Spin alignment of vector mesons in holographic model

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INFN
Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

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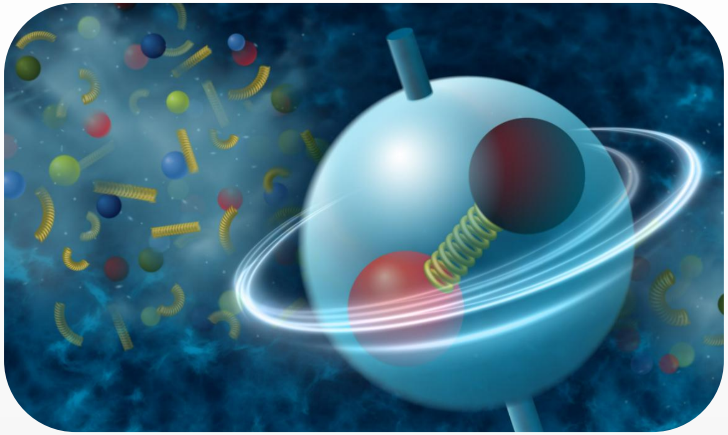

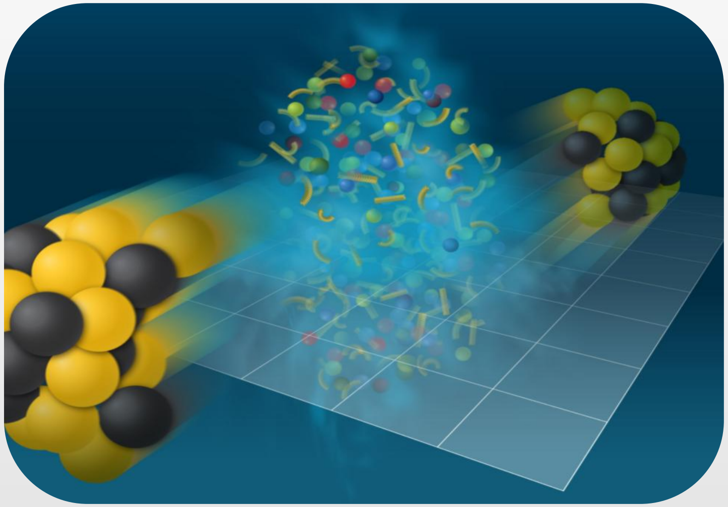

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Outline

- Introduction
- Anisotropy of strong field
- Spin alignment in holographic model
- Summary

Based on:

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023); PRD 109, 036004 (2024).

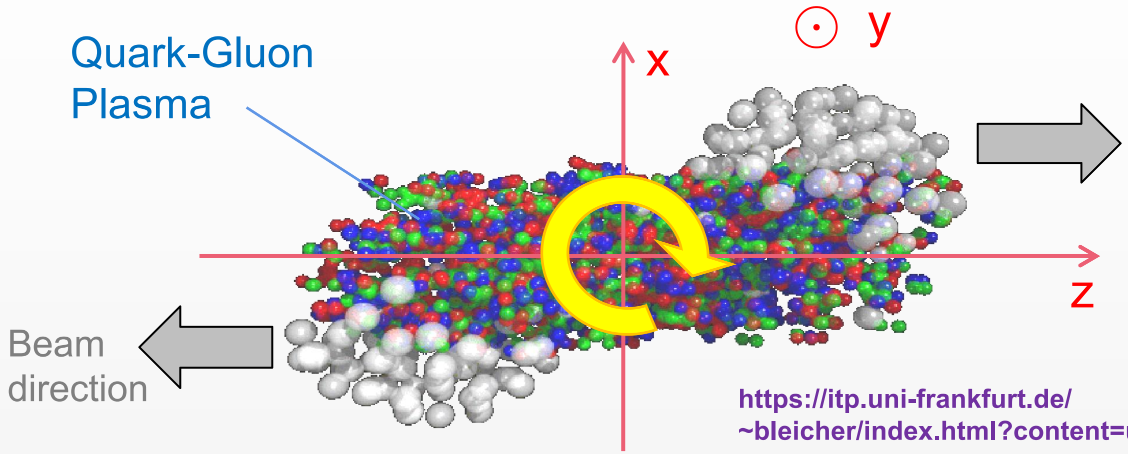
XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv:2403.07522

Y.-Q. Zhao, XLS, S.-W. Li, D. Hou, arXiv:2403.07468

Heavy-ion collisions

Relativistic heavy-ion collisions generate strongly interacting matter with vorticity and magnetic fields



https://itp.uni-frankfurt.de/~bleicher/index.html?content=urqmd

Initial orbital angular momentum → Vorticity field / Magnetic field → Polarized quark/gluon →

Spin polarization for spin-1/2 or spin-3/2 baryons, Λ, Σ^0, Δ^{++}, Ω^-, ...

Spin alignment for vector mesons, ϕ, K^{*0}, ρ^0, ...

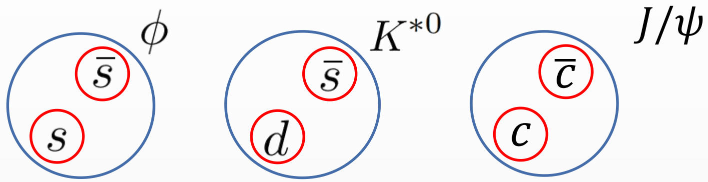
S. A. Voloshi, nucl-th/0410089

Z.-T. Liang, X.-N. Wang, PRL 94, 102301 (2005) [Erratum: PRL 96, 039901 (2006)]; PLB 629, 20 (2005)

F. Becattini, F. Piccinini, J. Rizzo, PRC 76, 044901 (2007)

Spin alignment

- Spin alignment for a vector meson ($J^P = 1^-$) is 00-element ρ_{00} of its normalized spin density matrix, probability of spin-0 state, $\rho_{00} = 1/3$ if no polarization



$$\rho_{rs}^{S=1} = \begin{pmatrix} \rho_{+1,+1} & \rho_{+1,0} & \rho_{+1,-1} \\ \rho_{0,+1} & \rho_{00} & \rho_{0,-1} \\ \rho_{-1,+1} & \rho_{-1,0} & \rho_{-1,-1} \end{pmatrix} = \frac{1}{3} + \frac{1}{2} P_i \Sigma_i + T_{ij} \Sigma_{ij}$$

Vector polarization (3 components, not measurable)

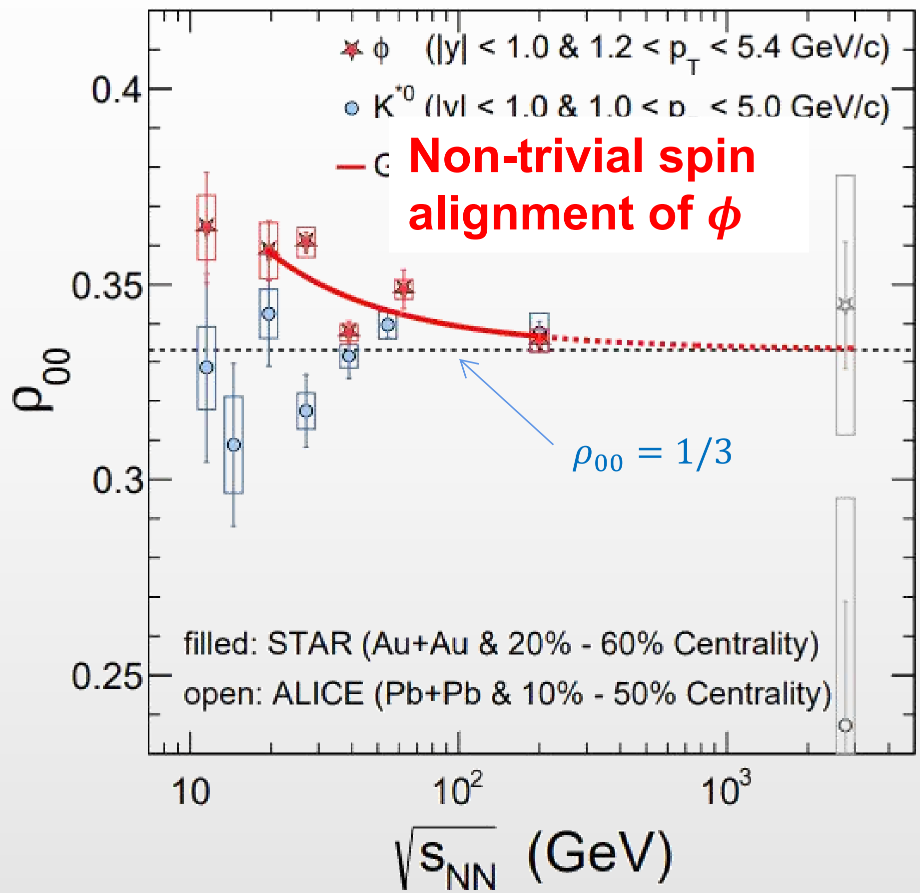
Tensor polarization (5 components, measurable)

- Measured through polar angle distribution of decay products

Processes	Examples	Polar angle distribution $W(\theta)$	Spin is converted to
Strong p-wave decay	$K^{*0} \to K^+ + \pi^-$ $\phi \to K^+ + K^-$	$\frac{3}{4}\left[1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta\right]$	OAM
Dilepton decay	$J/\psi \to \mu^+ + \mu^-$	$\frac{3}{8}\left[1 + \rho_{00} + (1 - 3\rho_{00})\cos^2\theta\right]$	Spin

K. Schilling, P. Seyboth, G. E. Wolf, NPB 15, 397 (1970) [Erratum-ibid. B 18, 332 (1970)].
P. Faccioli, C. Lourenco, J. Seixas, H. K. Wohri, EPJC 69, 657-673 (2010)

Global spin alignment



Theory prediction:
XLS, L. Oliva, Q. Wang, PRD 101, 096005 (2020); PRD 105, 099903 (2022) (erratum)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Article | Published: 18 January 2023

Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

Nature **614**, 244–248 (2023) | Cite this article

3084 Accesses | **8** Citations | **165** Altmetric | Metrics

Spin alignment along direction of global angular momentum

STAR, Nature 614, 244 (2023)

Vorticity field?
Magnetic field?

