

Vector-Meson Spin Alignment Across Flavors from Holographic Spectral Functions

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Outline

1. Spin alignment: concepts and motivation
2. Holographic framework and model
3. Results and physical interpretation
4. Summary and discussion

The concept of vector-meson spin alignment

Spin-1 mesons: $m = +1, 0, -1$ along $\hat{n}$

Spin density matrix:

$$\rho = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1,-1} \\ \rho_{01} & \rho_{00} & \rho_{0,-1} \\ \rho_{-1,1} & \rho_{-1,0} & \rho_{-1,-1} \end{pmatrix}, \quad \rho = \rho^\dagger, \quad \text{Tr} \rho = 1$$

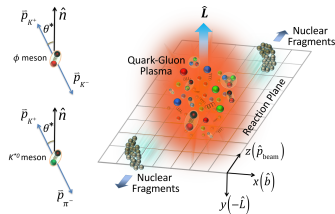
$$\rho_{00} = \frac{N_0}{N_{+1} + N_0 + N_{-1}} \quad \text{Alignment: } \rho_{00} \neq 1/3$$

Unpolarized ensemble: $\rho = I_3/3$.

Decay angular distribution for $V \rightarrow P_1 P_2$ (two pseudoscalars):

$$\frac{1}{N} \frac{dN}{d \cos \theta^*} = \frac{3}{4} [(1 - \rho_{00}) + (3\rho_{00} - 1) \cos^2 \theta^*].$$

θ^* is defined in the meson rest frame. Azimuthal angle integrated out. Theory: Sheng et al., Acta Phys. Sin. 72, 072502 (2023).

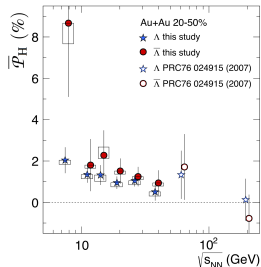


Global alignment: $\hat{n} \parallel \mathbf{L}$, normal to the reaction plane.

Geometry: STAR, Nature 614, 244 (2023), Fig. 1.

Experimental landmarks in heavy-ion collisions

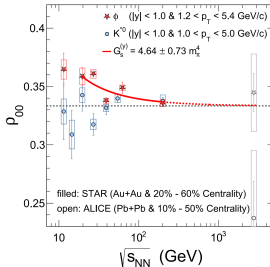
Baryons: $\Lambda, \bar{\Lambda}$



Positive global polarization supports a vortical medium.

STAR, Nature 548, 62 (2017), Fig. 4.

Light mesons: ϕ, K^{*0}

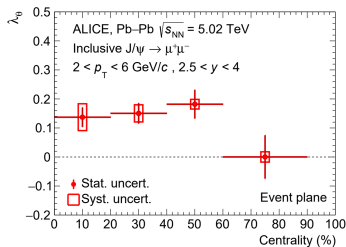


STAR: $\rho_{00}^{\phi} > 1/3$, while K^{*0} is consistent with $1/3$.

STAR, Nature 614, 244 (2023), Fig. 3.

Open points: ALICE, PRL 125, 012301 (2020).

Charmonium: J/ψ



ALICE: $\lambda_{\theta} > 0$, hence $\rho_{00} < 1/3$ in midcentral bins.

ALICE, PRL 131, 042303 (2023), Fig. 2(a).

Flavor-dependent signals constrain the spin response of QCD matter.

Different energies and kinematic cuts. Red curve: model fit. For $J/\psi \rightarrow \mu^+ \mu^-$, $\rho_{00} = (1 - \lambda_{\theta})/(3 + \lambda_{\theta})$.

Proposed mechanisms of spin alignment

- Vorticity and shear
- Local spin correlations
- Magnetic-field effects
- In-medium spectral splitting
- ...

Selected references

Liang and Wang, PLB 629, 20 (2005).
Wagner et al., PRR 5, 013187 (2023).
Sheng et al., PRL 131, 042304 (2023).
Kumar et al., PRD 108, 016020 (2023).
Sheng et al., EPJC 84, 299 (2024).
Chen and Lin, PRD 111, 074002 (2025).
Dong et al., PRD 109, 056025 (2024).
Sheng et al., PRD 110, 056047 (2024).

...

Our approach: holographic modeling of spin alignment

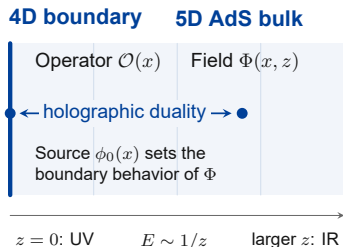
Compute polarization-resolved spectral functions in a strongly coupled medium.

