Global spin alignment of vector mesons in heavy-ion collisions

Xin-Li Sheng

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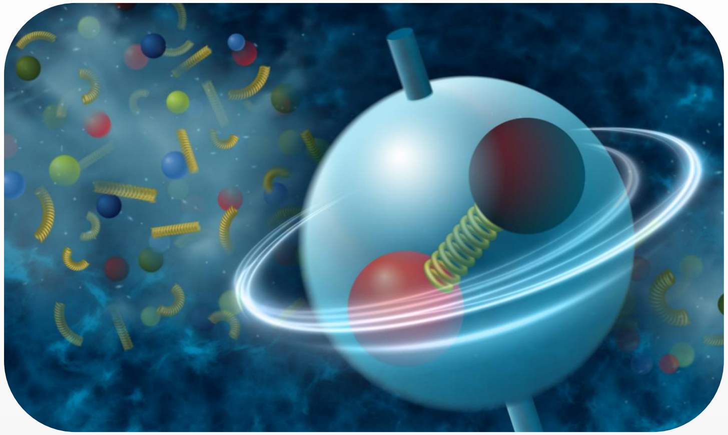

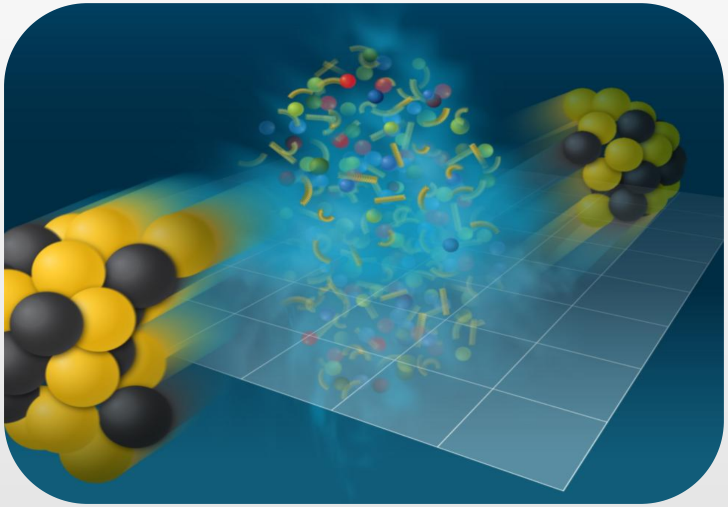

www.bnl.gov/newsroom/news.php?a=120967

"ExHIC-p workshop on polarization phenomena in nuclear collisions"

Mar. 14-17, 2024

Outline

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- Introduction
- Kinetic theory for vector meson
- Anisotropic strong field fluctuation
- Global spin alignment of J/ψ
- Summary

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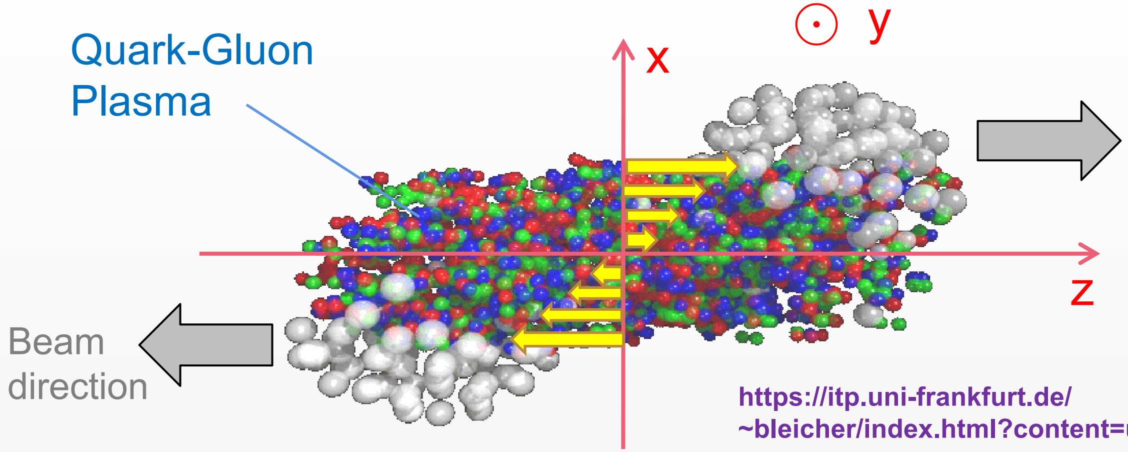
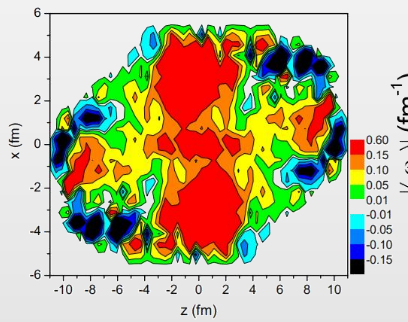
Relativistic heavy-ion collisions generate strongly interacting matter with vorticity and magnetic fields



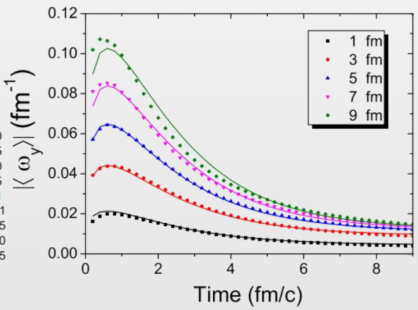
https://itp.uni-frankfurt.de/~bleicher/index.html?content=urqmd

Vorticity fields $\omega \sim 10^{21} s^{-1}$

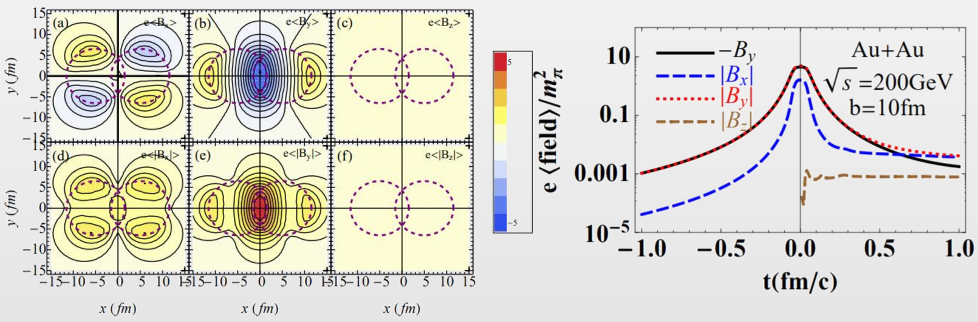
Magnetic fields $B \sim 10^{18}$ Gauss



F. Becattini, L. Csernai, D.J. Wang, PRC 88, 034905 (2013); PRC 93, 069901 (2016)

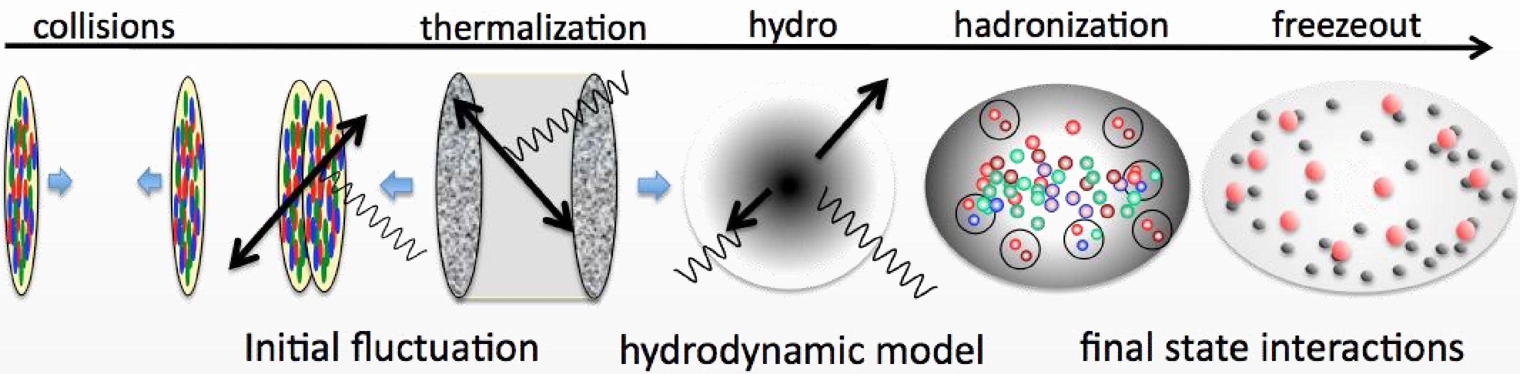


Y. Jiang, Z.-W. Lin, J. Liao, PRC 94, 044910 (2016); PRC 95,049904 (2017)



W.-T. Deng, X.-G. Huang, PRC 85, 044907 (2012).

