Spin-spin correlation in heavy-ion collisions

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SEZIONE DI FIRENZE

Meeting of the SIM
and PRIN 2022SM5YAS projects

July 2 - 3, 2025

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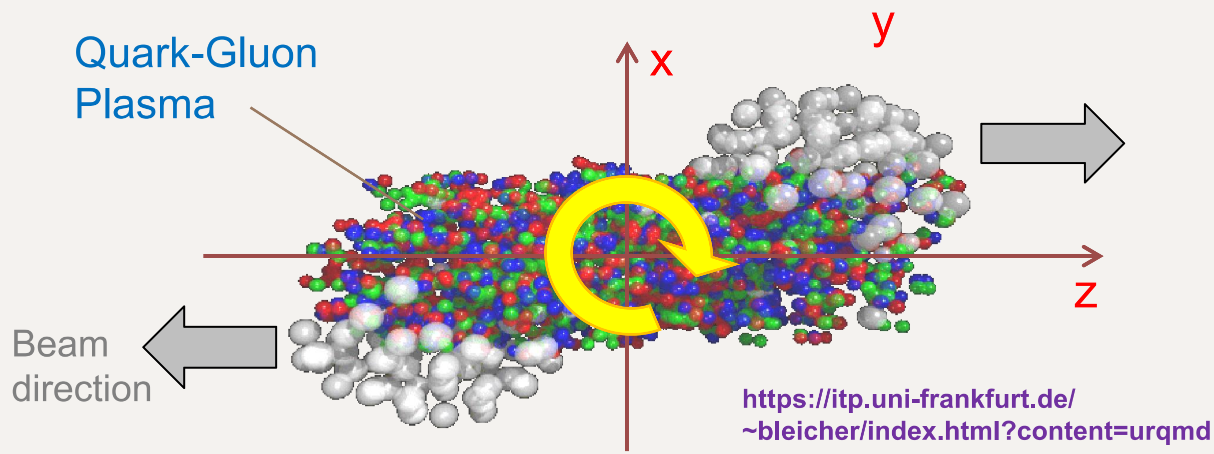
- Spin correlation between hyperons
- Summary

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, X.-Y. Wu, D. H. Rischke, X.-N. Wang, in preparation

Heavy-ion collisions

Strongly interacting matter with vorticity and magnetic fields



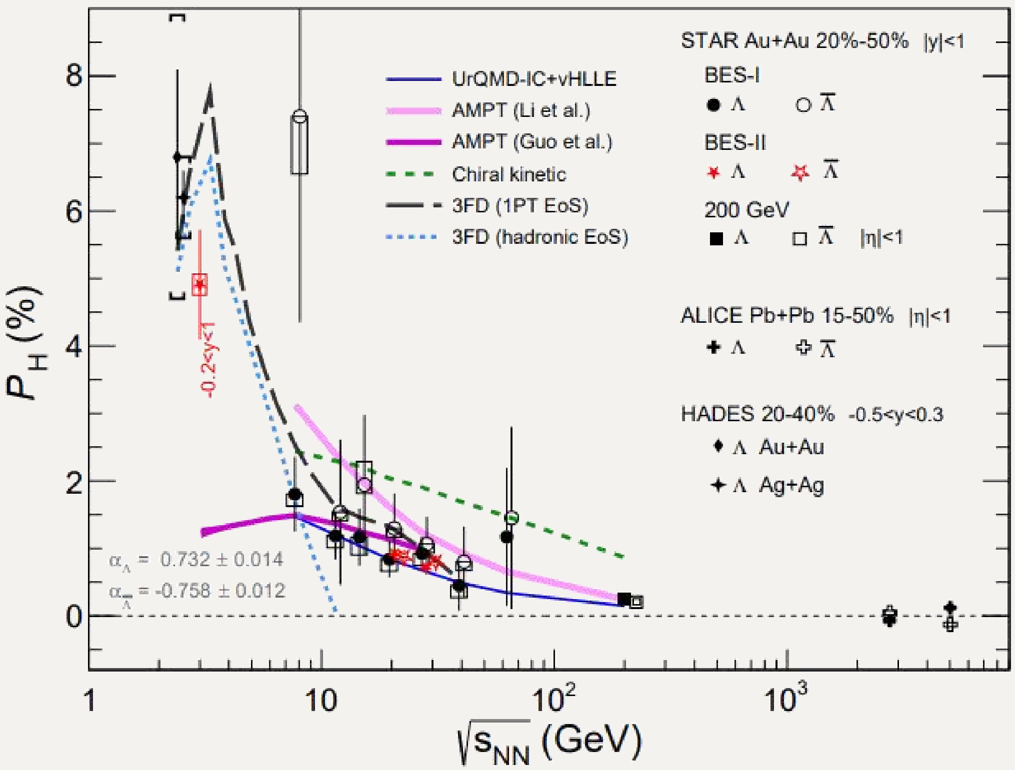
Initial orbital angular momentum → Vorticity field, Magnetic field, Strong field → Polarized quark/gluon → Spin polarization for baryons, Λ, Σ^0, Δ^{++}, Ω^-, ...; Spin alignment for vector mesons, ϕ, K^{*0}, ρ^0, ...

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)

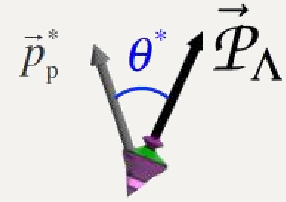
F. Becattini, F. Piccinini, J. Rizzo, PRC 76, 044901 (2007)