Review: Sheng, Liang and Wang, Acta Phys. Sin. 72, 072502 (2023).



AdS/CFT: the gauge/gravity correspondence

Canonical example: 4D $\mathcal{N} = 4$ $SU(N_c)$ SYM $\longleftrightarrow$ type IIB strings on $AdS_5 \times S^5$



Strong coupling $\longleftrightarrow$ **classical gravity**

Large N_c and large $\lambda = g_{\text{YM}}^2 N_c$.

Operators $\longleftrightarrow$ **bulk fields**

Bulk dynamics yield boundary correlators.

Thermal plasma $\longleftrightarrow$ **black brane**

The Hawking temperature sets the field-theory temperature: $T = T_{\text{Hawking}}$.

$$Z_{\text{CFT}}[\phi_0] = Z_{\text{string}}[\phi_0] \simeq \exp[-S_{\text{grav,ren,on-shell}}^E[\phi_0]]$$

Differentiate $\ln Z$ with respect to sources ϕ_0 to obtain correlation functions.

Maldacena, ATMP 2, 231 (1998); Gubser, Klebanov and Polyakov, PLB 428, 105 (1998);

Witten, ATMP 2, 253 (1998). Diagram: schematic dictionary; the internal S^5 is suppressed.

Model setup: background and meson sectors

$$S_{5D} = S_B^{\text{EMD}} + S_M^{N_f=4}$$

$$ds_e^2 = \frac{e^{2A_e(z)}}{z^2} \left[-f(z)dt^2 + \frac{dz^2}{f(z)} + e^{B(z)}(dr^2 + r^2 d\theta^2) + e^{-2B(z)}dx_3^2 \right]$$

Einstein frame. A_e : warp factor; f : blackening function; B : anisotropy. Rotation axis: x_3 .

S_B : EMD background

Einstein–Maxwell–dilaton theory.

Background for a medium at (T, μ, Ω) .

S_M : four-flavor soft-wall sector

Condensates and vector mesons: u, d, s, c .

Fluctuations yield polarized meson spectra.

Probe approximation: solve the background first; neglect the backreaction of the matter sector S_M on the EMD background.

Background: Chen et al., PRD 111, 046006 (2025); four-flavor sector: Chen and Huang, PRD 105, 026021 (2022).

EMD background: action and input functions

Background action in the Einstein frame

$$S_B = \frac{1}{16\pi G_5} \int d^5x \sqrt{-g_e} \left[R_e - \frac{1}{2} \partial_M \phi \partial^M \phi - V_e(\phi) - \frac{h(\phi)}{4} F_{MN} F^{MN} \right]$$

Gauge-field ansatz near the rotation axis

$$A_M = (A_t(z), 0, \Omega r^2, 0, 0), \quad x^M = (t, r, \theta, x_3, z)$$

$$A_z = 0, \quad A_t(0) = \mu, \quad A_t(z_h) = 0; \quad F_{MN} = \partial_M A_N - \partial_N A_M.$$

Warp factor and gauge coupling

$$A_e(z, \Omega) = d \ln[1 + (a + w\Omega^2)z^2] + d \ln[1 + (b + w^2\Omega^4)z^4]$$

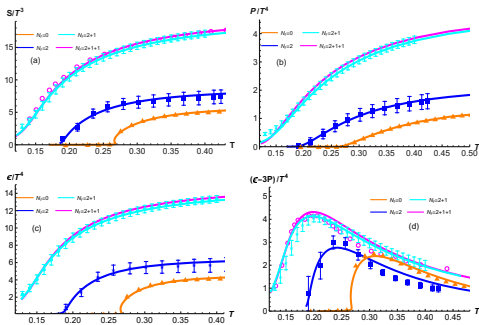
$$h(\phi(z)) = \exp[cz^2 - A_e(z, \Omega) + k]$$

Input A_e and h ; reconstruct $V_e(\phi)$ from the background equations.

Ansatz as used in this work. Nonrotating background: Chen–Huang, JHEP 02, 123 (2025);
rotating EMD framework: Chen et al., PRD 111, 046006 (2025).

Background calibration against lattice QCD

Equation of state: $\mu = \Omega = 0$

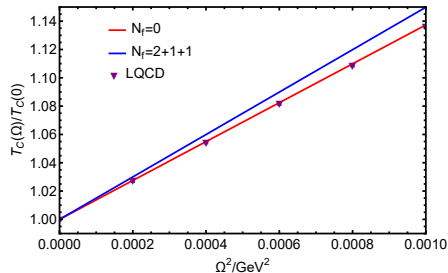


Curves: EMD; symbols: lattice data. T in GeV.

