Global spin alignment of vector mesons in heavy-ion collisions

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INFN Istituto Nazionale di Fisica Nucleare
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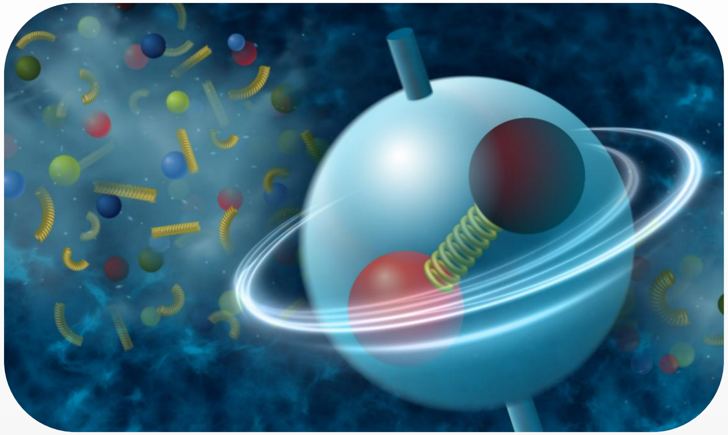
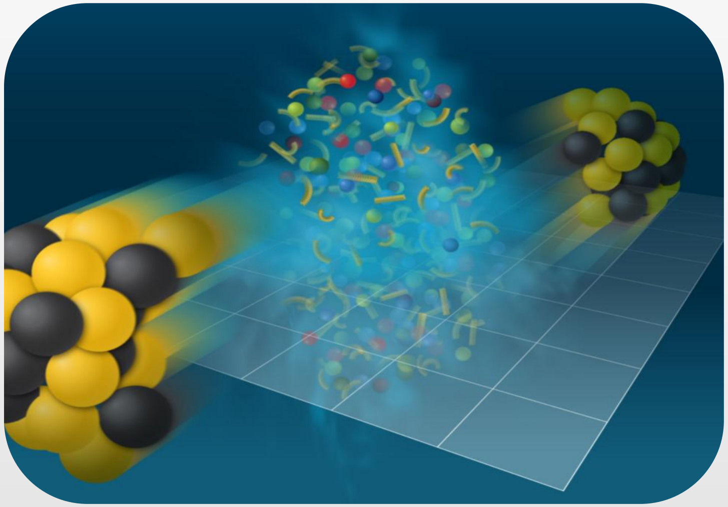
“Florence Theory Group Day”