Global spin polarization



F. Becattini, M. Buzzegoli, T. Niida, S. Pu, A.-H. Tang, Int. J. Mod. Phys. E 33, 2430006 (2024).

Measured by pairty-violating weak decay



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

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

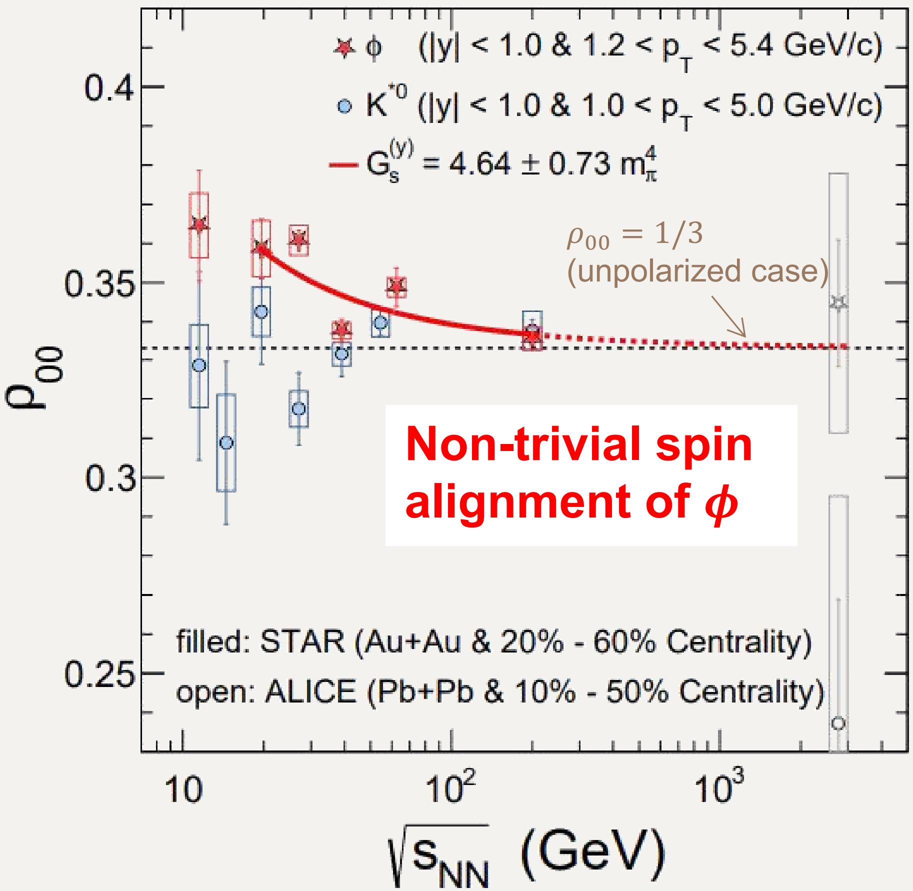
α_H: decay constant
$\vec{P}_H$: Λ polarization
$\vec{p}_p^{\,*}$: proton momentum

Evidence for vorticity field !

Magnetic field

→ Difference between Λ and $\bar{\Lambda}$ polarization

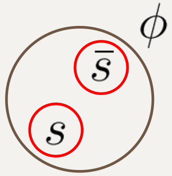
→ Has not been confirmed



Experiment: STAR, Nature 614, 244 (2023)

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

Non-relativistic spin coalescence



Spin triplet

$$\begin{cases} \uparrow\uparrow \\ (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \\ \downarrow\downarrow \end{cases}$$

In global OAM direction.
spins of constituent quark/antiquark tend to align in opposite directions

Significant spin correlation

$$\langle P_s^y P_{\bar{s}}^y \rangle < 0$$

Z.-T. Liang, X.-N. Wang, PLB 629, 20 (2005)

Spin alignment

- Polarizations of $s/\bar{s}$ in a thermal equilibrium system

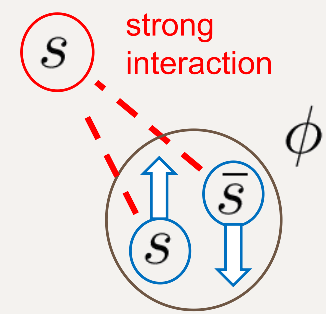
$$P^{\mu}_{s/\bar{s}}(x,p) \approx \frac{1}{4m_s}\epsilon^{\mu\nu\rho\sigma}p_\nu\left[\omega_{\rho\sigma} \pm \frac{Q_s}{(u\cdot p)T}F_{\rho\sigma} \pm \frac{g_\phi}{(u\cdot p)T}F^{\phi}_{\rho\sigma}\right] + \cdots$$

Thermal vorticity field (rotation and acceleration)

Classical electromagnetic field

Vector ϕ field

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



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

Anisotropy of fluctuations in meson's rest frame!

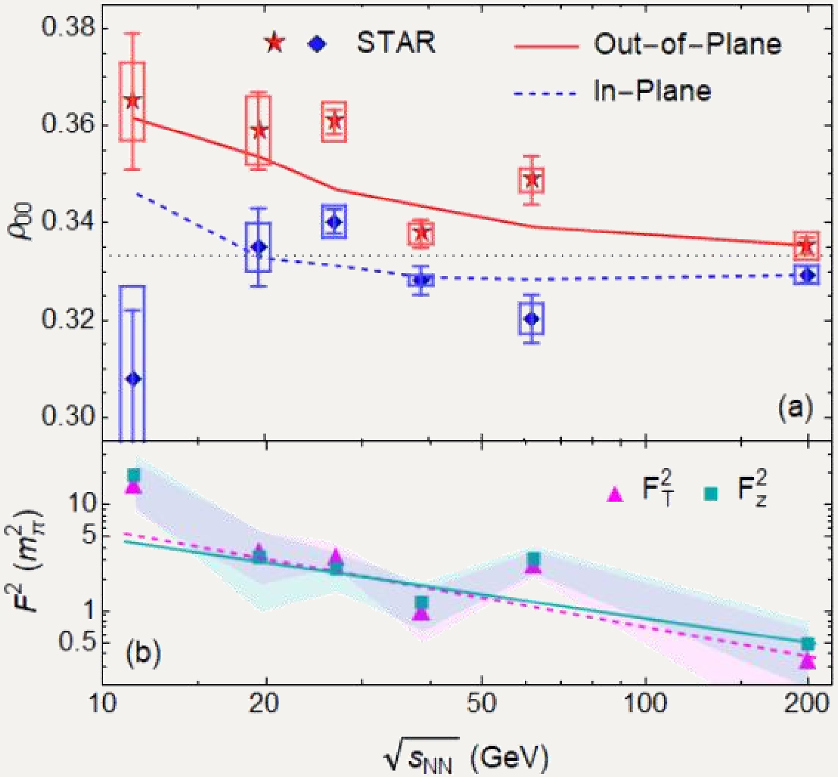
$$\begin{aligned}\rho_{00} \approx\ & \frac{1}{3} + C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\omega}')^2\right] \\ & + C_1\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\varepsilon}')^2\right]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

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

Vector ϕ field → Zero mean value large fluctuations

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

Spin alignment



Experiment: STAR, Nature 614, 244 (2023)
Model calculation: XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