Heavy-ion collisions

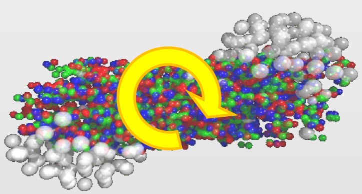


Quarks and gluons

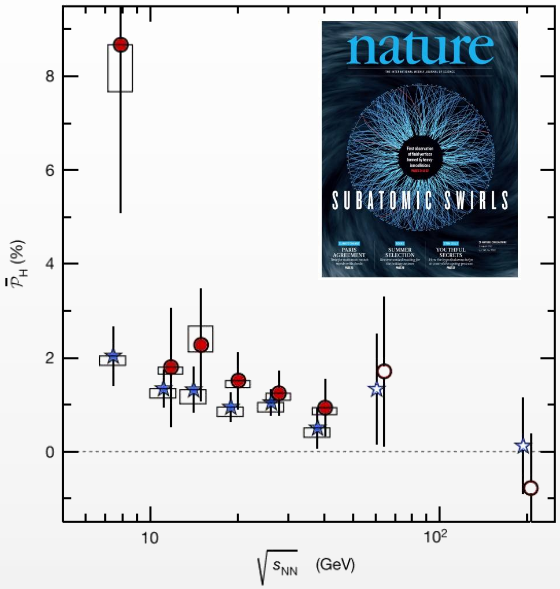
Baryons and mesons

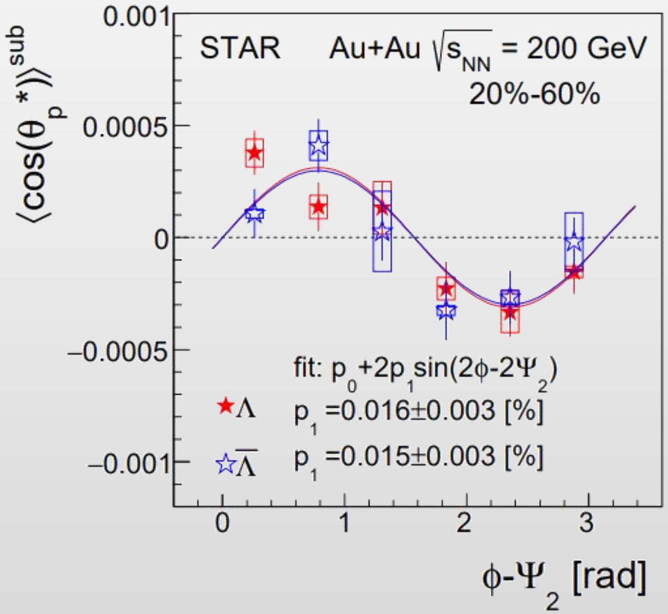
Initial orbital angular momentum → Vorticity field, Magnetic field → Polarized quark/gluon → Spin polarization for spin-1/2 or spin-3/2 baryons, Λ, Σ^0, Δ^{++}, Ω^-, ...

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



Λ's spin polarization





Λ's global (local) spin polarizations along direction of global angular momentum (beam direction)

STAR, Nature 548, 62 (2017)
PRL 123, 132301 (2019)

$$\Lambda \to p + \pi^-$$

Parity-violating weak decay

Vorticity field, shear stress tensor, spin Hall effect, EM field

Recent reviews:

Q. Wang, Nucl. Phys. A 967, 225 (2017)

F. Becattini, M. Lisa, Ann. Rev. Nuccle. Part. Sci. 70, 395 (2020)

X.-G. Huang, J. Liao, Q. Wang, X.-L. Xia, Lect. Notes Phys. 987, 281 (2021)

J. Gao, Z.-T. Liang, Q. Wamg, X.-N. Wang, Lect. Notes Phys. 987, 195 (2021)

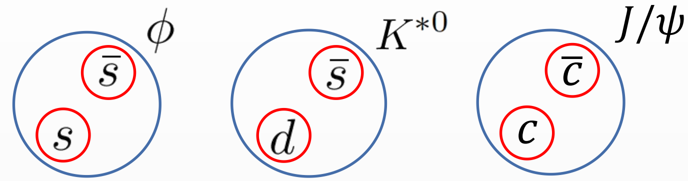
F. Becattini, Rept. Prog. Phys. 85, 122301 (2022)

Y. Hidaka, S. Pu, Q. Wang, D.-L. Yang, Part. Nucl. Phys. 127, 103989 (2022)

F. Becattini, M. Buzzegoli, T. Niida, S. Pu, A.-H. Tang, Q. Wang, arXiv: 2402.04540

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



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

P_i: Vector polarization (3 components, not measurable)

T_{ij}: 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

nature

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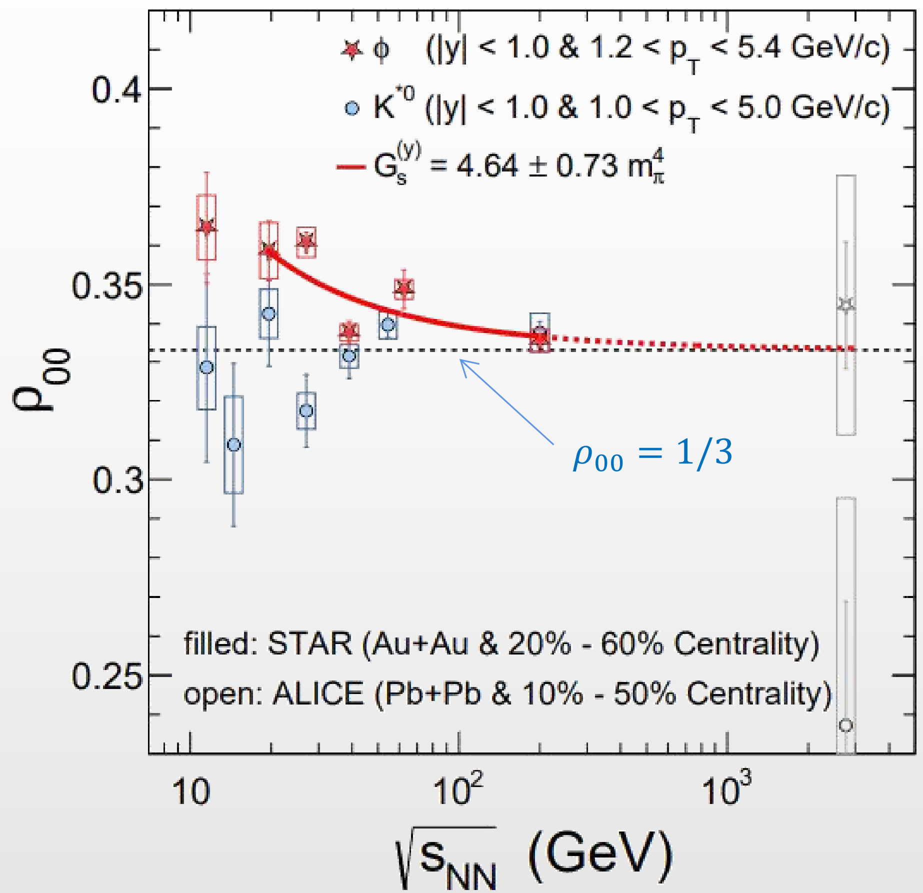
Article | Published: 18 January 2023

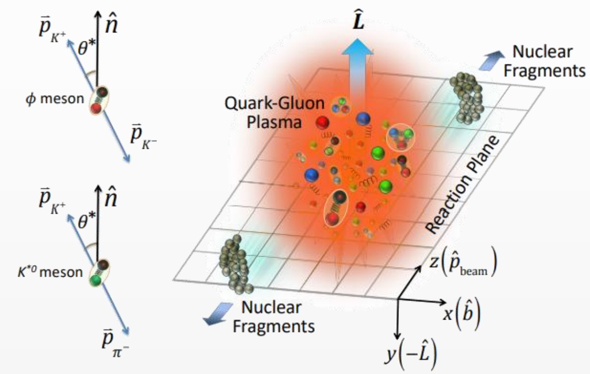
Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

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

Global spin alignment





Theory prediction:
XLS, L. Oliva, Q. Wang, PRD 101, 096005 (2020); PRD 105, 099903 (2022) (erratum)

Spin alignment along direction of global angular momentum

STAR, Nature 614, 244 (2023)

Vorticity field?
Magnetic field?

Relation to quark polarization

Spin Alignment of Vector Mesons in Non-central $A + A$ Collisions

PLB 629, 20 (2005).

