Global spin alignment of vector mesons in heavy-ion collisions

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INFN Istituto Nazionale di Fisica Nucleare
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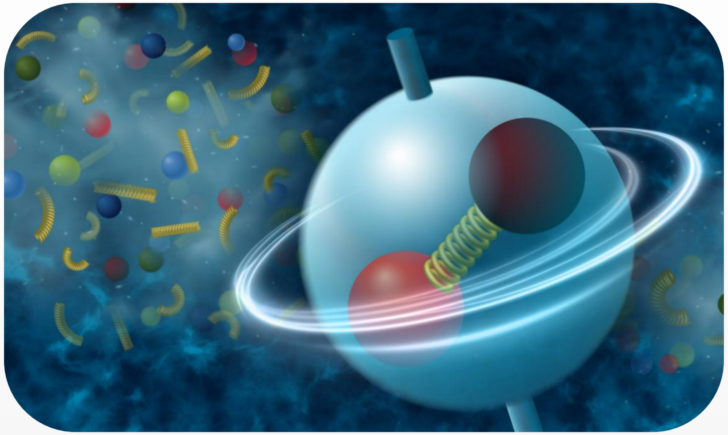
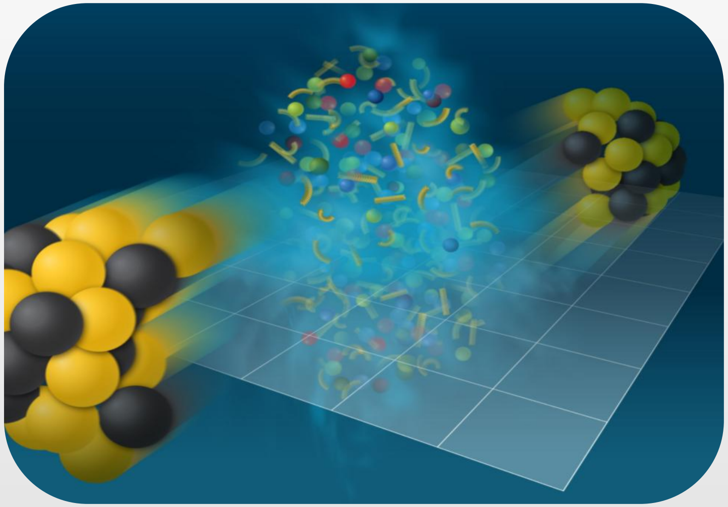
"Florence Theory Group Day"
Feb. 22, 2023





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Heavy-ion collisions

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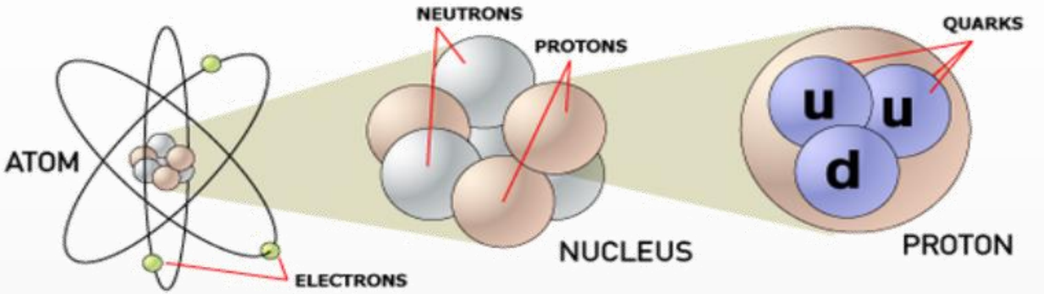
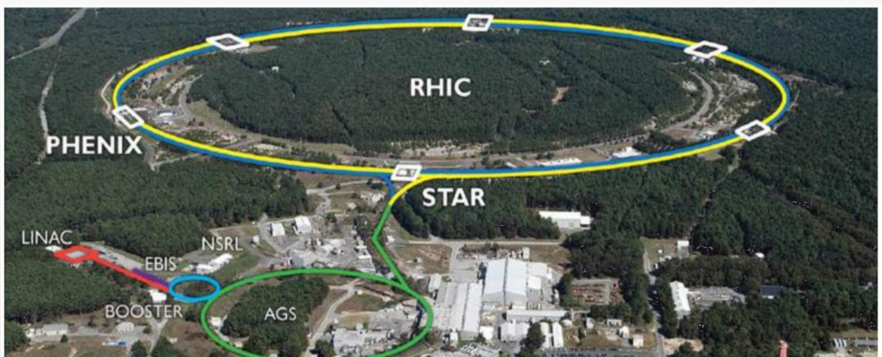
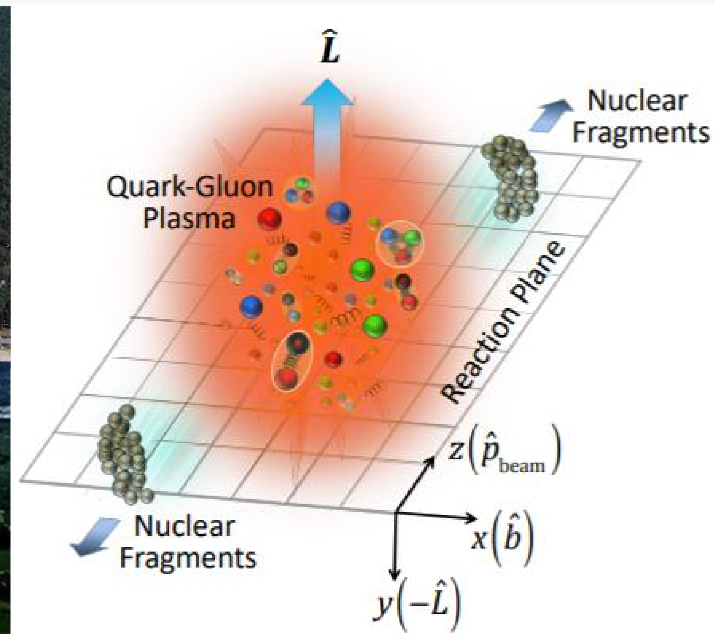
Relativistic heavy-ion collisions provide an opportunity to study properties of matter under extreme conditions.