Chen and Huang, JHEP 02, 123 (2025), Fig. 8.

Parameters are fixed by fits to lattice EoS and the pure-gluon $T_c(\Omega)$.

Rotation dependence of T_c



Pure-gluon lattice fit: $w = 92.08$.

The same w is used for $N_f = 2 + 1 + 1$.

Lattice: Braguta et al., PRD 103, 094515 (2021).

Matter action and the four-flavor spectrum

$$S_M = - \int d^5x \sqrt{|g_s|} e^{-\Phi_m} \text{Tr} \left[|DX|^2 + m_5^2(z) |X|^2 - \kappa |X|^4 + \frac{F_L^2 + F_R^2}{4g_5^2} \right] + S_H$$

$$S_H = - \int d^5x \sqrt{|g_s|} e^{-\Phi_m} \sum_{q=s,c} \text{Tr} [|DH_q|^2 + V(|H_q|)]$$

Bulk fields $\longleftrightarrow$ QCD operators

$$A_{L/R,\mu}^a \leftrightarrow \bar{q}_{L/R} \gamma_\mu t^a q_{L/R}$$

$$X \leftrightarrow \bar{q}_L q_R$$

$$V_\mu^a = \frac{1}{2} (A_L + A_R)_\mu^a \leftrightarrow \bar{q} \gamma_\mu t^a q$$

Effective soft-wall inputs

$$\Phi_m(z) = \mu_g^2 z^2$$

$$m_{5,q}^2(z) = -3 - \mu_q^2 z^2, \quad q = l, s, c$$

Φ_m is a matter-sector profile.

μ_q controls flavor-dependent scalar profiles.

H_s, H_c : neutral-channel mass splitting.

Meson spectrum (MeV)

Meson	n	Model	Experiment	Meson	n	Model	Experiment
ρ	0	773	775.26 ± 0.23	ϕ	0	1016	1019.460 ± 0.016
	1	1206	1282 ± 37	D^*	0	1999	2006.85 ± 0.05
	2	1510	1465 ± 25		1	2751	2627 ± 10
	3	1759	1720 ± 20	D_s^*	0	1807	2106.6 ± 3.4
a_1	0	1342	1230 ± 40		1	2491	2714 ± 5
	1	1622	1655 ± 16	J/ψ	0	3087	3096.900 ± 0.009
	2	1857	1930^{+30}_{-70}	Fitted parameters			
	3	2066	2096 ± 122	$\mu_g = 451 \text{ MeV}$	$\kappa = -240$		
K^*	0	892	891.67 ± 0.26	$\mu_l = 316 \text{ MeV}$	$\mu_s = 1068 \text{ MeV}$		
	1	1361	1414 ± 15	$\mu_c = 3834 \text{ MeV}$	$h_s = 47 \text{ MeV}$		
	2	1683	1718 ± 18	$h_c = 300 \text{ MeV}$			

$n = 0$: ground state. Low- T pole masses at $T = 28.1 \text{ MeV}$.

String-frame action; spectrum and fit parameters: this work. The D_s^* mass is underestimated.

From spectral functions to spin alignment

1. Common decay-rate structure (angle integrated; instantaneous freeze-out)

$$n_c \equiv \frac{dN_c}{d^4x d^4p} = \frac{\mathcal{C}_c(M^2) n_B(\omega)}{D_V(M^2)} P_{\mu\nu} \varrho^{\mu\nu}, \quad D_V = (M^2 - m_V^2)^2 + m_V^2 \Gamma^2$$

$$V \rightarrow \ell^+ \ell^- : \quad \mathcal{C}_{\ell\ell}(M^2) = \frac{2g_{V\ell\ell}^2 M^2}{3(2\pi)^5} \left(1 + \frac{2m_\ell^2}{M^2}\right) \sqrt{1 - \frac{4m_\ell^2}{M^2}}, \quad n_B(\omega) = \frac{1}{e^{\omega/T} - 1}$$

$$M^2 = \omega^2 - \mathbf{p}^2; P_{\mu\nu} = \sum_{\lambda=0,\pm 1} v_\mu(\lambda) v_\nu^*(\lambda); \mathcal{C}_c: \text{channel-dependent decay factor.}$$