Fit exp. data for $\rho_{00}^{x,y}$ vs $\sqrt{s_{\rm NN}}$

Extract parameters as functions of $\sqrt{s_{\rm NN}}$

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

$$\left\langle (g_\phi \mathbf{B}^\phi_{z}/T_{\rm h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{z}/T_{\rm h})^2 \right\rangle \equiv F_z^2$$

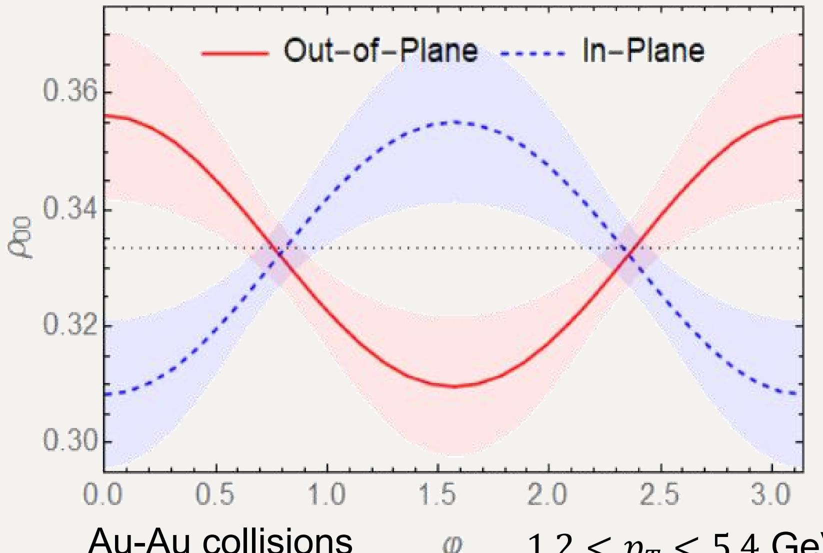
Predict ρ_{00} vs p_T, y, ϕ...

- Stronger fluctuations at lower energies
- Nearly isotropic in lab frame

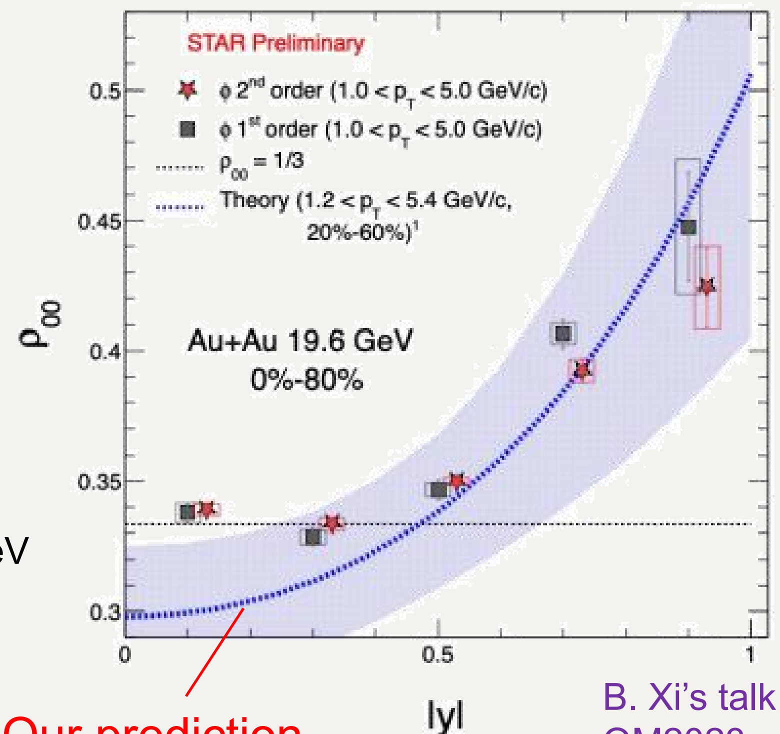
Anisotropy in meson's rest frame dominated by motion relative to QGP

Model predictions

- Predictions for azimuthal angle dependence and rapidity dependence



Au-Au collisions at 200 GeV/A $1.2 < p_T < 5.4$ GeV



Our prediction

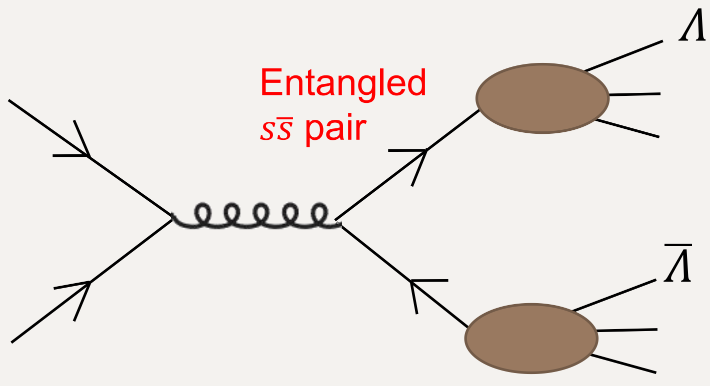
XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

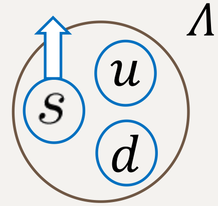
XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