RHIC:
Relativistic
Heavy Ion
Collider



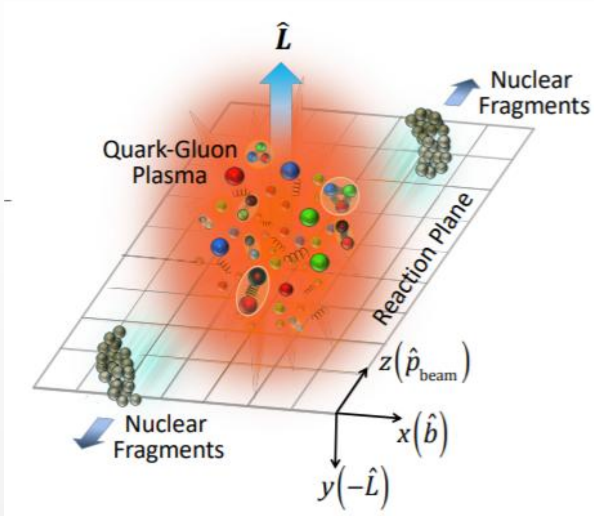
LHC:
Large
Hadron
Collider



Nature 614 (2023) 7947, 244-248

Heavy-ion collisions

Heavy-ion collsions create the most vortical system human ever made, along with strong EM fields.



