Overview on
Spin Alignment and Spin Correlation

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EMMI

International Symposium on Spin Polarization
in Relativistic Heavy Ion Collisions 2026

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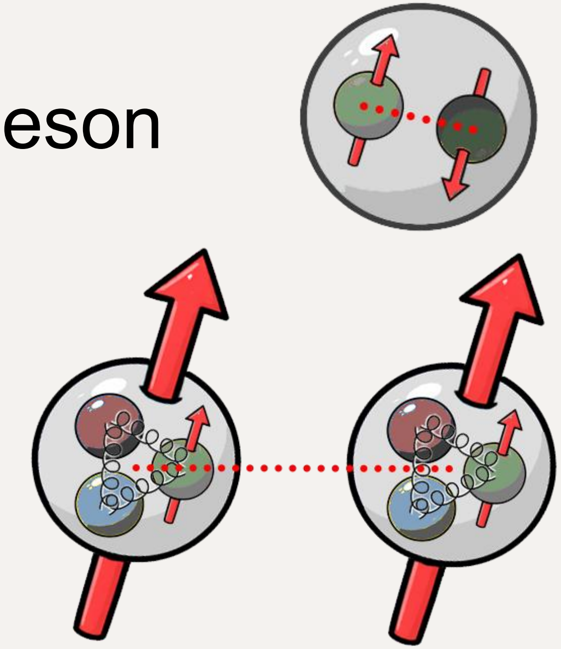
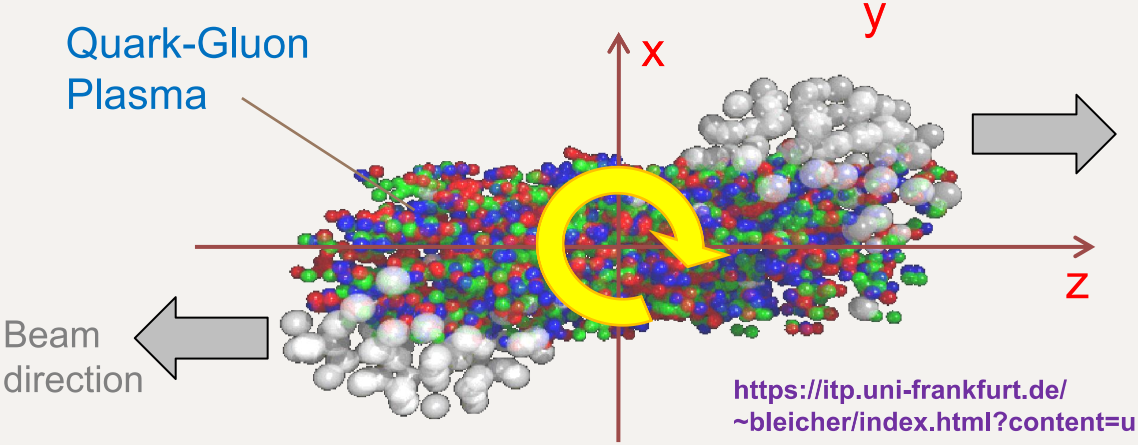
Contents

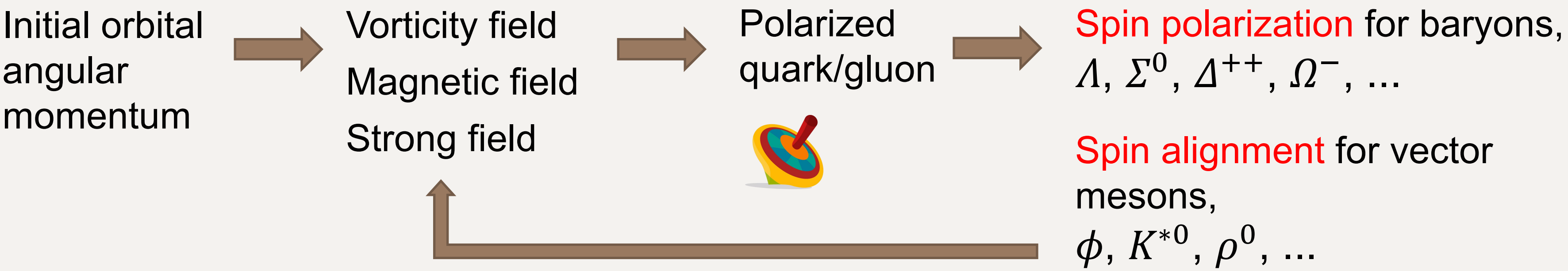


Heavy-ion collisions

Strongly interacting matter with vorticity and magnetic fields



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



Initial orbital angular momentum → Vorticity field, Magnetic field, Strong field → Polarized quark/gluon → Spin polarization for baryons, Λ, Σ^0, Δ^{++}, Ω^-, …

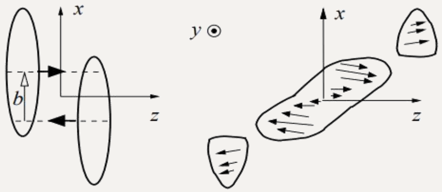
Spin alignment for vector mesons, ϕ, K^{*0}, ρ^0, …

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)

Spin polarization



$$P_q = -\pi\mu\, p/4E(E+m_q)$$

Quark global polarization
(Spin-orbit coupling)

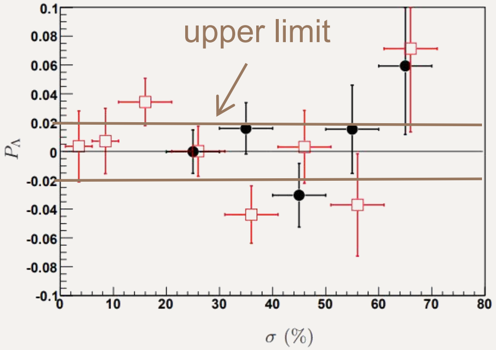
Liang & Wang, PRL 2005

$$\mathbf{\Pi}_0 = \frac{1}{2}\tanh\frac{\omega}{2T}\left[\frac{\varepsilon}{m}\hat{\boldsymbol{\omega}} - \frac{\hat{\boldsymbol{\omega}}\cdot\mathbf{pp}}{m(\varepsilon+m)}\right]$$

$$\omega^{\alpha} = \frac{1}{4}\epsilon^{\alpha\mu\nu\sigma}u_{\mu}\left(\partial_{\nu}u_{\sigma} - \partial_{\sigma}u_{\nu}\right)$$

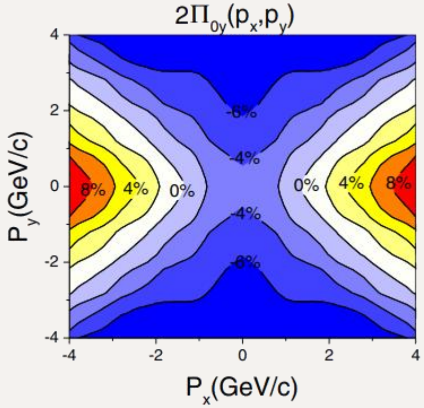
Hydrodynamic description
(Vorticity-induced polarization)

Becattini, Piccinini, Rizzo, PRC 2008



First measurement

STAR, PRC 2007



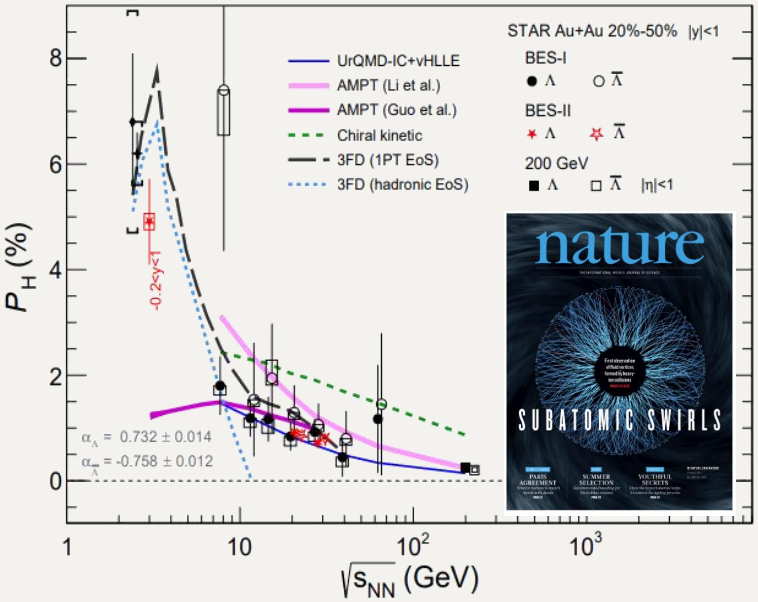
Hydrodynamic simulation

Becattini, Csernai, Wang PRC 2013

(other early simulations

Becaattini, Inghirami, et. al., EPJC 2015;

Karpendko & Becattini, EPJC 2017)



Recent review

Becattini, Buzzegoli, Niida, Pu, Tang, IJMPE 2024

"Spin sign puzzle"
for local polarization

➡ Talk by F. Becattini

Spin alignment

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

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

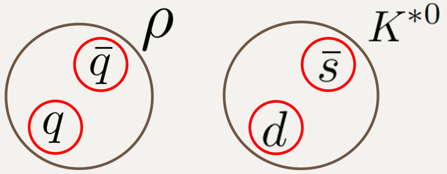
$$= \frac{1}{3} + \frac{1}{2} P_i \Sigma_i + T_{ij} \Sigma_{ij}$$

Spin alignment
=1/3 for unpolarized meson

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

Tensor polarization
(5 components, measurable, parity even)

- A meson's spin is determined by its constituent q & $\bar{q}$
Z.-T. Liang & X.-N. Wang, PLB 629, 20 (2005)

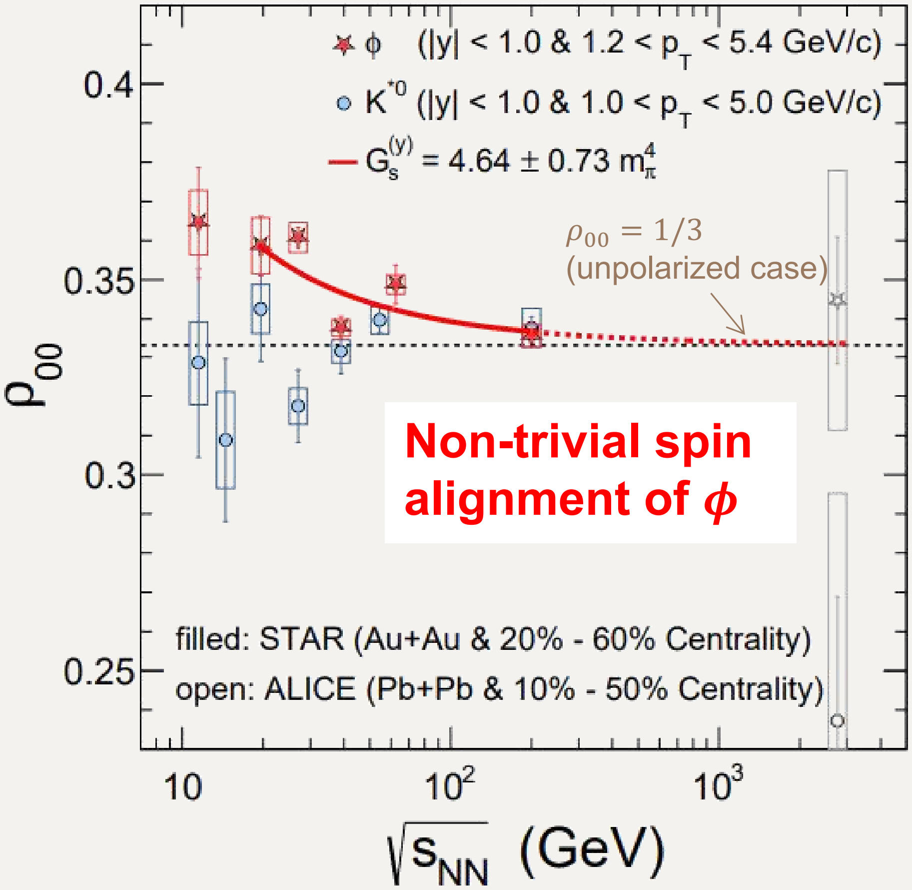


$$\rho_{00}^{\rho(\mathrm{rec})} = \frac{1 - P_q^2}{3 + P_q^2} \qquad \rho_{00}^{K^*(\mathrm{rec})} = \frac{1 - P_q P_s}{3 + P_q P_s}$$

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

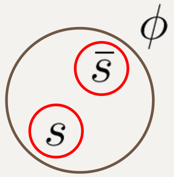


Non-trivial spin alignment of ϕ

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

$$\left\{ \begin{array}{l} \uparrow\uparrow \\ (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \\ \downarrow\downarrow \end{array} \right.$$

In global OAM direction, spins of constituent quark/antiquark tend to align oppositely ??