B. Xi's talk in QM2023

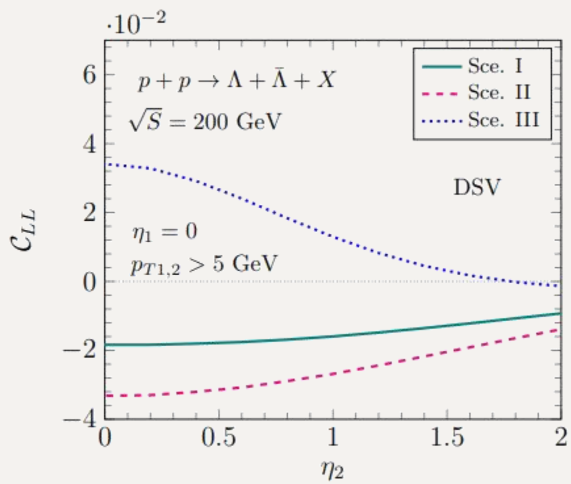
Hyperon spin correlation

- Λ-$\bar{\Lambda}$ spin-spin correlation in pp collisions

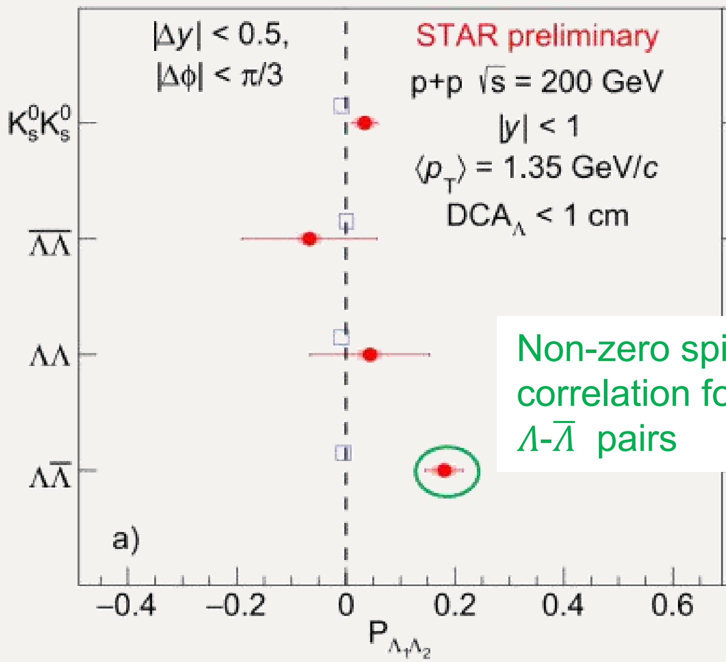




- Model prediction for Λ-$\bar{\Lambda}$ spin correlation in pp collisions



H.-C. Zhang, S.-Y. Wei, Phys. Lett. B 839, 137821 (2023)



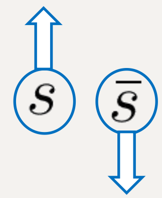
Non-zero spin correlation for Λ-$\bar{\Lambda}$ pairs

Jan Vanek (STAR) @ QM 2025

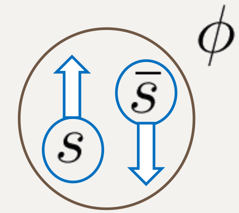
- Vector meson spin alignment vs hyperon spin correlation

Produced from the same g or γ^* (pp collisions)

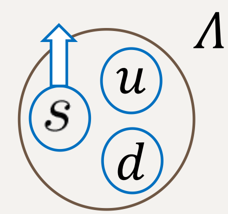
Interaction with QGP (AA collisions)

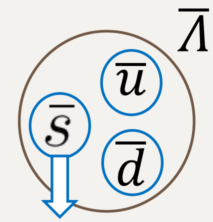


Short range ($\lesssim$ meson size)



Long/short range





- Definition of two particle spin correlation

$$C_{12}^{\mu\nu}(p_1,p_2) \equiv \langle P_1^{\mu}(x_1,p_1) P_2^{\nu}(x_2,p_2)\rangle$$

4×4 Lorentz tensor

Polarization vector → 3 components in rest frame

$$P_i^{\mu}(x_i,p_i) = \sum_{a=x,y,z} n_{i,a}^{\mu}(p_i)\mathcal{P}_{i,a}^{\text{rest}}(x_i,p_i)$$

$$c_{12}^{ab}(p_1,p_2) \equiv n_{1,a}^{\mu}(p_1) n_{2,b}^{\nu}(p_2) C_{\mu\nu}^{12}(p_1,p_2), \quad a,b = x,y,z.$$

Correlation between spins in two particle's respective rest frames

3×3 tensor

Hyperon spin polarization

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- Spin polarization of Λ

$$P^\mu_\Lambda(x,p) \approx P^\mu_s(x, R_s p) \qquad R_s \equiv m_s/m_\Lambda$$

> In non-relativistic quark coalescence model, spin of Λ is fully determined by spin of s quark

- Spin polarization of s quark at local thermal equilibrium

Hydrodynamic fields: $P^\mu_\omega + P^\mu_{\text{shear}} + P^\mu_{\text{SHE}}$

Strong force field: P^μ_ϕ

$$P^\mu_{s/\bar{s}}(x,p) = P^\mu_\omega + P^\mu_{\text{shear}} + P^\mu_{\text{SHE}} + P^\mu_\phi$$

> Assumption: no correlation between hydrodynamic fields and strong force fields

- Spin correlation

$$C^{\mu\nu}_{12}(p_1,p_2) = \frac{1}{N_{\text{event}}} \sum_{\text{event}} \frac{\int d\Sigma(x_1)\cdot p_1 \int d\Sigma(x_2)\cdot p_2 \, P^\mu_1 \, P^\nu_2 \, f_1 \, f_2}{\left[\int d\Sigma(x_1)\cdot p_1 \, f_1\right]\left[\int d\Sigma(x_2)\cdot p_2 \, f_2\right]}$$

$P^\mu_1 \, P^\nu_2 \, f_1 \, f_2$: functions of $\{x_i, p_i\}$

$1, 2$ denotes $\Lambda, \bar{\Lambda}$

XLS, X.-Y. Wu, D. H. Rischke, X.-N. Wang, in preparation

Spin correlation

- Correlation of strong force field

$$\frac{g_\phi^2}{T(x_1)T(x_2)} F_{ij}^{\phi}(x_1) F_{ij}^{\phi}(x_2) = \begin{cases} F_T^2\, G(x_1 - x_2) & (i,j) = (0,1),\ (0,2),\ (2,3),\ (3,1), \\ F_z^2\, G(x_1 - x_2) & (i,j) = (0,3),\ (1,2), \end{cases}$$