Vorticity, magnetic field

spin-orbit / magnetic coupling

Spin of hadrons

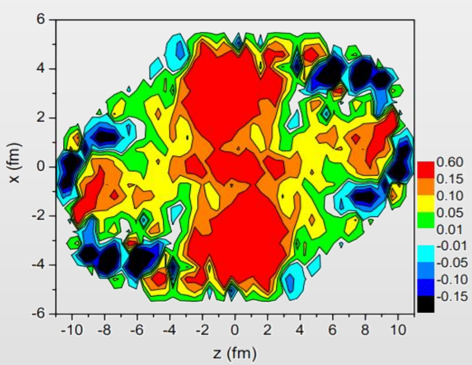
weak / strong p-wave decay

Measurements

Λ's global polarization

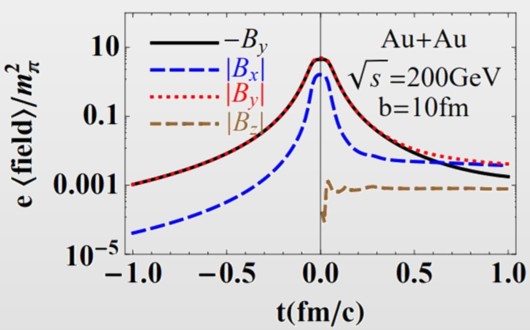
Talk by Eduardo Grossi

Vorticity fields

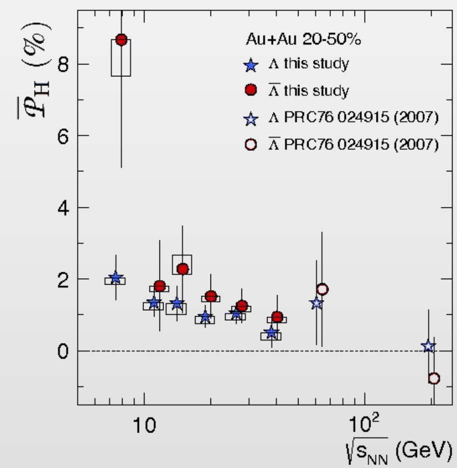


F. Becattini, L. Csernai, D.J. Wang, PRC 88, 034905 (2013); PRC 93, 069901 (2016)

Electromagnetic fields



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



L. Adamczyk, et al. (STAR), Nature 548 (2017) 62.

Spin alignment

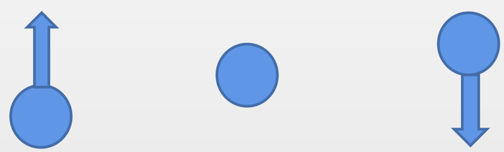
- Polarization for quarks (spin-1/2) or other spin-1/2 hadrons

spin-up spin-down

$S_z = \; +1/2 \quad -1/2$

$$P = \frac{f_{+1/2} - f_{-1/2}}{f_{+1/2} + f_{-1/2}}$$

- Spin alignment for vector mesons (spin-1) is the 00-element of the normalized spin density matrix



spin-up spin-zero spin-down

$S_z = \; +1 \quad 0 \quad -1$

$$\rho_{00} = \frac{f_0}{f_{+1} + f_0 + f_{-1}} = \frac{1}{3} + \ldots$$

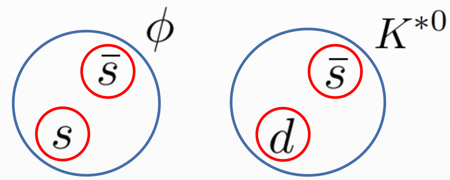
$$\rho^{S=1}_{rs} = \begin{pmatrix} \rho_{+1,+1} & \rho_{+1,0} & \rho_{+1,-1} \\ \rho_{0,+1} & \rho_{00} & \rho_{0,-1} \\ \rho_{-1,+1} & \rho_{-1,0} & \rho_{-1,-1} \end{pmatrix}$$

$$\text{tr}\,\rho^{S=1} = 1$$

Spin alignment

- Vector mesons decay to pseudo-scalar mesons parity-odd strong decay

$$\phi \to K^+ + K^-$$
$$K^{*0} \to K^+ + \pi^-$$
$$J^P \quad 1^- \quad 0^- \quad 0^-$$



- Spin angular momentum of vector meson
  → orbital angular momentum of decay products

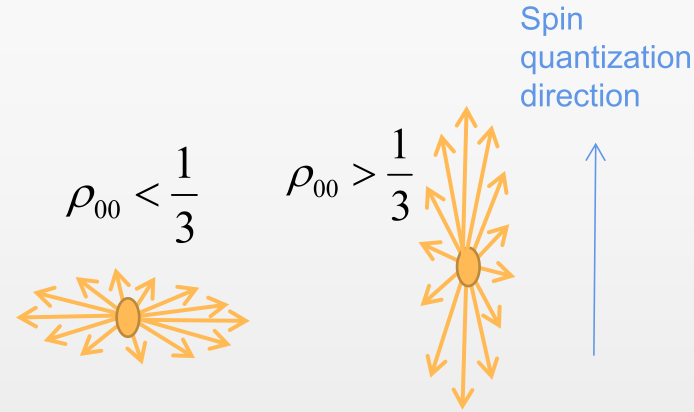
  For a meson with $S = 1$, $S_z = m$, angular distribution of decay products: $dN/d\Omega \propto |Y_{1,m}(\theta,\phi)|^2$

  Y.-G. Yang, R.-H. Fang, Q. Wang, X.-N. Wang, PRC 97, 034917 (2018).