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]
[1]Department of Physics, Shandong University, Jinan, Shandong 250100, China
'uclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 947
(Dated: November 5, 2018)

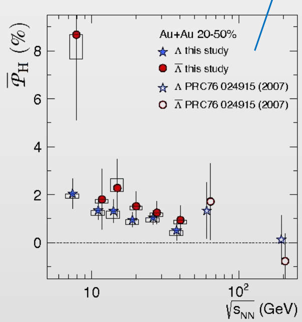
- Spin alignment of vector meson is determined by spin polarizations of constitute quark/antiquark

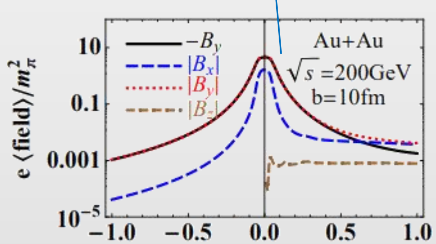
$$\rho_{00}^{V\,(\mathrm{rec})} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}} \approx \frac{1}{3} - \frac{4}{9} P_q P_{\bar{q}}$$

$$\langle P_{q/\bar{q}} \rangle \approx \frac{1}{2}\langle \omega_y \rangle \pm \frac{Q_s}{2 m_s T}\langle B_y \rangle \;\Rightarrow\; \rho_{00}^{\phi} \approx \frac{1}{3} - \frac{1}{9}\langle \omega_y \rangle^2 + \frac{Q_s^2}{9 m_s^2 T^2}\langle B_y \rangle^2$$

$\lesssim 0.02$ $\qquad$ $\lesssim 0.1 m_\pi^2$

4×10^{-5} $\qquad$ 1×10^{-5}





- Contributions from vorticity and magnetic are negligible

Spin alignment

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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]
- c_F: Fragmentation [1]
- c_A: Turbulent color field [15]
- c_h: Helicity polarization [16]
- c_{strong}: Strong force (ϕ meson fields, gluon fields) [4,17-19]

[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, arXiv:2303.01897
[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] B. Muller, D.-L. Yang, PRD 105, 1 (2022).
[16] J.-H. Gao, PRD 104, 076016 (2021)
[17] XLS, L. Oliva, Z.-T. Liang, Q. Wang, X.-N. Wang, PRL 131, 042304 (2023); PRD 109, 036004 (2024)
[18] A. Kumar, B. Muller, D.-L. Yang, PRD 108, 016020 (2023)
[19] XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

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Green function and MVSD

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- Two-point Green function expressed in terms of matrix valued spin-dependent distributions (MVSD)

$$G^{<}_{\mu\nu}(x,p) = \int d^4y\, e^{ip\cdot y/\hbar} \langle A^{\dagger}_{\nu}(x_2) A_{\mu}(x_1)\rangle$$

$$A^{\mu}_{V}(x) = \sum_{\lambda=0,\pm1} \int \frac{d^3\mathbf{p}}{(2\pi\hbar)^3} \frac{1}{2E^V_{\mathbf{p}}} \times \left[\epsilon^{\mu}(\lambda,\mathbf{p}) a_V(\lambda,\mathbf{p}) e^{-ip\cdot x/\hbar} + \epsilon^{*\mu}(\lambda,\mathbf{p}) a^{\dagger}_V(\lambda,\mathbf{p}) e^{ip\cdot x/\hbar}\right]$$

$$G^{<}_{\mu\nu}(x,p) = 2\pi\hbar \sum_{\lambda_1,\lambda_2} \delta\left(p^2 - m_V^2\right) \times \left\{\theta(p^0)\epsilon_{\mu}(\lambda_1,\mathbf{p})\,\epsilon^{*}_{\nu}(\lambda_2,\mathbf{p})\, f_{\lambda_1\lambda_2}(x,\mathbf{p}) + \theta(-p^0)\epsilon^{*}_{\mu}(\lambda_1,-\mathbf{p})\,\epsilon_{\nu}(\lambda_2,-\mathbf{p}) \times \left[\delta_{\lambda_2\lambda_1} + f_{\lambda_2\lambda_1}(x,-\mathbf{p})\right]\right\},$$

polarization vector for a meson with spin λ

creation/anihilation operator a_V, $b^{\dagger}_V$ if meson is not self-conjugate

- MVSD for vector meson

$$f_{\lambda_1\lambda_2}(x,\mathbf{p}) \equiv \int \frac{d^4u}{2(2\pi\hbar)^3}\delta(p\cdot u)e^{-iu\cdot x/\hbar}\left\langle a^{\dagger}_V\left(\lambda_2,\mathbf{p}-\frac{\mathbf{u}}{2}\right) a_V\left(\lambda_1,\mathbf{p}+\frac{\mathbf{u}}{2}\right)\right\rangle$$

$$= 2E^V_{\mathbf{p}} \int \frac{dp^0}{2\pi\hbar}\theta(p^0)\epsilon^{*\mu}(\lambda_1,\mathbf{p})\epsilon^{\nu}(\lambda_2,\mathbf{p})G^{<}_{\mu\nu}(x,p)$$

Relation to Wigner function

$$= 3f(x,\mathbf{p})\rho_{\lambda_1\lambda_2}(x,\mathbf{p})$$

Relation to spin-averaged distribution and normalized density matrix

$$f(x,\mathbf{p}) \equiv \frac{1}{3}\sum_{\lambda=0,\pm1} f_{\lambda\lambda}(x,\mathbf{p}), \qquad \sum_{\lambda=0,\pm1}\rho_{\lambda\lambda}(x,\mathbf{p}) = 1$$

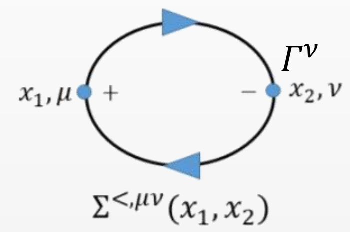
Kadanoff-Baym equation

- With help of Schwinger-Keldysh (closed-time path) formalism, we derive Kadanoff-Baym equation at leading order in spatial gradient

P. Martin, J. S.Schwinger, PR 115 (1959) 1342.
L. P. Kadanoff and G. Baym, Quantum Statistical Mechanics (Benjamin, New York, 1962).
L.V. Keldysh, Zh. Eksp. Teor. Fiz. 47 (1964) 1515.

$$L^{\mu}_{\eta} G^{<,\mu\eta}(x,p)$$
$$= -\frac{i\hbar}{2}\int \frac{d^4p'}{(2\pi\hbar)^4}\left\{G^{<,\mu}{}_{\alpha}(x,p)\mathrm{Tr}\left[\Gamma^{\alpha}S^{>}(x,p+p')\Gamma^{\nu}S^{<}(x,p')\right]\right.$$
$$\left.-G^{>,\mu}{}_{\alpha}(x,p)\,\mathrm{Tr}\left[\Gamma^{\alpha}S^{<}(x,p+p')\Gamma^{\nu}S^{>}(x,p')\right]\right\} + \mathcal{O}(\hbar^2)$$

Green functions on the closed-time path contour



One-loop self-energy

$$L^{\mu}_{\eta} \equiv -g^{\mu}_{\eta}\left(p^2 - m_V^2\right) + p^{\mu}p_{\eta} + i\hbar\left[g^{\mu}_{\eta}p\cdot\partial_x - \frac{1}{2}\left(p_{\eta}\partial^{\mu}_{x} + p^{\mu}\partial^{x}_{\eta}\right)\right]$$

- Comparing Kadanoff-Baym equation with its Hermitian conjugate, we are able to derive

Boltzmann equation $\quad p\cdot\partial_x G^{<,\mu\nu} - \frac{1}{4}\left(p^{\mu}\partial^{x}_{\eta}G^{<,\eta\nu} + p^{\nu}\partial^{x}_{\eta}G^{<,\mu\eta}\right) = \cdots$

Mass-shell condition $\quad -(p^2 - m_V^2)G^{<,\mu\nu} + \left(p^{\mu}p_{\eta}G^{<,\eta\nu} + p^{\nu}p_{\eta}G^{<,\mu\eta}\right) = \cdots$

Boltzmann equation

- Dyson-Schwinger equation
  - ⇨ Kadanoff-Baym equation for Wigner function
  - ⇨ Matrix-form Boltzmann equation

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRD 109, 036004 (2024).

$$k \cdot \partial_x f^V_{\lambda_1\lambda_2}(x,\mathbf{k}) = \frac{1}{8}\left[\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\mathbf{k}) - f^V_{\lambda_1\lambda_2}(x,\mathbf{k})\mathcal{C}_{\text{diss}}(x,\mathbf{k})\right]$$

Dilute gas limit

$$f_q \sim f_{\bar{q}} \sim f_V \ll 1$$

Meson polarization vectors

Coalescence

$$q + \bar{q} \to V$$

Dissociation (independent from quark distributions)

$$V \to q + \bar{q}$$

- Contribution from coalescence

$$\begin{aligned}\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\mathbf{k}) = \int \frac{d^3\mathbf{p}'}{(2\pi\hbar)^2}\frac{1}{E^{\bar{q}}_{\mathbf{p}'}E^{q}_{\mathbf{k}-\mathbf{p}'}}\delta\left(E^V_{\mathbf{k}} - E^{\bar{q}}_{\mathbf{p}'} - E^{q}_{\mathbf{k}-\mathbf{p}'}\right) \\ \times \text{Tr}\left\{\Gamma^\nu(p'\cdot\gamma - m_{\bar{q}})\left[1+\gamma_5\gamma\cdot P^{\bar{q}}(x,\mathbf{p}')\right]\right. \\ \left.\times\Gamma^\mu\left[(k-p')\cdot\gamma + m_q\right]\left[1+\gamma_5\gamma\cdot P^q(x,\mathbf{k}-\mathbf{p}')\right]\right\} \\ \times f_{\bar{q}}(x,\mathbf{p}')f_q(x,\mathbf{k}-\mathbf{p}'),\end{aligned}$$