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

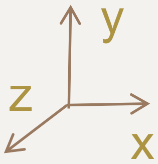
Quark/antiquark are globally polarized

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

Quark spin correlation

- Local polarization

$$(P^x, P^y, P^z)$$



- Spin correlation in quantization direction

$$\uparrow\uparrow \quad \boxed{\rho^y_{00} < \frac{1}{3}} \qquad (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \quad \boxed{\rho^y_{00} > \frac{1}{3}}$$

- Spin correlation in transverse direction

$$\rightarrow\rightarrow = \frac{1}{2}(\uparrow\uparrow + \downarrow\downarrow) + \frac{1}{\sqrt{2}}\left[\frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow)\right]$$

$S_y = +1$	1/4
$S_y = 0$	1/2
$S_y = -1$	1/4

$$\boxed{\rho^y_{00} > \frac{1}{3}} \quad \begin{array}{l} \left\langle P^x_q P^x_{\bar{q}} \right\rangle > 0 \\ \left\langle P^y_q P^y_{\bar{q}} \right\rangle = 0 \end{array}$$

$$\frac{1}{\sqrt{2}}(\rightarrow\leftarrow + \leftarrow\rightarrow) = \frac{1}{\sqrt{2}}(\uparrow\uparrow - \downarrow\downarrow)$$

$S_y = +1$	1/2
$S_y = 0$	0
$S_y = -1$	1/2

$$\boxed{\rho^y_{00} < \frac{1}{3}}$$

Non-relativistic

- Spin alignment ⟷ Anisotropy of spin correlation

$$\boxed{\rho_{00} = \frac{1}{3} + \frac{4}{9}\left[\frac{1}{2}\left\langle \mathbf{P}^T_q \cdot \mathbf{P}^T_{\bar{q}} \right\rangle - \left\langle P^L_q P^L_{\bar{q}} \right\rangle\right]}$$

X.-L. Xia, X.-G. Huang, PLB 817, 136325 (2021)

J.-H. Chen, Z.-T. Liang, Y.-G. Ma, XLS, Q. Wang, Sci.China Phys.Mech.Astron. 68, 211001 (2025)。

- Internal spin-spin interaction
  - Significant $q\bar{q}$ spin correlation
  - No spin alignment

$$\Delta H = -\mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} = -\frac{1}{2}[(\mathbf{S}_q + \mathbf{S}_{\bar{q}})^2 - \mathbf{S}_q^2 - \mathbf{S}_{\bar{q}}^2]$$

Independent of S_y

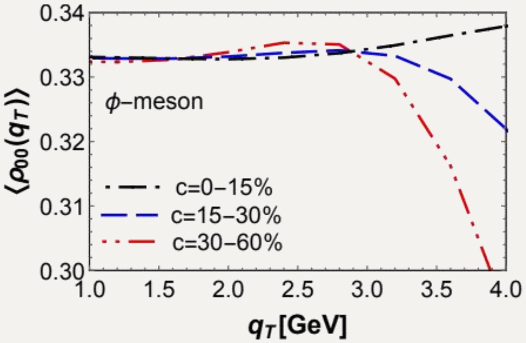
Traditional mechanisms

- Spin alignment induced by vorticity and magnetic field

$$\langle P_{q/\bar{q}}\rangle \approx \frac{1}{2}\underset{\lesssim 0.02}{\langle\omega_y\rangle} \pm \frac{Q_s}{2m_sT}\underset{\lesssim 0.1m_\pi^2}{\langle B_y\rangle} \Longrightarrow \rho^{\phi}_{00} \approx \frac{1}{3} - \underbrace{\frac{1}{9}\langle\omega_y\rangle^2}_{\sim 10^{-4}} + \underbrace{\frac{Q_s^2}{9m_s^2T^2}\langle B_y\rangle^2}_{\sim 10^{-5}}$$

- Hydrodynamic contributions to spin alignment are of $O(\partial^2)$

  Numerical calculation including $O(\partial^2)$ contributions
  A. Kumar, D.-L. Yang, P. Gubler, PRD 109, 5 (2024)



- Shear-induced spin alignment $O(\partial)$ contribution

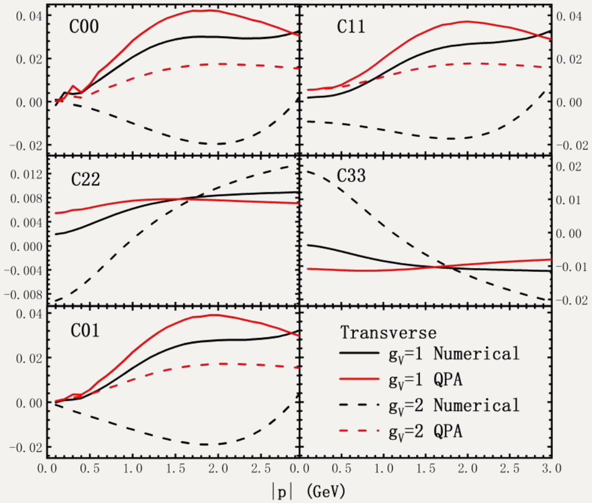
$$\delta\rho_{00}(\mathbf{p}) = \delta\rho_{00}^{(\xi=0)}(\mathbf{p}) + \boxed{\xi_{\mu\nu}C^{\mu\nu}(\mathbf{p})}$$

Coefficient is $\sim 10^{-2}$

D. Wagner, N. Weickgenannt, E. Speranza, PRR 5, 013187 (2023)

F. Li, S. Liu, arXiv: 2206.11890

W.-B. Dong, Y.-L. Yin, XLS, S.-Z. Yang, Q. Wang, PRD 109, 5 (2024)



Strong-force field

- Effective Lagrangian with strong interaction mediated by scalar and vector mesons

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

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

$$\partial_\mu V^{\mu\nu} + m_V^2 V^\nu = J^\nu \Longrightarrow \phi^\mu \approx -(g_\phi / m_\phi^2) J_s^\mu$$

current-field identity in vector dominance model

Vector ϕ field might be generated from $s - \bar{s}$ asymmetry in their PDFs, or fluctuating strangeness current

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

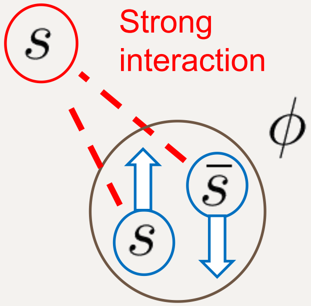
$$P^\mu_{s/\bar{s}}(x,p) \approx \frac{1}{4m_s}\epsilon^{\mu\nu\rho\sigma} p_\nu \left[\omega_{\rho\sigma} \pm \frac{Q_s}{(u\cdot p)T} F_{\rho\sigma} \pm \frac{g_\phi}{(u\cdot p)T} F^\phi_{\rho\sigma}\right] + \cdots$$

Thermal vorticity field (rotation and acceleration)

Classical electromagnetic field

Vector ϕ field

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



L. P. Csernai, J. I. Kapusta, T. Wellwe, PRC 99, 2 (2019)
XLS, L. Oliva, Q. Wang, PRD 101, 9 (2020)

Kinetic theory

- Kadanoff-Baym equation → Matrix-form Boltzmann equation

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

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

Meson polarization vectors

Coalescence kernel

Dissociation kernel (independent of quark distributions)

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

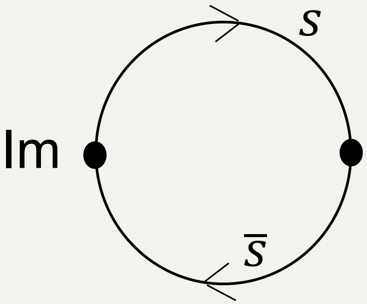
Energy conservation

$q\bar{q}$V vertex

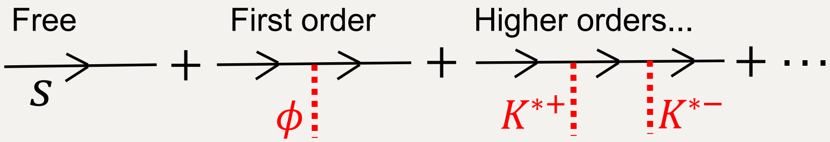
Polarizations of quark/antiquark

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

- **Cutting rule:** Probability of $s+\bar{s}\rightarrow\phi$ is related to



Quark's full propagator



$\propto(\gamma\cdot p+m)(1+\gamma_5\gamma\cdot P_q)$

ϕ meson spin alignment

- Spin alignment of ϕ meson measured along direction of $\boldsymbol{\epsilon}_0$

$$\left.\begin{aligned}\rho_{00} \approx\ & \frac{1}{3}+C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}'-(\boldsymbol{\epsilon}_0\cdot\boldsymbol{\omega}')^2\right]\\ & +C_1\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}'-(\boldsymbol{\epsilon}_0\cdot\boldsymbol{\varepsilon}')^2\right]\end{aligned}\right\}\text{small}$$

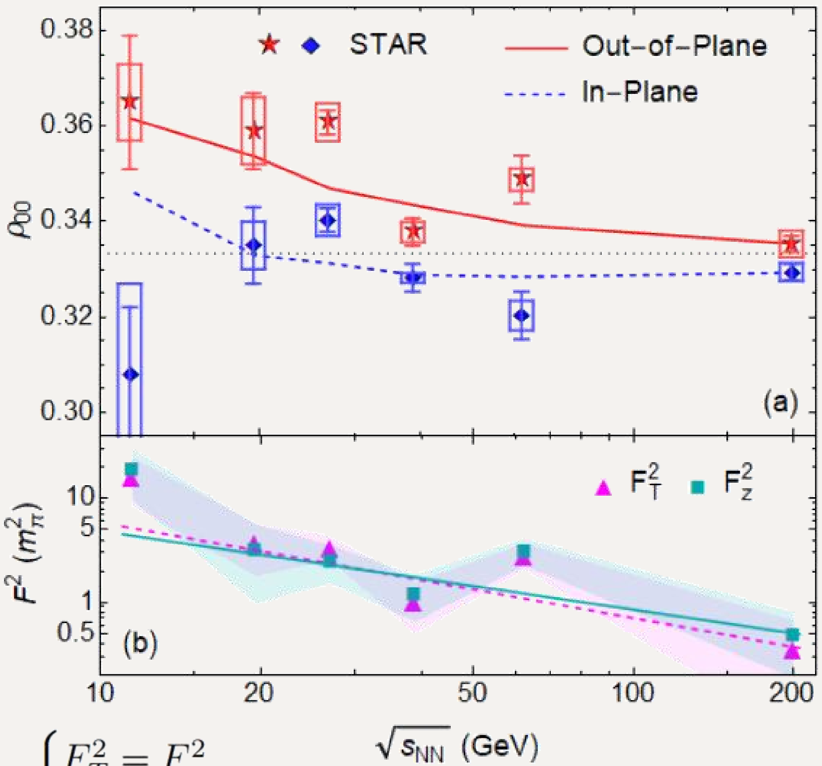
$$-\frac{4g_\phi^2}{m_\phi^2T_h^2}C_1\left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi-(\boldsymbol{\epsilon}_0\cdot\mathbf{B}'_\phi)^2\right]$$

$$-\frac{4g_\phi^2}{m_\phi^2T_h^2}C_2\left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi-(\boldsymbol{\epsilon}_0\cdot\mathbf{E}'_\phi)^2\right]$$