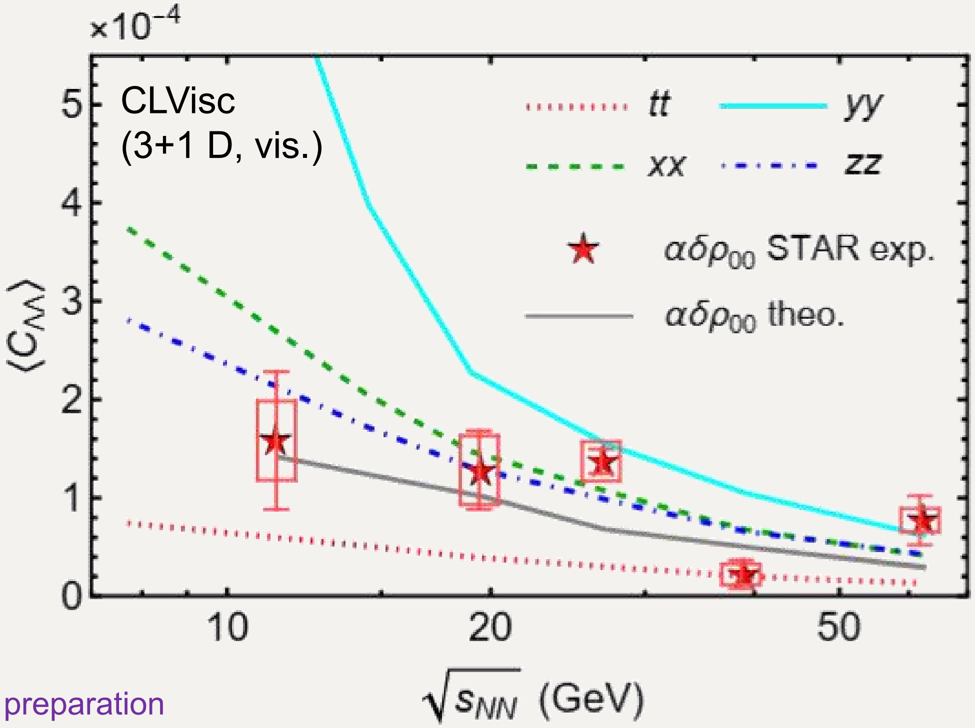
Fluctuation determined by fit of ρ_{00}

$$\ln(F_{T,z}^2/m_\pi^2) = a_{T,z} - b_{T,z} \ln(\sqrt{s_{\rm NN}}/\text{GeV})$$

Gaussian smearing

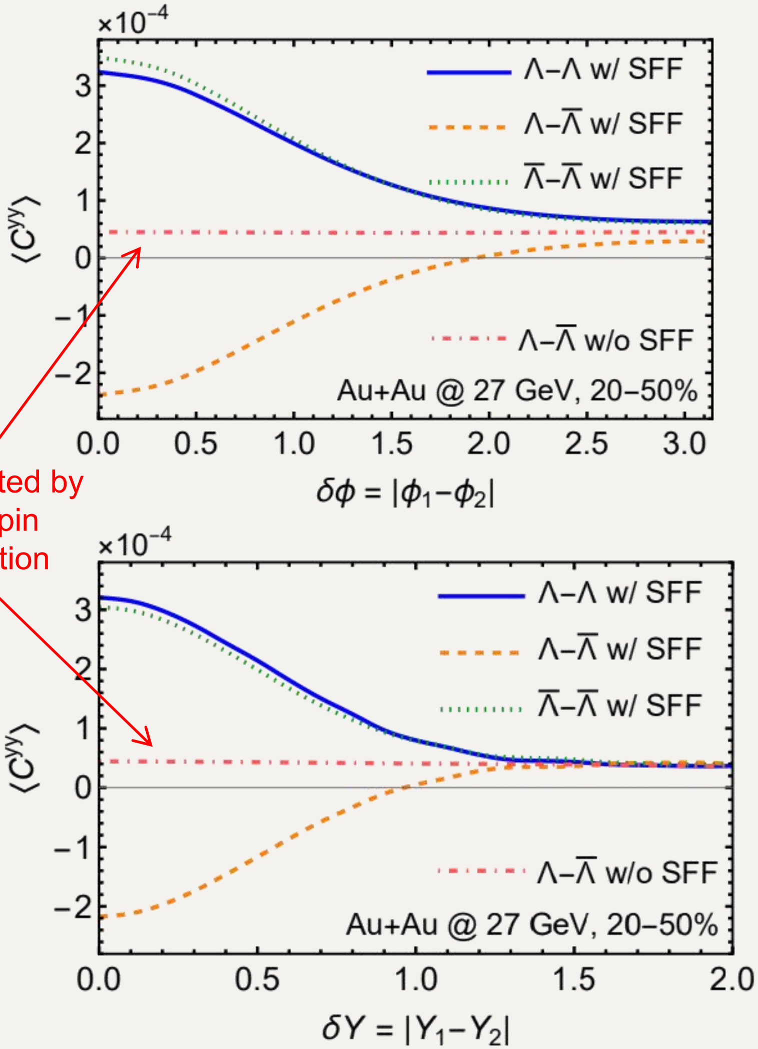
$$G(x_1 - x_2) \equiv \exp\left[-\frac{(t_1-t_2)^2}{\sigma_t^2} - \frac{(\mathbf{x}_1 - \mathbf{x}_2)^2}{\sigma_x^2}\right] \quad \sigma_t = \sigma_x = 0.6 \text{ fm}$$

- Energy denpendence of spin correlation is similar to ϕ meson's spin alignment
- Difference between yy and xx components is from global spin polarization
- Spin correlation induced by strong force field $\propto\ \sigma$



XLS, X.-Y. Wu, D. H. Rischke, X.-N. Wang, in preparation

Spin correlation



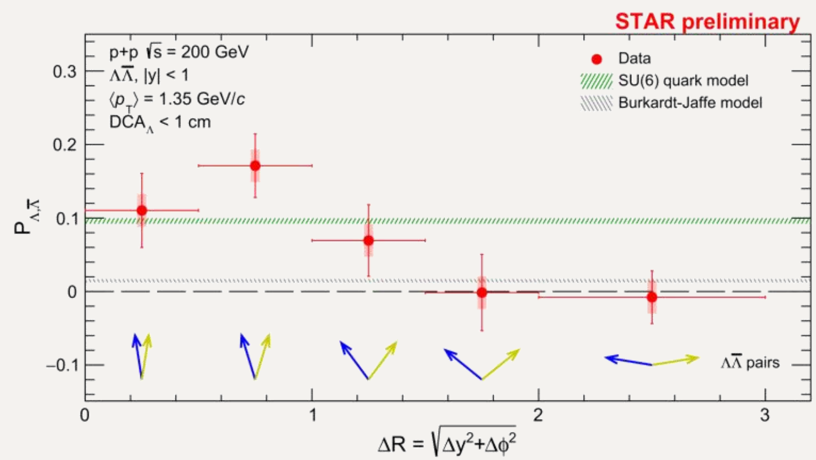
Dominated by global spin polarization

$$\langle C_{12}^{yy}\rangle \equiv \langle P_1^y P_2^y\rangle$$

- **Hydrodynamic fields:** independent to $\delta\phi$ and δY same for Λ-Λ, $\bar{\Lambda}$-$\bar{\Lambda}$, and Λ-$\bar{\Lambda}$
- **Strong force field (SFF):** stronger spin correlation at smaller $\delta\phi$ or δY Λ-Λ ($\bar{\Lambda}$-$\bar{\Lambda}$) opposite to Λ-$\bar{\Lambda}$