Energy conservation (all particles are on their normal mass shells)

Quark-antiquark-meson vertex

Polarizations of quark/antiquark

unpolarized quark/antiquark distributions

Spin alignment

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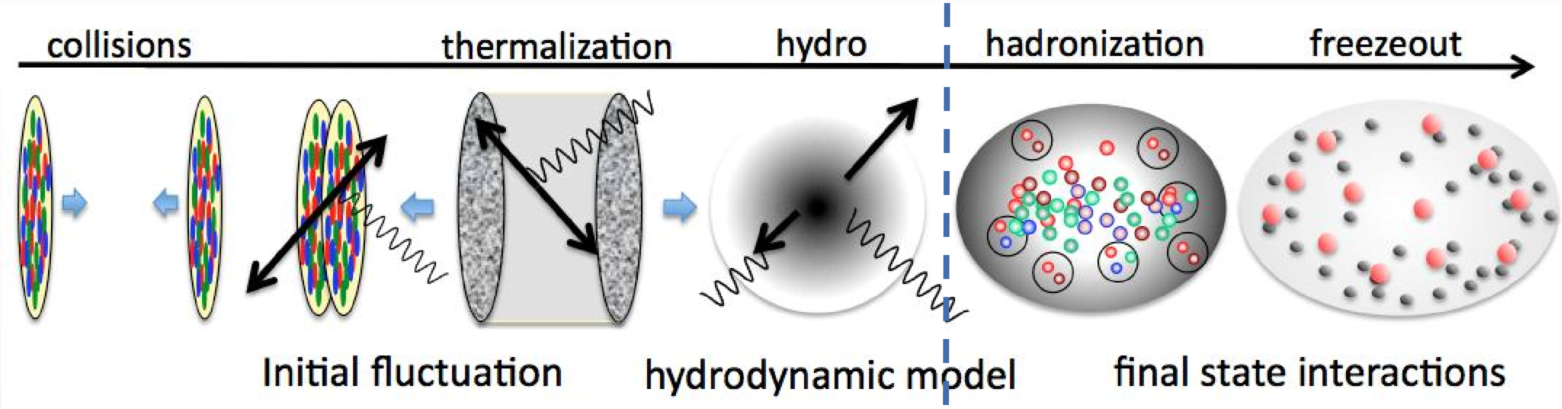


No vector meson $f^V_{\lambda_1\lambda_2} = 0$ t_0

- Neglecting space-derivatives and assuming that $f^V_{\lambda_1\lambda_2} = 0$ before hadronization stage t_0, we obtain formal solution

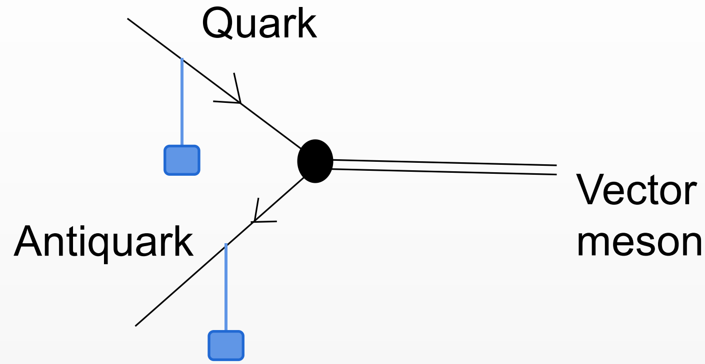
$$f^V_{\lambda_1\lambda_2}(x,\mathbf{k}) \sim \frac{1-\exp[-\mathcal{C}_{\rm diss}(x,\mathbf{k})\Delta t]}{\mathcal{C}_{\rm diss}(x,\mathbf{k})}\left[\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k})\right] \qquad \Delta t = t - t_0$$

- Spin alignment only depend on coalescence process

$$\rho_{00} \equiv \frac{f^V_{00}}{f^V_{+1,+1}+f^V_{00}+f^V_{-1,-1}} = \frac{\epsilon^*_\mu(0,\mathbf{k})\epsilon_\nu(0,\mathbf{k})\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k})}{\sum_{\lambda=0,\pm1}\epsilon^*_\mu(\lambda,\mathbf{k})\epsilon_\nu(\lambda,\mathbf{k})\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k})}$$

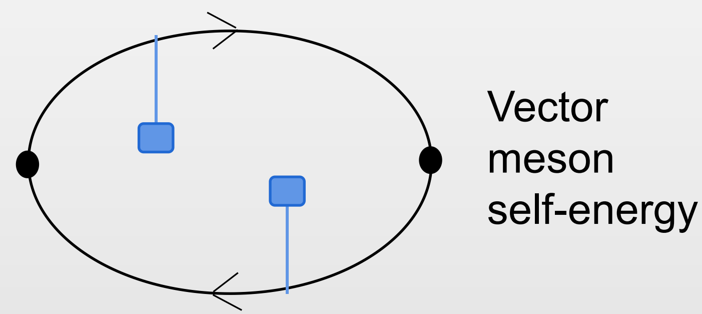
XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRD 109, 036004 (2024)

- **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).

- **Spectral function method**
  - Vector meson's self-energy modified by external field
  - Meson at thermodynamical equilibrium



Vector meson's in-medium spectral function

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

→ talks by HyungJoo Kim and by Philipp Gubler

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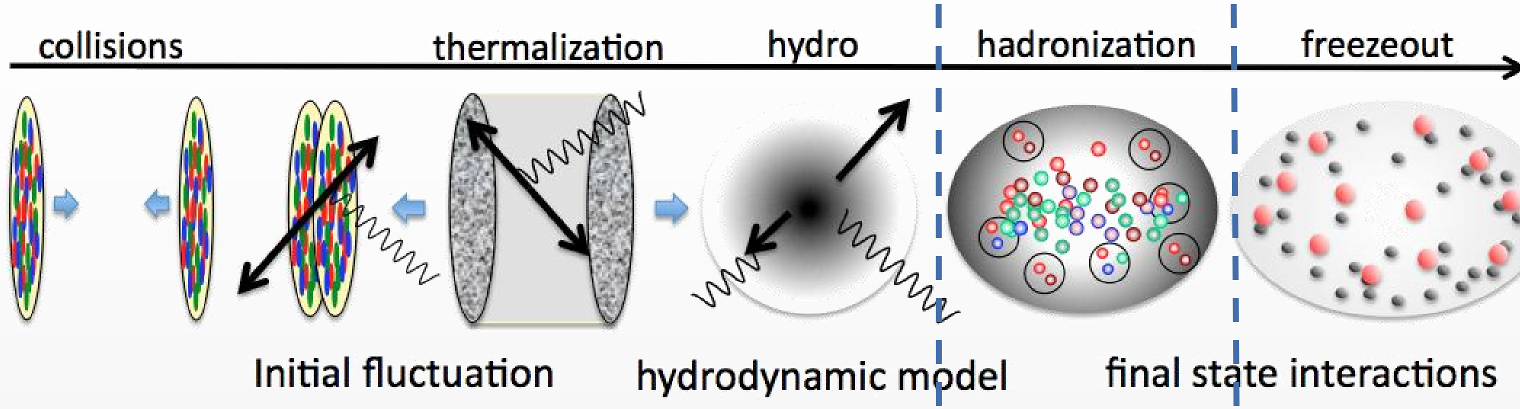
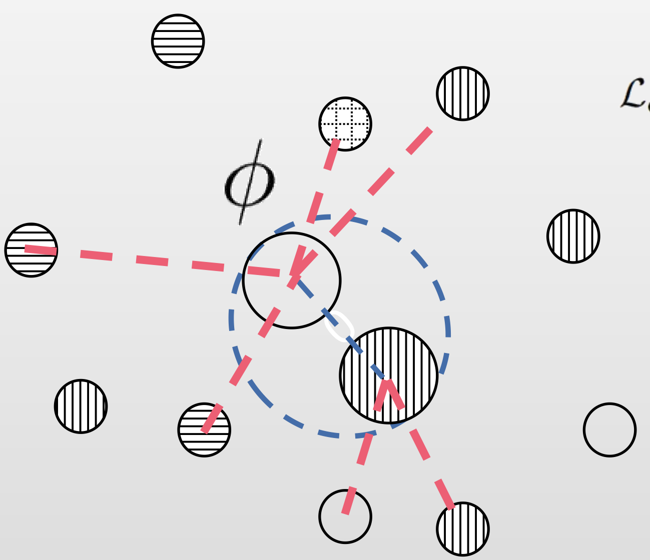
Quark-meson model



Decreasing T

Theories:	QCD	Quark-meson model	Hadron gas model



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

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

Vector meson field

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

Short wave-length: quantum fields (particles)

Long wave-length: classical fields

Quark polarization

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

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).