Mar. 25, 2024

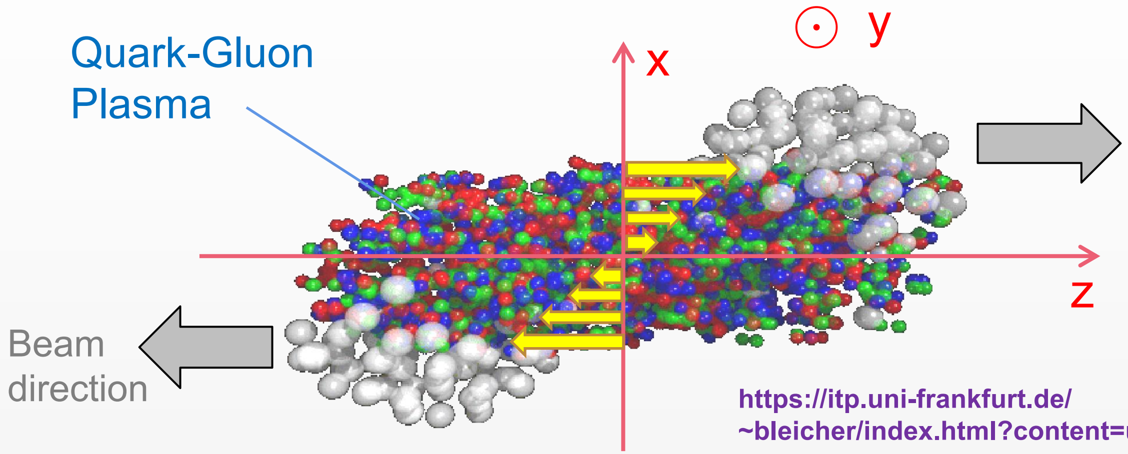




www.bnl.gov/newsroom/news.php?a=120967

Heavy-ion collisions

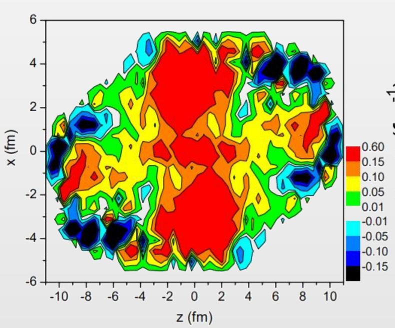
Relativistic heavy-ion collisions generate strongly interacting matter with vorticity and magnetic fields

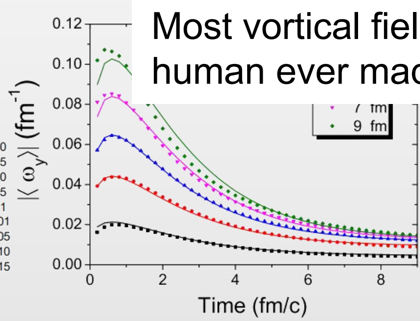


https://itp.uni-frankfurt.de/~bleicher/index.html?content=urqmd

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

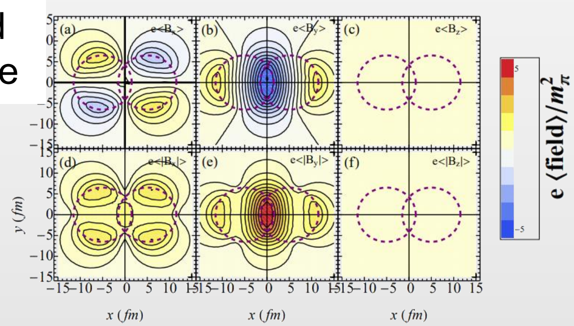
Magnetic fields $B \sim 10^{18}$ Gauss

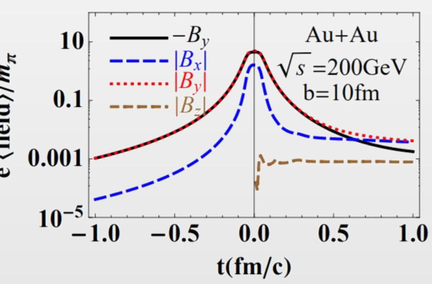




F. Becattini, L. Csernai, D.J. Wang, PRC 88, 034905 (2013); PRC 93, 069901 (2016)

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

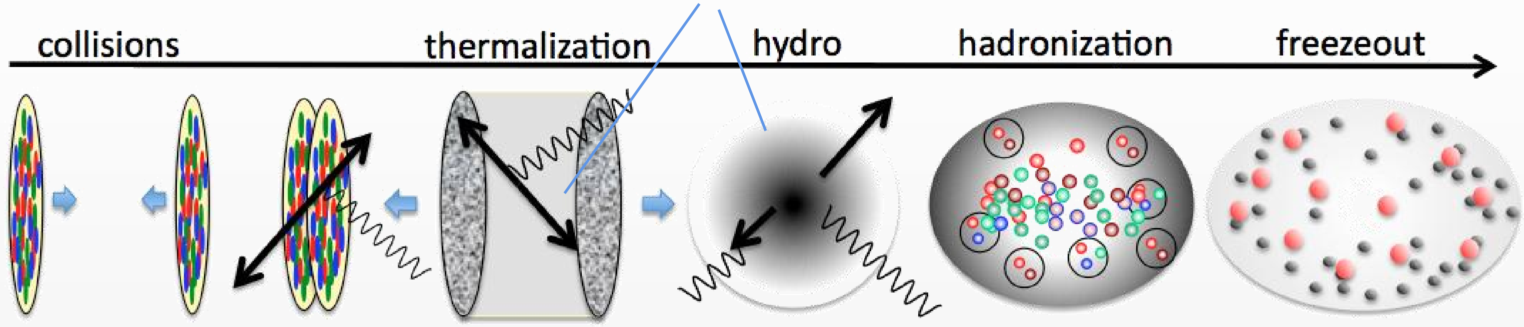




W.-T. Deng, X.-G. Huang, PRC 85, 044907 (2012).