Distinct behaviours by hydrodynamic fields and SFF

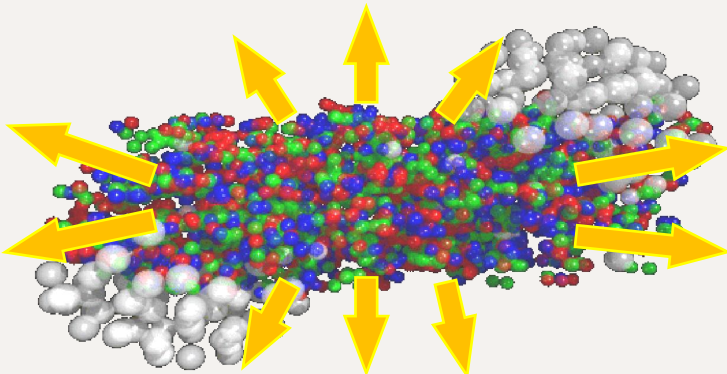
Similar to pp collisions



Jan Vanek (STAR) @ QM 2025

XLS, X.-Y. Wu, D. H. Rischke, X.-N. Wang, in preparation

Spin correlation



$$\langle z \rangle \propto p_z \propto Y$$

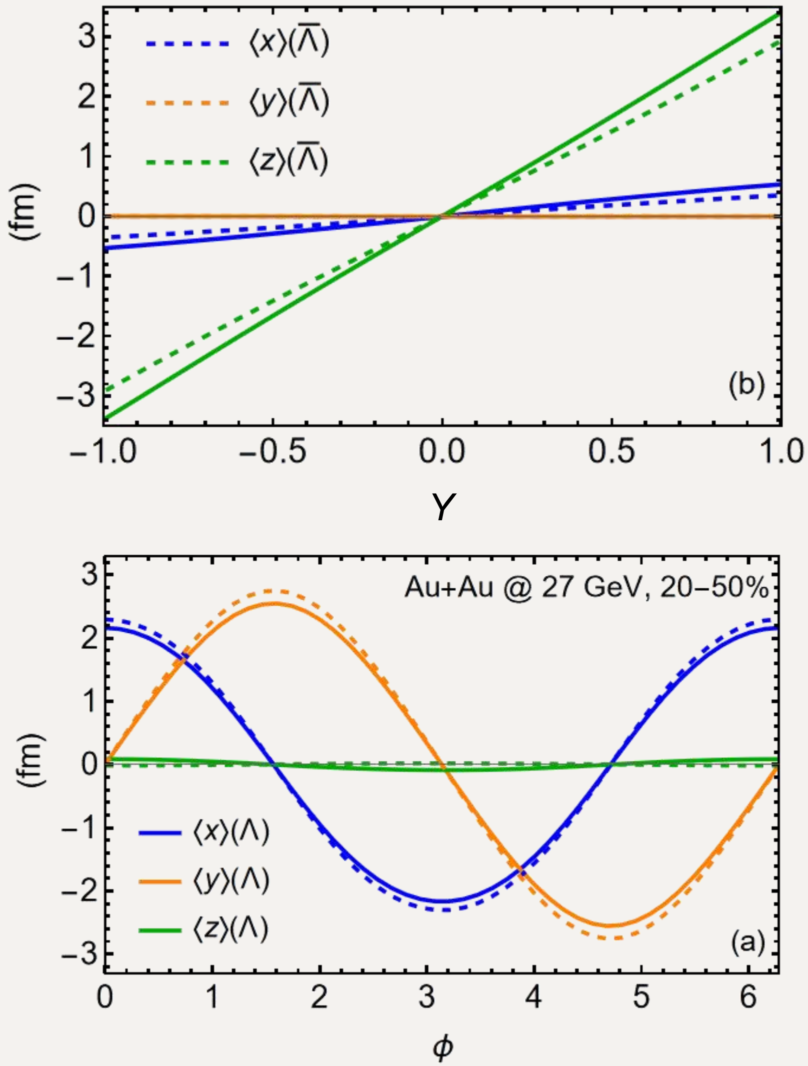
$$\langle \mathbf{x}_T \rangle \propto \hat{\mathbf{p}}_T = (\cos\phi, \sin\phi)$$

Short-distance in momentum space

➡ Short-distance in coordinate space

➡ Significant SFF correlation

➡ Significant spin-spin correlation



XLS, X.-Y. Wu, D. H. Rischke, X.-N. Wang, in preparation

Summary

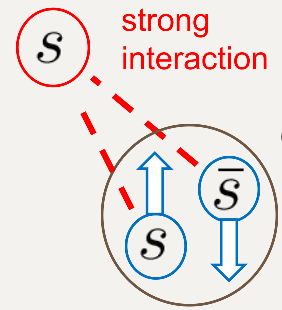
- Vector meson spin alignment

  ⟺ Anisotropy of short-range spin correlation

  ⟺ Anisotropy of strong field fluctuation

  ↑ motion of meson relative to QGP

  - Extracted strength of fluctuation from exp.
  - Predicted rapidity and azimuthal angle dependence



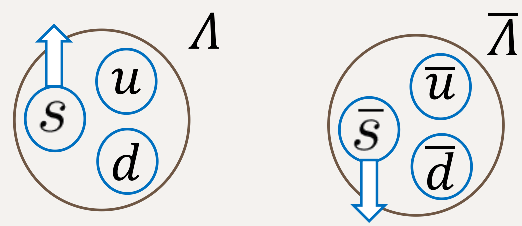
- Hyperon spin correlation

  ⟺ Long/short-range spin correlation $\sim r_{\Lambda\bar{\Lambda}}$

  Hydrodynamic fields: same for $\Lambda\Lambda$, $\Lambda\bar{\Lambda}$, $\bar{\Lambda}\bar{\Lambda}$

  Strong field: $\Lambda\Lambda$, $\bar{\Lambda}\bar{\Lambda}$ opposite to $\Lambda\bar{\Lambda}$