↑ Lorentz transform

Fields in lab frame

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



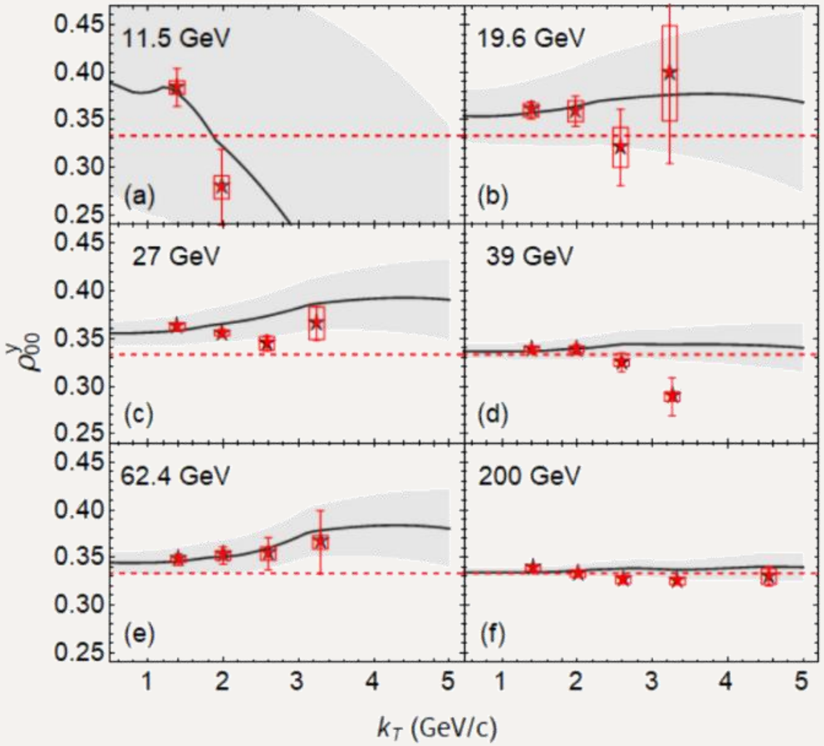
- Cancellation for mixing terms (because of CP and reflection symmetries)

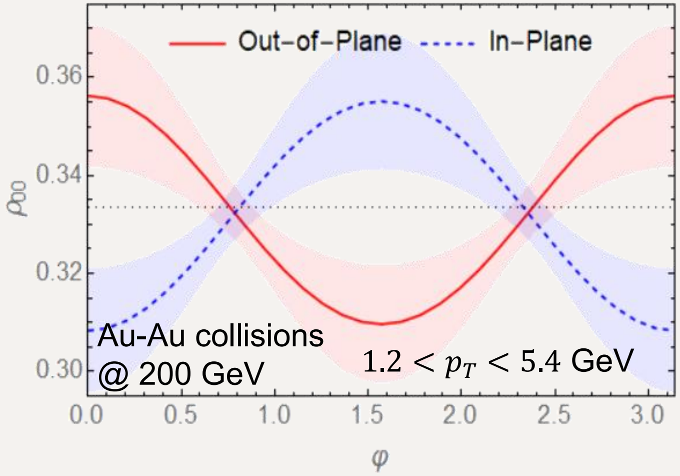
- All field contributions appear quadratically, spin alignment measures anisotropy of fluctuations in meson's rest frame

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

ϕ meson spin alignment

- Predictions for differential measurements

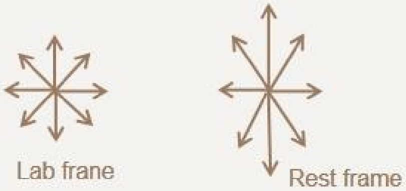


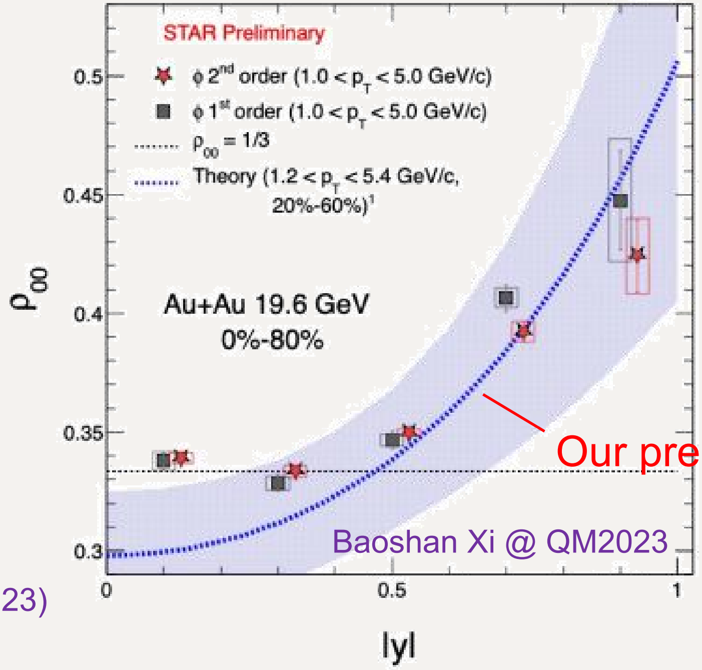


Au-Au collisions @ 200 GeV

$1.2 < p_T < 5.4$ GeV

- Anisotropy induced by motion relative to background





Our prediction

Baoshan Xi @ QM2023

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

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

Color fields

- Color field (QCD) $\xrightarrow[\text{Low temperature}]{\text{Effective description}}$ Vector meson field

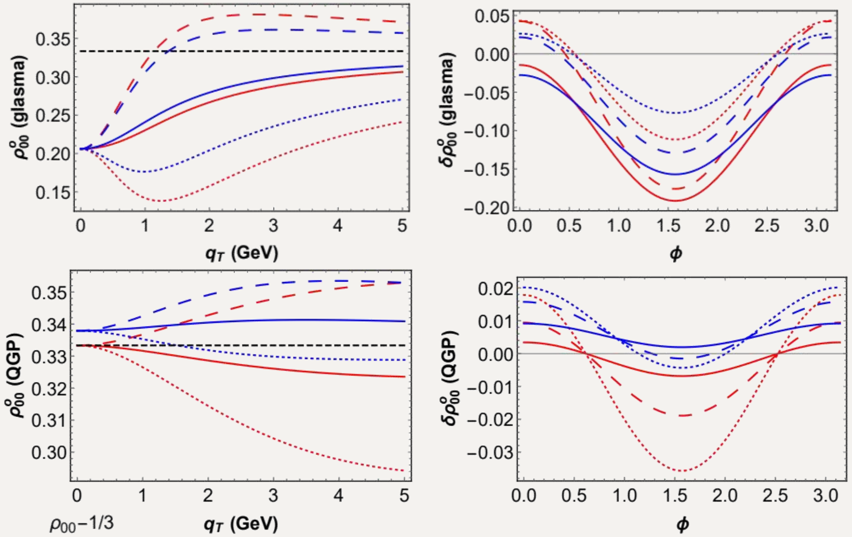
Early stage / heavy quarkonium

Freeze-out stage, light vector meson

- Global spin alignment induced by glasma fields / QGP color field fluctuations

A. Kumar, B. Mueller, D.-L. Yang, PRD 107, 7 (2023); PRD 108,1 (2023)
D.-L. Yang, X. Yao, PR 110, 7 (2024)
D.-L. Yang, PRD 111, 5 (2025)

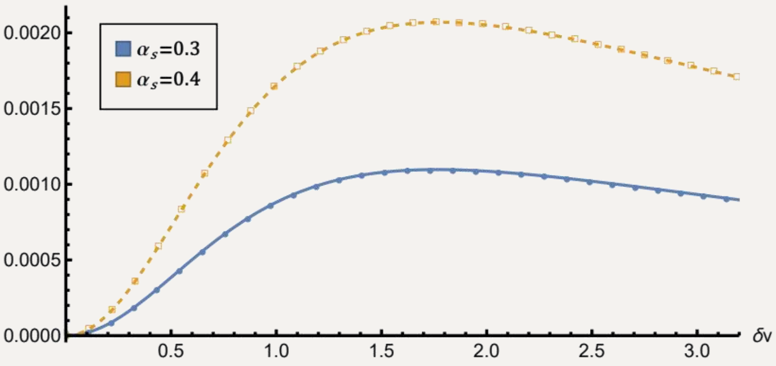
Talk by D.-L. Yang



- In meson's rest frame, chromomagnetic field becomes anisotropic, leading to spin-dependent dissociation rates

Z. Chen, S. Lin, PRD 111, 7 (2025)
G. Yan, S. Lin, PRD 113, 5 (2026)

Talk by Shu Lin



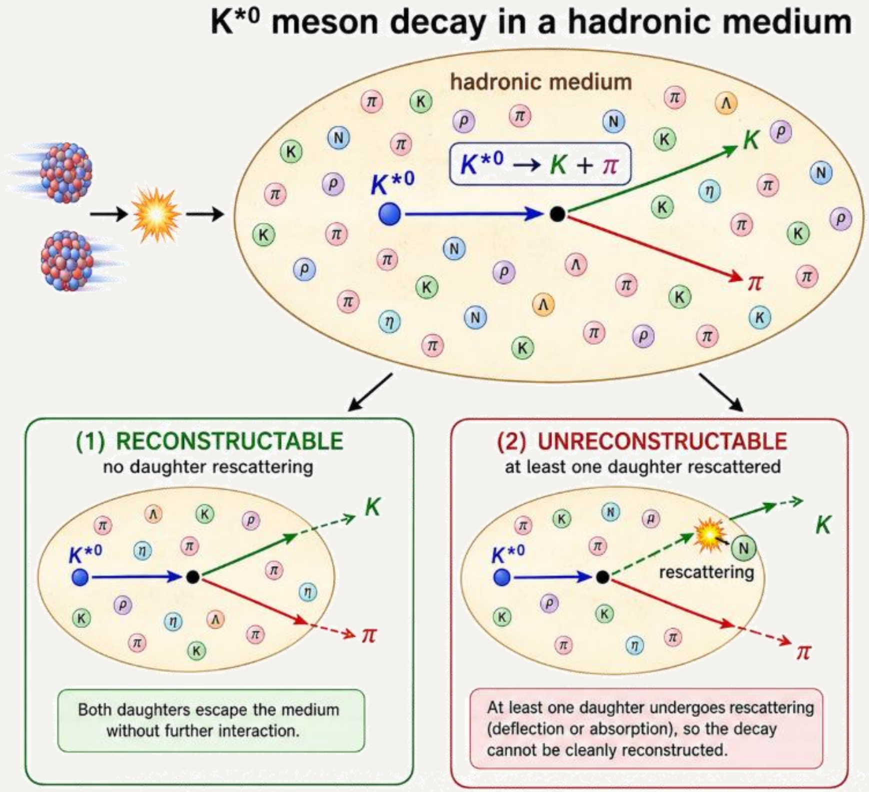
Rescattering effect

- For K^{*0} or ρ^0, their lifetimes are comparable to time between chemical freeze-out and kinetic freeze-out

Z. Li, W. Zha, Z. Tang, PRC 106, 6 (2022)

Z. Liu, Z. Li, W. Zha, Z. Tang, PLB 873, 140161 (2026)

- Significant for spin alignment w.r.t. production plane for K^{*0} or ρ^0



K*0 meson decay in a hadronic medium

(1) RECONSTRUCTABLE
no daughter rescattering

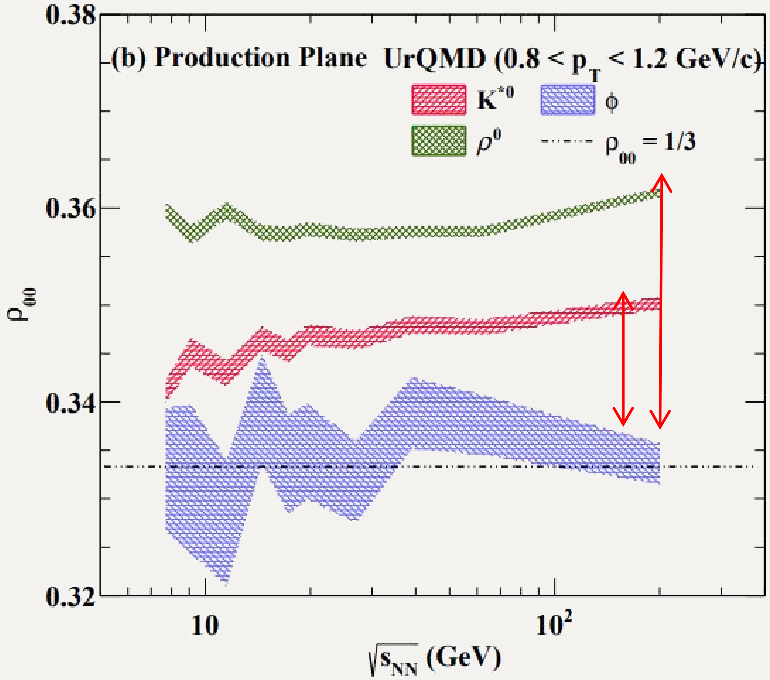
Both daughters escape the medium without further interaction.