Also see: talk by Sushant Kumar Singh

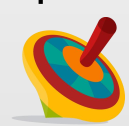
Quark-Gluon Plasma



Initial fluctuation | hydrodynamic model | final state interactions

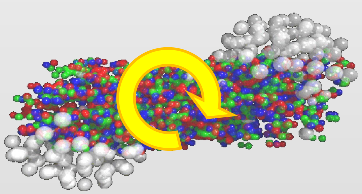
Quarks and gluon | Baryons and mesons

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

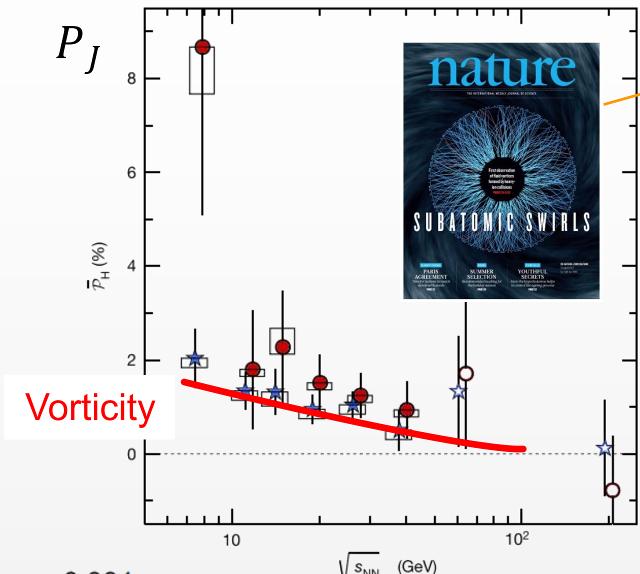


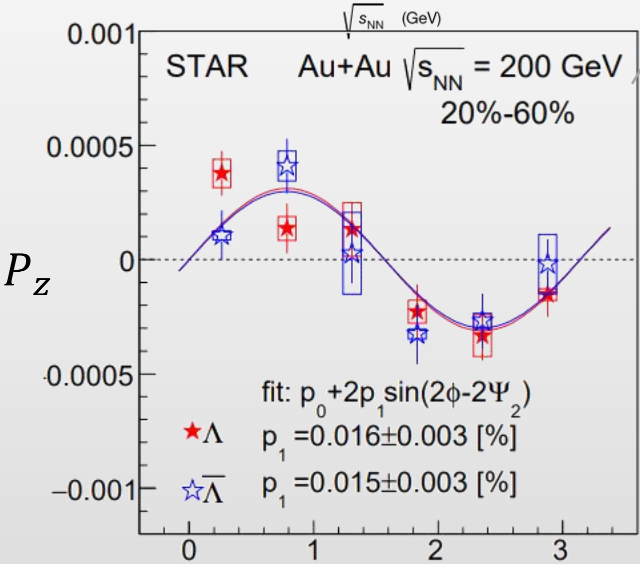
Spin polarization for spin-1/2 or spin-3/2 baryons, Λ, Σ^0, Δ^{++}, Ω^-, ...

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

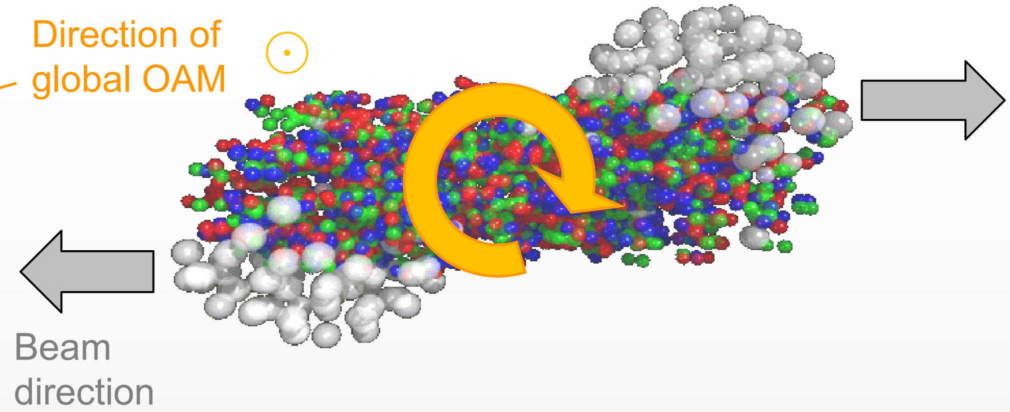


Λ's spin polarization





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



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

Parity-violating weak decay

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

Recent reviews:

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

Possible contributions at second order in gradient: gradients of vorticity or shear stress tensor, etc.

XLS, F. Becattini, X.-G. Huang, Z.-H. Zhang, in preparation

Global spin alignment

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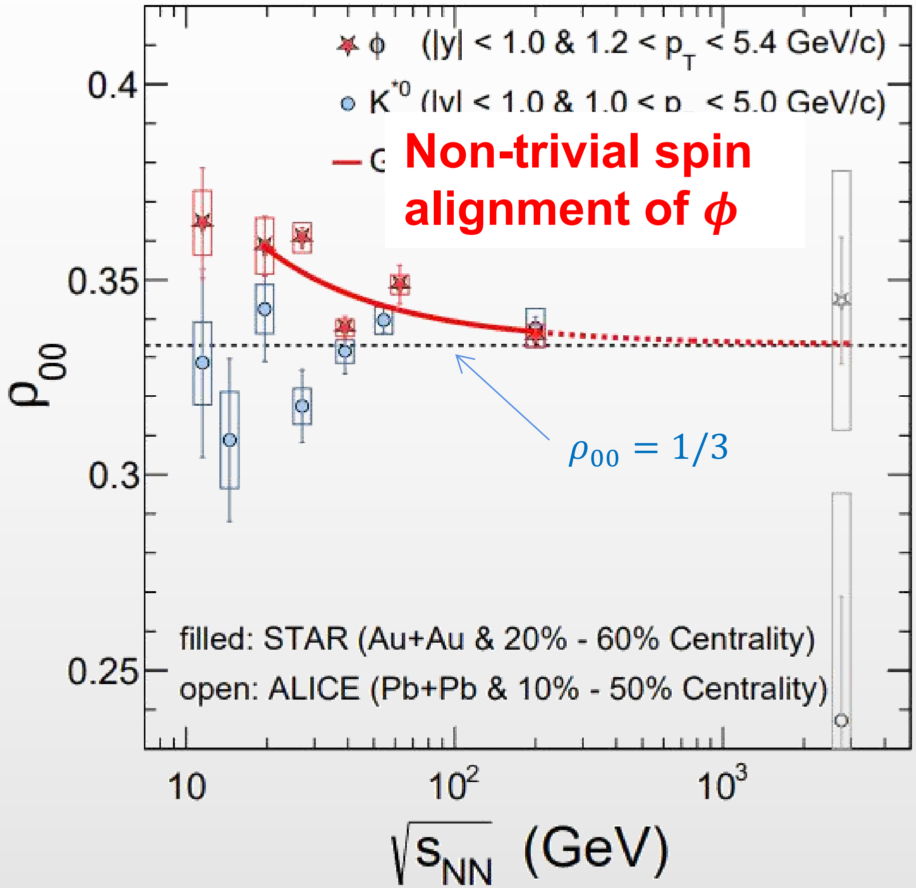


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Article | Published: 18 January 2023

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

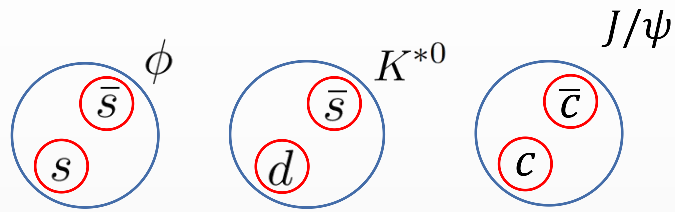
STAR, Nature 614, 244 (2023)

Vorticity field?
Magnetic field?