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

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

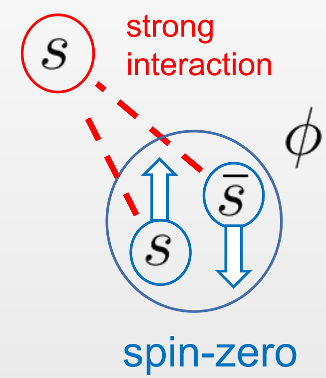
thermal vorticity field (rotation and acceleration)

classical electromagnetic field

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

vector ϕ field (long wave-length components)

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



- Vector ϕ field has been used to explain the difference between polarizations of Λ and $\bar{\Lambda}$

L.P.Csernai, J.I.Kapusta, T.Welle, PRC 99, 021901 (2019)

Spin alignment

- Spin alignment of the ϕ meson in its rest frame measuring along the direction of ϵ_0

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

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

Rotation and acceleration → $\lesssim 10^{-3}$ in heavy-ion collisions

Vector ϕ field → Mean value is zero, but can incorporate large fluctuations

Temperature at hadronization time (T_h)

- Contribution from classical electromagnetic field to spin alignment is $\lesssim 10^{-3}$

XLS, L.Oliva, Q.Wang, PRD 101, 096005 (2020);

- Important features:

  - Cancellation for mixing terms (because of CP and reflection symmetries)

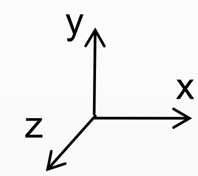
  - All fields appear in squares, spin alignment measures anisotropy of fluctuations in meson's rest frame

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

Fluctuation-induced ρ_{00}

For example, contribution from $\mathbf{B}'_\phi$ to spin alignment along *y*-direction

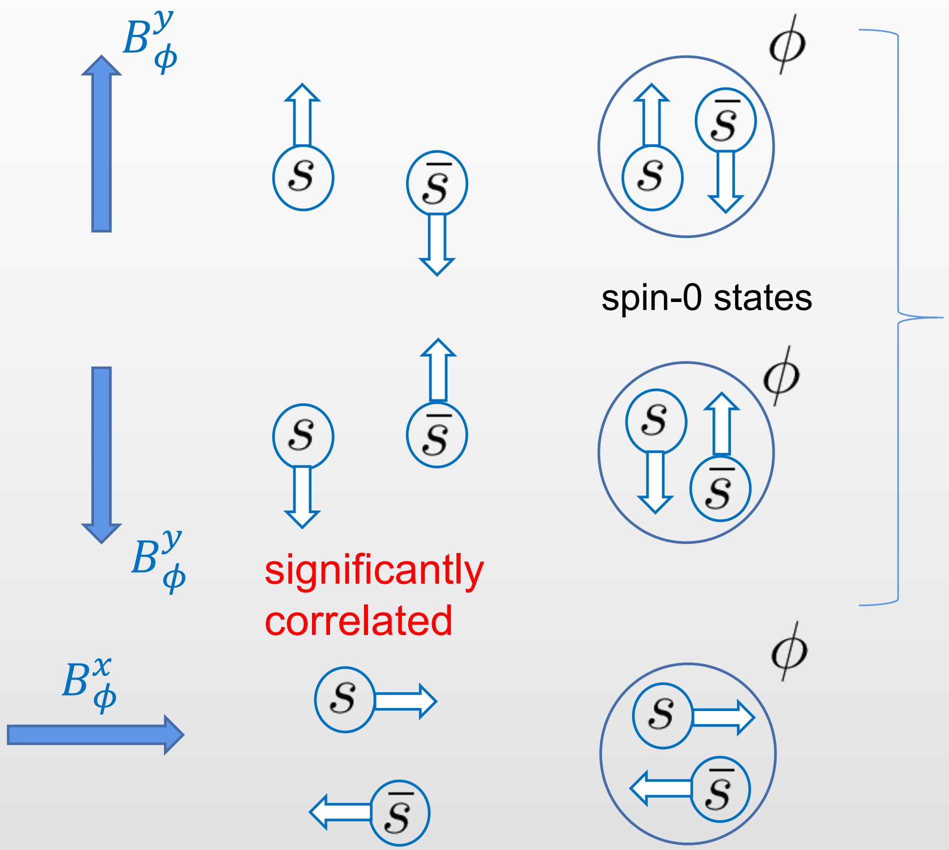
$$\propto (B'_{\phi,y})^2 - \frac{(B'_{\phi,x})^2 + (B'_{\phi,z})^2}{2}$$



Case 1

Case 2

Case 3



$\langle B^y_\phi \rangle = 0,$

$\langle (B^y_\phi)^2 \rangle \neq 0$

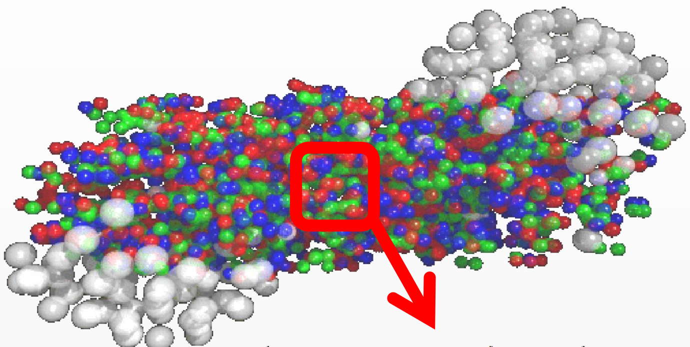
$\rho^y_{00} > 1/3$

$\rho^x_{00} > 1/3$

$\rho^y_{00}, \rho^z_{00} < 1/3$

$\rho^x_{00} + \rho^y_{00} + \rho^z_{00} = 1$

Fluctuations



In center region of QGP,
transverse fluctuation
$\neq$ longitudinal fluctuation

$$\left\langle g_\phi^2 \mathbf{B}_\phi^i \mathbf{B}_\phi^j / T_{\rm h}^2 \right\rangle = \left\langle g_\phi^2 \mathbf{E}_\phi^i \mathbf{E}_\phi^j / T_{\rm h}^2 \right\rangle = \underbrace{F^2 \delta^{ij}}_{\text{Isotropic}} + \underbrace{\Delta \hat{\mathbf{a}}^i \hat{\mathbf{a}}^j}_{\text{Anisotropy of QGP}} \quad \begin{cases} F_T^2 = F^2 \\ F_z^2 = F^2 + \Delta \end{cases}$$

Isotropic

Anisotropy of QGP

Transformation of fields between lab frame and particle's rest frame

$$\begin{aligned} \mathbf{B}'_\phi &= \gamma \mathbf{B}_\phi - \gamma \mathbf{v} \times \mathbf{E}_\phi + (1-\gamma) \frac{\mathbf{v} \cdot \mathbf{B}_\phi}{v^2} \mathbf{v} \\ \mathbf{E}'_\phi &= \gamma \mathbf{E}_\phi + \gamma \mathbf{v} \times \mathbf{B}_\phi + (1-\gamma) \frac{\mathbf{v} \cdot \mathbf{E}_\phi}{v^2} \mathbf{v} \end{aligned}$$

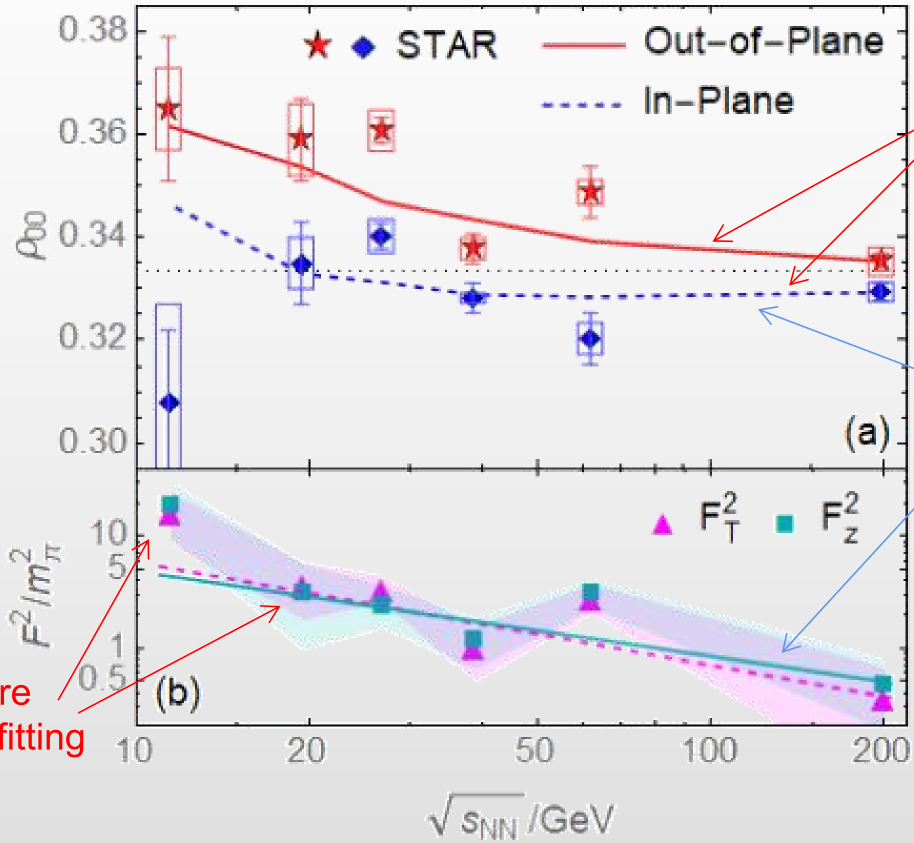
Anisotropy induced by motion relative to background

