

重离子碰撞中的自旋极化与自旋关联

Xin-Li Sheng
盛欣力

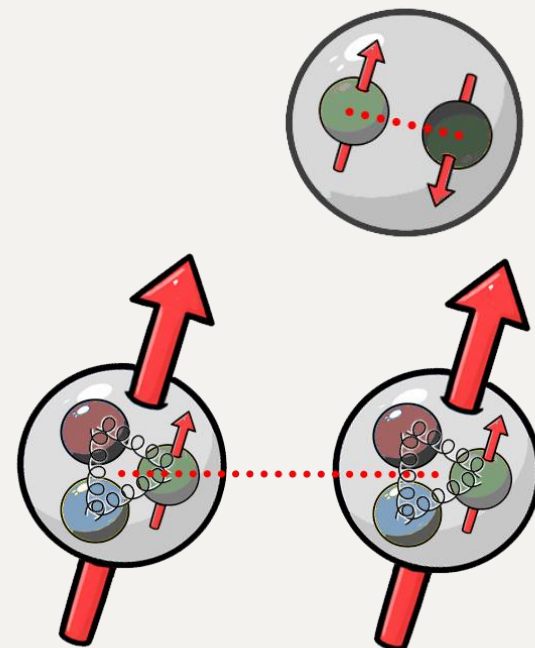


GSI Helmholtzzentrum für Schwerionenforschung GmbH

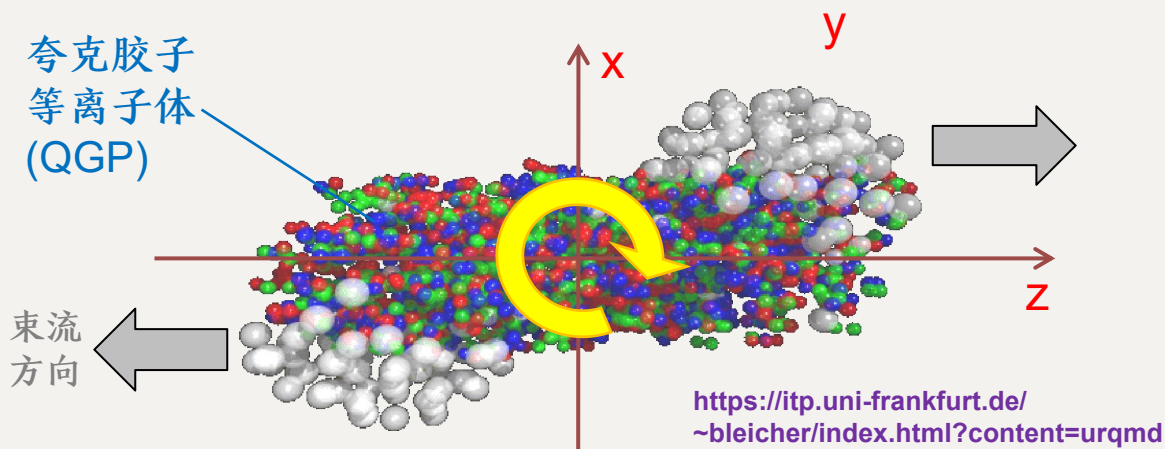


高能与低能核物理交叉学术研讨会
2026年5月15—18日
上海

- 重离子碰撞中的自旋极化
- 矢量介子自旋排列
- 超子自旋关联
- 00 碰撞中的自旋
- 总结



Strongly interacting
matter with vorticity
and magnetic fields



初始轨道
角动量

涡旋场
电磁场
强相互作用场

极化的
部分子



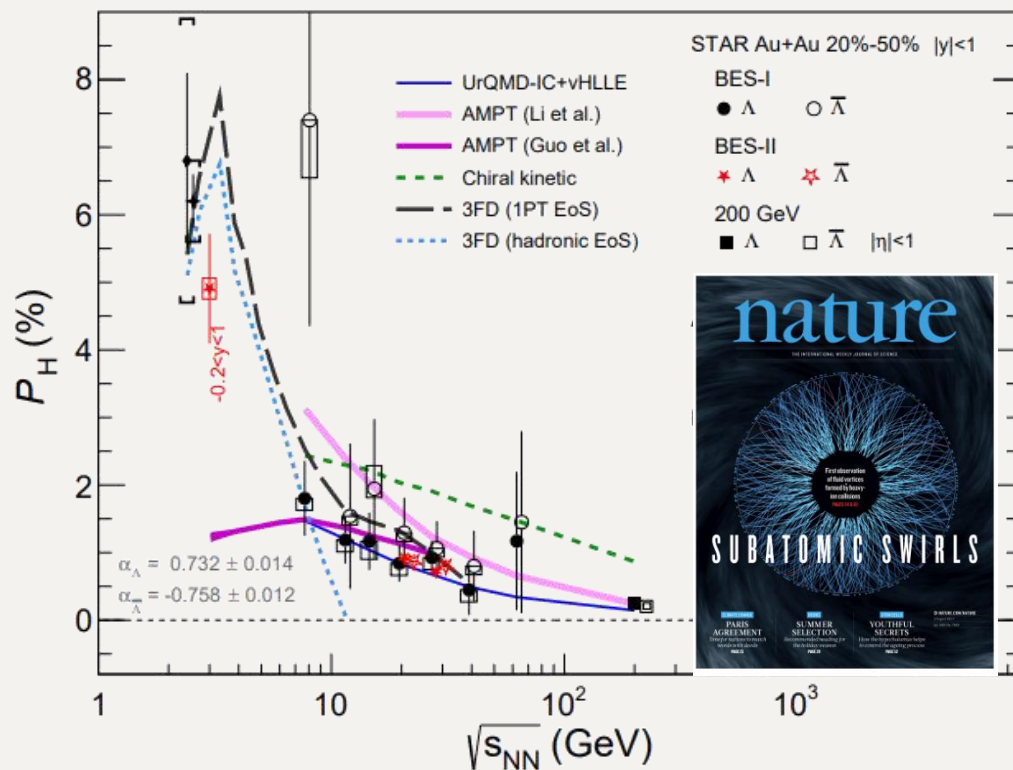
重子的自旋极化(Spin
polarization)
 Λ , Σ^0 , Δ^{++} , Ω^- , ...