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

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

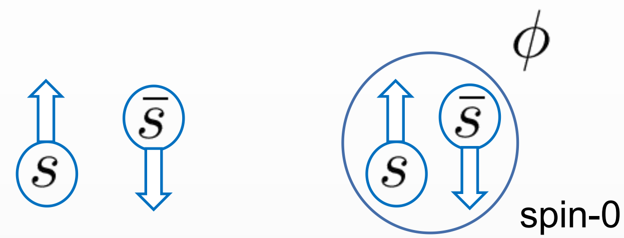
Processes	Examples	Polar angle distribution $W(\theta)$	Spin is converted to
Strong p-wave decay	$K^{*0} \to K^+ + \pi^-$ $\phi \to K^+ + K^-$	$\frac{3}{4}\left[1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta\right]$	OAM
Dilepton decay	$J/\psi \to \mu^+ + \mu^-$	$\frac{3}{8}\left[1 + \rho_{00} + (1 - 3\rho_{00})\cos^2\theta\right]$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

Relation to quark polarization

- Combination of quark/antiquark

  Z.-T. Liang and X.-N. Wang,
  Phys. Lett, B 629, 20 (2005).



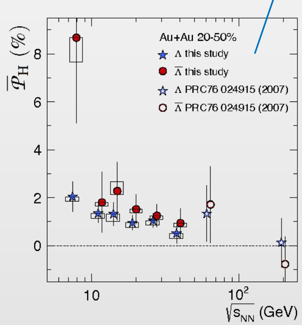
- Spin alignment of vector meson is determined by spin polarizations of constitute quark/antiquark

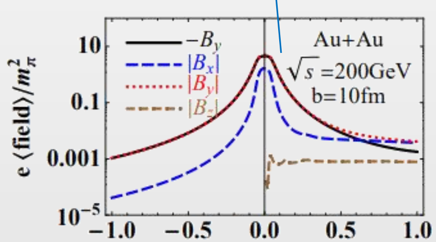
$$\rho_{00}^{V\,(\mathrm{rec})} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}} \approx \frac{1}{3} - \frac{4}{9} P_q P_{\bar{q}}$$