(2) UNRECONSTRUCTABLE
at least one daughter rescattered

At least one daughter undergoes rescattering (deflection or absorption), so the decay cannot be cleanly reconstructed.

Note:
Reconstructable = no daughter rescattering
Unreconstructable = at least one daughter rescattered

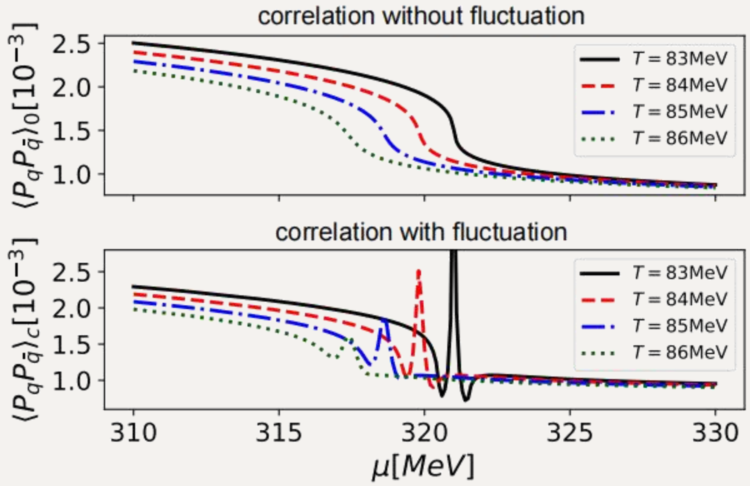
ChatGPT



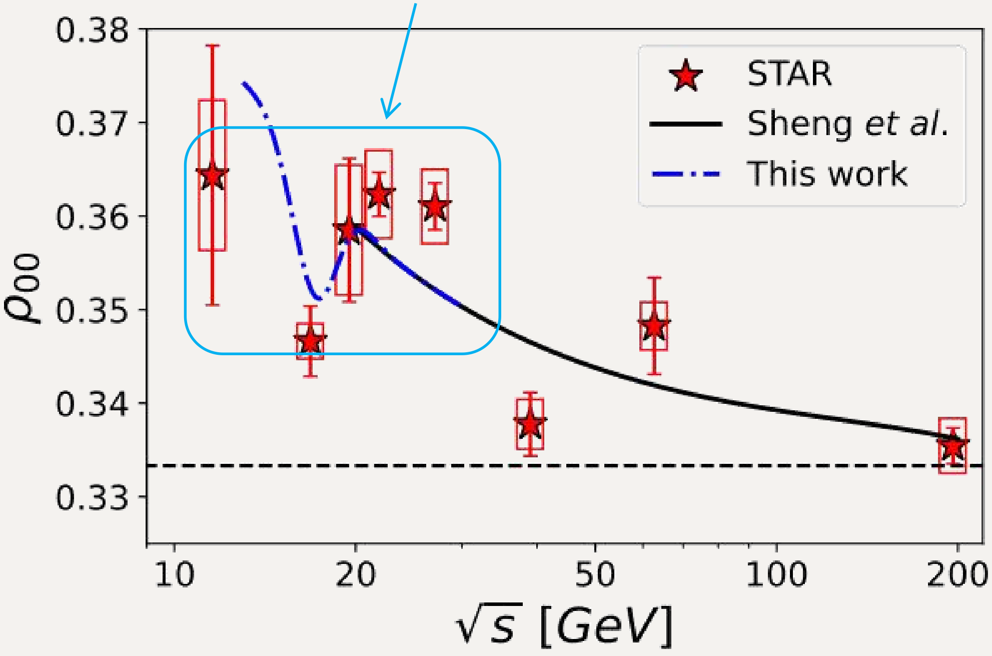
Spin alignment near critical point

- Near QCD critical point, vorticity-induced spin correlation can be significantly enhanced

H.-L. Chen, W.-J. Fu, X.-G. Huang, G.-L. Ma,
PRL 135, 3 (2025)

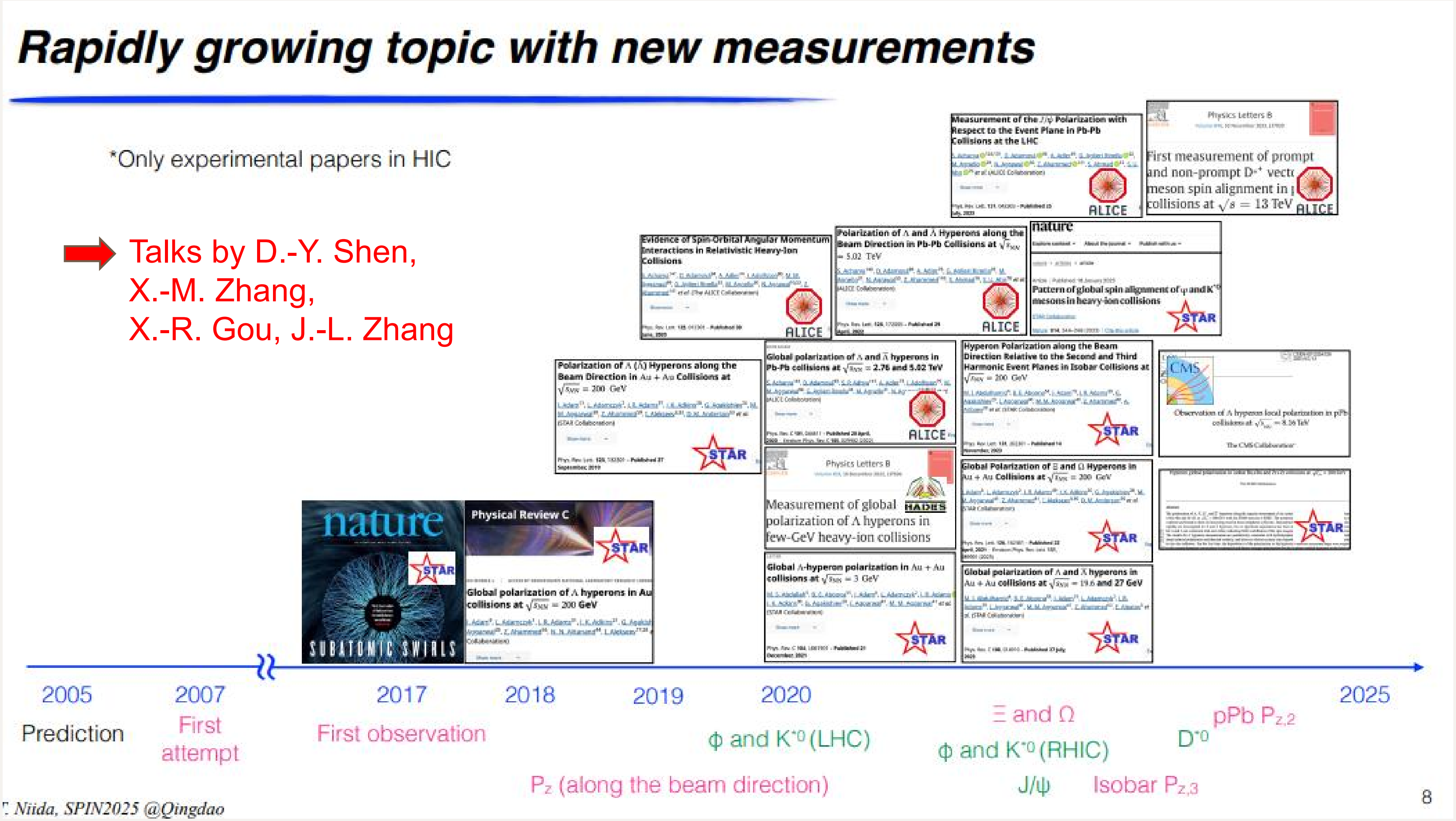


Non-monotonic behavior



Could strong-field-induced spin alignment show similar behavior??

Expeiment progress



Rapidly growing topic with new measurements

*Only experimental papers in HIC

Talks by D.-Y. Shen,
X.-M. Zhang,
X.-R. Gou, J.-L. Zhang

nature
SUBATOMIC SWIRLS

Physical Review C

Global polarization of Λ hyperons in Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Polarization of Λ ($\bar{\Lambda}$) Hyperons along the Beam Direction in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

Global polarization of Λ and $\bar{\Lambda}$ hyperons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV

Polarization of Λ and $\bar{\Lambda}$ Hyperons along the Beam Direction in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Physics Letters B

Measurement of global polarization of Λ hyperons in few-GeV heavy-ion collisions

Global Λ-hyperon polarization in Au + Au collisions at $\sqrt{s_{NN}} = 3$ GeV

Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

nature

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

Hyperon Polarization along the Beam Direction Relative to the Second and Third Harmonic Event Planes in Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV

Global Polarization of Ξ and Ω Hyperons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

Global polarization of Λ and $\bar{\Lambda}$ hyperons in Au + Au collisions at $\sqrt{s_{NN}} = 19.6$ and 27 GeV

Physics Letters B

First measurement of prompt and non-prompt D^{*+} vect meson spin alignment in collisions at $\sqrt{s} = 13$ TeV

Observation of Λ hyperon local polarization in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

The CMS Collaboration

2005
Prediction

2007
First attempt

2017
First observation

2018

2019

2020
ϕ and K^{*0} (LHC)

P_z (along the beam direction)

Ξ and Ω

ϕ and K^{*0} (RHIC)

J/ψ

Isobar $P_{z,3}$

D^{*0}

pPb $P_{z,2}$

2025

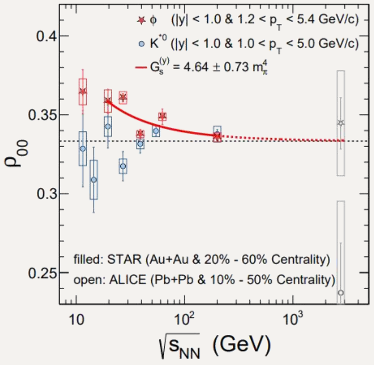
T. Niida, SPIN2025 @Qingdao

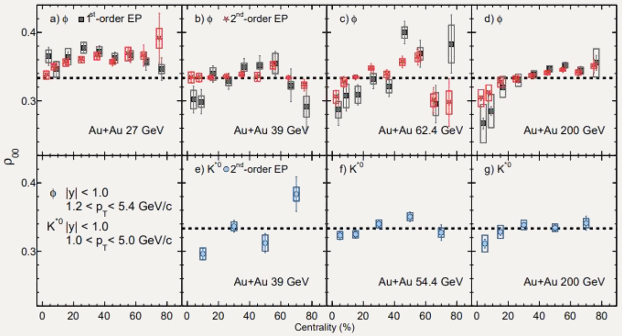
8

Different colliding systems

- ϕ and K^{*0} @ RHIC

  STAR, Nature 614, 244 (2023)