Spin alignment

Cannot explain large positive deviation from 1/3

$$\rho_{00} \approx \frac{1}{3} + c_{\text{hydro}} + c_{\text{EM}} + c_F + c_A + c_h + c_{\text{strong}}$$

- c_{hydro}: Hydrodynamic gradient (vorticity, acceleraction, shear tensor, second order) [1-13]
- c_{EM}: Electromagnetic fields [3,4,14,15]
- c_F: Fragmen-tation [1]
- c_A: Anomalous color field [16]
- c_h: Helicity polarization [17]
- c_{strong}: Anisotropic strong force [4,18-21]

[1] Z.-T. Liang, X.-N. Wang, PLB 629, 20 (2005)
[2] F. Becattini, L. Csernai, D.-J. Wang, PRC 88, 034905 (2013)
[3] Y.-G. Yang, R.-H. Fang, Q. Wang, X.-N. Wang, PRC 97, 034917 (2018)
[4] XLS, L. Oliva, Q. Wang, PRD 101, 096005 (2020)
[5] X.-L. Xia, H. Li, X.-G. Huang, H.-Z. Huang, PLB 817, 136325 (2021)
[6] F. Li, S. Liu, arXiv: 2206.11890
[7] D. Wagner, N. Weickgenannt, E. Speranza, PRR 5, 013187 (2023)
[8] M. Wei, M. Huang, CPC 47, 104105 (2023)
[9] P. H. D. Moura, K. J. Goncalves, G. Torrieri, PRD 108, 034032 (2023)
[10] A. Kumar, P. Gubler, D.-L. Yang, arXiv:2312.16900
[11] S. Fang, S. Pu, D.-L. Yang, arXiv:2311.15197.
[12] W.-B. Dong, Y.-L. Yin, XLS, S.-Z. Yang, Q. Wang, arXiv:2311.18400.
[13] F. Sun, J. Shao, R. Wen, K. Xu, M. Huang, arXiv: 2402.16595.
[14] XLS, S.-Y. Yang, Y.-L. Zou, D. Hou, arXiv:2209.01872
[15] Y.-Q. Zhao, XLS, S.-W. Li, D. Hou, arXiv: 2403.07468
[16] B. Muller, D.-L. Yang, PRD 105, 1 (2022).
[17] J.-H. Gao, PRD 104, 076016 (2021)
[18] XLS, L. Oliva, Z.-T. Liang, Q. Wang, X.-N. Wang, PRL 131, 042304 (2023); PRD 109, 036004 (2024)
[19] A. Kumar, B. Muller, D.-L. Yang, PRD 108, 016020 (2023)
[20] XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).
[21] XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv: 2403.07522

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XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

Quark polarization

- Polarizations of strange quark/antiquark in a thermal equilibrium system

$$P_s^\mu(x,\mathbf{p}) \approx \frac{1}{4m_s}\epsilon^{\mu\nu\alpha\beta}p_\nu\left[\omega_{\rho\sigma} + \frac{Q_s}{(u\cdot p)T}F_{\rho\sigma} + \frac{g_\phi}{(u\cdot p)T}F^\phi_{\rho\sigma}\right]$$

$$P_{\bar{s}}^\mu(x,\mathbf{p}) \approx \frac{1}{4m_s}\epsilon^{\mu\nu\alpha\beta}p_\nu\left[\omega_{\rho\sigma} - \frac{Q_s}{(u\cdot p)T}F_{\rho\sigma} - \frac{g_\phi}{(u\cdot p)T}F^\phi_{\rho\sigma}\right]$$

Thermal vorticity field (rotation and acceleration)

Classical electromagnetic field

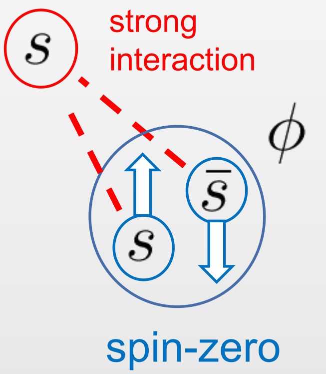
$$\frac{e^2}{4\pi} \sim \frac{1}{137}$$

Vector ϕ field (long wave-length components)

$$\frac{g_\phi^2}{4\pi} \sim \mathcal{O}(1) \gg \frac{e^2}{4\pi}$$

- Strong interaction between quarks are carried by effective vector meson fields (quark-meson model, $\sim T_{\rm de}$)

- Polarize $s/\bar{s}$ in a similar way as classical EM field



F.Becattini, V.Chandra, L.Del Zanna, E.Grossi, Annals Phys. 338, 32 (2013)
Y.-G. Yang, R.-H. Fang, Q. Wang, and X.-N. Wang, Phys.Rev.C 97, 3 (2018).
XLS, L.Oliva, Q.Wang, PRD 101, 096005 (2020);
XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023); PRD 109, 036004 (2024).

Spin alignment

- Spin alignment of the ϕ meson in its rest frame measuring along the direction of $\boldsymbol{\epsilon}_0$

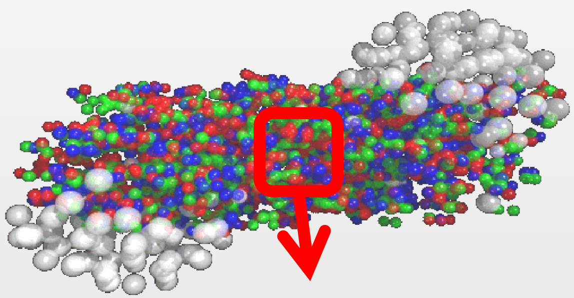
$$C_1 = \frac{8m_s^4 + 16m_s^2 m_\phi^2 + 3m_\phi^4}{120 m_s^2(m_\phi^2 + 2m_s^2)},$$
$$C_2 = \frac{8m_s^4 - 14m_s^2 m_\phi^2 + 3m_\phi^4}{120 m_s^2(m_\phi^2 + 2m_s^2)}.$$

$$\rho_{00} \approx \frac{1}{3} - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_1 \left[\frac{1}{3}\mathbf{B}'_\phi \cdot \mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{B}'_\phi)^2\right] - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_2 \left[\frac{1}{3}\mathbf{E}'_\phi \cdot \mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{E}'_\phi)^2\right]$$

Temperature at hadronization time

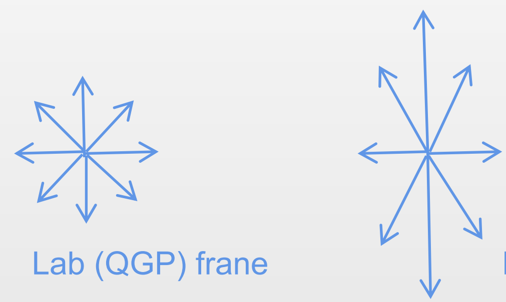
Vector ϕ field: mean value is zero, but can incorporate large fluctuations

- Spin alignment measures anisotropy of fluctuations in meson's rest frame



$$\left\langle g_\phi^2 \mathbf{B}_\phi^i \mathbf{B}_\phi^j / T_\mathrm{h}^2 \right\rangle = \left\langle g_\phi^2 \mathbf{E}_\phi^i \mathbf{E}_\phi^j / T_\mathrm{h}^2 \right\rangle$$
$$= F^2 \delta^{ij} + \Delta \hat{\mathbf{a}}^i \hat{\mathbf{a}}^j$$

Isotropic — Anisotropy of QGP



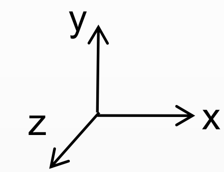
Motion-induced anisotropy

$$\rho_{00}^y - \frac{1}{3} \propto \frac{1}{3}\mathbf{p}\cdot\mathbf{p} - p_y^2$$

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023); PRD 109, 036004 (2024).

Fluctuation-induced ρ_{00}

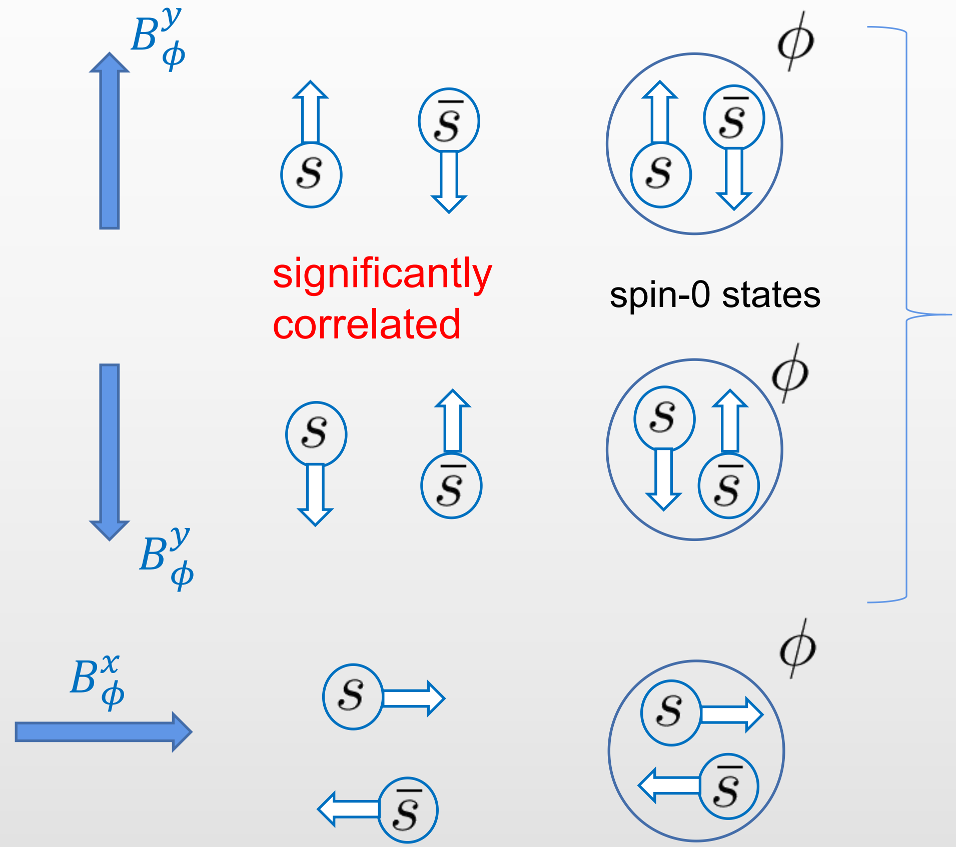
- Example: spin alignment induced by magnetic-like component of strong field



Case 1

Case 2

Case 3



$\langle B_\phi^y \rangle = 0,$

$\langle \left(B_\phi^y\right)^2 \rangle \neq 0$

$\rho_{00}^y > 1/3$

Fluctuation (instead of mean value) induce spin alignment !!!