- Polar angle distribution

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

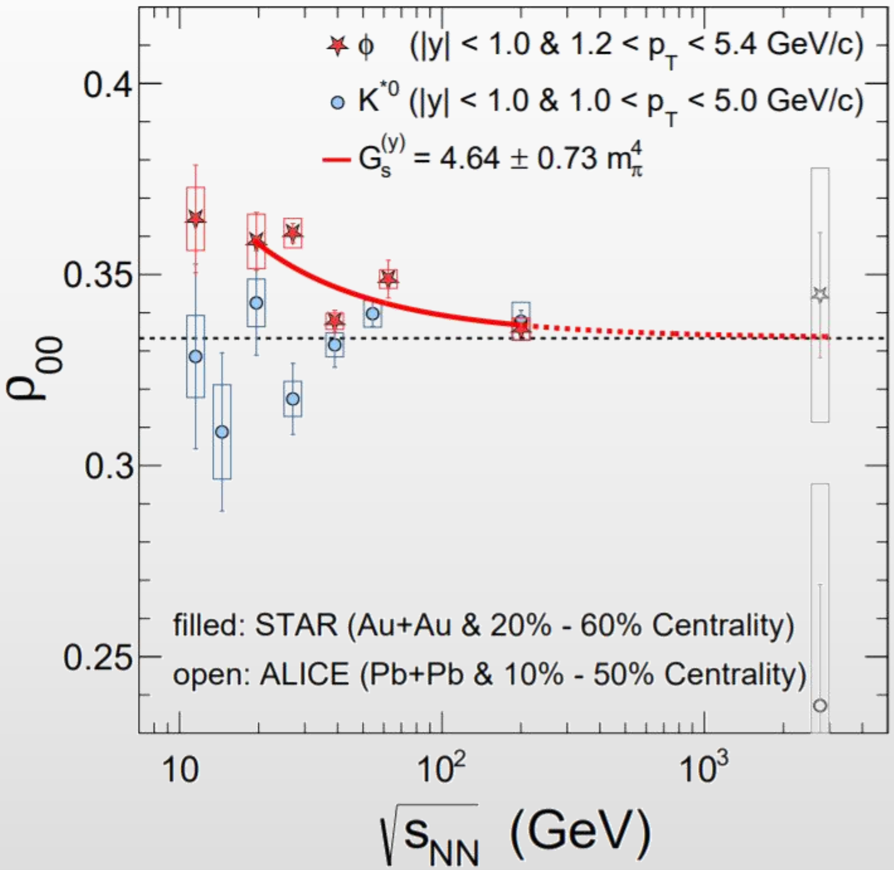
K. Schilling, P. Seyboth, G. E. Wolf, NPB 15, 397 (1970) [Erratum-ibid. B 18, 332 (1970)].



More decay products in transverse direction	More decay products in longitudinal direction
$\|S, S_z\rangle = \|1,+1\rangle$, $\|1,-1\rangle$	$\|1,0\rangle$
Transversely polarized	Longitudinally polarized

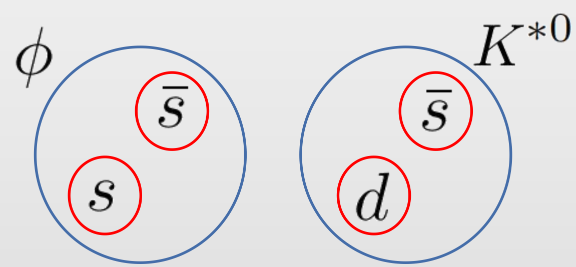
Pattern of Global Spin Alignment of ϕ and K^{*0} mesons in Heavy-Ion Collisions

Nature 614 (2023) 7947, 244-248



ϕ meson's ρ_{00} is significantly larger than 1/3 (unpolarized case) for collision energies of 62 GeV and below (8.4σ !!)

"Global" refer to direction of global angular momentum



Theory works

- **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

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

- Non-relativistic spin-spin coupling

$|S, S_z\rangle$ for quark/antiquark

$$\left|\frac{1}{2}, +\frac{1}{2}\right\rangle$$

$$\left|\frac{1}{2}, -\frac{1}{2}\right\rangle$$

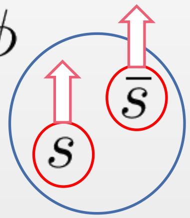
$|S, S_z\rangle$ for vector meson

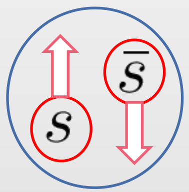
$$|1, +1\rangle = \left|\frac{1}{2}, +\frac{1}{2}\right\rangle \left|\frac{1}{2}, +\frac{1}{2}\right\rangle$$

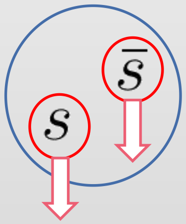
$$|1, 0\rangle = \frac{1}{\sqrt{2}}\left(\left|\frac{1}{2}, +\frac{1}{2}\right\rangle \left|\frac{1}{2}, -\frac{1}{2}\right\rangle + \left|\frac{1}{2}, -\frac{1}{2}\right\rangle \left|\frac{1}{2}, +\frac{1}{2}\right\rangle\right)$$

$$|1, -1\rangle = \left|\frac{1}{2}, -\frac{1}{2}\right\rangle \left|\frac{1}{2}, -\frac{1}{2}\right\rangle$$