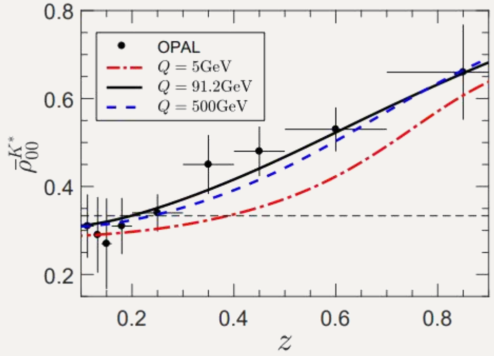




K^{*0} in e^+e^- collisions

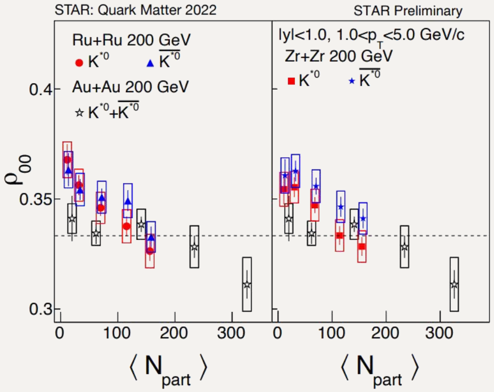
Exp.: OPAL, PLB 412, 210 (1997)

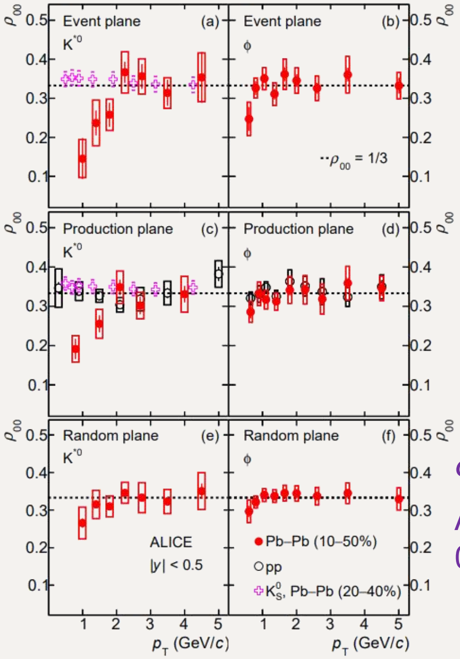
Theo.: K.-B. Chen, W.-H. Yang, Y.-J. Zhou, Z.-T. Liang, PRD 95, 3 (2017)



- K^{*0} @ RHIC Isobar

  STAR Preliminary @ QM2022





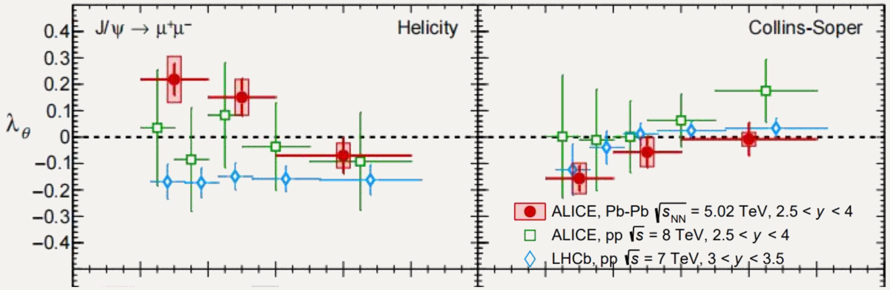
ϕ and K^{*0} @ LHC

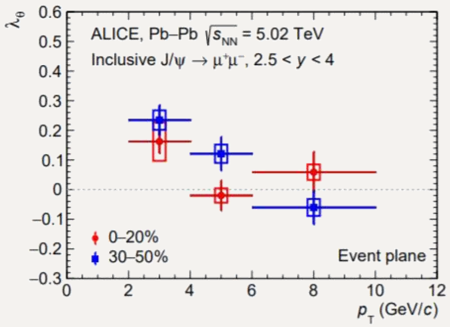
ALICE, PRL 125, 012301 (2020)

Meson spin alignment varies across different colliding systems

Heavy-flavor mesons

- Spin alignment of J/ψ @ LHC   ALICE, PLB 815, 136146 (2021); PRL 131, 042303 (2023)

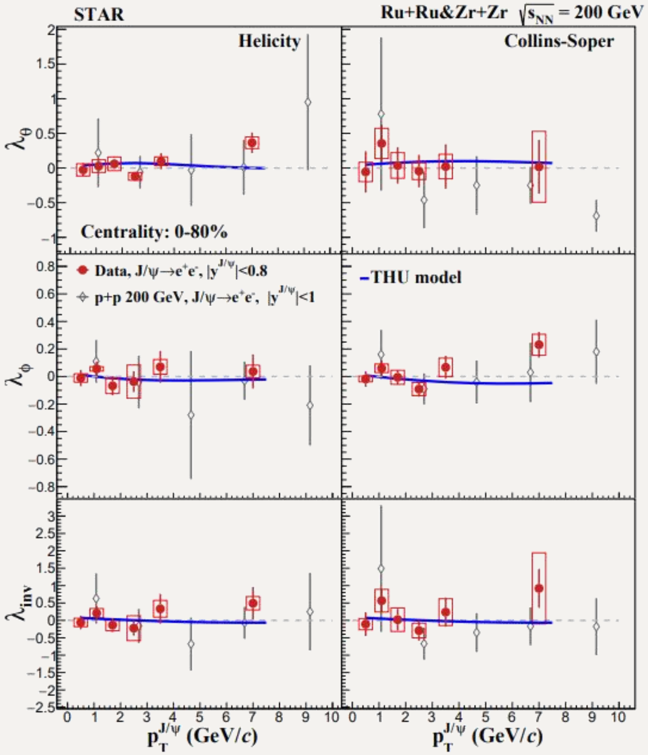




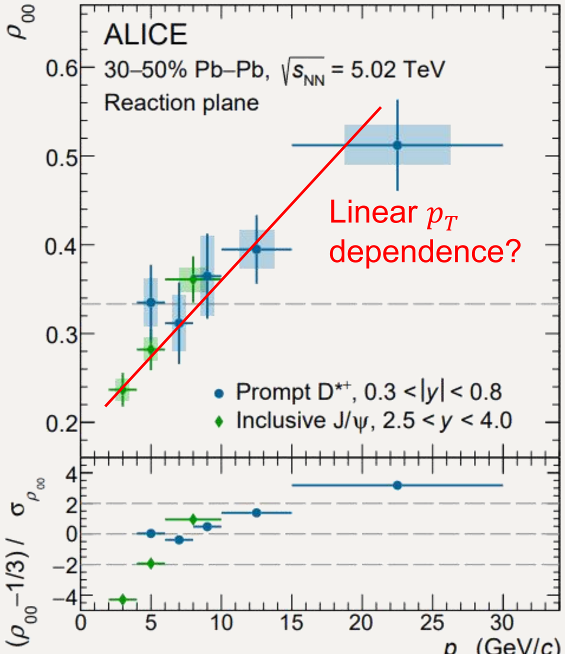
$\rho_{00} < 1/3$

- No spin alignment of J/ψ @ RHIC isobar collisions

STAR, arXiv: 2604.07005



- Spin alignment of D^{*0} @ LHC



Linear p_T dependence?

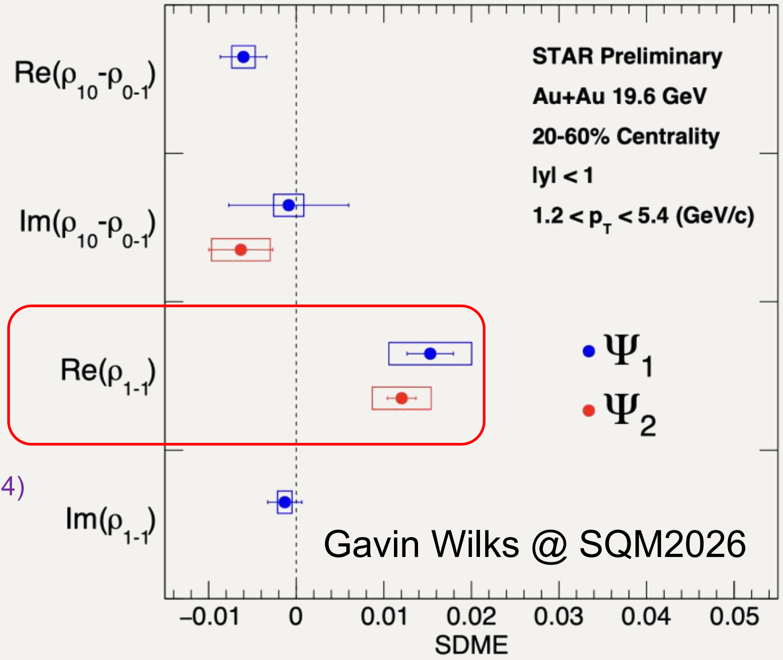
Off-diagonal elements

- Off-diagonal elements of spin density matrix

$$\begin{aligned}
\mathrm{Re}\rho^y_{1,-1} &\approx \frac{1}{3}\langle P^z_q P^z_{\bar{q}} - P^x_q P^x_{\bar{q}}\rangle \\
\mathrm{Im}\rho^y_{1,-1} &\approx -\frac{1}{3}\langle P^z_q P^x_{\bar{q}} + P^x_q P^z_{\bar{q}}\rangle \\
\mathrm{Re}(\rho^y_{10} - \rho^y_{-1,0}) &\approx \frac{\sqrt{2}}{3}\langle P^y_q P^z_{\bar{q}} + P^z_q P^y_{\bar{q}}\rangle \\
\mathrm{Im}(\rho^y_{10} - \rho^y_{-1,0}) &\approx -\frac{\sqrt{2}}{3}\langle P^y_q P^x_{\bar{q}} + P^x_q P^y_{\bar{q}}\rangle
\end{aligned}$$

J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, X.-N. Wang, PRD 109, 11 (2024)

J.-H. Chen, Z.-T. Liang, Y.-G. Ma, XLS, Q. Wang, Sci.China Phys.Mech.Astron. 68, 1 (2025)

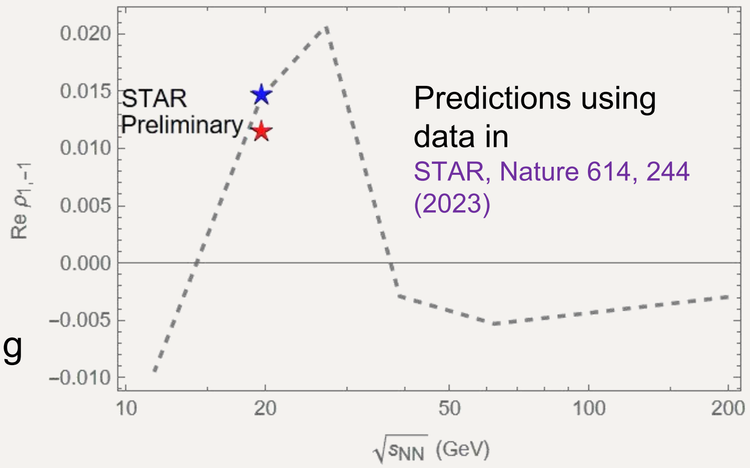


Gavin Wilks @ SQM2026

- This can be easily proven by rotating the density matrix:

$$\boxed{\mathrm{Re}\rho^y_{1,-1} = \frac{1}{2}\left(\rho^y_{00} - \frac{1}{3}\right) + \left(\rho^x_{00} - \frac{1}{3}\right)}$$