$\rho_{00}^x > 1/3$

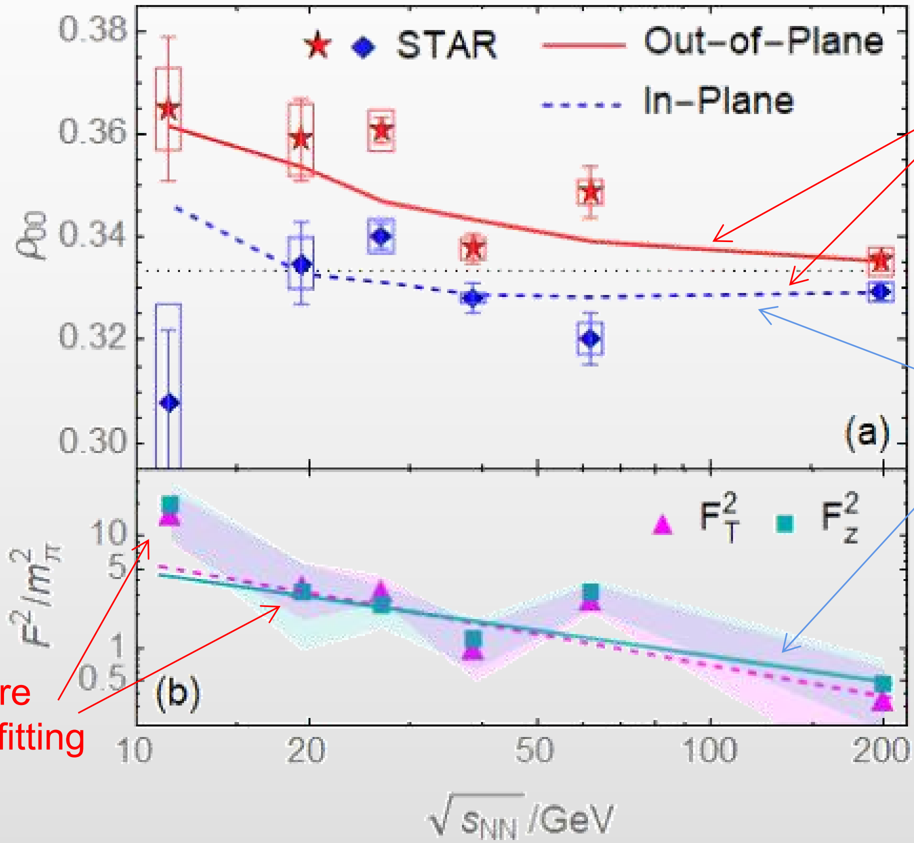
$\rho_{00}^y, \rho_{00}^z < 1/3$

$\rho_{00}^x + \rho_{00}^y + \rho_{00}^z = 1$

Fitting experiment datas

- Taking fluctuations of transverse and longitudinal fields as two independent parameters.

$$\langle (g_\phi \mathbf{B}^\phi_{x,y}/T_\mathrm{h})^2 \rangle = \langle (g_\phi \mathbf{E}^\phi_{x,y}/T_\mathrm{h})^2 \rangle \equiv F_T^2 \qquad \langle (g_\phi \mathbf{B}^\phi_{z}/T_\mathrm{h})^2 \rangle = \langle (g_\phi \mathbf{E}^\phi_{z}/T_\mathrm{h})^2 \rangle \equiv F_z^2$$



Difference induced by v_2

Energy-dependent parameters fitted by

$$\ln(F_T^2/m_\pi^2) = 3.90 - 0.924 \ln \sqrt{s_{\mathrm{NN}}}$$
$$\ln(F_z^2/m_\pi^2) = 3.33 - 0.760 \ln \sqrt{s_{\mathrm{NN}}}$$

$$F_T^2 \approx F_z^2$$

Parameters are evaluated by fitting STAR data

STAR, Nature 614, 244 (2023)

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

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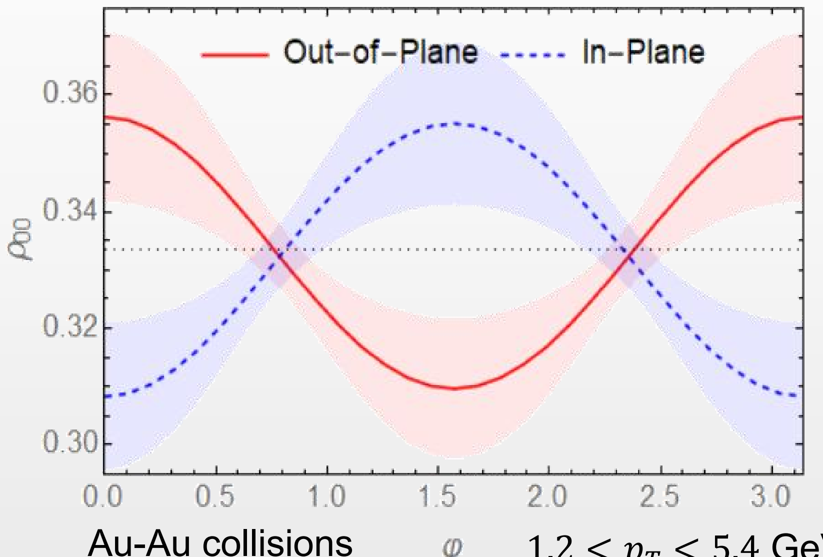
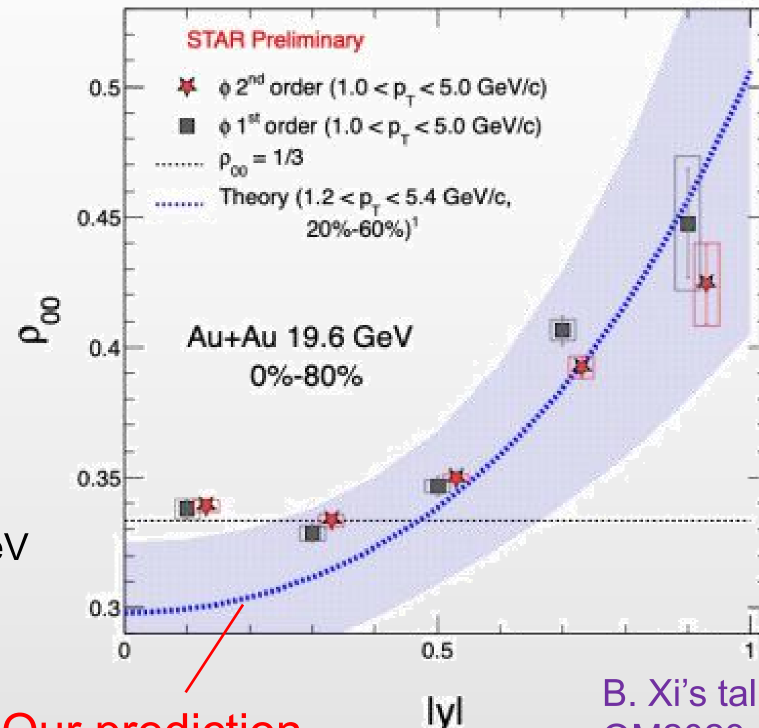
- Predictions for azimuthal angle dependence and rapidity dependence

  Dominated by breaking symmetry because of meson's motion relative to background



Au-Au collisions at 200 GeV/A

$1.2 < p_T < 5.4$ GeV



Our prediction

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

B. Xi's talk in QM2023

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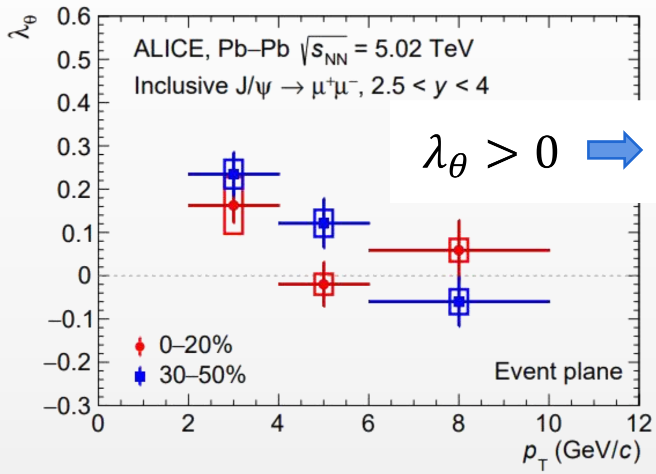
Y.-Q. Zhao, XLS, S.-W. Li, D. Hou, arXiv:2403.07468

J/ψ vs ϕ

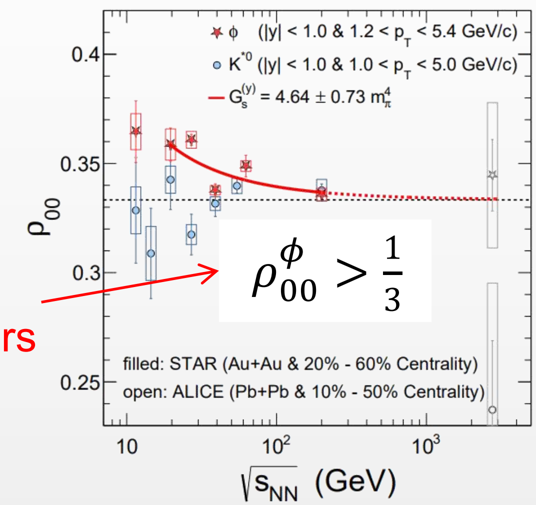
- Spin alignment of J/ψ is opposite to that of ϕ



$\lambda_\theta > 0 \Rightarrow \rho_{00}^{J/\psi} < \frac{1}{3}$

ALICE Collaboration, PRL 131. 042303 (2023)

Opposite behaviours



$\rho_{00}^{\phi} > \frac{1}{3}$

STAR, Nature 614, 244 (2023)

- Universal theory including strong interaction such as: QCD sum rule, NRQCD, holographic QCD ...