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRD 109, 036004 (2024).
XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

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

Parameters are evaluated by fitting STAR data

Energy-dependent parameters fitted by

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

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

STAR, Nature 614, 244 (2023)

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

Model predictions

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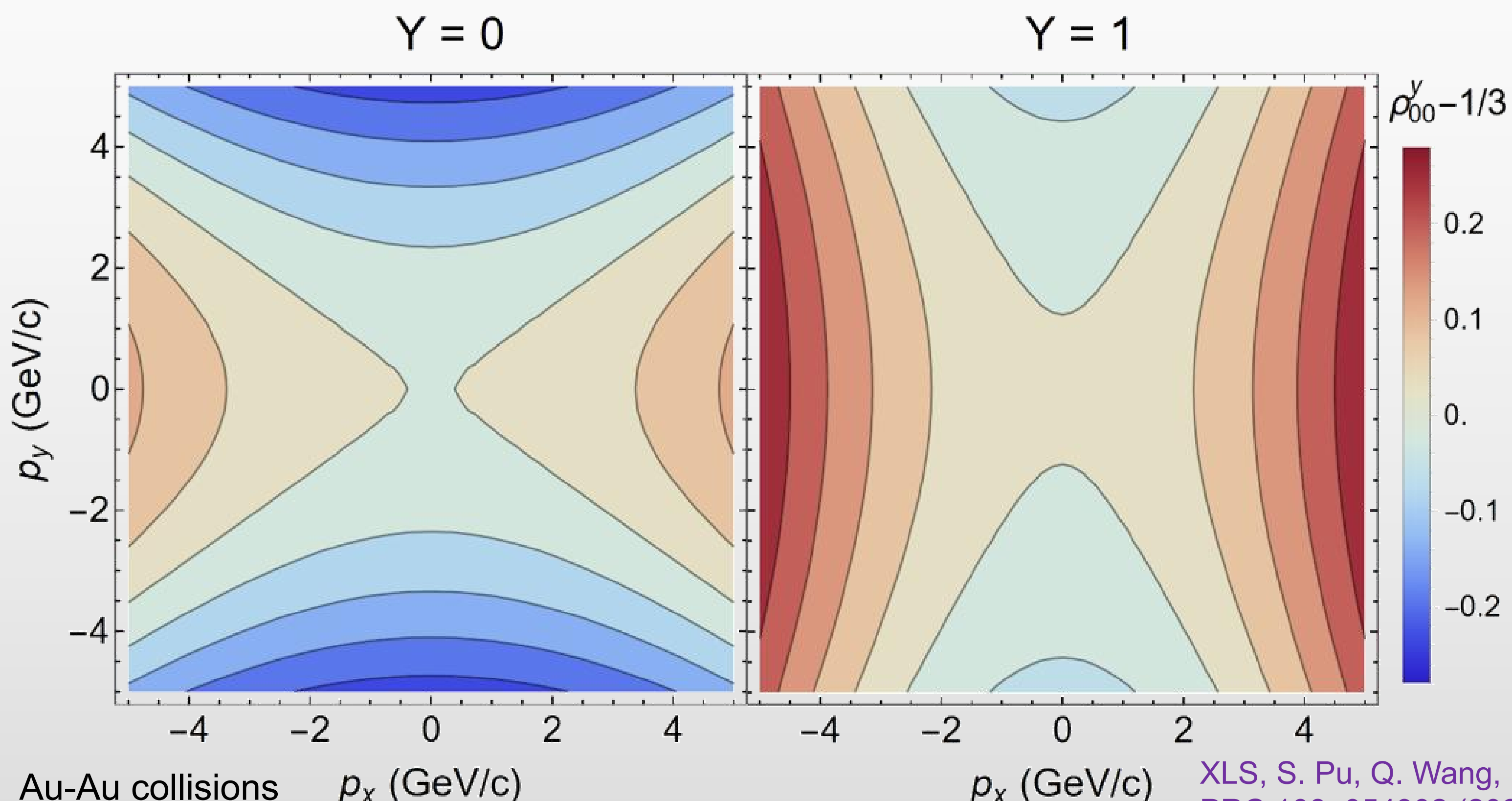
Dominant!

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

$$\langle \delta \rho_{00}^y \rangle (\mathbf{p}) \propto \frac{1}{2} p_T^2 \left[3 \cos(2\varphi) - 1 \right] + \sqrt{m_\phi^2 + p_T^2} \sinh^2 Y$$



Au-Au collisions at 200 GeV/A

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

Model predictions

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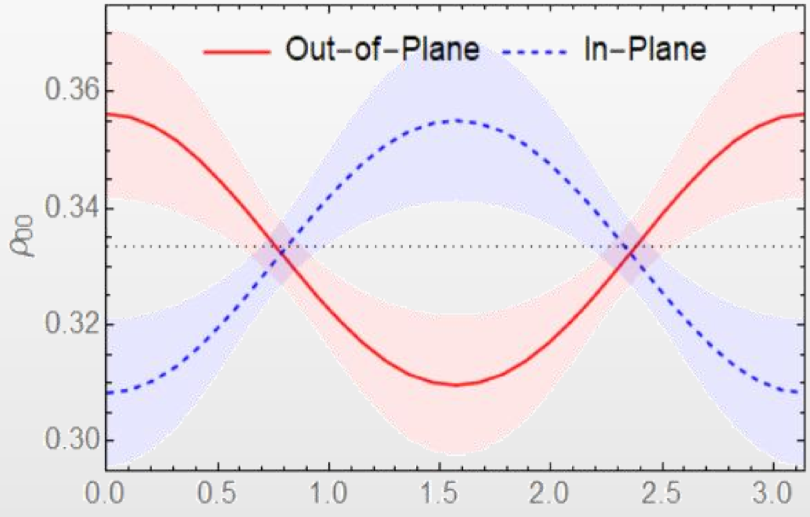
Dominant!

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

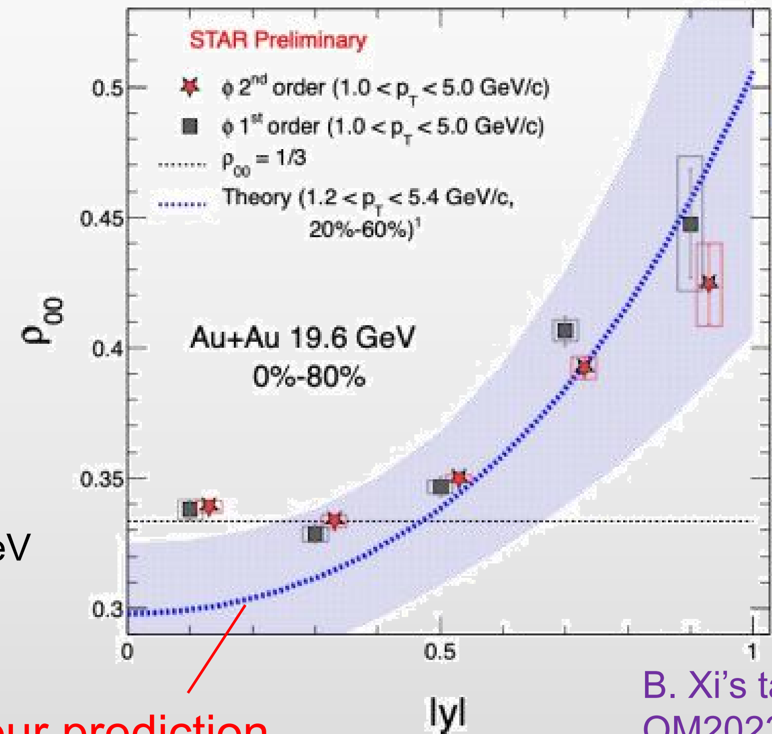
$$\langle \delta \rho_{00}^y \rangle (\mathbf{p}) \propto \frac{1}{2} p_T^2 \left[3\cos(2\varphi) - 1\right] + \sqrt{m_\phi^2 + p_T^2 \sinh^2 Y}$$