2. Project onto spin states

$$\tilde{\varrho}_{\lambda\lambda} = v_\mu(\lambda) v_\nu^*(\lambda) \varrho^{\mu\nu}, \quad \varrho^{\mu\nu} = -\text{Im } G_R^{\mu\nu}$$

$$n_{c,\lambda} = \frac{\mathcal{C}_c(M^2) n_B(\omega)}{D_V(M^2)} \tilde{\varrho}_{\lambda\lambda}$$

Spin alignment at fixed $\mathbf{p}$

$$\rho_{00}(\mathbf{p}) = \frac{\int d\omega n_{c,0}}{\sum_{\lambda=0,\pm 1} \int d\omega n_{c,\lambda}}$$

Here: spin quantization axis $\parallel x_3$.

3. Narrow-width limit: $\Gamma \ll m_V$; evaluate at the vacuum mass shell

$$\rho_{00} \simeq \frac{\tilde{\varrho}_{00}}{\sum_\lambda \tilde{\varrho}_{\lambda\lambda}} \Big|_{M=m_V} = \frac{\tilde{\varrho}_{00}}{\tilde{\varrho}_{00} + 2\tilde{\varrho}_{11}} \Big|_{M=m_V} \quad (\text{here } \tilde{\varrho}_{11} = \tilde{\varrho}_{-1,-1})$$

Method: X.-L. Sheng et al., Phys. Rev. D 110, 056047 (2024), Sec. II, Eqs. (5)–(12).

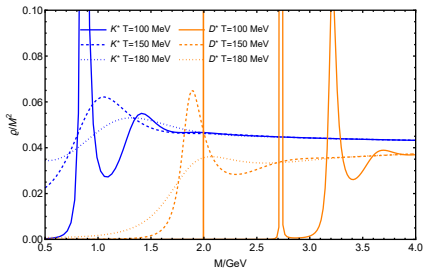
Spectral functions and polarization splitting

$$G_{\mu\nu}^R(p) = - \frac{\delta^2 S_{\text{ren, on-shell}}^{(2)}}{\delta V_0^\mu(-p) \delta V_0^\nu(p)} \Big|_{V_0=0}^{\text{ret}}$$

$$\varrho_{\mu\nu}(p) = -\text{Im } G_{\mu\nu}^R(p)$$

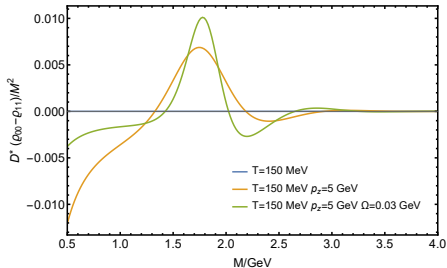
V_0^μ : boundary source for J_μ ; renormalized UV action; infalling waves select the retarded response.

Thermal spectra: $p = 0, \Omega = 0$



Rising T : broader peaks; excited states melt.

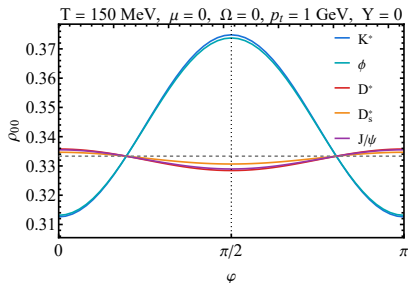
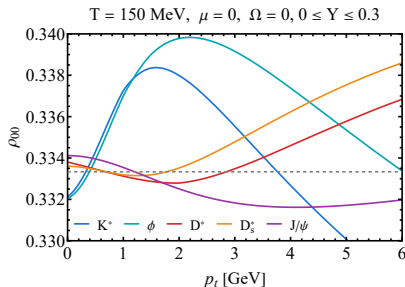
Spin splitting: $D^*, T = 150$ MeV



Finite p_z splits spectra; rotation enhances this peak.

Figures: this work. Retarded prescription: Son and Starinets, JHEP 09, 042 (2002).