ϕ







Theory works

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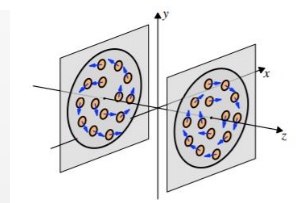
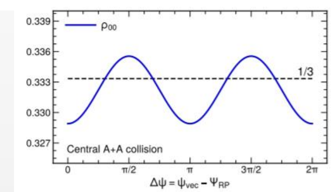
- If a field can polarize quark/antiquark, it can also result in $\rho_{00} \neq 1/3$

- Contributions from global vorticity and magnetic field:
  Y.-G. Yang, R.-H. Fang, Q. Wang, X.-N. Wang, PRC 97, 034917 (2018).

	$\mathscr{P}_\phi$	ρ_{00}^{ϕ}	$\mathscr{P}_\Lambda$	
$\mathscr{P}(\omega)$ or $\rho_{00}^{\phi}(\omega)$	$\frac{2}{3}\beta\omega$	$\frac{1}{3}-\frac{1}{9}(\beta\omega)^2$	$\frac{1}{2}\beta\omega$	
$\mathscr{P}(B)$ or $\rho_{00}^{\phi}(B)$	0	$\frac{1}{3}+\frac{4}{9}(\beta\mu_{ms}B)^2$	$\beta\mu_{ms}B$	$\frac{1}{3}\beta B($
$\mathscr{P}(B)$	$\frac{2}{3}\beta\mu_{m\phi}B$	$\frac{1}{3}-\frac{1}{9}(\beta\mu_{m\phi}B)^2$	$\beta\mu_{m\Lambda}B$	

- Local vorticity:
  X.-L. Xia, H. Li, X.-G. Huang, H.-Z. Huang, PLB 817,136325 (2021).





- Helicity alignment: J.-H. Gao, PRD 104, 076016 (2021).

  Turbulent color fields: B. Mueller, D.-L. Yang, PRD 105, 1 (2022).

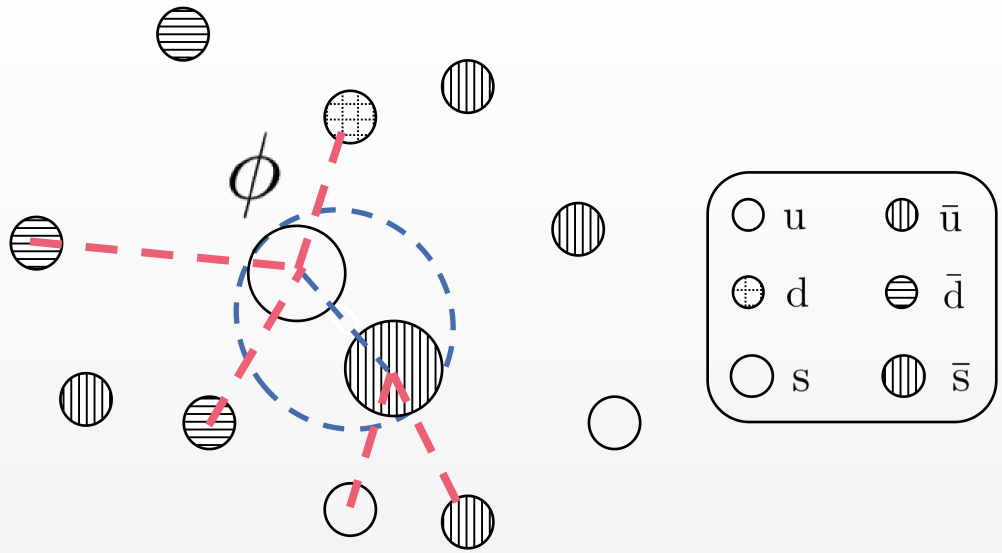
  Shear-induced spin alignment: F.Li, S.Liu, arXiv:2206.11890. D.Wagner, N.Weickgenannt, E.Speranza, arXiv:2207.0111.

- Fluctuating strong force field: XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, arXiv: 2206.05868; arXiv: 2205.15689. XLS, Q.Wang, X.-N.Wang, PRD 102, 056013 (2020). XLS, L.Oliva, Q.Wang, PRD 101, 096005 (2020).

Strong force

- Strong force is a fundamental interaction that acts between quarks.

- At high energies, strong interactions are mediated by gluons. (Quantum Chromodynamics)



- At low energies, strong interactions are mediated by mesons, proposed by Yukawa in 1935.

  H. Yukawa, Proc. Phys. Math. Soc. Jap. 17, 48 (1935)

- Effective Lagrangian for a quark-meson model with scalar and vector mesons.