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

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

4×10^{-5} $\qquad$ 1×10^{-5}

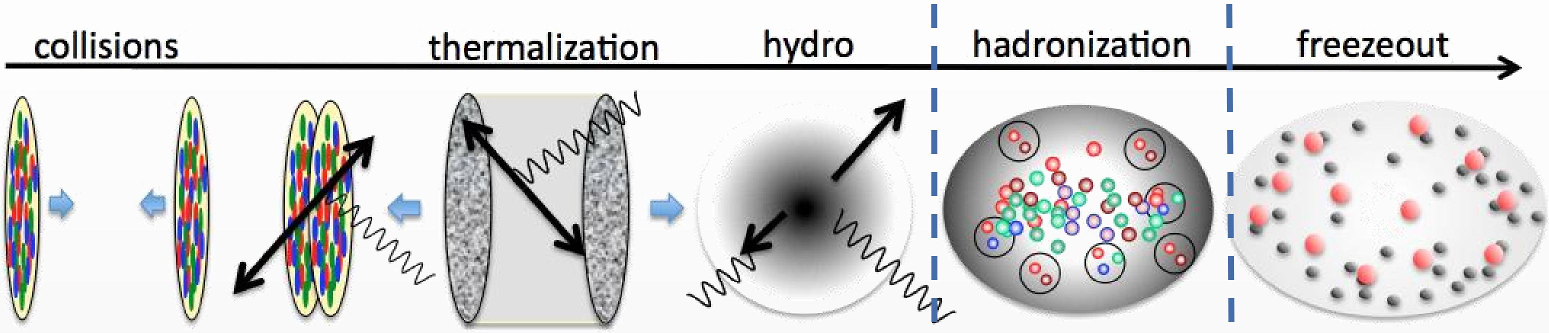




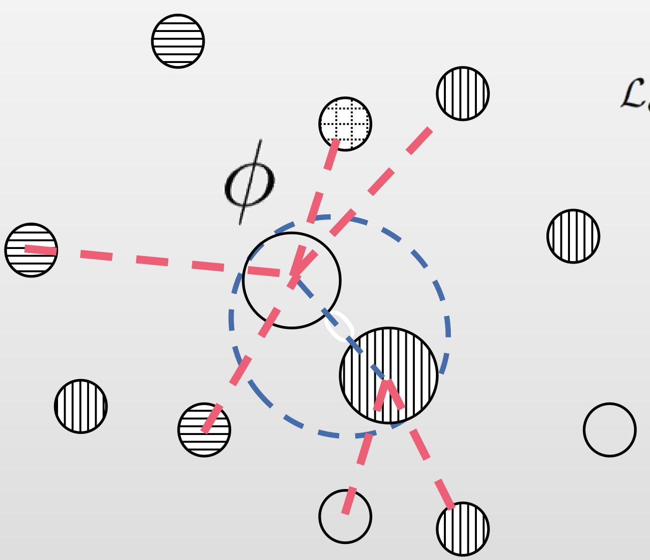
➢ Contributions from vorticity and magnetic are negligible

Strong interaction?

Quark-meson model



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



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

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

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

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- 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)

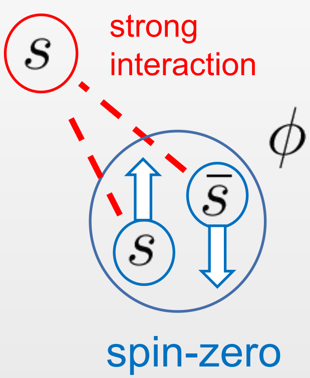
$$\frac{g_\phi^2}{4\pi} \sim \mathcal{O}(1) \gg \frac{e^2}{4\pi}$$

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).

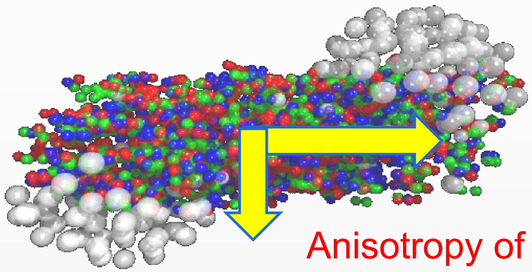
XLS, L.Oliva, Q.Wang, PRD 101, 096005 (2020);

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

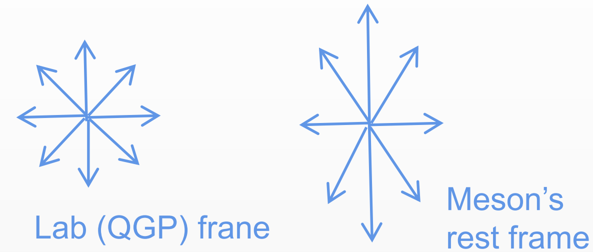


- Vector ϕ field polarize strange quark/antiquark in a similar way as classical electromagnetic field