- Predictions for azimuthal angle dependence and rapidity dependence



Au-Au collisions at 200 GeV/A

$1.2 < p_T < 5.4$ GeV



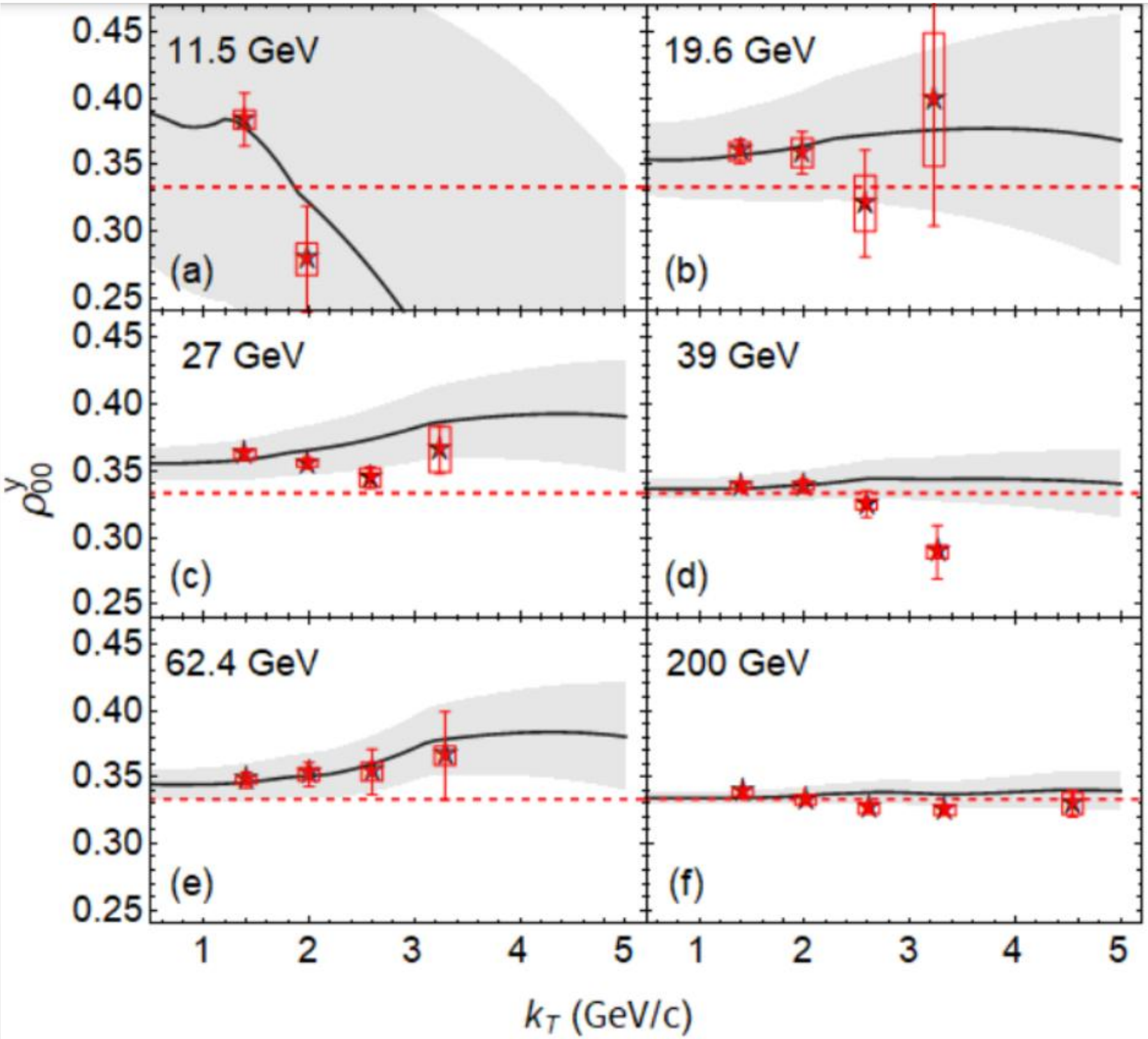
XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

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

our prediction

B. Xi's talk in QM2023

p_T dependence



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

Calculated ρ_{00}^y as functions of ϕ meson's transverse momentum, in comparison with STAR data for Au+Au collisions in 0-80% centrality region.

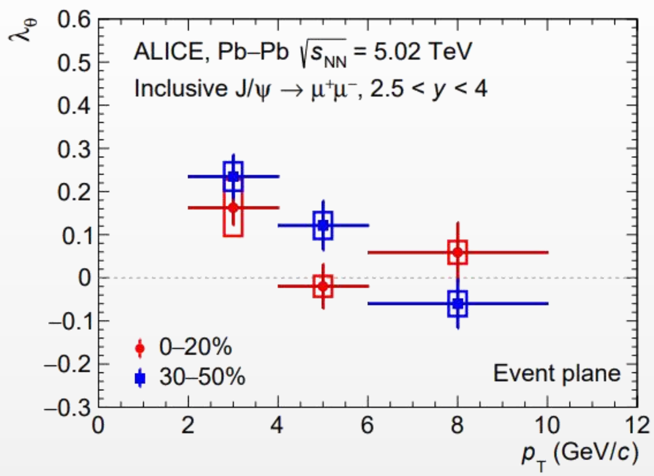
STAR, Nature 614, 244 (2023)

Shaded error bands from uncetainties of extracted parameters F_T^2 and F_z^2.

Outline

- Introduction
- Kinetic theory for vector meson
- Anisotropic strong field fluctuation
- **Global spin alignment of J/ψ**
- Summary

- Global spin alignment, measured in event-plane direction



- Relation between λ_θ and ρ_{00}

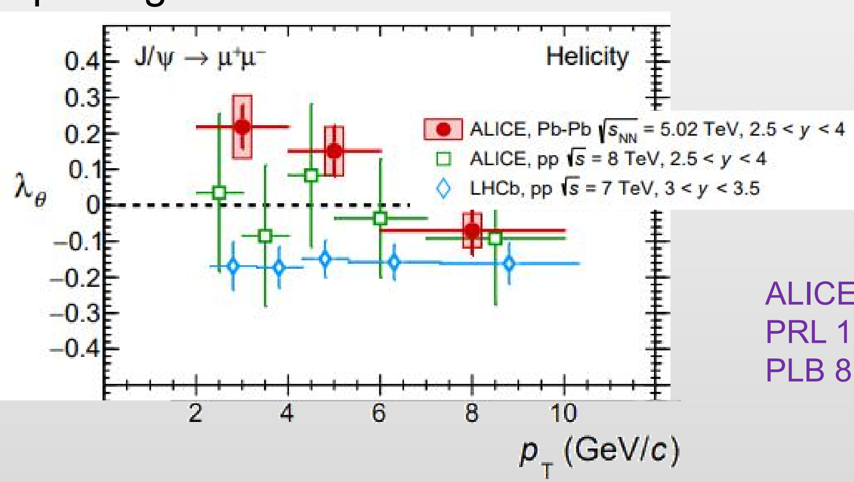
$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}} \approx -\frac{9}{4}\left(\rho_{00}-\frac{1}{3}\right)$$

$\rho^h_{00}, \rho^y_{00} < 1/3$

Different behaviours?

For ϕ meson, $\rho^y_{00} > 1/3$

- Spin alignment measured in momentum direction



ALICE Collaboration,
PRL 131. 042303 (2023)
PLB 815, 136146 (2021)

Spin alignment of J/ψ

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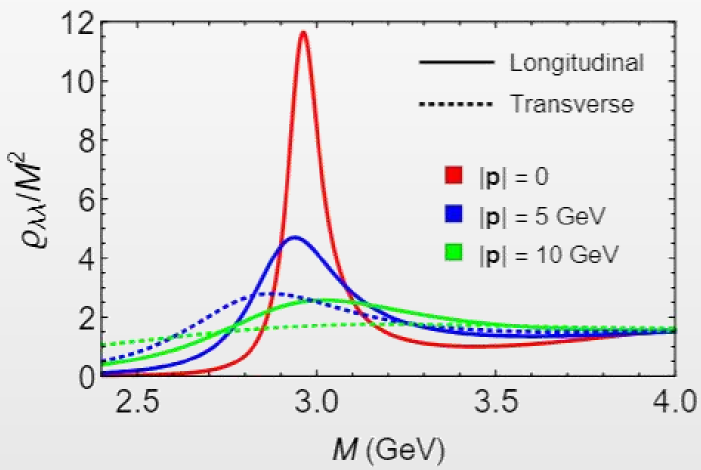
Holographic spin alignment for vector mesons

