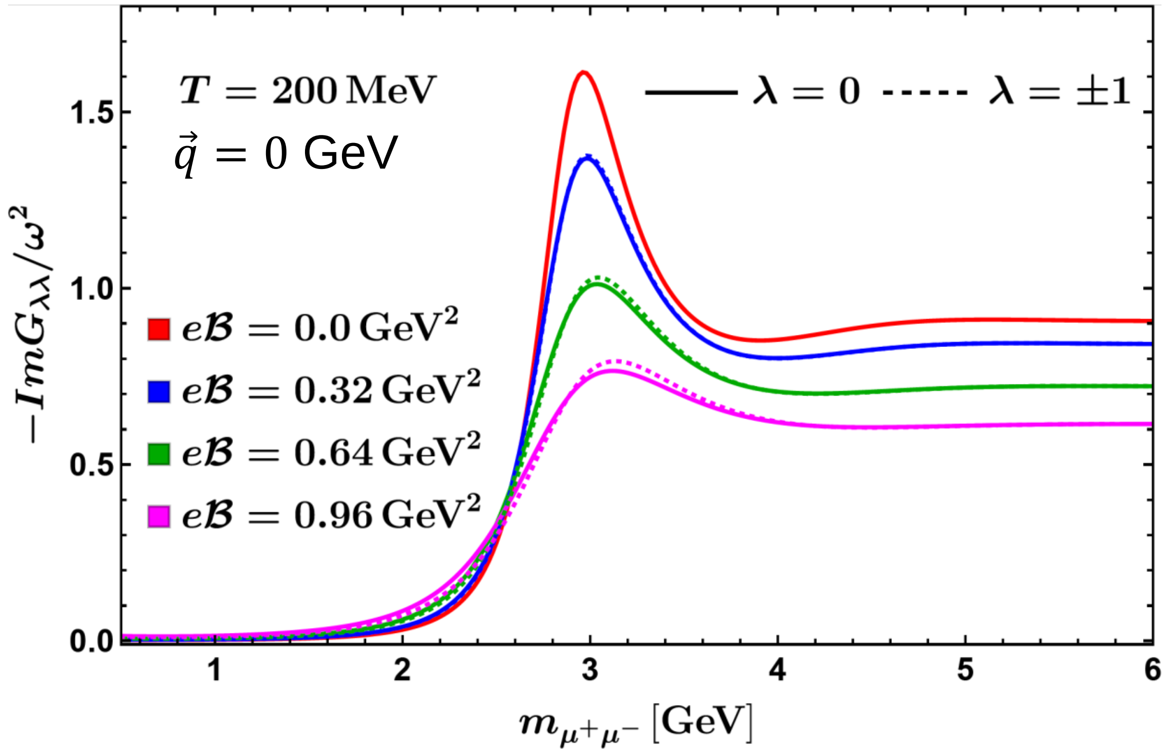
$(e\mathfrak{B}=0\ \text{GeV}^2 \quad \vec{q}=0\ \text{GeV})$

$$T = \frac{1}{4\pi}\left|\frac{4}{\zeta_h} - \frac{2}{3}\frac{(e\mathfrak{B})^2}{1.6^2}\zeta_h^3\right|$$