Effective vector meson field ✗

Heavy quarkonium are formed at $T > T_{\rm de}$ (deconefinment temperature for light quarks)

AdS/CFT correspondence

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- AdS/CFT correspondence

$$Z_{\mathrm{QFT}}\left[A_\mu^{(0)}\right] = Z_{\mathrm{gravity}}\left[A_\mu\right]$$

Vector field at boundary

Vector field in bulk

Partition function for a dual Quantum Field Theory at boundary (strongly coupled)

$$Z_{\mathrm{QFT}}\left[A_\mu^{(0)}\right] = \left\langle \exp\left\{\int_{\partial\mathcal{M}} J^\mu A_\mu^{(0)} d^4x\right\}\right\rangle$$

Partition function for a bulk gravity theory (weakly coupled)

$$Z_{\mathrm{gravity}}\left[A_\mu\right] = \exp\left\{-S_{\mathrm{bulk}}\left[A_\mu\right]\right\}$$

- Current-current correlation

$\phi, J/\psi \leftrightarrow s, c$ quark current

$$\langle [J^\mu, J^\nu]\rangle = D^{\mu\nu} \propto \frac{\delta^2 Z_{QFT}}{\delta A_\mu^{(0)}\delta A_\nu^{(0)}} = \frac{\delta^2 Z_{\mathrm{gravity}}}{\delta A_\mu^{(0)}\delta A_\nu^{(0)}}$$

J. M. Maldacena, Adv. Theor. Math. Phys. 2. 231 (1998)

E. Witen, Adv. Theor. Math. Phys. 2, 253 (1998)

G. Policastro, D. T. Son, A. Starinets, JHEP 09, 043 (2002)

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L. A. H. Mamani, A. S. Miranda, H. BoschiFilho, N. R. F. Braga, JHEP 03, 058 (2014)

- Action for vector field

$$S_{\mathrm{bulk}} = -\int d^4x\, d\zeta\, Q(\zeta)\, F_{MN}F^{MN}$$

Soft-wall model

$$Q(\zeta) = e^{-\Phi(\zeta)}\sqrt{-g}/(4g_5^2)$$

$$\Phi(\zeta) = c\zeta^2$$

Vector meson's mass in vacuum (n-th excited state) can reproduce the Regge behaviour $M_n^2 = 4c(n+1)$

- Background geometry

$$ds^2 = \frac{L^2}{\zeta^2}\left(-f(\zeta)dt^2 + dx^2 + dy^2 + dz^2 + \frac{d\zeta^2}{f(\zeta)}\right) \qquad f(\zeta) = 1 - \zeta^4/\zeta_h^4$$

Location of horizon depends on temperature

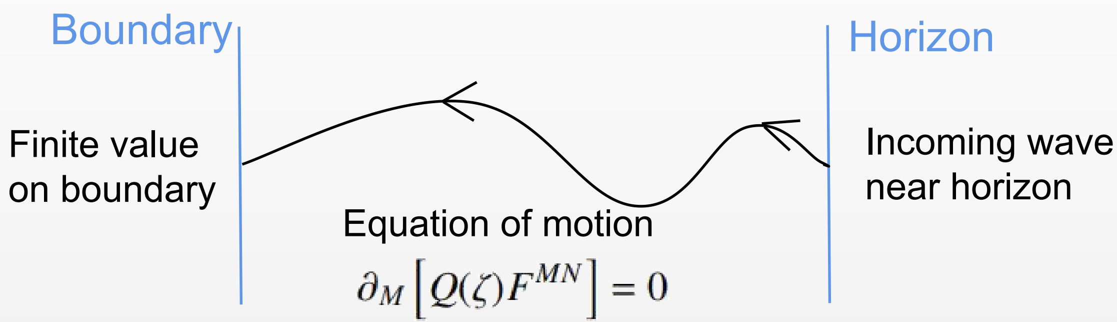
Dilepton production

- Current-current correlation from holographic model

$$D^{\mu\nu}(p) = \lim_{\zeta\to 0} g^{\zeta\zeta} g^{\mu\alpha} Q(\zeta) \left. \frac{\delta\left[\partial_\zeta A_\alpha(p,\zeta)\right]}{\delta A_\nu(p,\zeta)} \right|_{A_\mu(p,0)=0}$$

- $A_\mu(p,\zeta)$ is a solution with definite momentum p

  Location of horizon depends on temperature



- Dilepton production rate from decay of spin-λ states

$$\frac{dN_\lambda}{d^4x\, d^4p} = -\frac{2g^2_{Vl\bar{l}}}{3(2\pi)^5}\left(1-\frac{2m_l^2}{p^2}\right)\sqrt{1+\frac{4m_l^2}{p^2}}\,\frac{p^2 n_B(\omega)\widetilde{\varrho}_{\lambda\lambda}(p)}{(p^2+m_V^2)^2+m_V^2\Gamma_V^2}$$

Bose-Einstein distribution

Probability of q-$\bar{q}$ pair

$$-\epsilon^{*\mu}_\lambda(p)\epsilon^\nu_\lambda(p)\mathrm{Im}D_{\mu\nu}(p)$$

Coupling between meson and dilepton

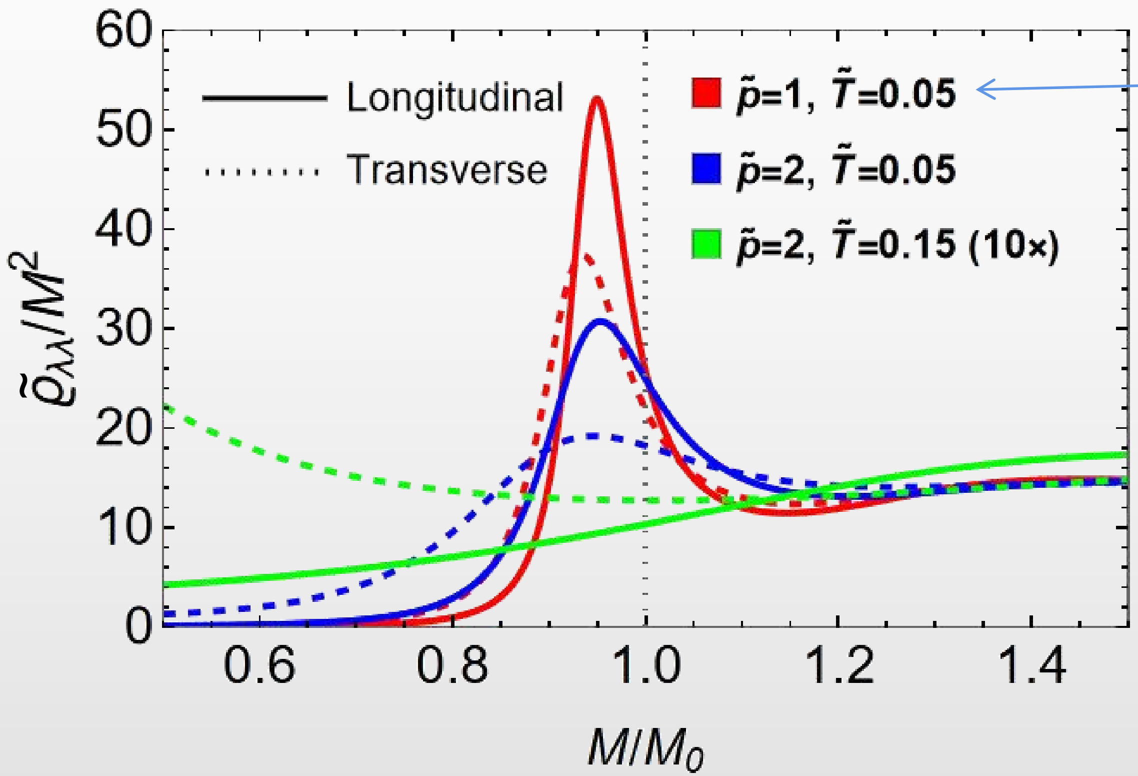
Lepton's mass

Vector meson's vacuum mass and width

XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv:2403.07522

q-$\bar{q}$ pair probability

- Probability of q-$\bar{q}$ pair as function of invariant mass, spatial momentum, and temperature



Momentum and temperature, normalized by vacuum mass $M_0 = \sqrt{4c}$

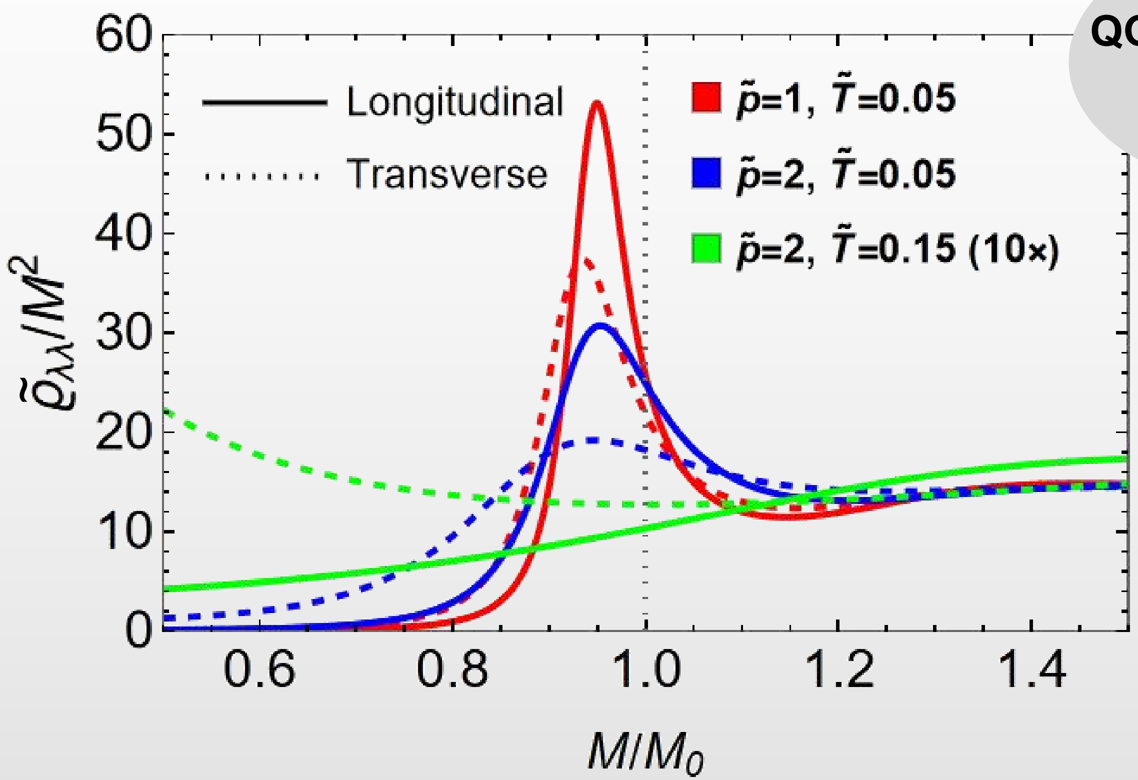
① Shift of peak mass

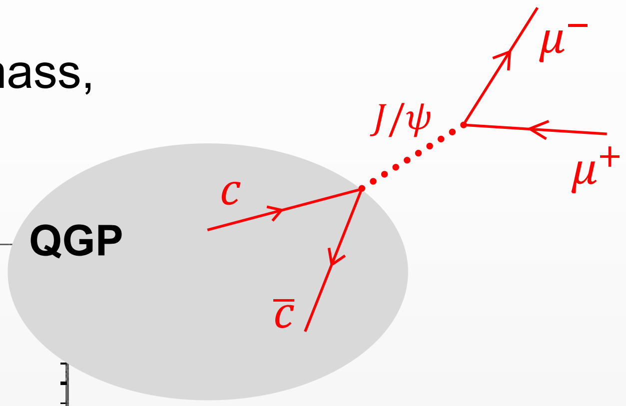
② Width broadening

③ Difference between L and T modes

q-$\bar{q}$ pair probability

- Probability of q-$\bar{q}$ pair as function of invariant mass, spatial momentum, and temperature