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

strong interactions between $s/\overline{s}$ quarks are mediated by vector ϕ field

Polarization

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

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

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

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, arXiv:2205.15689, 2206.05868.

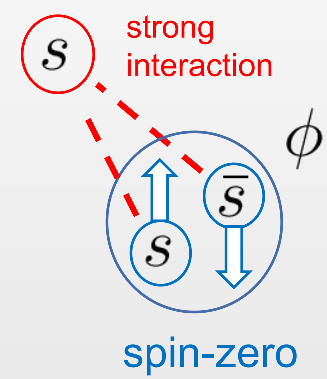
thermal vorticity field (rotation and acceleration)

classical electromagnetic field

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

vector ϕ field (strong force field coupled to $s/\bar{s}$)

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



- 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

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

$$
\begin{aligned}
\rho_{00} \approx\; & \frac{1}{3} + C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}' - (\epsilon_0\cdot\boldsymbol{\omega}')^2\right] \\
& + C_1\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}' - (\epsilon_0\cdot\boldsymbol{\varepsilon}')^2\right] \\
& - \frac{4e^2}{9m_\phi^2 T_h^2} C_1\left[\frac{1}{3}\mathbf{B}'\cdot\mathbf{B}' - (\epsilon_0\cdot\mathbf{B}')^2\right] \\
& - \frac{4e^2}{9m_\phi^2 T_h^2} C_2\left[\frac{1}{3}\mathbf{E}'\cdot\mathbf{E}' - (\epsilon_0\cdot\mathbf{E}')^2\right] \\
& - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_1\left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi - (\epsilon_0\cdot\mathbf{B}'_\phi)^2\right] \\
& - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_2\left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi - (\epsilon_0\cdot\mathbf{E}'_\phi)^2\right]
\end{aligned}
$$

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

Classical electromagnetic fields → $\lesssim 10^{-3}$ in heavy-ion collisions

Strong force field → Mean value is zero, but can incorporate large fluctuations

Temperature at hadronization time (T_h)

- Important features:

  - Cancellation for mixing terms

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

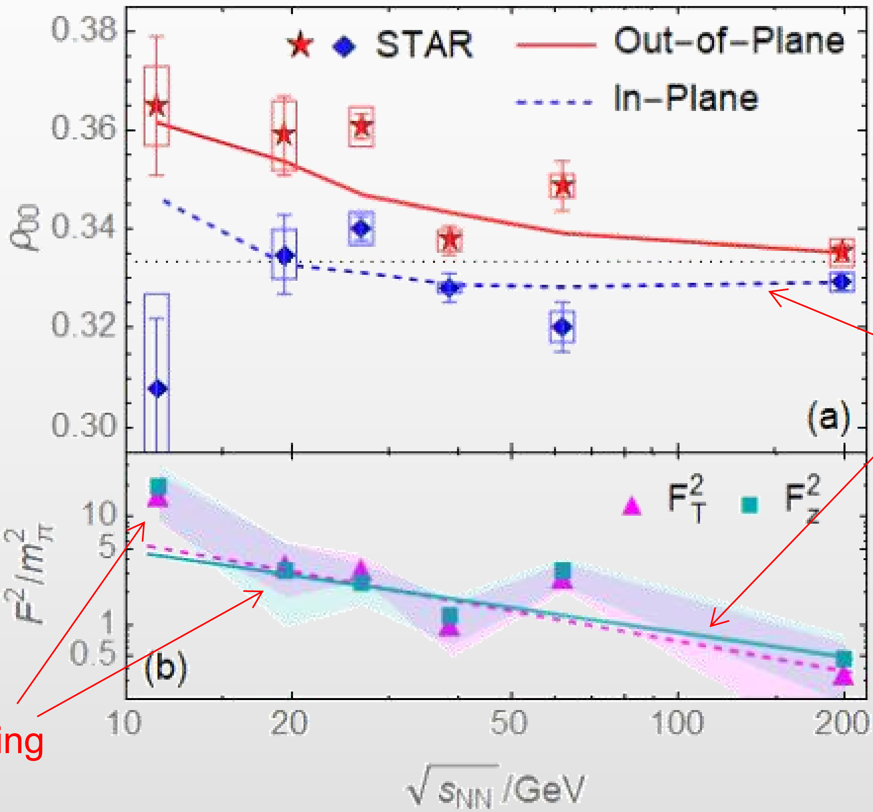
  e.g., contribution from $\mathbf{B}'_\phi$ to spin alignment along *y*-direction $\propto (B'_{\phi,y})^2 - \frac{(B'_{\phi,x})^2 + (B'_{\phi,z})^2}{2}$

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, arXiv:2205.15689, 2206.05868.