Two opposite patterns across five mesons



Low- p_t average

$K^*, \phi : \bar{\rho}_{00} < 1/3$

$D^*, D_s^*, J/\psi :$

$\bar{\rho}_{00} > 1/3$

Opposite angular patterns

At $\varphi = \pi/2$:

light: maximum;

charmed: minimum.

$$p^\mu = (m_T \cosh Y, m_T \sinh Y, p_t \cos \varphi, p_t \sin \varphi), \quad m_T = \sqrt{m_V^2 + p_t^2}$$

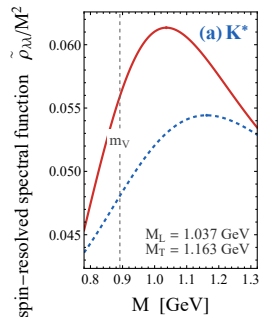
$$\bar{\rho}_{00}(p_t, Y) = \frac{1}{2\pi} \int_0^{2\pi} d\varphi w(\varphi) \rho_{00}(p_t, Y, \varphi), \quad w(\varphi) = 1 + 2v_2 \cos(2\varphi), \quad v_2 = 0.15$$

x_1 : beam; x_3 : spin axis. φ : momentum azimuth. Left: $0 \leq Y \leq 0.3$ averaged; right: $Y = 0, p_t = 1 \text{ GeV}$.

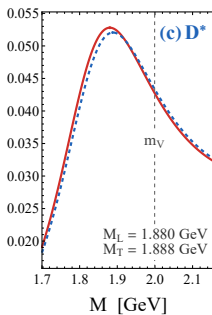
This work, Fig. 7. $T = 150 \text{ MeV}, \mu = \Omega = 0$. The low- p_t signs do not hold over the entire momentum range.

Opposite sides of the vacuum mass shell

$T = 150 \text{ MeV}$, $\mu = \Omega = 0$, $p_t = 1 \text{ GeV}$, $Y = 0.3$, $\varphi = \pi/2$. Red: $\lambda = 0$; blue dashed: $\lambda = \pm 1$.



K^* (also ϕ)
Low-mass flank
 $m_V < M_L < M_T$
 $\tilde{\rho}_{00}(m_V) > \tilde{\rho}_{11}(m_V)$
 $\rho_{00} > 1/3$



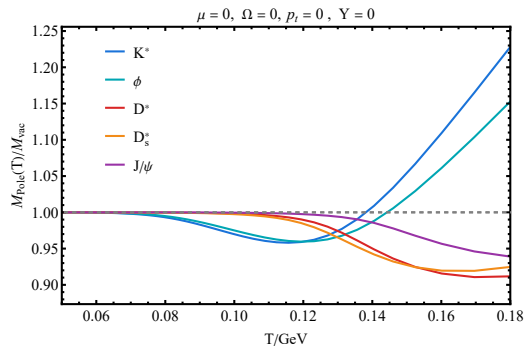
D^* (also D_s^* , J/ψ)
High-mass flank
 $M_L < M_T < m_V$
 $\tilde{\rho}_{00}(m_V) < \tilde{\rho}_{11}(m_V)$
 $\rho_{00} < 1/3$

Vertical dashed line: vacuum m_V ; M_L , M_T : in-medium peak positions.

These signs are at fixed $\varphi = \pi/2$; they differ from the low- p_t azimuthal averages.

This work, Fig. 8(a,c). Full on-shell strengths also depend on peak heights, widths and the spectral background.

Thermal pole shifts explain the two patterns



Around $T = 150$ MeV

$K^*, \phi : M_{\text{pole}} > m_V$

Vacuum shell below the thermal peak.

$D^*, D_s^*, J/\psi : M_{\text{pole}} < m_V$

Vacuum shell above the thermal peak.

$\mathbf{p} = 0$: spin states are degenerate.

Finite momentum splits the common peak.

Thermal shifts + polarization splitting $\longrightarrow$ unequal spectral strengths at m_V .

Spin alignment probes this full on-shell imbalance: peak positions, heights, widths and background.

T, Y, μ, Ω reshape the same competition; their effects need not be universally monotonic.

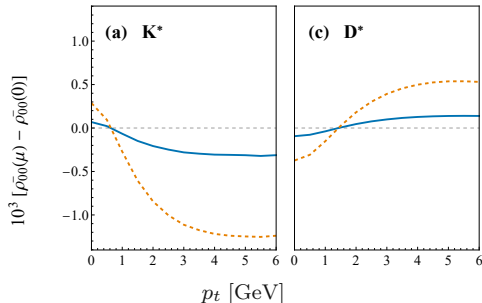
This work, Fig. 9 and the spectral-origin / Discussion paragraphs. $\mu = \Omega = 0, \mathbf{p} = 0$; masses normalized by vacuum values.

Chemical-potential and rotation dependence

$T = 150$ MeV, $Y = 0.3$; azimuthal average with $v_2 = 0.15$.