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

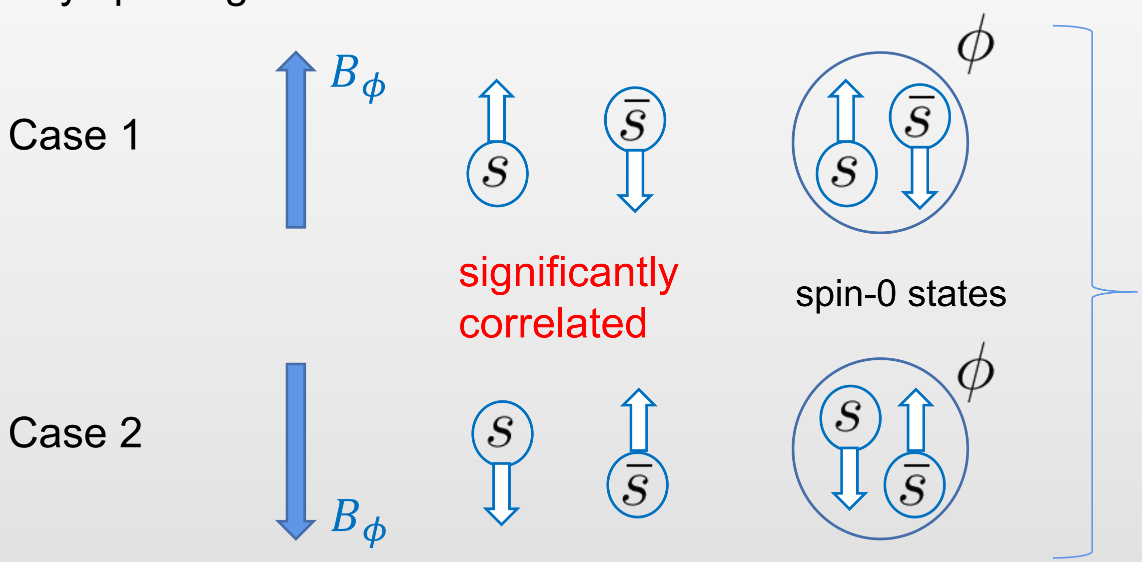


Anisotropy of QGP: longitudinal expansion > transverse expansion



Anisotropy induced by motion relative to background

- Why spin alignment is related to fluctuation?



Vanishing mean value but non-vanishing fluctuation:

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

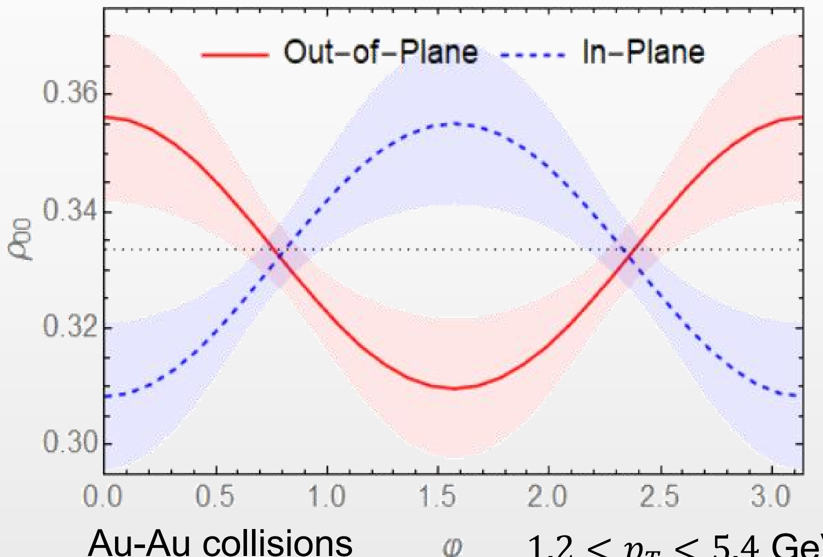
$$\langle (B_\phi)^2 \rangle \neq 0$$

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

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

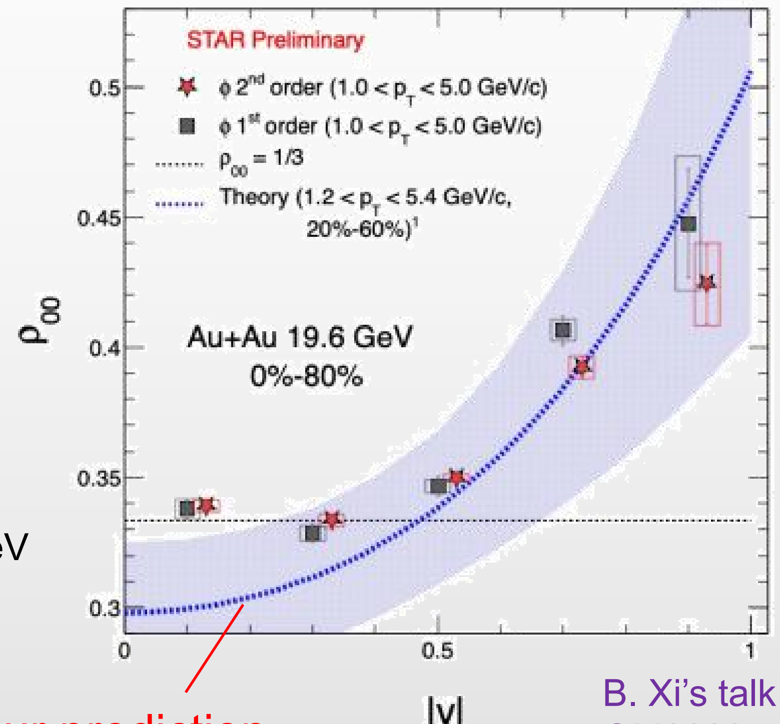
Model predictions

- 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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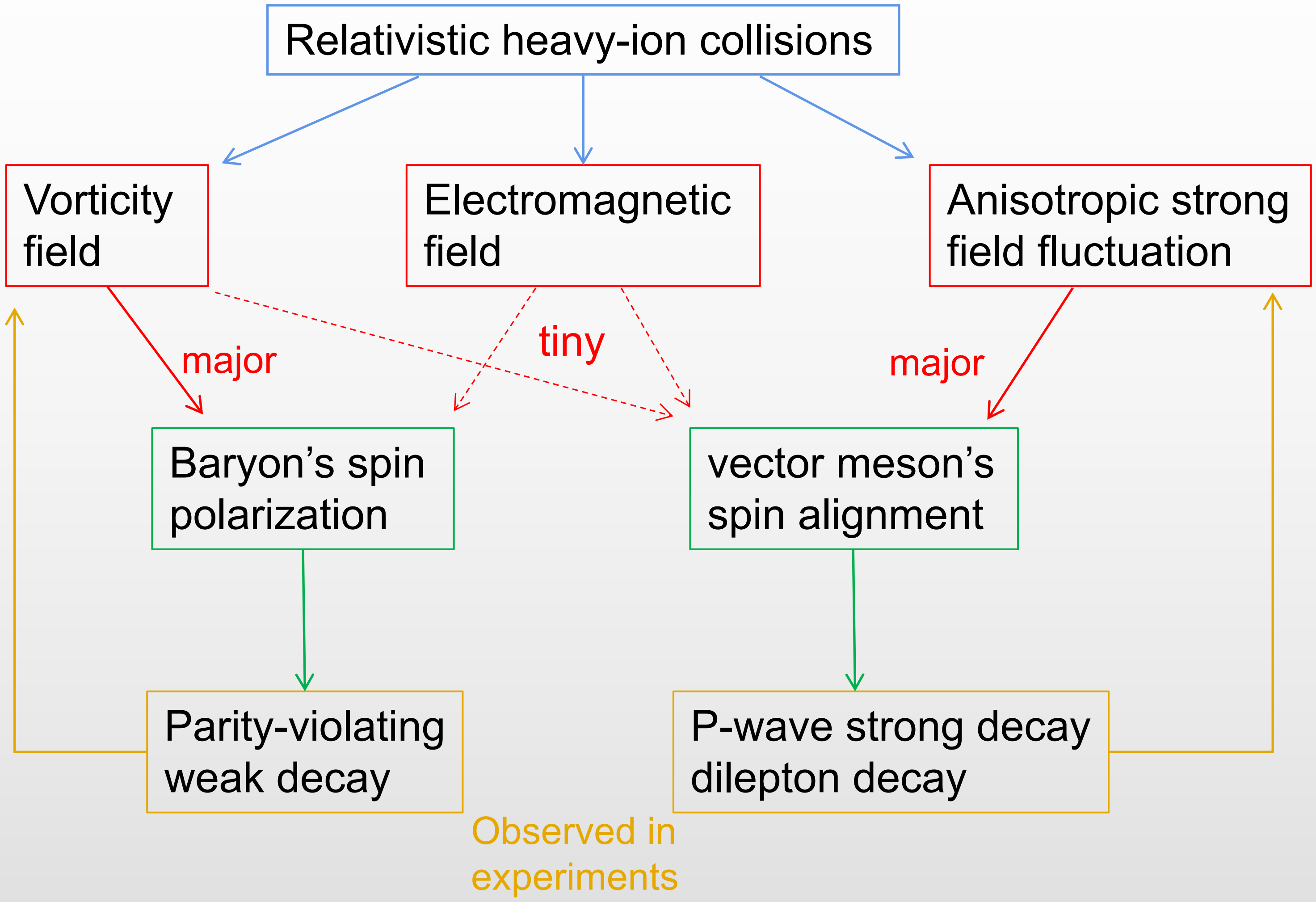

Summary

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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!