Probability of vector meson

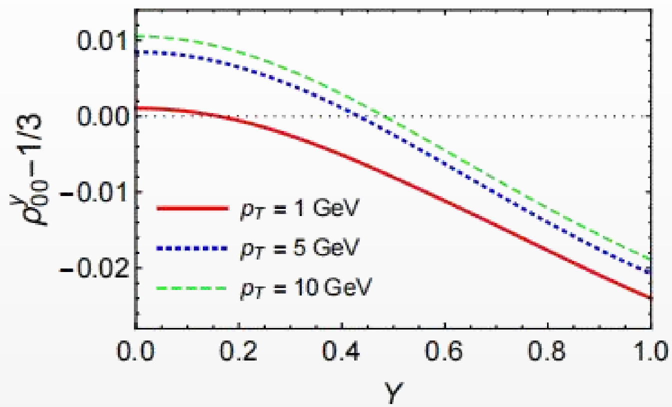
$$\sim \frac{p^2 n_B(\omega)\tilde{\varrho}_{\lambda\lambda}(p)}{(p^2+m_V^2)^2+m_V^2\Gamma_V^2}$$

Only q-$\bar{q}$ with $M \approx M_0$ survive

⇒ q-$\bar{q}$ probability around $M \approx M_0$ controls spin alignment

Model predictions

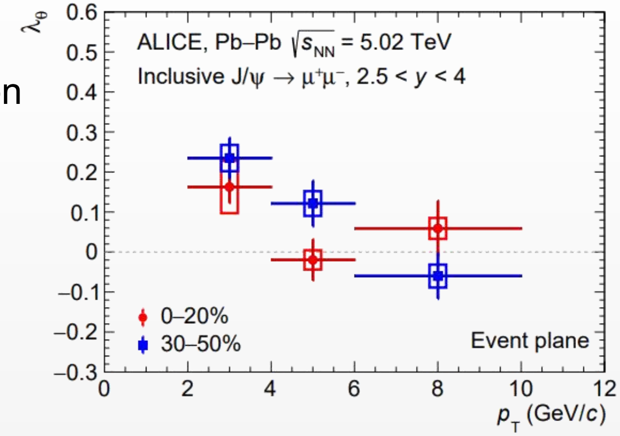
- Global spin alignment of J/ψ



In forward rapidity region

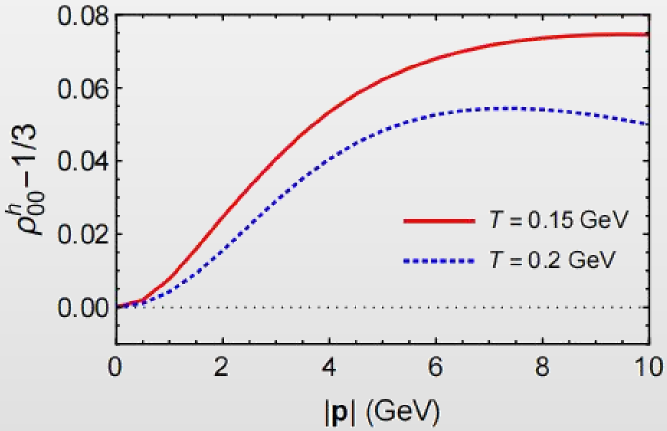
$\rho^y_{00} < \frac{1}{3} \Rightarrow \lambda^y_\theta > 0$

Consistent with experiment 🙂



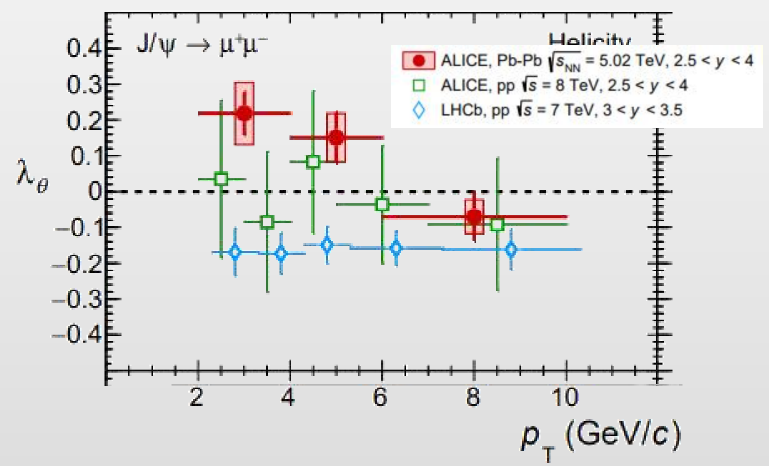
ALICE Collaboration, PRL 131. 042303 (2023)

- Spin alignment of J/ψ in helicity frame (measured in direction of momentum)



$\rho^h_{00} > \frac{1}{3} \Rightarrow \lambda^h_\theta < 0$

Not consistent with experiment 🙃

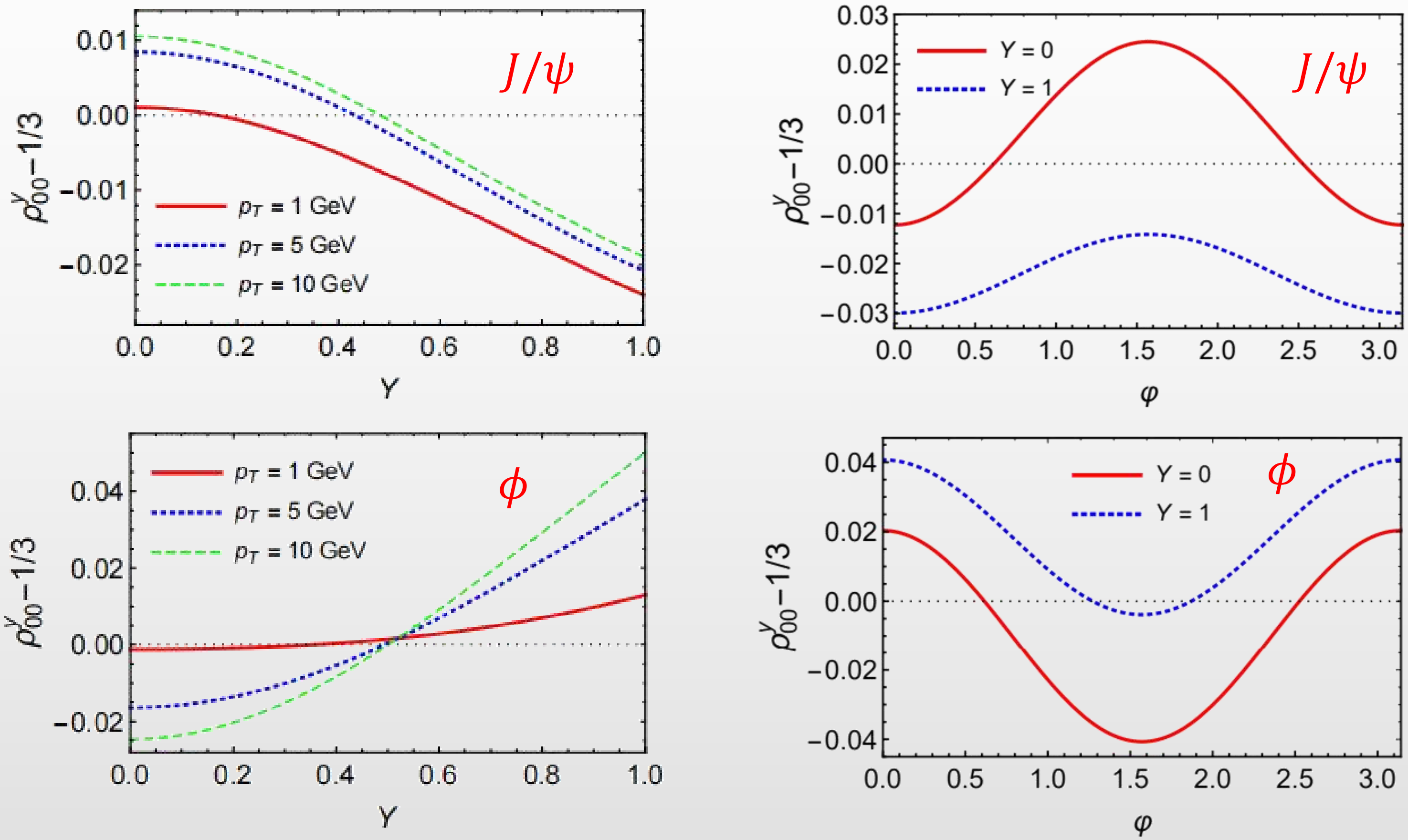


XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv:2403.07522

ALICE Collaboration, PLB 815, 136146 (2021)

Comparing J/ψ with ϕ

- Opposite behaviours of J/ψ and ϕ within same model
- Results for ϕ agree with predictions from vector field fluctuations



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XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