Fitting experiment datas

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

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



Parameters are evaluated by fitting STAR data

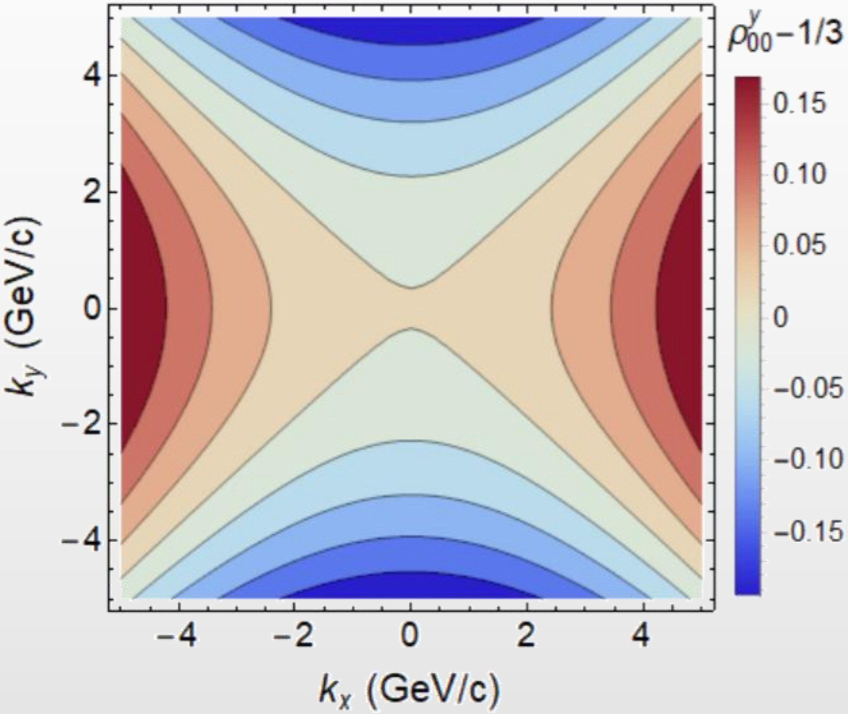
Energy-dependent parameters can be fitted by

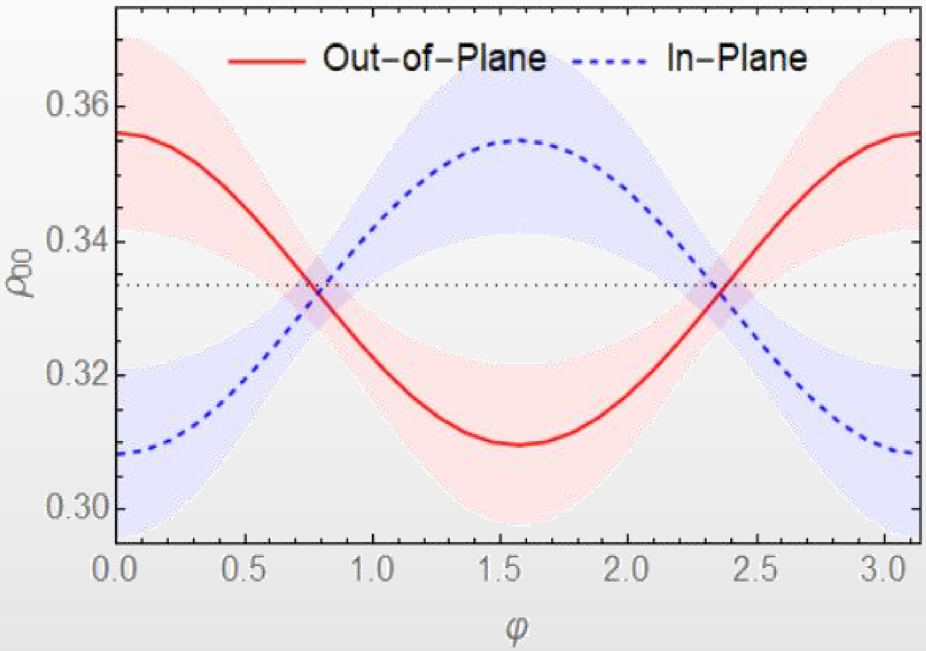
$$\ln(F_T^2/m_\pi^2) = 3.90 - 0.924 \ln \sqrt{s_{\mathrm{NN}}}$$
$$\ln(F_z^2/m_\pi^2) = 3.33 - 0.760 \ln \sqrt{s_{\mathrm{NN}}}$$

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, arXiv:2205.15689.