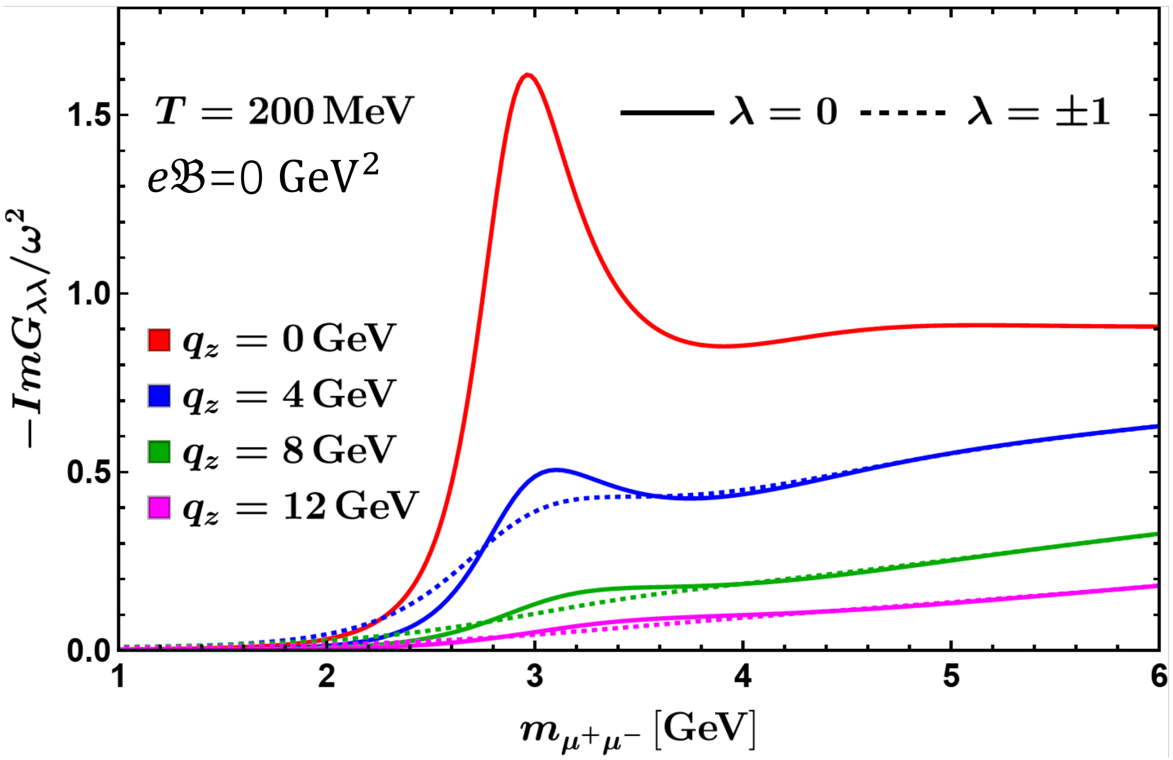


Result @ Spectral function

Magnetic field dependence:

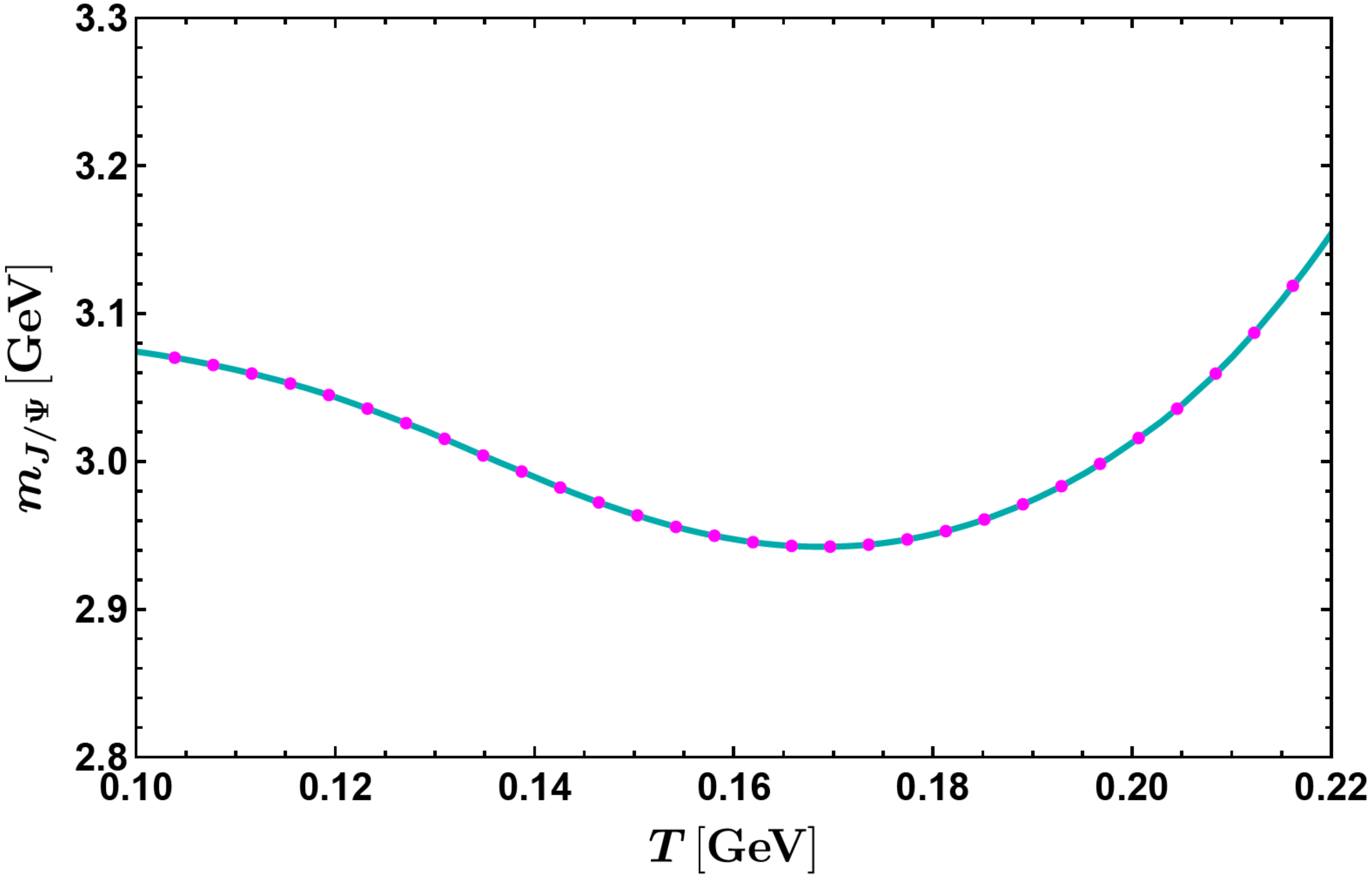


Momentum dependence:



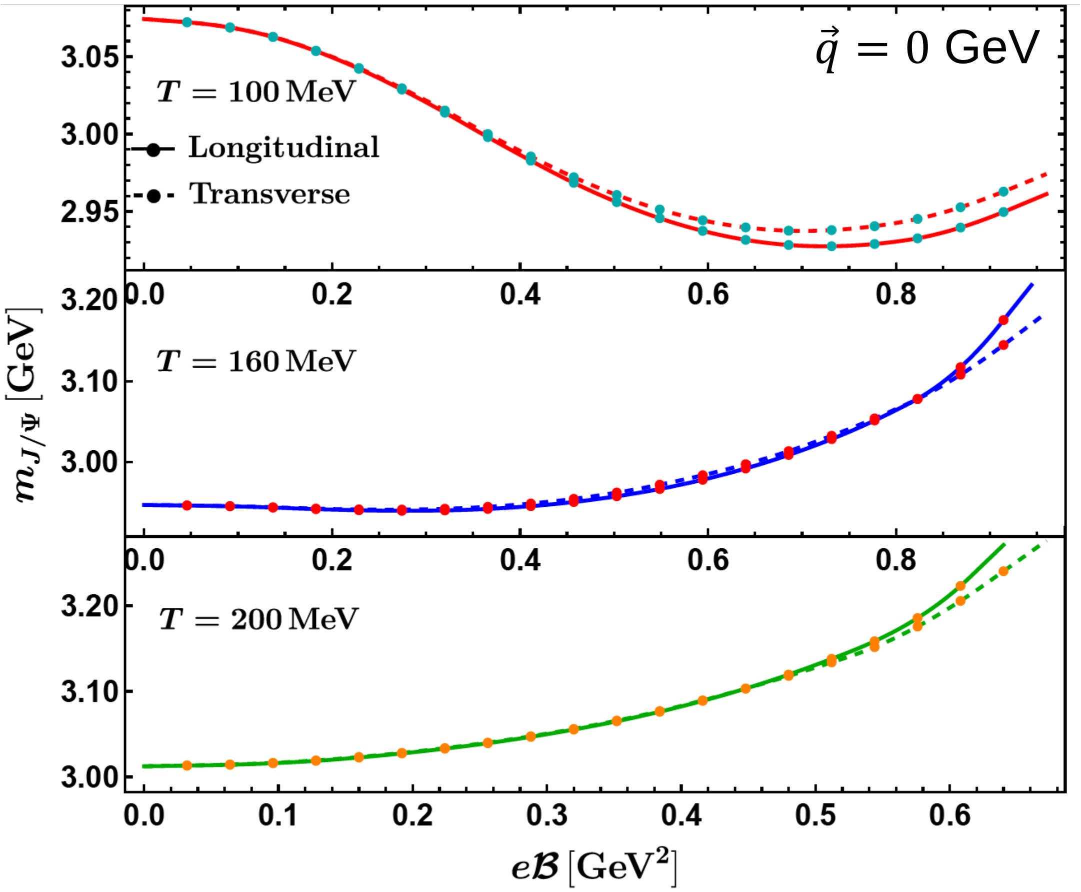
Result @ Effective mass

Temperature dependence: $e\mathfrak{B}$=0 GeV^2 $\vec{q}$ = 0 GeV

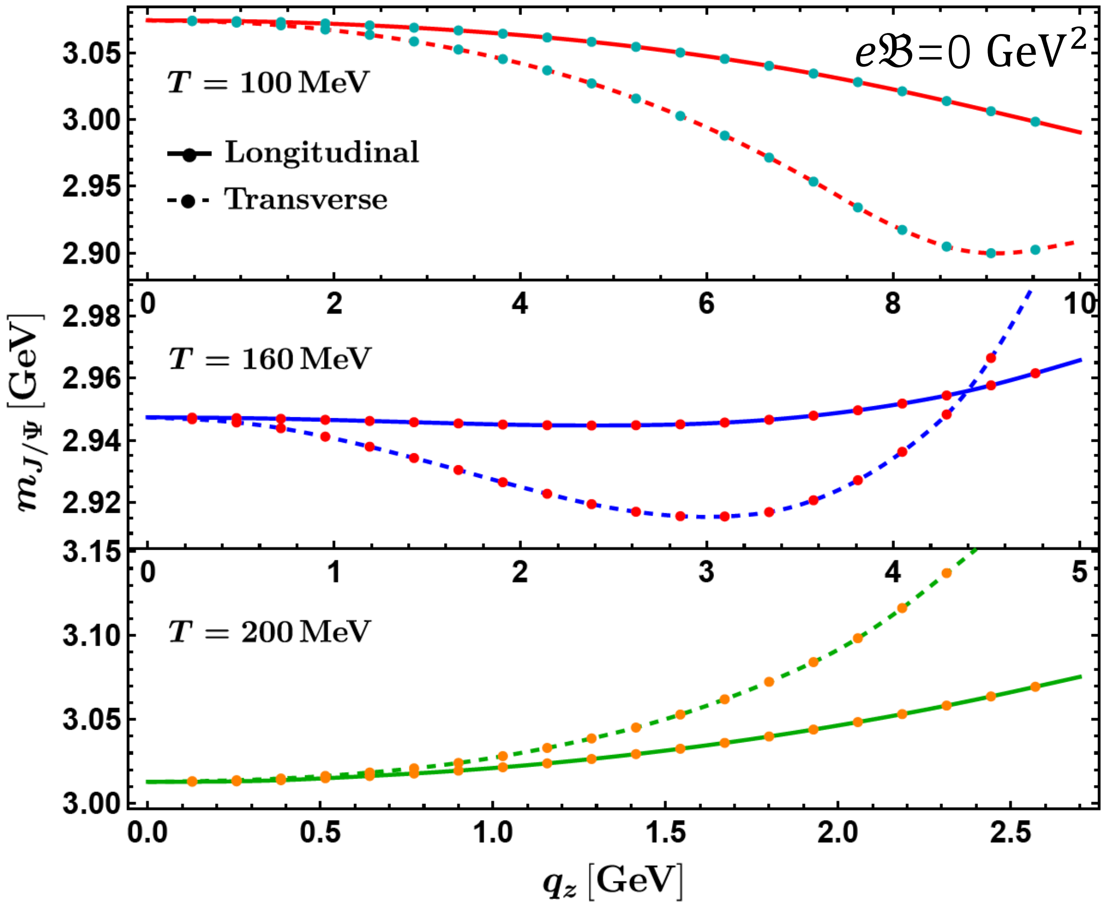


Result @ Effective mass

Magnetic field dependence:



Momentum dependence:



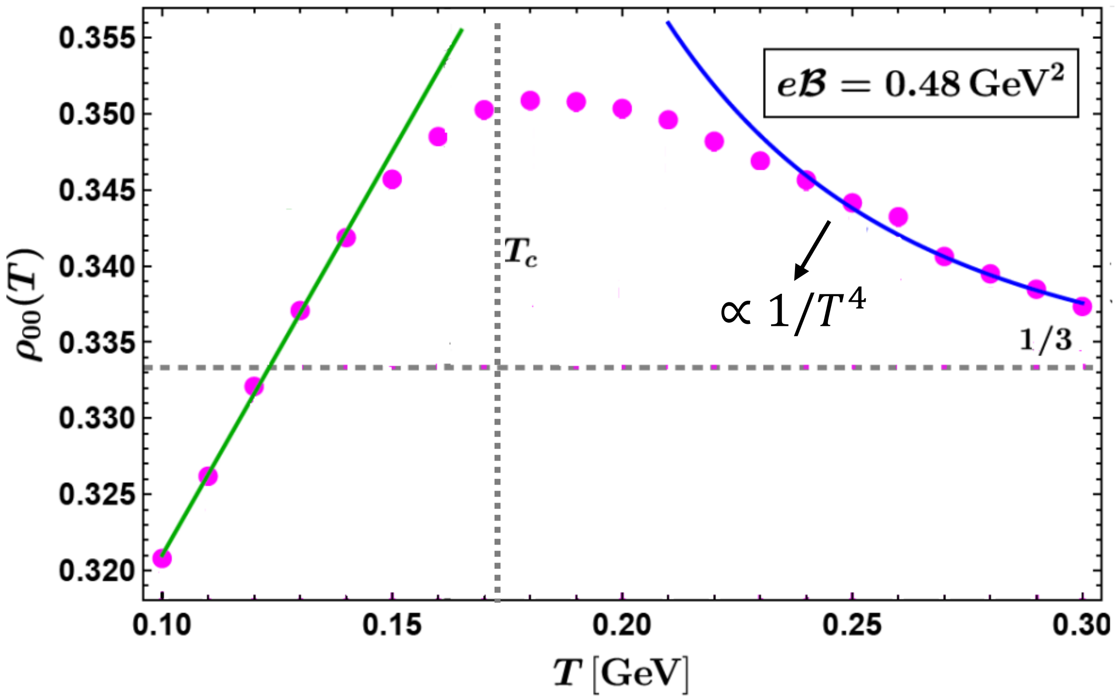
Inverse magnetic catalysis (IMC) at lower temperature and magnetic catalysis (MC) at higher temperature.

Result @ Spin alignment

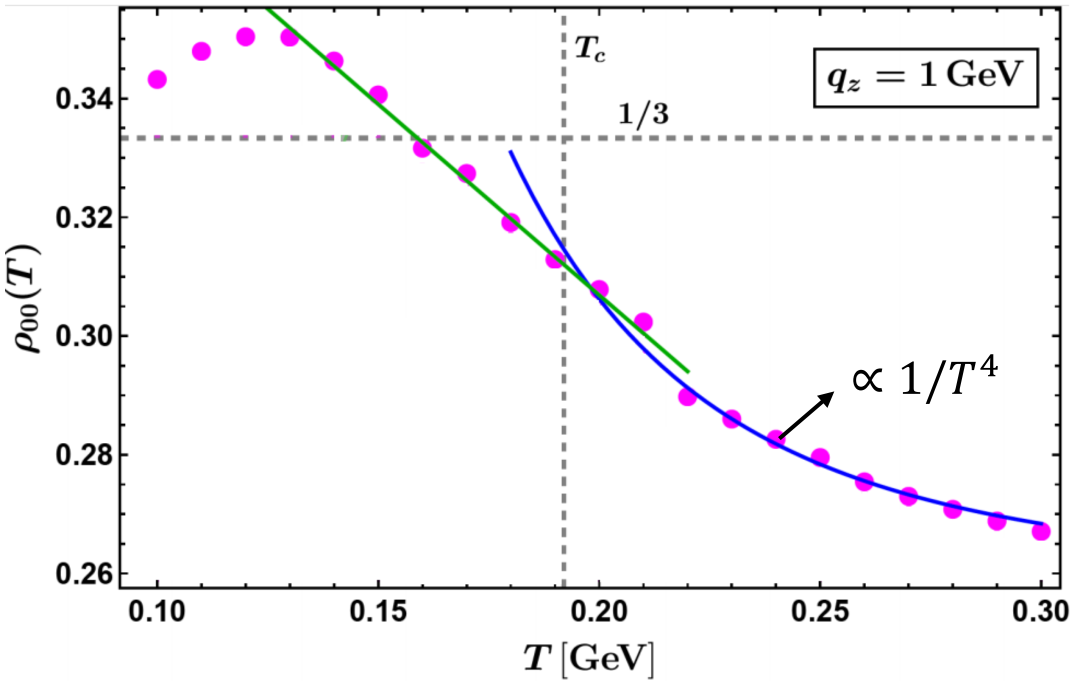
Spin alignment as a function of temperature T:

$$T = \frac{1}{4\pi}\left|\frac{4}{\zeta_h} - \frac{2}{3}\frac{(e\mathfrak{B})^2}{1.6^2}\zeta_h^3\right|$$

Induced by magnetic field $e\mathfrak{B}$:

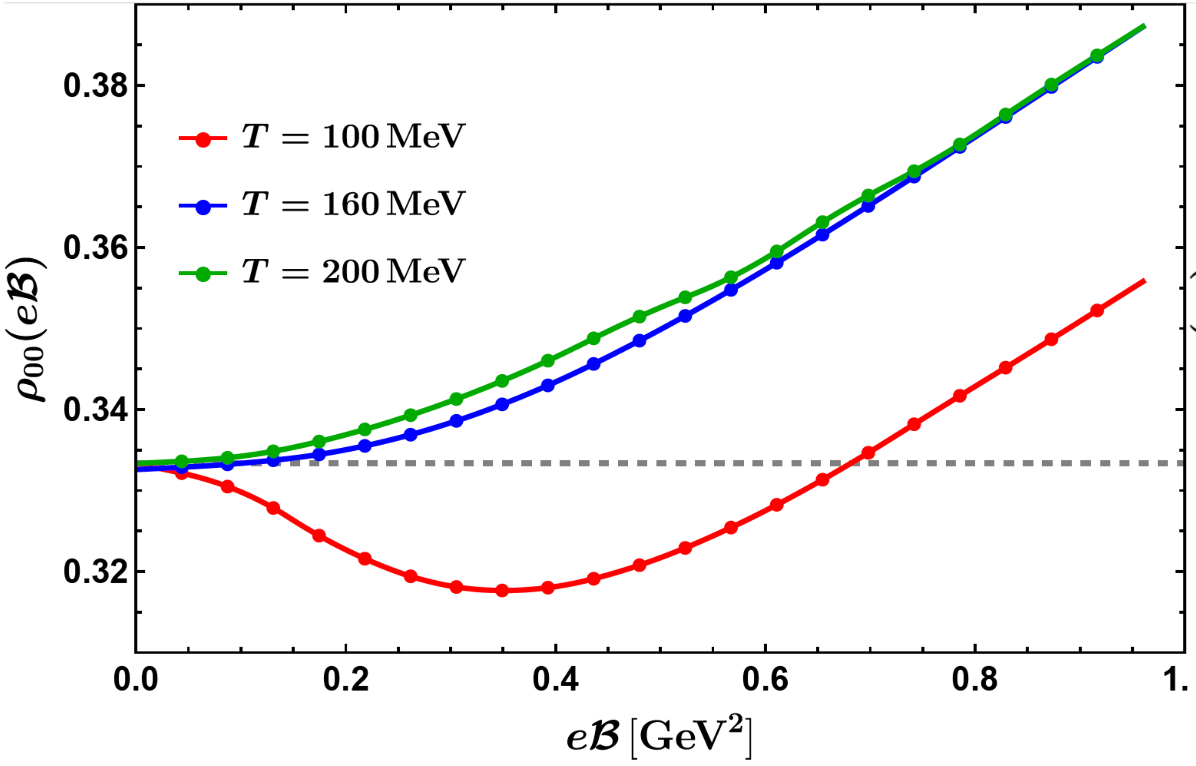


Induced by momentum $\boldsymbol{q_z}$:

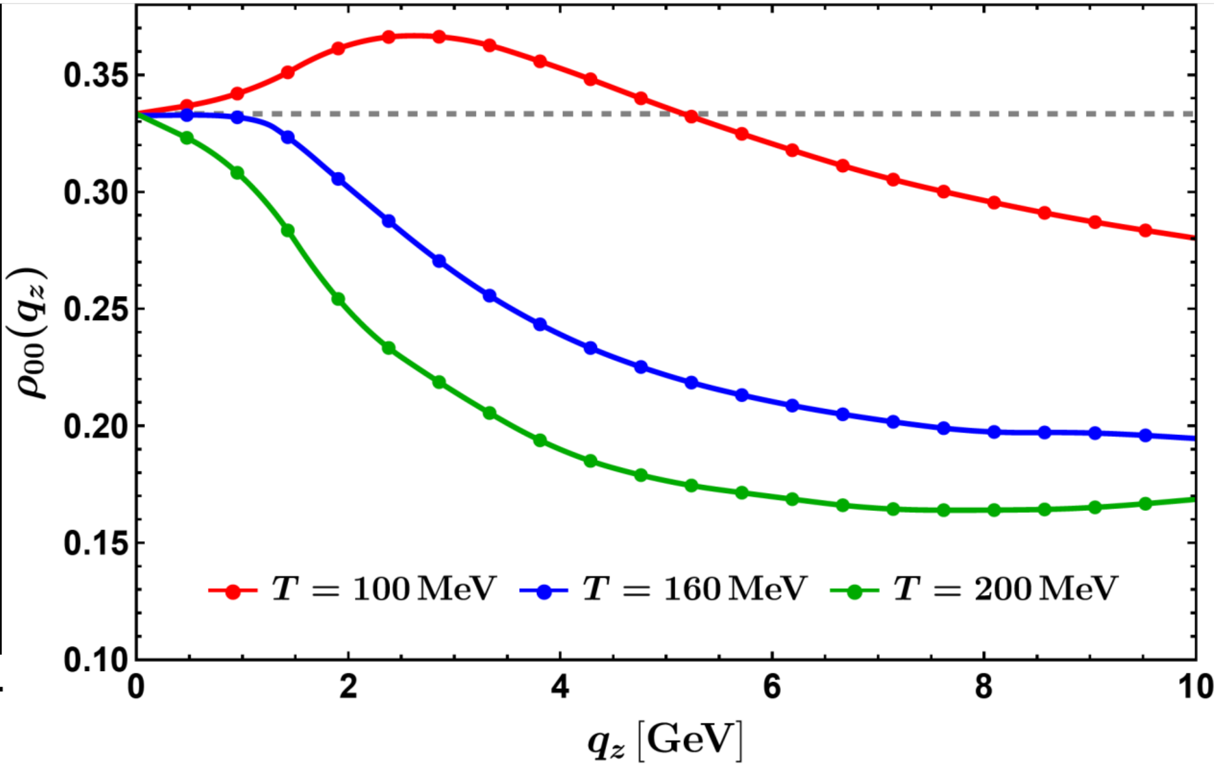


Result @ Spin alignment

Spin alignment as a function of magnetic field $e\mathfrak{B}$: $(\vec{q} = 0 \text{ GeV})$



Spin alignment as a function of momentum q_z : ($e\mathfrak{B}$=0 GeV^2)



Summary

- Derive spectral functions for J/ψ mesons in a magnetic field or with finite momentum.
- Heights for spectral function peaks decrease for increasing $T, e\mathfrak{B}$, and q_z, indicating that dilepton production rates are suppressed.
- Study J/ψ meson's resonance mass and spin alignment as functions of $T, e\mathfrak{B}$, and q_z.
- At high temperatures, $\delta\rho_{00}$ induced by $e\mathfrak{B}$ is positive, while $\delta\rho_{00}$ induced by q_z is negative. At low temperatures, $\delta\rho_{00}$ shows a non-monotonic structure.

Thanks!