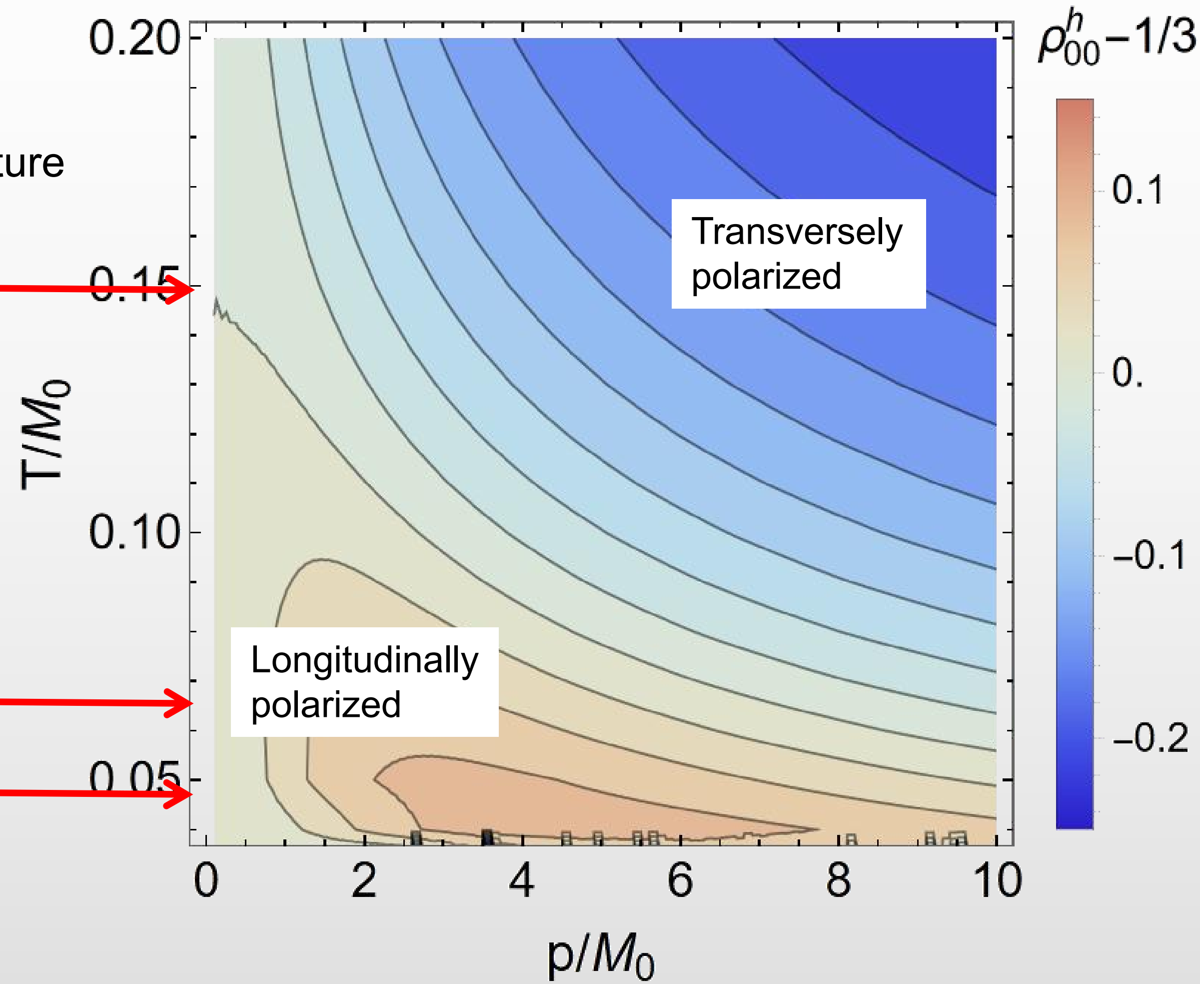
Comparing J/ψ with ϕ

- Spin alignment in helicity frame as a function of dimensionless spatial momentum and temperature

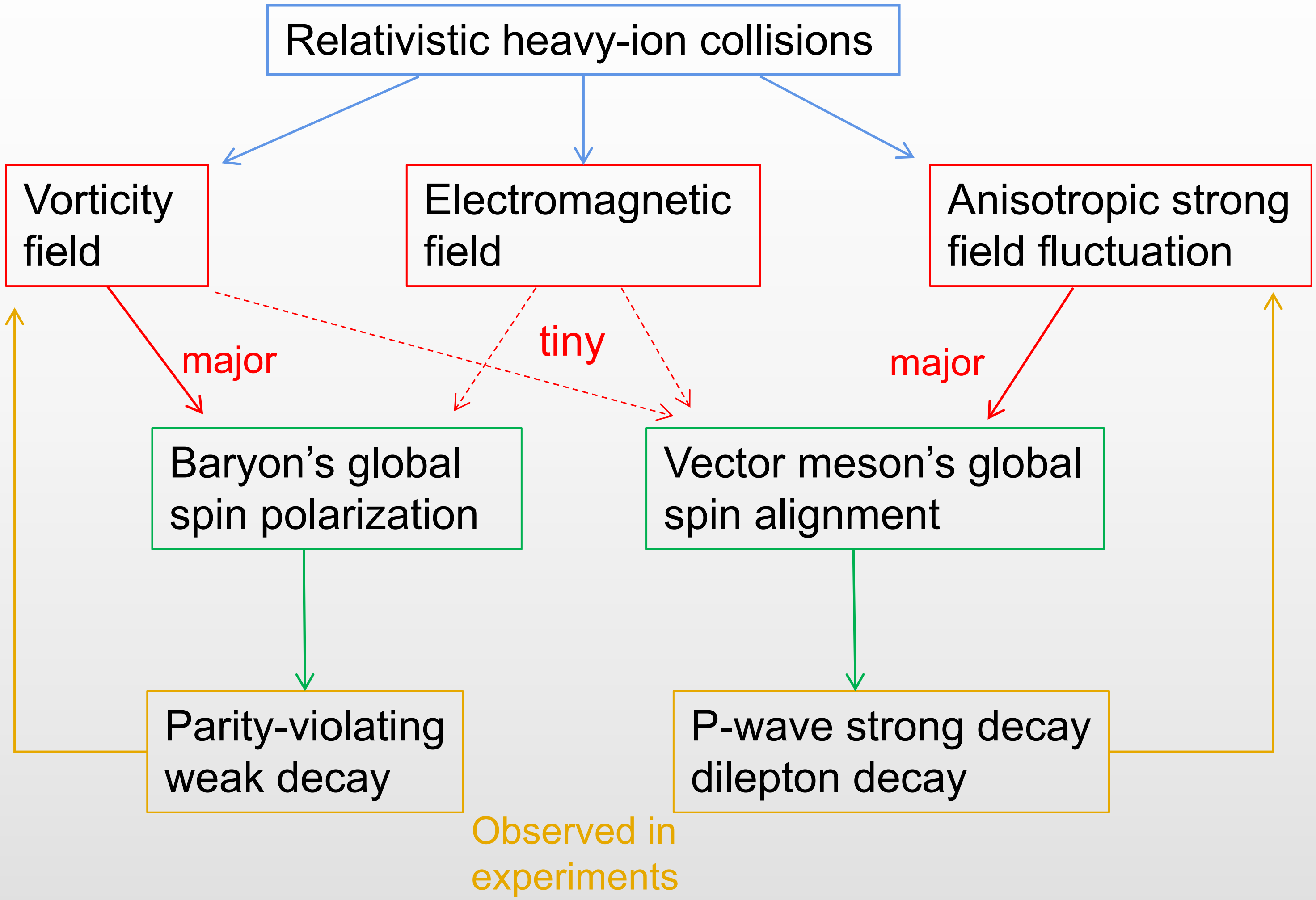
ϕ @ $T = 150$ MeV

J/ψ @ $T = 200$ MeV

J/ψ @ $T = 150$ MeV



Summary


Relativistic heavy-ion collisions
Vorticity field
Electromagnetic field
Anisotropic strong field fluctuation
major
tiny
major
Baryon's global spin polarization
Vector meson's global spin alignment
Parity-violating weak decay
P-wave strong decay dilepton decay
Observed in experiments

Summary

- Spin alignment measures anisotropy of strong field fluctuations in meson's rest frame, which mainly attribute to anisotropy induced by motion of meson relative to background

- Spin alignment is related to imaginary part of current-current correlation, which can be calculated in holographic models for a strongly coupled system

- Soft-wall model
  - Global spin alignment of J/ψ qualitatively agree with experiment
  - Spin alignment of J/ψ in helicity frame is not consistent with experiment
  - Opposite behaviours of J/ψ and ϕ

- More discussions in a forward rapidity ...
  ($2.5 < \mathrm{Y} < 4$ for J/ψ in experiment, $\mathrm{Y} < 1$ in our work)

- Spin-spin correlation ... → Talks by Qun Wang, Monday 15:30
  Xin-Nian Wang, Wednesday 12:30

Thanks for your attention!

Backup

Theoretical approaches

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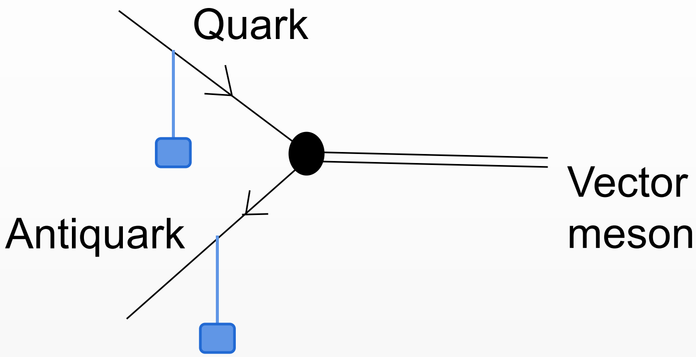
- Coalescence model with spin
  - Quark/antiquark polarized by external field
  - Non-equilibrium process described by kinetic theory



Z.-T. Liang, X.-N. Wang, PLB 629, 20 (2005).
XLS, Q. Wang, X.-N. Wang PRD 102, 056013 (2020).
X.-L. Xia, H. Li, X.-G. Huang, H.-Z. Huang, PLB 817, 136325 (2021).
A. Kumar, B. Mueller, D.-L. Yang, PRD 108, 016020 (2023).
XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023); PRD 109, 036004 (2024).
XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

- Spectral function method
  - Splitting between spectral functions of longitudinal and transverse modes due to external fields or motion relative to a thermal background, calculated by QFT, NJL model, holographic model...
  - Meson at thermodynamical equilibrium

XLS, S.-Y. Yang, Y.-L. Zou, D. Hou, arXiv: 2209.01872.
A. Kumar, B. Mueller, D.-L. Yang, PRD 108, 016020 (2023).
M. Wei, M. Huang, CPC 47, 104105 (2023).
W.-B. Dong, Y.-L. Yin, XLS, S.-Z. Yang, Q. Wang, arXiv:2311.18400.
XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv:2403.07522
Y.-Q. Zhao, XLS, S.-W. Li, D. Hou, arXiv:2403.07468

- Spin kinetic equation

D. Wagner, N. Weickgenannt, E. Speranza, PRR 5, 013187 (2023)

S. Fang, S. Pu, D.-L. Yang, PRD 109, 034034 (2024)

Y.-L. Yin, W.-B. Dong, J.-Y. Pang, S. Pu, Q. Wang, arXiv:2402.03672

- Linear response theory

F. Li, S. Liu, arXiv: 2206.11890

W.-B. Dong, Y.-L. Yin, XLS, S.-Z. Yang, Q. Wang, arXiv:2311.18400.