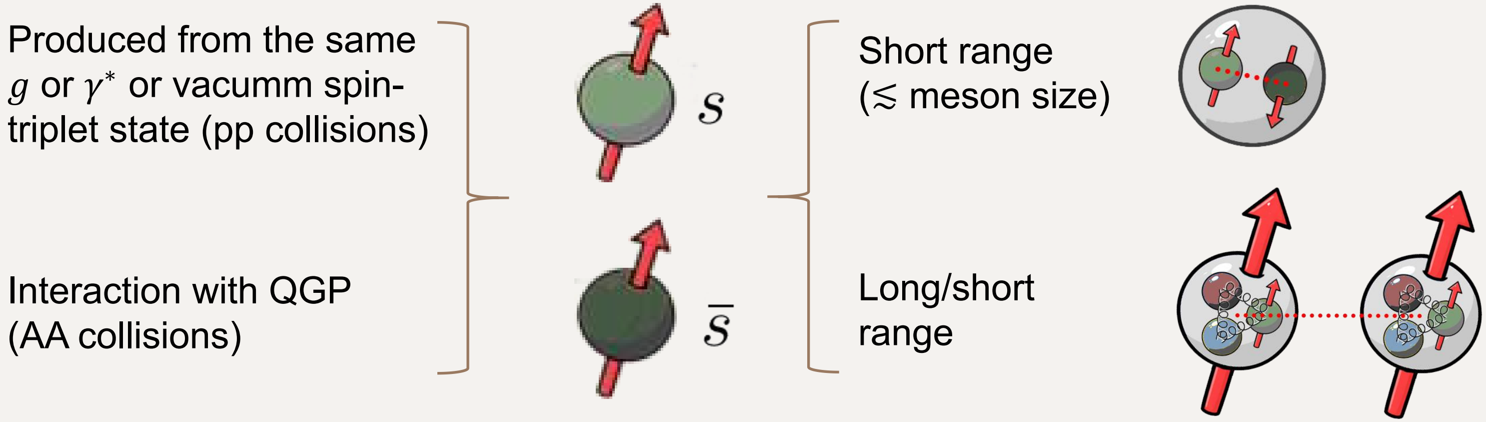
- Energy dependence provides a cross-check for previous data
- Differential measurements are important for probing anisotropy of quark spin correlations



Predictions using data in STAR, Nature 614, 244 (2023)

Hyperon spin correlation

- Vector meson spin alignment vs. hyperon spin correlation



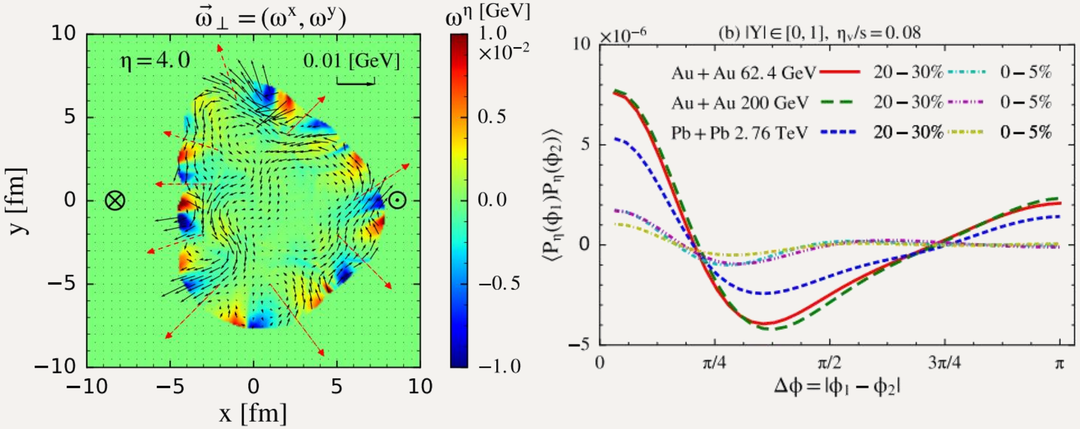
Produced from the same g or γ^* or vacumm spin-triplet state (pp collisions)

Interaction with QGP (AA collisions)

Short range (≲ meson size)

Long/short range

- Hyperon spin correlation induced by local vorticity [$O(\partial^2)$]



L.-G. Pang, H. Petersen, Q. Wang, X.-N. Wang, PRL 117, 19 (2016)

Vorticity-induced correlations are small. What about strong interaction?

Hyperon spin correlation

- Hyperon spin correlation:

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

4 × 4 Lorentz tensor

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

Correlation between spins in two particle's respective rest frames

$$\boxed{\frac{9}{\alpha_1\alpha_2}\langle\cos\theta_a^*\cos\theta_b^*\rangle}$$

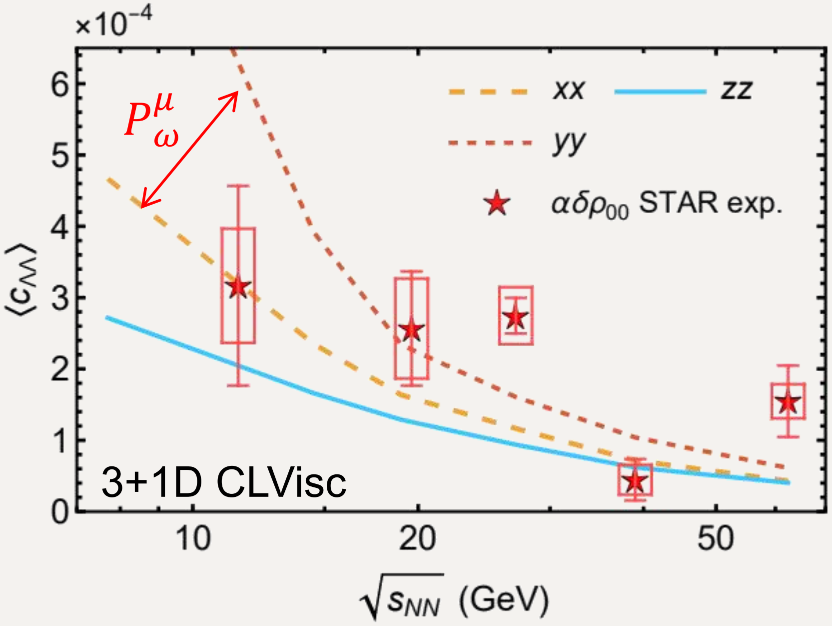
D. Shen, J. Chen, A. Tang, arXiv: 2407.21291

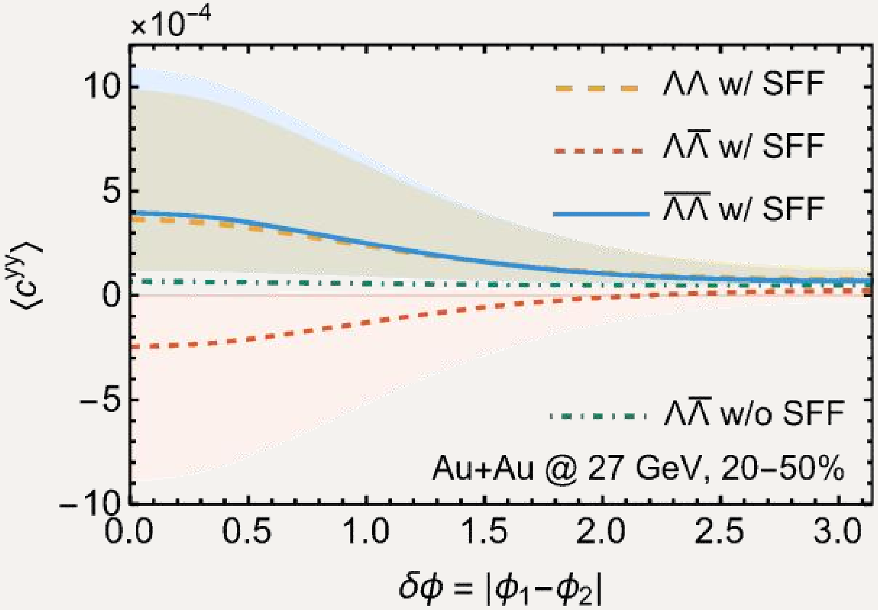
- Relating hyperon polarization to quark polarization

$$P_\Lambda^\mu(x,p) \approx P_s^\mu(x,R_s p)$$

$$P_{s/\bar{s}}^\mu(x,p) = \underbrace{P_\omega^\mu + P_{\text{shear}}^\mu + P_{\text{SHE}}^\mu}_{\text{Hydrodynamic effects}} + \boxed{P_\phi^\mu}$$

Strong force field (fluctuation extracted from ϕ spin alignment)



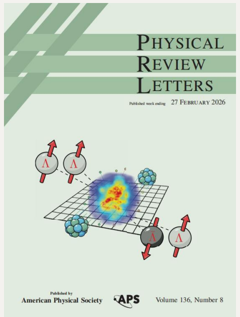


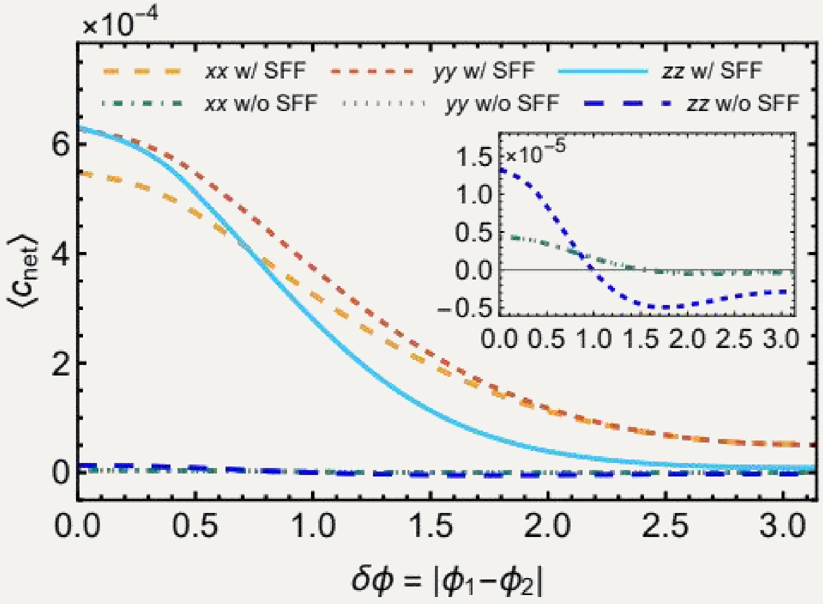
Net spin correlation

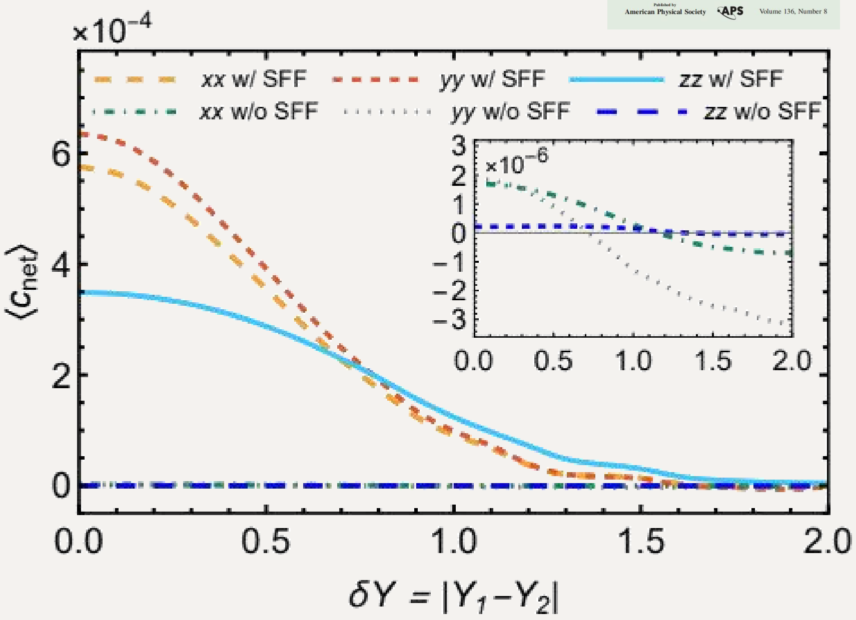
- Net spin correlation:
  difference between “same-sign” and “opposite-sign” pairs

$$c^{ab}_{\rm net} \equiv \frac{1}{2}\left(c^{ab}_{\Lambda\Lambda} + c^{ab}_{\bar{\Lambda}\bar{\Lambda}}\right) - c^{ab}_{\Lambda\bar{\Lambda}}$$

XLS, X.-Y. Wu,
X.-N. Wang,
PRL 136, 8 (2026)







- Spin correlation is small ($\sim 10^{-4}$)
- Converge to zeros at large $\delta\phi$ or δY (short-range)
- Hydrodynamic effect is suppressed by 1-2 orders of magnitude