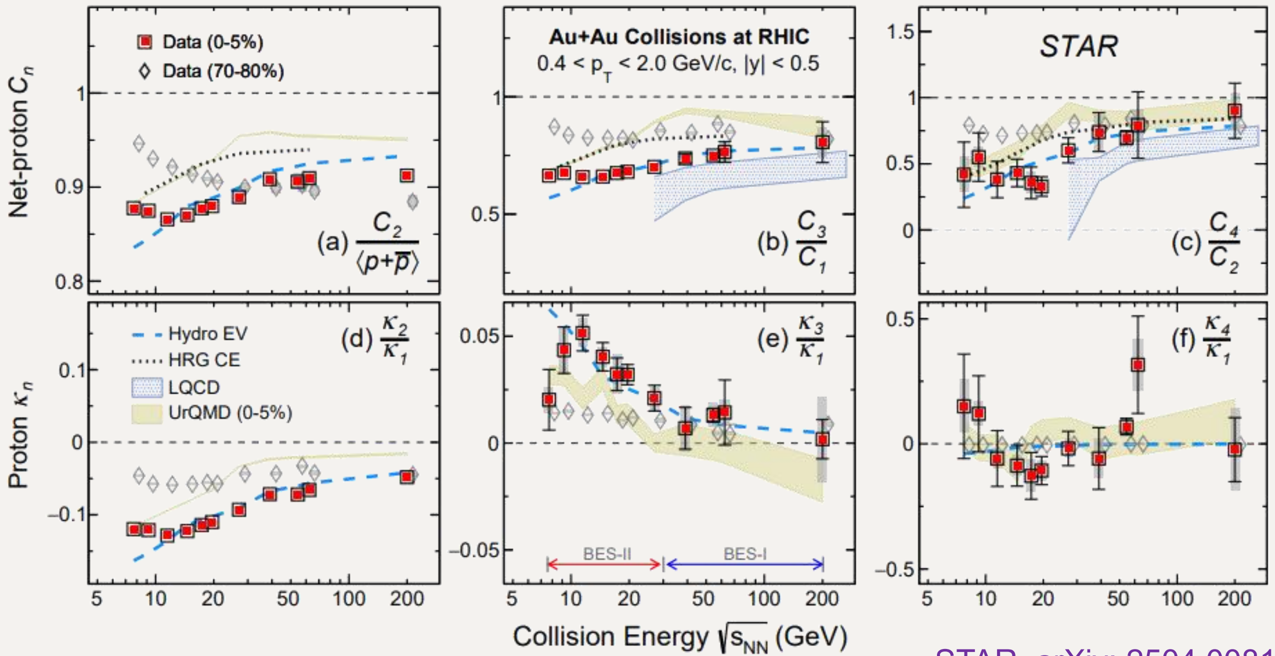
  - Provides a way to test our understanding on spin correlation/alignment



Open a potential new avenue for studying behaviour of strong interaction

Outlook

- Relation between spin alignment/correlation and baryon number fluctuation (critial end point)?



STAR, arXiv: 2504.00817

Thanks for your attention!

Backup

Spin alignment

- Spin density matrix for vector meson ($J^P = 1^-$)

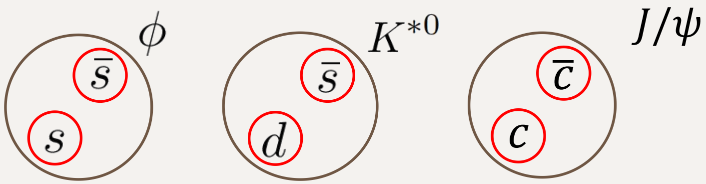
$$\rho_{rs}^{S=1} = \begin{pmatrix} \rho_{+1,+1} & \rho_{+1,0} & \rho_{+1,-1} \\ \rho_{0,+1} & \rho_{00} & \rho_{0,-1} \\ \rho_{-1,+1} & \rho_{-1,0} & \rho_{-1,-1} \end{pmatrix}$$

$$= \frac{1}{3} + \frac{1}{2} P_i \Sigma_i + T_{ij} \Sigma_{ij}$$

Spin alignment
=1/3 for unpolarized meson

Vector polarization
(3 components, not measurable, parity odd)

Tensor polarization
(5 components, measurable, pairty even)



Parity-conserving decays: distribution determined by angular momentum conservation

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)

Quark coalescence

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

Meson polarization vectors

Coalescence $q+\bar q \to V$

Dissociation (independent from quark distributions) $V \to q + \bar q$

- Contribution from coalescence

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

Energy conservation

$q\bar q V$ vertex

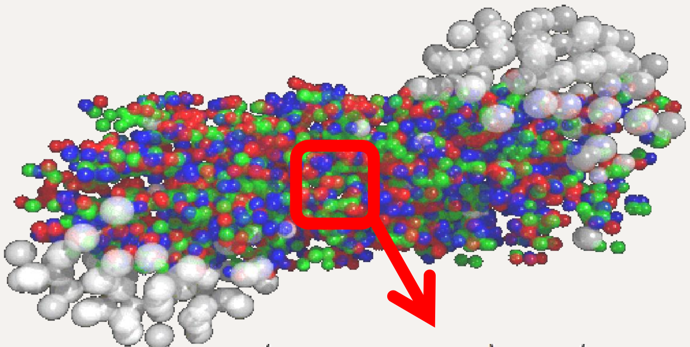
Polarizations of quark/antiquark

unpolarized quark/antiquark distributions

Spin density matrix

$$\rho^V_{\lambda_1\lambda_2}(x,\mathbf{k}) = \frac{\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\mathbf{k})}{\sum_{\lambda=0,\pm1}\epsilon^*_\mu(\lambda,\mathbf{k})\epsilon_\nu(\lambda,\mathbf{k})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\mathbf{k})}$$

Anisotropy



- Intrinsic geometry of QGP, transverse fluctuation $\neq$ longitudinal fluctuation