Xin-Li Sheng[a,b], Yan-Qing Zhao[b], Si-Wen Li[c], Francesco Becattini[d], Defu Hou[b]

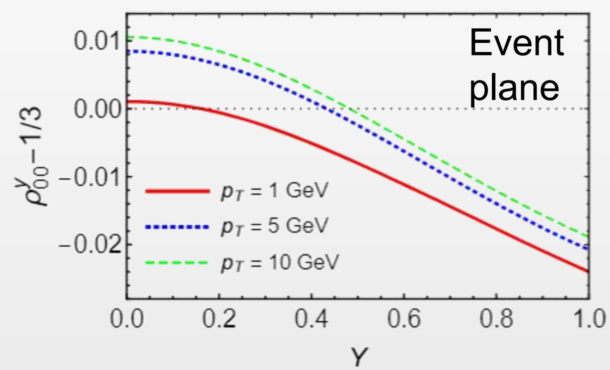
arXiv: 2403.07522

- Motion of J/ψ relative to a thermal background breaks symmetry between longitudinally polarized state and transversely polarized state

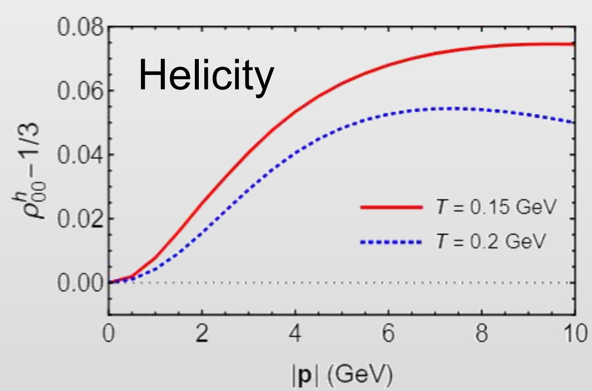
- Mass spectral function for J/ψ



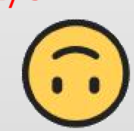
- Spin alignment



$\rho_{00}^{y} < 1/3$ in a forward rapidity region



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



Spin alignment of J/ψ

INFN Istituto Nazionale di Fisica Nucleare
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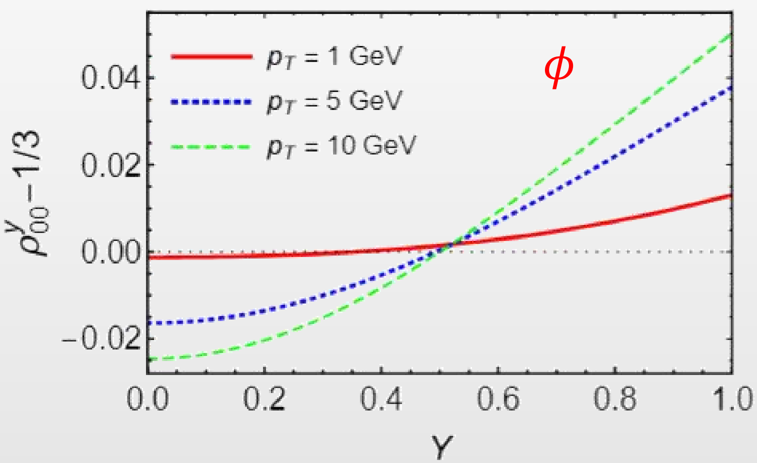
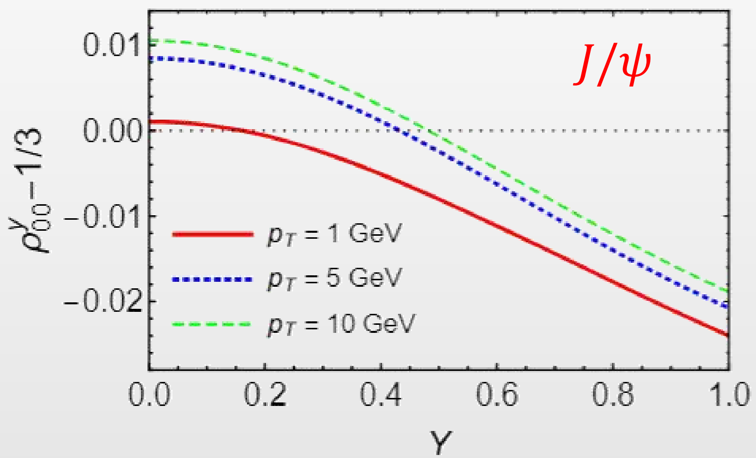
Holographic spin alignment for vector mesons

Xin-Li Sheng[a,b], Yan-Qing Zhao[b], Si-Wen Li[c], Francesco Becattini[d], Defu Hou[b]

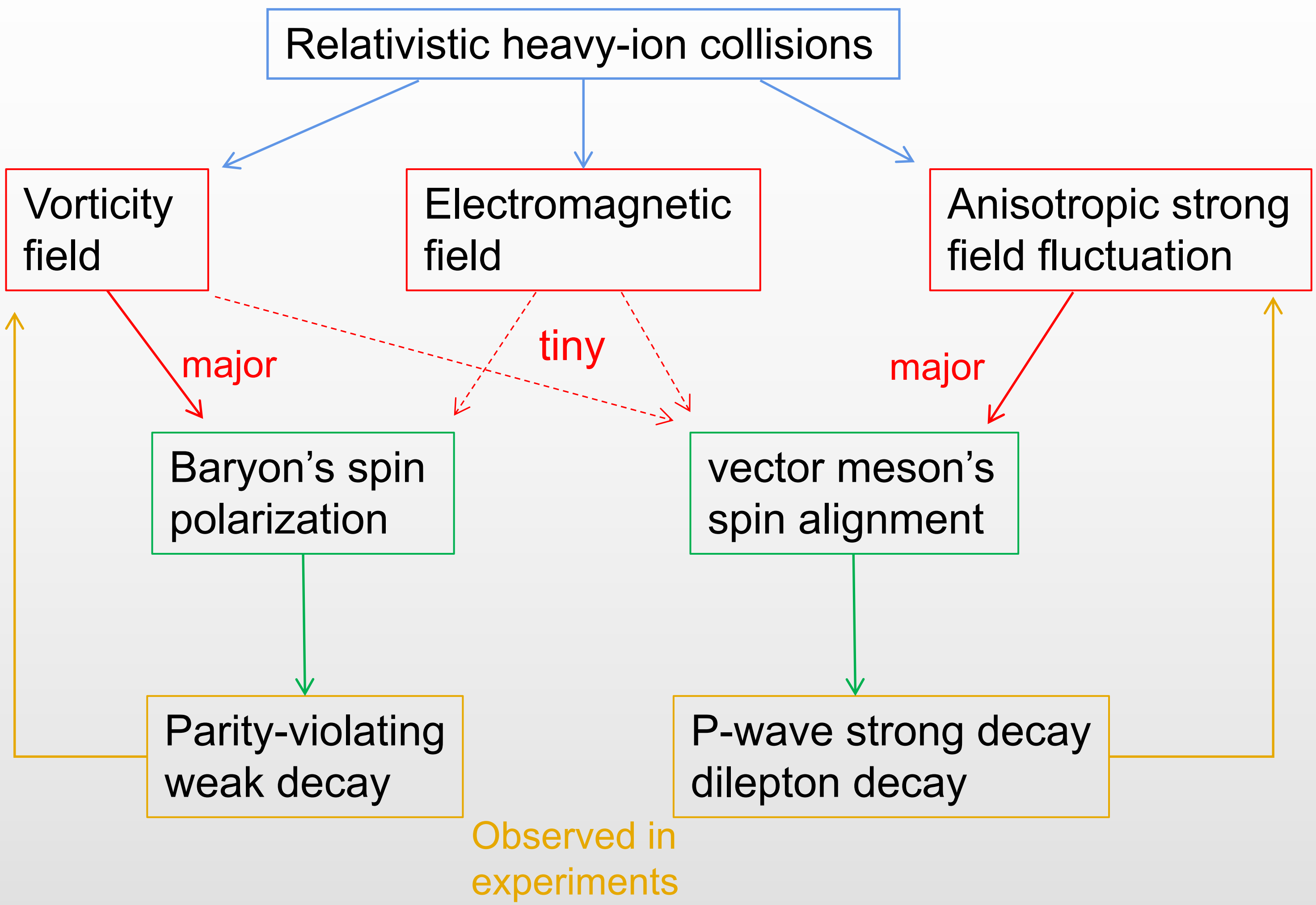
arXiv: 2403.07522

- Motion of J/ψ relative to a thermal background breaks symmetry between longitudinally polarized state and transversely polarized state
- Opposite bahaviours of ϕ and J/ψ





Summary


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

Summary

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- Spin alignment measures anisotropy of strong field fluctuations in meson's rest frame.
- Dominate contribution to anisotropy may be motion of meson relative to background
- Predictions for momentum dependence of spin alignment need to be tested by more experiment results

Thanks for your attention!