Initial spin density

- Participant nucleons carry random spins

↓

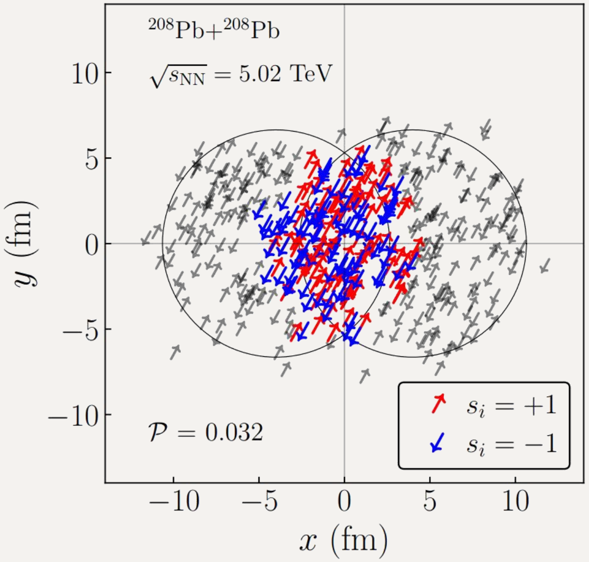
A nonzero initial net spin polarization

↓

Spin correlation of final hadrons

G. Giacalone, E. Speranza, arXiv: 2502.13102

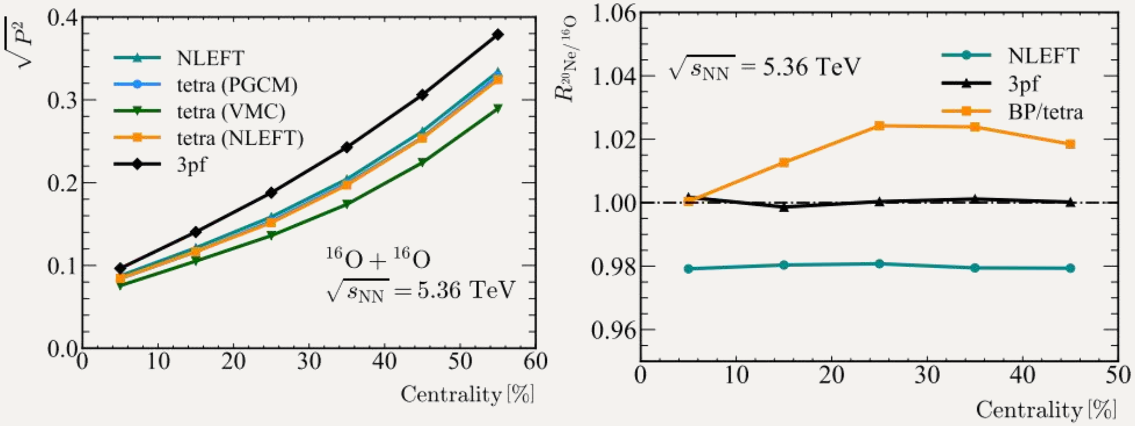
→ Talk by E. Speranza



- Studying α-cluster structure in light nuclei using spin correlation

$$R_{^{20}\mathrm{Ne}/^{16}\mathrm{O}} \equiv \frac{\left(\sqrt{\langle \mathcal{P}^2\rangle}\right)^{^{20}\mathrm{Ne}+^{20}\mathrm{Ne}}_{\mathrm{scaled}}}{\left(\sqrt{\langle \mathcal{P}^2\rangle}\right)^{^{16}\mathrm{O}+^{16}\mathrm{O}}_{\mathrm{scaled}}}$$

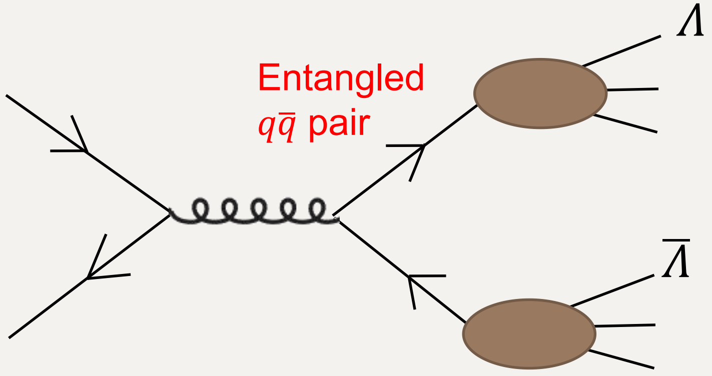
X. Fan, J.-Q. Tao, Z.-F. Jiang, B.-W. Zhang, arXiv:2512.24079



Strong short-range spin–isospin correlation in α

Quark fragmentation

- Hyperon spin correlation in s-channel $q\bar{q} \to q\bar{q} \to \Lambda\bar{\Lambda}X$

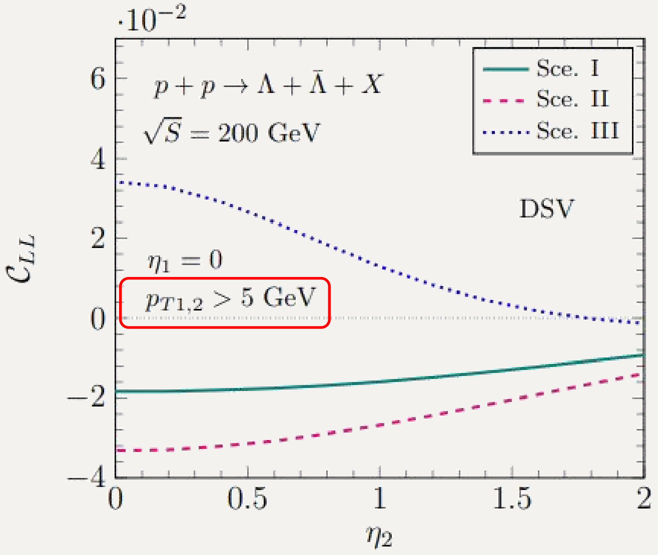


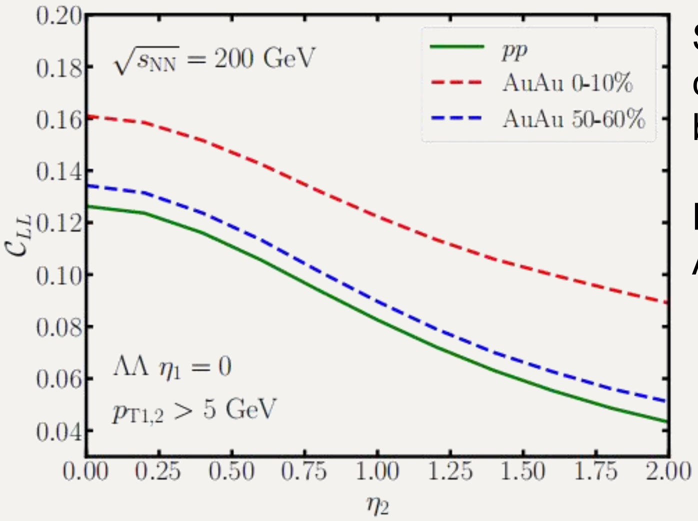
Quark spin transfer to Λ through spin-dependent fragmentation functions

⟶ measurable in $e^+e^- \to Z^0 \to q\bar{q} \to \Lambda X$

D. Floreian, M. Strtmann, W. Vogelsang, PRD 57, 5811 (1998)
H.-C. Zhang, S.-Y. Wei, PLB 839, 13 (2023)
X. Li, Z.-X. Chen, S. Cao, S.-Y. Wei, PRD 109, 01 (2024)
S.-J. Lin, M.-J. Liu, D. Y. Shao, S.-Y. Wei, JHEP 11, 082 (2025)

- Λ hyperon helicity correlation in pp & AA collisions



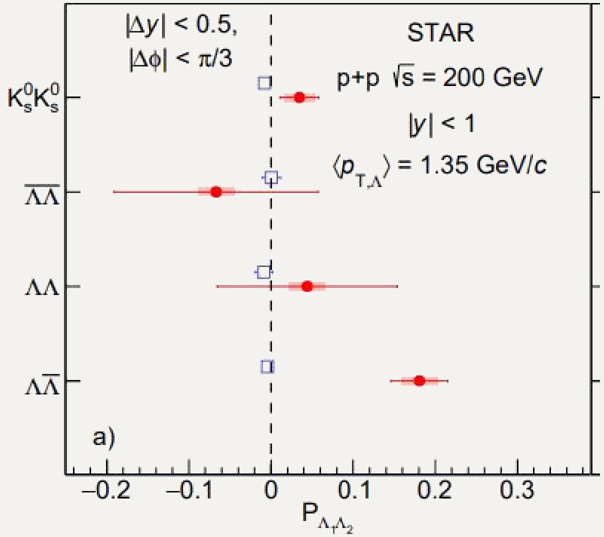


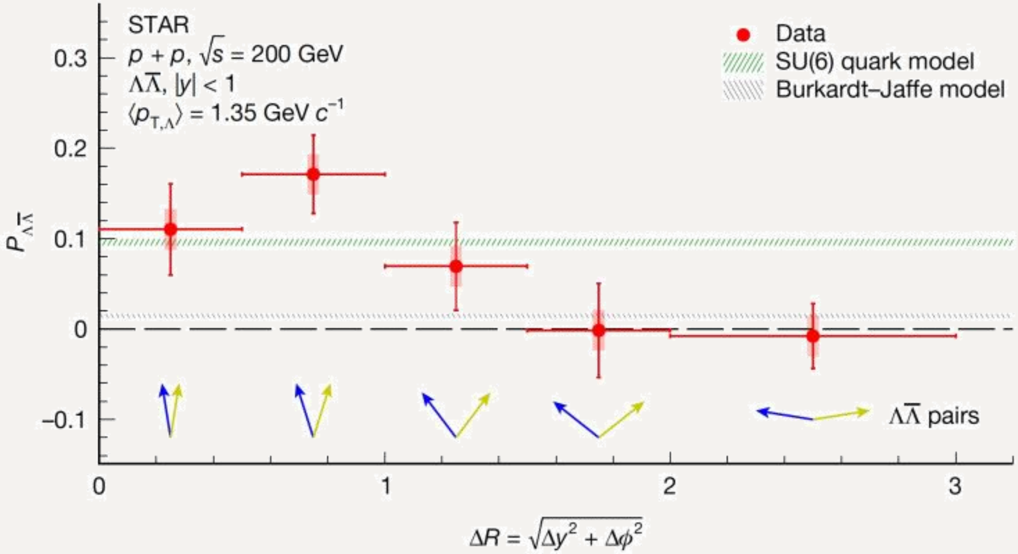
Strong $\Lambda\Lambda$ spin correlation (dominated by t-channel)

Enhanced correlation in AA collisions

Experimental results

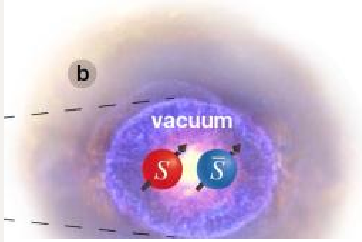
- Hyperon spin correlation in p+p collisions @ RHIC ➡ Talks by X.-R. Gou, J.-L. Zhang





- Significant positive spin correlation for $\Lambda\bar{\Lambda}$
- No significant spin correlation for $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$
- Converge to zero at large ΔR
- Evidence of quark condensate? (virtual pairs in vacuum are in spin triplet states)

STAR, Nature 650, 44-45 (2026)