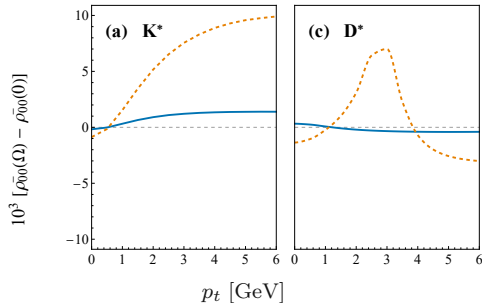
Chemical potential ($\Omega = 0$)

— $\mu = 0.15$ GeV - - $\mu = 0.30$ GeV



Angular velocity ($\mu = 0$)

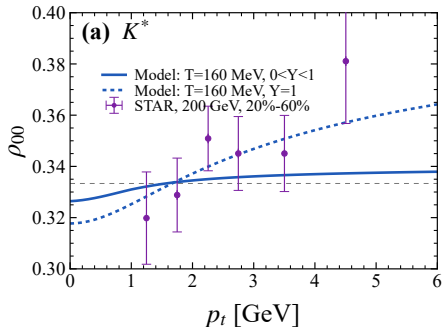
— $\Omega = 0.02$ GeV - - $\Omega = 0.04$ GeV



Small density response; modest, nonuniversal rotational corrections.

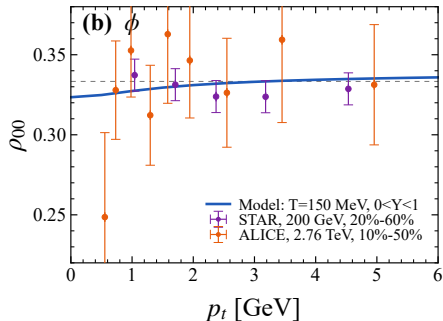
This work, parameter-dependence appendix: selected K^* and D^* panels.

Comparison with experiment: strange mesons



The low- p_t suppression and subsequent rise are qualitatively consistent with the STAR result.

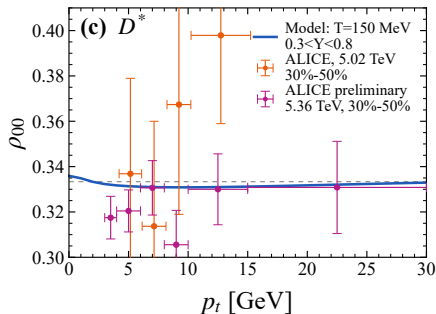
STAR, Nature 614, 244 (2023).



ALICE also observes low- p_t suppression. The model does not generate the larger alignment reported by STAR at lower collision energies.

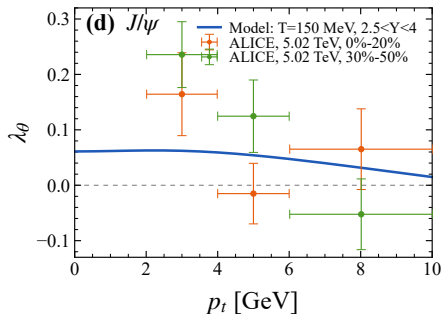
STAR, Nature 614, 244; ALICE, PRL 125, 012301.

Comparison with experiment: charm mesons



The published data agree qualitatively at low/intermediate p_t , but differ at high p_t . The preliminary data are broadly compatible with the calculation.

ALICE: JHEP 10, 094 (2025); preliminary ALI-PREL-633288.



The trend is qualitatively consistent with ALICE's transverse polarization. Uncertainties and centrality coverage preclude a stringent quantitative conclusion.

ALICE, PRL 131, 042303 (2023).



Summary and discussion

Mechanism

Polarization-dependent spectral strength near the **vacuum mass shell** determines ρ_{00} . Thermal shifts and spin splitting explain the opposite flavor patterns.

Comparison with experiment

Several low- and intermediate- p_t trends are qualitatively reproduced.

The low-energy STAR ϕ enhancement and published high- p_t D^* data remain challenging; preliminary D^* data are broadly compatible.

This work, Discussion and Conclusion; arXiv:2608.30930.

Equilibrium medium response

The classical background captures the ensemble-averaged response of an **equilibrium medium**.

No dynamical fireball evolution, stochastic bulk fluctuations or hard-production sector is included.

A baseline for additional physics

This is an **equilibrium baseline**. Robust discrepancies may signal additional contributions, after accounting for model limitations and experimental uncertainties.

Thank you

Questions and discussion

An equilibrium baseline for vector-meson spin alignment across flavors.

Ruixiang Chen | [arXiv:2608.30930](https://arxiv.org/abs/2608.30930)

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