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

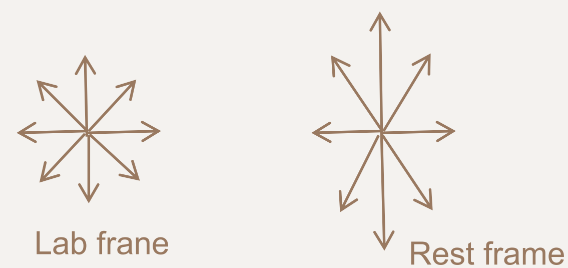
Isotropic

Anisotropy of QGP

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

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

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

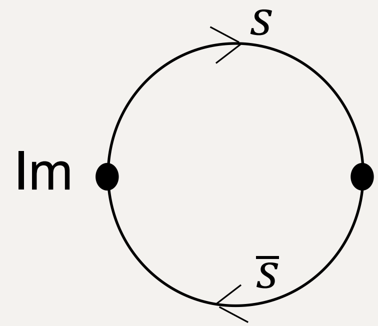


Anisotropy induced by motion relative to background

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

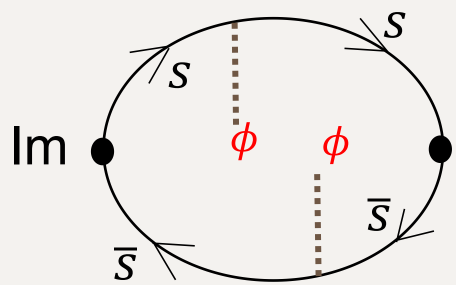
Vector meson fields

- Production of ϕ meson from $s\bar{s}$ coalescence

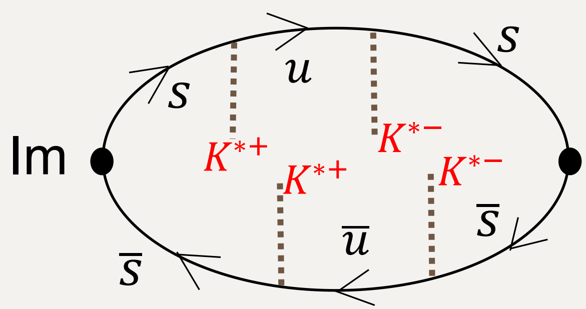


$$:\begin{pmatrix} \frac{\omega+\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega-\rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \overline{K}^{*0} & \phi \end{pmatrix}$$

- Spin alignment induced by vector meson field



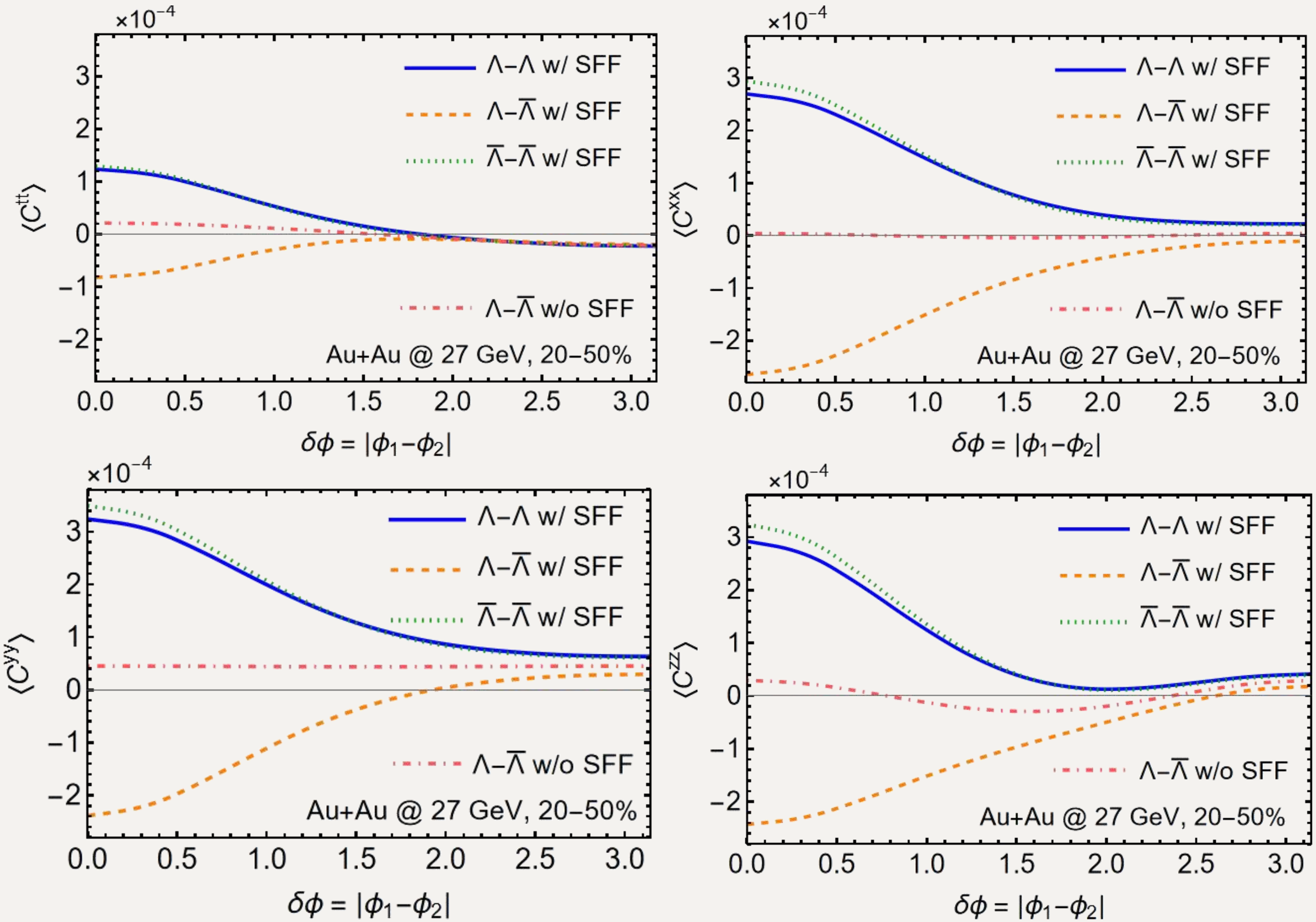
$$\left\langle F^{\phi}_{\mu\nu} F^{\phi}_{\alpha\beta} \right\rangle$$



$$\left\langle F^{K^{*+}}_{\mu\nu} F^{K^{*+}}_{\alpha\beta} F^{K^{*-}}_{\rho\sigma} F^{K^{*-}}_{\lambda\tau} \right\rangle$$

Higher order correlation

Spin correlation



Diagonal elements of $C_{12}^{\mu\nu}$ have similar behavior

XLS, X.-Y. Wu, D. H. Rischke, X.-N. Wang, in preparation