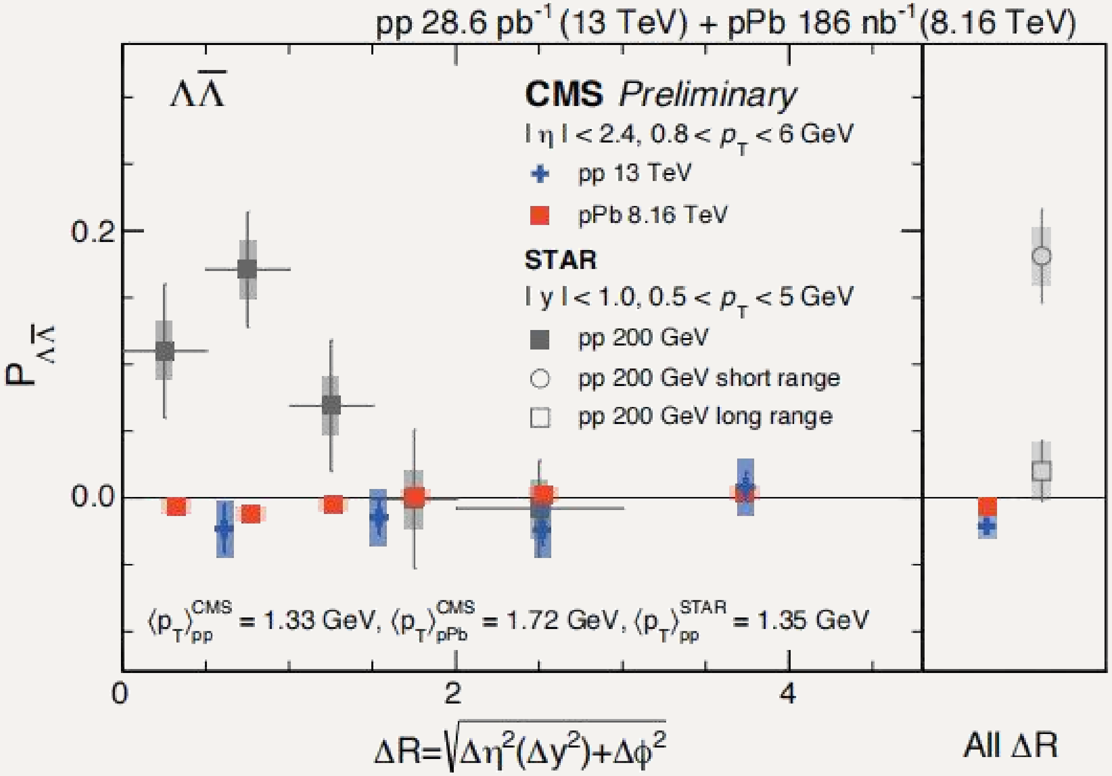


$$J^P = 0^+ \to L = S = 1$$

$$\langle \mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} \rangle = \frac{1}{2}\langle (\mathbf{S}_q + \mathbf{S}_{\bar{q}})^2 - \mathbf{S}_q^2 - \mathbf{S}_{\bar{q}}^2 \rangle > 0$$

Experimental results

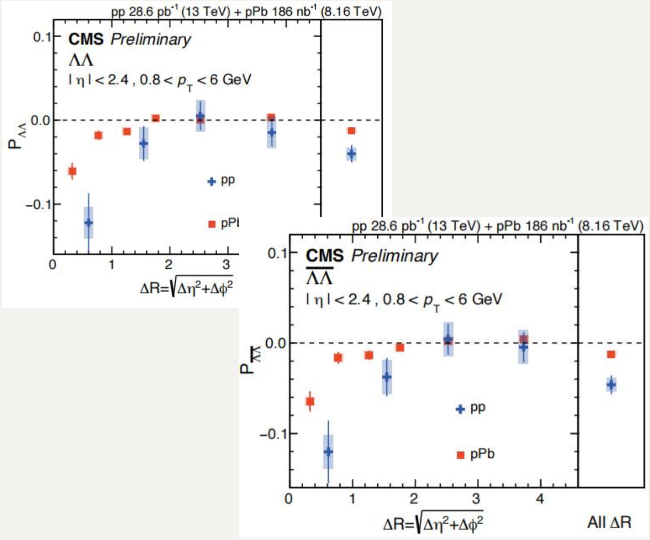
- Hyperon spin correlation in p+p (p+Pb) collisions @ CMS



pp 13TeV

pp 200GeV

pPb 8.16TeV



Jieke Wang @ DIS2026

- $\Lambda\bar{\Lambda}$: Consistent with zero within uncertainties (hint of negative value)
- $\Lambda\Lambda$ & $\bar{\Lambda}\bar{\Lambda}$: Negative spin correlation at small ΔR
- Might be due to different production mechanisms, e.g. fragmentation, $gg \to s\bar{s}$?

Top-quark pair

- Spin density matrix of a top-quark pair

$$\rho = \frac{\mathbb{I}_4 + \sum_{i=1}^{3}\left(B_i^+ \sigma^i \otimes \mathbb{I}_2 + B_i^- \mathbb{I}_2 \otimes \sigma^i\right) + \sum_{i,j=1}^{3} C_{ij}\sigma^i \otimes \sigma^j}{4}$$

Polarization of t, $\bar{t}$

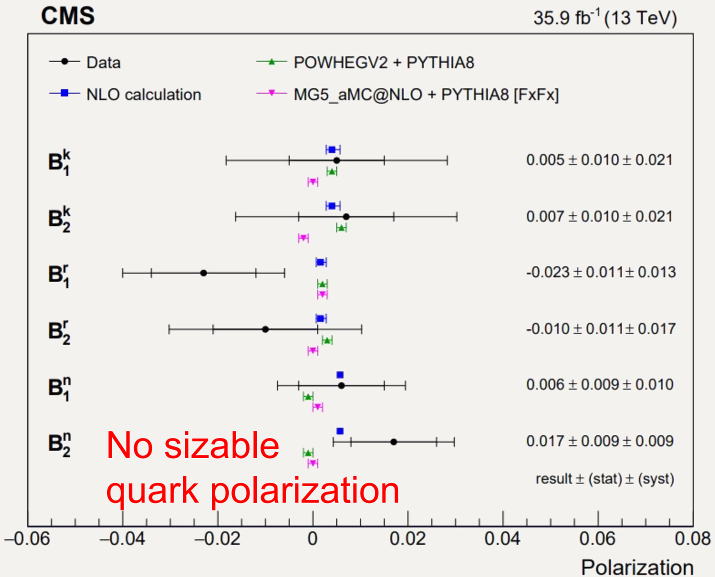
Spin correlation

$gg \rightarrow t\bar{t}$ (spin-singlet state)

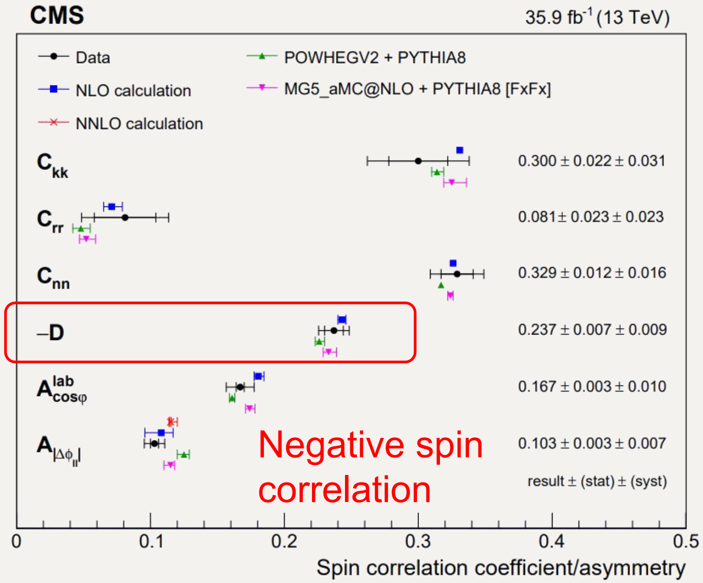
- Measured through angular distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1 \mathbf{B}_1 \cdot \hat{e}_1 + \alpha_2 \mathbf{B}_2 \cdot \hat{e}_2 + \alpha_1\alpha_2 \hat{e}_1 \cdot \mathbf{C} \cdot \hat{e}_2\right)$$

$\boxed{t \rightarrow b + W}$ Weak decay



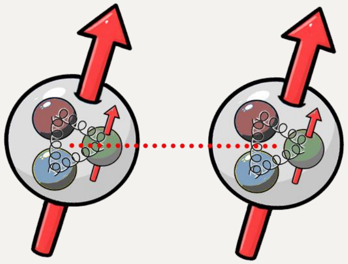
No sizable quark polarization



Negative spin correlation

CMS, PRD 100, 7 (2019)

Hyperons and hypernuclei



Λ spin = s quark spin?
Λ spin correlation = s quark spin correlation?

Valid at leading order in P_q

- Spin correlation between constituent quarks give high order corrections

$$P_\Lambda = P_{sz} - \frac{\delta\rho_\Lambda}{C_\Lambda},$$
$$\delta\rho_\Lambda = c_{iz}^{(us)} P_{di} + c_{iz}^{(ds)} P_{ui} + c_{iiz}^{(uds)}$$
$$C_\Lambda = 1 - c_{ii}^{(ud)} - P_{ui} P_{di}.$$

$$\langle P_\Lambda P_\Lambda \rangle = \langle P_s P_s \rangle + \mathcal{O}[(P_q)^4]$$

J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, X.-N. Wang, PRD 109, 11 (2024)

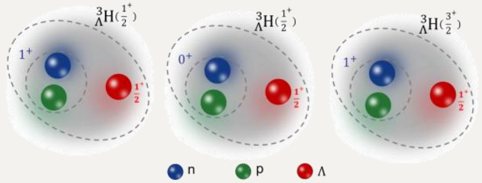
also see:

J.-P. Lv, Z.-H. Yu, X.-W. Li, Z.-T. Liang, arXiv:2603.15135

L. Oliva, Q. Wang, X.-N. Wang, arXiv: 2603.10427

- Spin of hypernuclei

$${}^3_\Lambda\mathrm{H} \rightarrow \pi^- + {}^3\,\mathrm{He},$$



Identifying internal spin structure through measuring its global polarization

$$J^\pi \doteq 2^-$$
$${}^4\mathrm{Li} \rightarrow {}^3\mathrm{He} + p$$

➡ Talk by K.-J. Sun

$$\begin{aligned}\frac{dN}{\sin\theta^* d\theta^*} &\approx \frac{1}{12}\Big\{5 \times \frac{1}{2}\Big[1 - \frac{7}{30}\left(\mathcal{P}_N^2 + 4\mathcal{P}_N\mathcal{P}_L + \mathcal{P}_L^2\right)(3\cos^2\theta^* - 1)\Big] \\ &+ 3 \times \frac{1}{2}\Big[1 - \frac{1}{6}\left(\mathcal{P}_N^2 - 4\mathcal{P}_N\mathcal{P}_L + \mathcal{P}_L^2\right)(3\cos^2\theta^* - 1)\Big] + \frac{1}{2} + 3 \times \frac{1}{2}\Big[1 - \frac{2}{3}\mathcal{P}_L^2(3\cos^2\theta^* - 1)\Big]\Big\} \\ &\approx \frac{1}{2}\Big[1 - \frac{1}{36}\left(5\mathcal{P}_N^2 + 8\mathcal{P}_N\mathcal{P}_L + 11\mathcal{P}_L^2\right)(3\cos^2\theta^* - 1)\Big].\end{aligned}$$

K.-J. Sun, D.-N. Liu, Y.-P. Zheng, J.-H. Chen, C. M. Ko, PRL 134, 2 (2025)

Y.-P. Zheng, D.-N. Liu, L.-W. Chen, et al. arXiv: 2509.15286

Summary

- Vector meson spin alignment

⟺ anisotropy of short-range quark spin correlation

⟺ strong-field fluctuations (vector meson field or color field)

⇧

anisotropy induced by motion of meson relative to QGP
or intrinsic anisotropy of field fluctuations

- Identify different mechanisms for hyperon spin correlation

		$\Lambda\Lambda$ & $\bar{\Lambda}\bar{\Lambda}$	$\Lambda\bar{\Lambda}$	**Net spin correlation**
Intrinsic	Excited vacuum 0^+ $q\bar{q}$	~ 0	$+$	$-$
	Partonic scattering / pair creation $gg \to q\bar{q},\ qq \to qq,\ q\bar{q} \to q\bar{q}$	$+$	− (*s*-channel) + (*t*-channel) + (total)	$+$
	Initial net spin polarization	$+$	?	?
Field-induced	Hydrodynamic effects	$+$	$+$	~ 0
	Strong-force field	$+$	$-$	$+$