Quark-meson model

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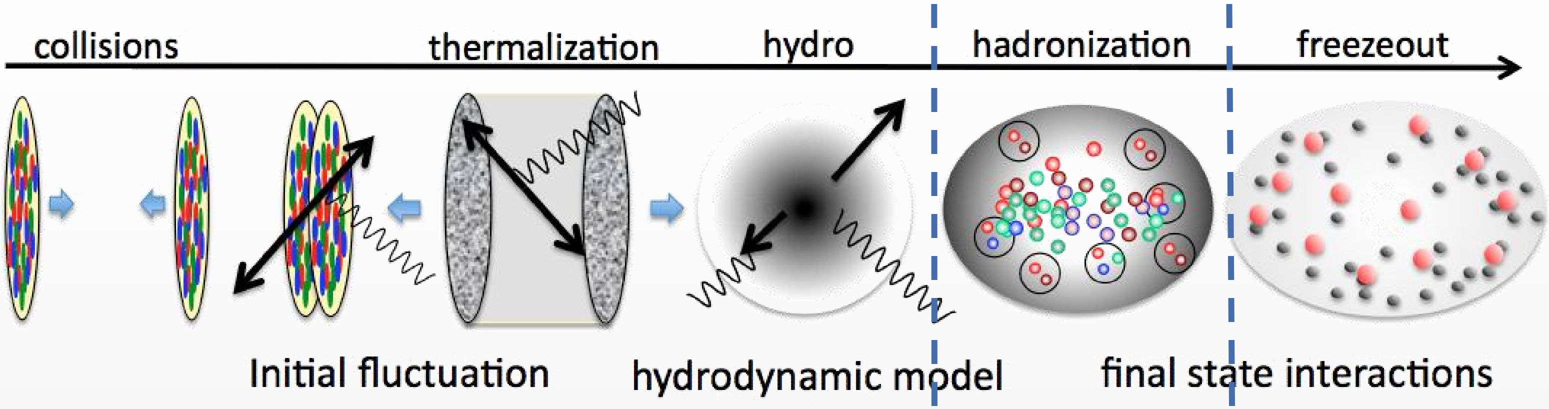
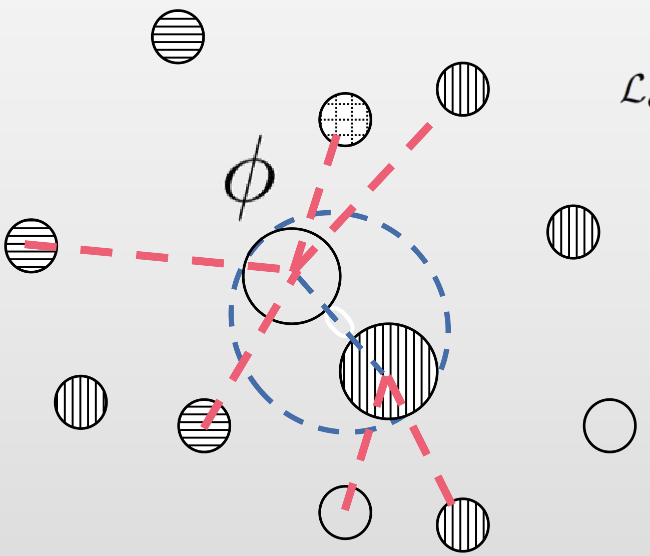


Decreasing T

Theories for strong interaction:	QCD	Quark-meson model	Hadron gas model



Quark effective mass — Dirac field $(u,d,s)^T$

$$\mathcal{L}_{\rm eff}(x) = \overline{\psi}(x)\left[i\partial\cdot\gamma - \boxed{(m_0 + g_\sigma \sigma)} - g_V \gamma\cdot V\right]\psi(x) + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{1}{4}V^{\mu\nu}V_{\mu\nu}$$

Vector meson field

$$\begin{pmatrix} \frac{\omega+\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega-\rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \overline{K}^{*0} & \boxed{\phi} \end{pmatrix} \qquad V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$$

Short wave-length: quantum fields (particles)

Long wave-length: classical fields

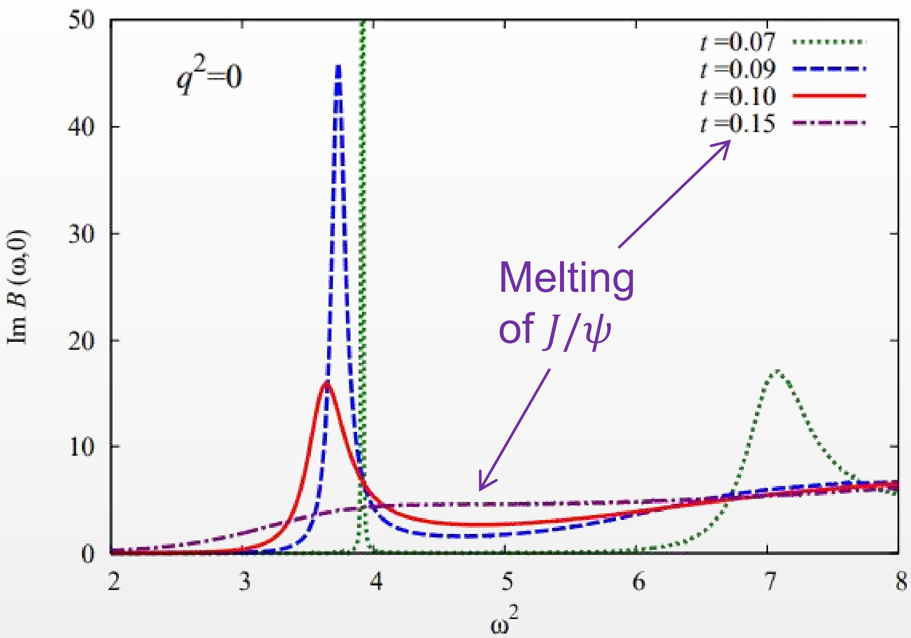
Heavy quarkonium

- Heavy quarkonium in strongly interacting matter

J/ψ's melting temperature from lattice QCD is not consistent with perturbative calculations

Non-perturbative

Spectral function from golographic QCD at finite temperature



- Soft-wall (with possible modification for dilaton field)

M. Fujita, K. Fukushima, T. Misumi, M. Murata, PRD 80, 035001 (2009)

L. Mamani, A. Miranda, H. Boschi-Filho, N. Barga, JHEP 2014, 3 (2014)

N. Braga, L. Ferreira, A. Vega, PLB 774. 476 (2017)

Y.-Q. Zhao, D. Hou, EPJC 82, 1102 (2022)

- Other models (D3/D7, KKSS,...)

R. C. Myers, A. O. Starinets, R. M. Thomson, JHEP 11, 091 (2007)

J. Erdmenger, N. Evans, I. Kirsch, E. Threlfall, EPJA 35, 81 (2008)

Y. Chen, D. Li, M. Huang, JHEP 07, 225 (2023)

D. Li, M. Huang, JHEP 11, 088 (2013)

AdS/CFT correspondence

- AdS/CFT correspondence

$$Z_{\mathrm{QFT}}\left[A_\mu^{(0)}\right] = Z_{\mathrm{gravity}}\left[A_\mu\right]$$

Vector field at boundary — Vector field in bulk

Partition function for a dual Quantum Field Theory at boundary (strongly coupled)

$$Z_{\mathrm{QFT}}\left[A_\mu^{(0)}\right] = \left\langle \exp\left\{\int_{\partial\mathcal{M}} J^\mu A_\mu^{(0)} d^4x\right\}\right\rangle$$

Partition function for a bulk gravity theory (weakly coupled)

$$Z_{\mathrm{gravity}}\left[A_\mu\right] = \exp\left\{-S_{\mathrm{bulk}}\left[A_\mu\right]\right\}$$

- Bulk action for vector field

$$S_{\mathrm{bulk}} = -\int d^4x\, d\zeta\, Q(\zeta)\, F_{MN}F^{MN}$$

$$F_{MN} = \partial_M A_N - \partial_N A_M$$

Equation of motion

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

J. M. Maldacena, Adv. Theor. Math. Phys. 2. 231 (1998)

E. Witen, Adv. Theor. Math. Phys. 2, 253 (1998)

G. Policastro, D. T. Son, A. Starinets, JHEP 09, 043 (2002)

- Radial gauge and Fourier transform

$$A_\zeta = 0 \qquad A_\mu(x,\zeta) = \int \frac{d^4p}{(2\pi)^4} e^{-ip\cdot x} A_\mu(p,\zeta)$$

- Current-current correlation

$$\langle [J^\mu, J^\nu]\rangle = D^{\mu\nu} \propto \frac{\delta^2 Z_{QFT}}{\delta A_\mu^{(0)}\delta A_\nu^{(0)}} = \frac{\delta^2 Z_{\mathrm{gravity}}}{\delta A_\mu^{(0)}\delta A_\nu^{(0)}}$$

$$D^{\mu\nu}(p) = \lim_{\zeta\to 0} g^{\zeta\zeta} g^{\mu\alpha} Q(\zeta) \left.\frac{\delta\left[\partial_\zeta A_\alpha(p,\zeta)\right]}{\delta A_\nu(p,\zeta)}\right|_{A_\mu(p,0)=0}$$

General equations

- AdS-like bulk geometry $$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + g_{\zeta\zeta}d\zeta^2$$
- Equation of motion

$$\partial_M \left[Q(\zeta)F^{MN}\right] = 0 \quad \Rightarrow \quad \begin{cases} \partial_\zeta \left[Q(\zeta)g^{\zeta\zeta}g^{\mu\nu}\partial_\zeta A_\nu(p,\zeta)\right] \\ \qquad - p_\alpha Q(\zeta)g^{\alpha\beta}g^{\mu\nu}\left[p_\beta A_\nu(p,\zeta) - p_\nu A_\beta(p,\zeta)\right] = 0 \\ g^{\mu\nu}p_\mu\partial_\zeta A_\nu(p,\zeta) = 0 \end{cases}$$