Model predictions

- With our theoretical model, we predict transverse momentum and azimuthal angle dependence of ϕ meson's spin alignment, which can be verified by future experiments.





XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, arXiv:2205.15689.

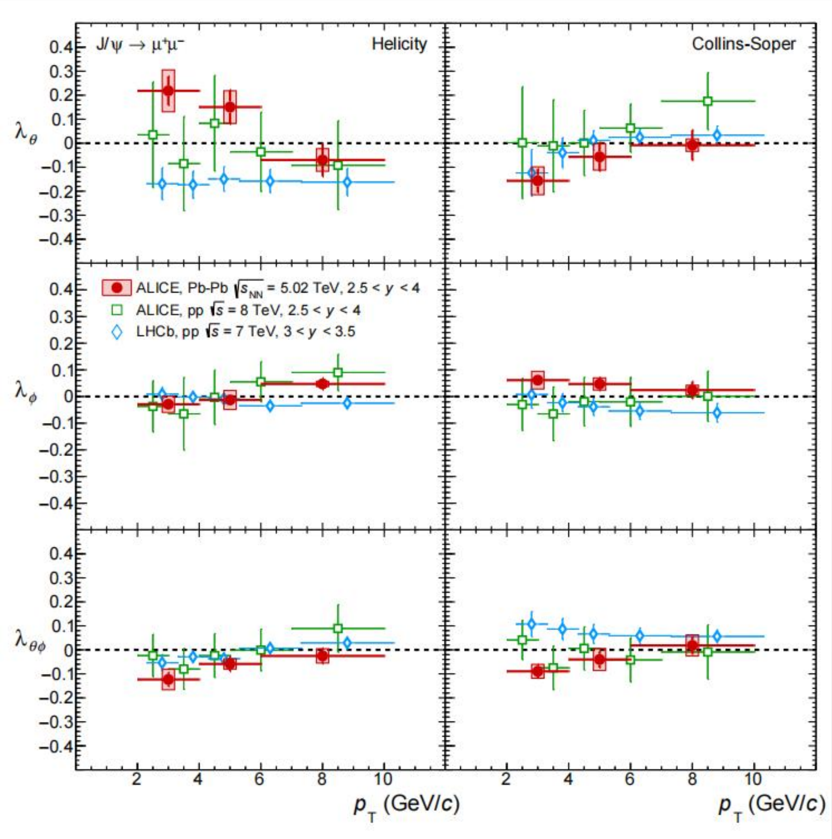
Conclusion

- Spin alignment is 00-element of vector meson's normalized spin density matrix, probability for $S_z = 0$.
- Spin alignment can be affected by various kinds of fields, such as vorticity, electromagnetic fields, ..., but only strong force fields can incorporate significant $\rho_{00} > 1/3$.
- Theoritical calculations show that spin alignment measures anisotropy of fluctuations in meson's rest frame.
- Using transverse and longitudinal fluctuations of strong force field as two parameters, which are obtained by fitting experiment datas, we give predictions for transverse momentum and azimuthal angle dependence of ρ_{00}.

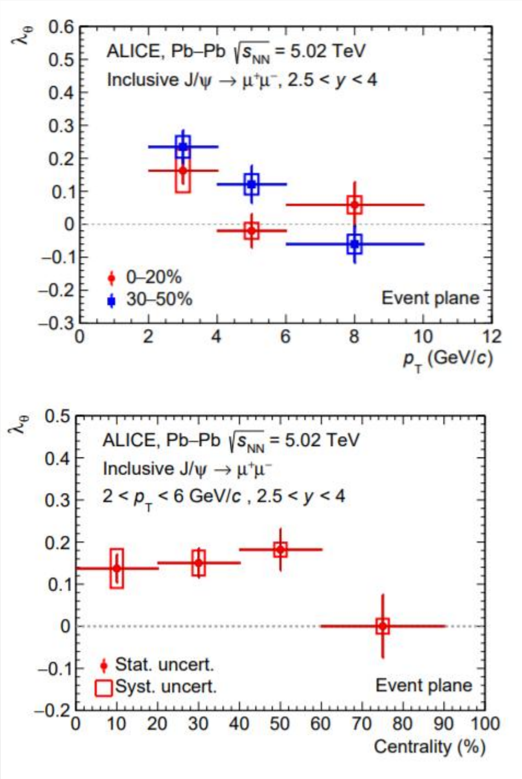
Thank you!

Outlook

- Spin alignment of heavy quarkonium (J/ψ in Pb-Pb collisions)



ALICE, Phys.Lett.B 815 (2021) 136146



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