Constraint equation

- Electric fields (three components)

$$E_i(p,\zeta) \equiv -p_0 A_i(p,\zeta) + p_i A_0(p,\zeta).$$

$$\partial_\zeta^2 E_i(p,\zeta) + \frac{\left[\partial_\zeta Q(\zeta)g^{\zeta\zeta}\right]}{Q(\zeta)g^{\zeta\zeta}}\partial_\zeta E_i(p,\zeta) - \frac{p^2}{g^{\zeta\zeta}}E_i(p,\zeta) + (p_i g_{0\mu} - p_0 g_{i\mu})(\partial_\zeta g^{\mu\nu})\left[\partial_\zeta A_\nu(p,\zeta)\right] = 0$$

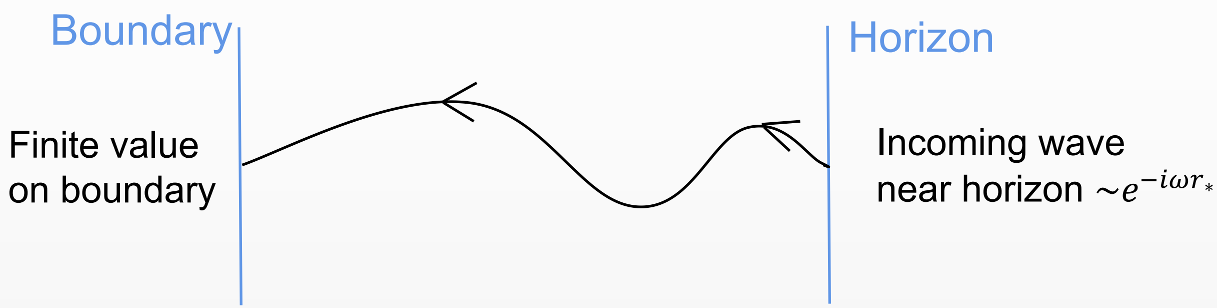
2nd order differential equation

Possible mixture between different components

$$\begin{aligned} \partial_\zeta A_i &= -\frac{1}{p_0}\left(\delta_i^j - \frac{p_i p^j}{p^2}\right)\partial_\zeta E_j, \\ \partial_\zeta A_t &= \frac{p^i}{p_0 p^0}\left(\delta_i^j - \frac{p_i p^j}{p^2}\right)\partial_\zeta E_j, \end{aligned}$$

XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv:2403.07522

Current-current correlation



- Taking a set of basis satisfying incoming wave condition near horizon and boundary condition $\lim_{\zeta\to 0} \widetilde{E}_i(e_j,\zeta) = \delta_{ij}$

- Current-current correlation

$$D^{\mu 0}(p) = -\lim_{\zeta\to 0} \frac{p_j}{p_0}\left(g^{\mu k} - \frac{p^\mu p^k}{p^2}\right)\frac{1}{\zeta}\partial_\zeta \widetilde{E}_k(e_j,\zeta)$$

$$D^{\mu i}(p) = \lim_{\zeta\to 0}\left(g^{\mu k} - \frac{p^\mu p^k}{p^2}\right)\frac{1}{\zeta}\partial_\zeta \widetilde{E}_k(e_i,\zeta)$$

Spin alignment?

$$p_\mu D^{\mu\nu}(p) = p_\nu D^{\mu\nu}(p) = 0$$

XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv:2403.07522

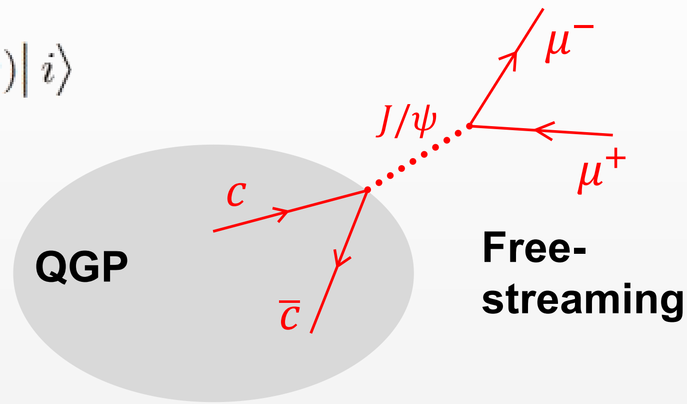
- S-matrix element for dilepton production through vector meson decay (e.g., $c+\bar{c}\rightarrow J/\psi\rightarrow\mu^{+}+\mu^{-}$)

$$S_{fi}=\int d^4x d^4y \langle f, l\bar{l} \,|J_\mu(y)G_R^{\mu\nu}(x-y)J_\nu^l(x)|\, i\rangle$$

① Vector meson production in QGP at finite temperature

② Propagation from point y to x

③ Decay to a dilepton pair in vacuum



- Dilepton production rate

$$\frac{dN}{d^4x}=2g_{Ml\bar{l}}^2\int\frac{d^3\mathbf{p}_+}{(2\pi)^3E_+}\int\frac{d^3\mathbf{p}_-}{(2\pi)^3E_-}n_B(\omega)$$
$$\times\left[p_\mu^+p_\nu^-+p_\mu^-p_\nu^+-g_{\mu\nu}(p_+\cdot p_-+m_l^2)\right]G_A^{\mu\alpha}(p)\varrho_{\alpha\beta}(p)G_R^{\beta\nu}(p)$$

Momentum of $l/\bar{l}$

Bose-Einstein distribution

$$G_{R/A}^{\mu\nu}=-\frac{\eta^{\mu\nu}+p^\mu p^\nu/p^2}{p^2+m_V^2\pm i m_V\Gamma}$$

Meson's retarded/advanced propagators in vacuum

Coupling between meson and dilepton

lepton's mass

In-medium spectral function

Dilepton production

- Spectral function is related to the imaginary part of current-current correlation

$$\varrho^{\mu\nu} \equiv -\mathrm{Im}D^{\mu\nu} \qquad D^{\mu\nu}(p) \equiv \int d^4y\, \theta(y^0) \langle [J^\mu(y), J^\nu(0)] \rangle e^{-ip\cdot y}$$

Calculated by holographic models

- Decomposition on polarization vectors

$$\varrho^{\mu\nu}(p) = \sum_{\lambda,\lambda'=0,\pm1} v^\mu(\lambda,p) v^{*\nu}(\lambda',p) \tilde{\varrho}_{\lambda\lambda'}(p)$$

Polarization vectors

$$v^\mu(\lambda,p) = \left(\frac{\mathbf{p}\cdot\boldsymbol{\epsilon}_\lambda}{M}, \boldsymbol{\epsilon}_\lambda + \frac{\mathbf{p}\cdot\boldsymbol{\epsilon}_\lambda}{M(\omega+M)}\mathbf{p} \right)$$

3-vector in rest frame; Invariant mass $M \equiv \sqrt{\omega^2 - \mathbf{p}^2}$

Orthonormal & complete

$$\eta_{\mu\nu} v^\mu(\lambda,p) v^{*\nu}(\lambda',p) = \delta_{\lambda\lambda'}$$

$$\sum_\lambda v^\mu(\lambda,p) v^{*\nu}(\lambda,p) = (\eta^{\mu\nu} + p^\mu p^\nu / p^2)$$

- Dilepton production rate from decay of spin-λ states

$$n_\lambda(x,p) = -\frac{2g^2_{Ml\bar{l}}}{3(2\pi)^5}\left(1 - \frac{2m_l^2}{p^2}\right) \times \sqrt{1 + \frac{4m_l^2}{p^2}} \frac{p^2 n_B(\omega) \tilde{\varrho}_{\lambda\lambda}(p)}{(p^2+m_V^2)^2 + m_V^2\Gamma^2}$$

Spin alignment

$$\rho_{00} \equiv \frac{\int d\omega \int d^3\mathbf{p} \int d^4x\, n_0(x,p)}{\int d\omega \int d^3\mathbf{p} \int d^4x \sum_{\lambda=0,\pm1} n_\lambda(x,p)}$$

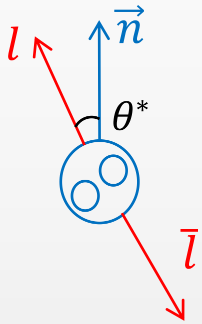
XLS, Y.-Q. Zhao, S.-W. Li, F. Becattini, D. Hou, arXiv:2403.07522

Other spin parameters

- Angular distribution of decay products

Y.-Q. Zhao, XLS, S.-W. Li, D. Hou, arXiv: 2403.07468

$$\frac{dN}{d^4p\, d\cos\theta^* d\varphi^*} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta^* + \lambda_\varphi \sin^2\theta^* \cos 2\varphi^* + \lambda_{\theta\varphi} \sin 2\theta^* \cos\varphi^* + \lambda_\varphi^\perp \sin^2\theta^* \sin 2\varphi^* + \lambda_{\theta\varphi}^\perp \sin 2\theta^* \sin\varphi^*\right)$$



- λ-parameters: related to tensor polarization

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}},\quad \lambda_\varphi = \frac{2\mathrm{Re}\rho_{1,-1}}{1+\rho_{00}},\quad \lambda_{\theta\varphi} = \frac{\sqrt{2}\mathrm{Re}(\rho_{01}-\rho_{0,-1})}{1+\rho_{00}},$$

$$\lambda_\varphi^\perp = \frac{-2\mathrm{Im}\rho_{1,-1}}{1+\rho_{00}},\quad \lambda_{\theta\varphi}^\perp = \frac{\sqrt{2}\mathrm{Im}(\rho_{01}+\rho_{0,-1})}{1+\rho_{00}}.$$

- Spin density matrix for dilepton decay

$$\rho_{\lambda\lambda'}(p) \equiv -\frac{2g_{Ml\bar{l}}^2}{3(2\pi)^5 C_N}\left(1-\frac{2m_l^2}{p^2}\right)\sqrt{1+\frac{4m_l^2}{p^2}}\frac{p^2 n_B(\omega)}{(p^2+m_M^2)^2+m_M^2\Gamma^2}\tilde{\varrho}_{\lambda\lambda'}(p)$$

Normalization factor

Meson's vacuum mass and width