矢量介子的自旋排列(Spin
alignment)
 ϕ , K^{*0} , ρ^0 , ...

S. A. Voloshi, nucl-th/0410089

Z.-T. Liang, X.-N. Wang, PRL 94, 102301 (2005); PLB 629, 20 (2005)

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



STAR, Nature 548, 62 (2017); Phys. Rev. C 104, L061901 (2021);
Phys. Rev. C 98, 014910 (2018); Phys. Rev. C 108, 014910 (2023)

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

沿碰撞系统总角动量方向的超子极化

Globally Polarized Quark-Gluon Plasma in Noncentral A + A Collisions

Zuo-Tang Liang¹ and Xin-Nian Wang^{2,1}

Show more

Phys. Rev. Lett. **94**, 102301 – Published 14 March, 2005
Erratum Phys. Rev. Lett. **96**, 039901 (2006)

- 无自旋的流体或输运模型模拟
- +
- 强子化超曲面上的 spin Cooper-Frye formula

涡旋场的实验证据!

$$P_{\Lambda} = P_s \quad \text{QGP 中的夸克被极化}$$

- 矢量介子 ($J^P = 1^-$) 的自旋排列 (spin alignment) 是其归一化的自旋密度矩阵的 00-分量 ρ_{00}

自旋投影为0的几率

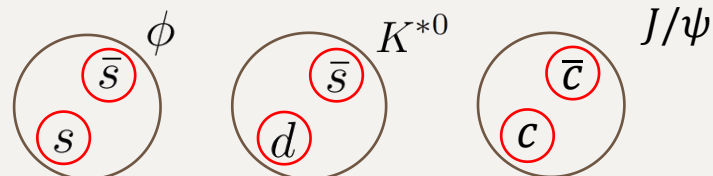
未极化的介子 $\rho_{00} = 1/3$

$$\rho_{rs}^{S=1} = \begin{pmatrix} \rho_{+1,+1} & \rho_{+1,0} & \rho_{+1,-1} \\ \rho_{0,+1} & \rho_{00} & \rho_{0,-1} \\ \rho_{-1,+1} & \rho_{-1,0} & \rho_{-1,-1} \end{pmatrix} = \frac{1}{3} + \frac{1}{2} P_i \Sigma_i + T_{ij} \Sigma_{ij}$$

$$\rho_{00} = \frac{1}{3} + \frac{4}{9} \left[\frac{1}{2} \langle \mathbf{P}_q^T \cdot \mathbf{P}_{\bar{q}}^T \rangle - \langle P_q^L P_{\bar{q}}^L \rangle \right]$$

矢量极化
(3 分量, 无法测量)

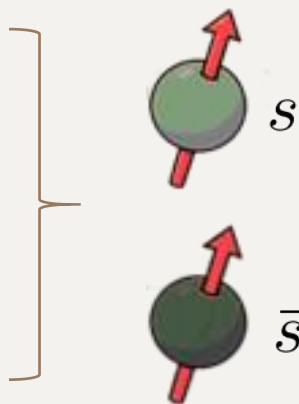
张量极化
(5 分量, 可通过衰变产物角分布测量)



- 从夸克自旋关联到矢量介子自旋排列与超子自旋关联

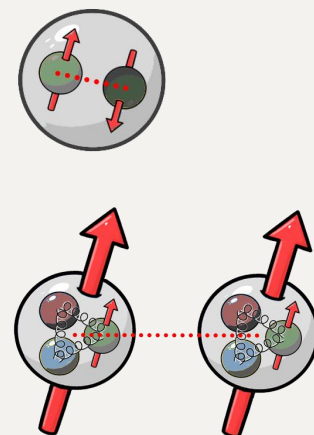
Intrinsic: 由同一个 g 或 γ^* 产生, 或通过散射产生关联 (pp collisions)

External: 与外场相互作用 (AA collisions)

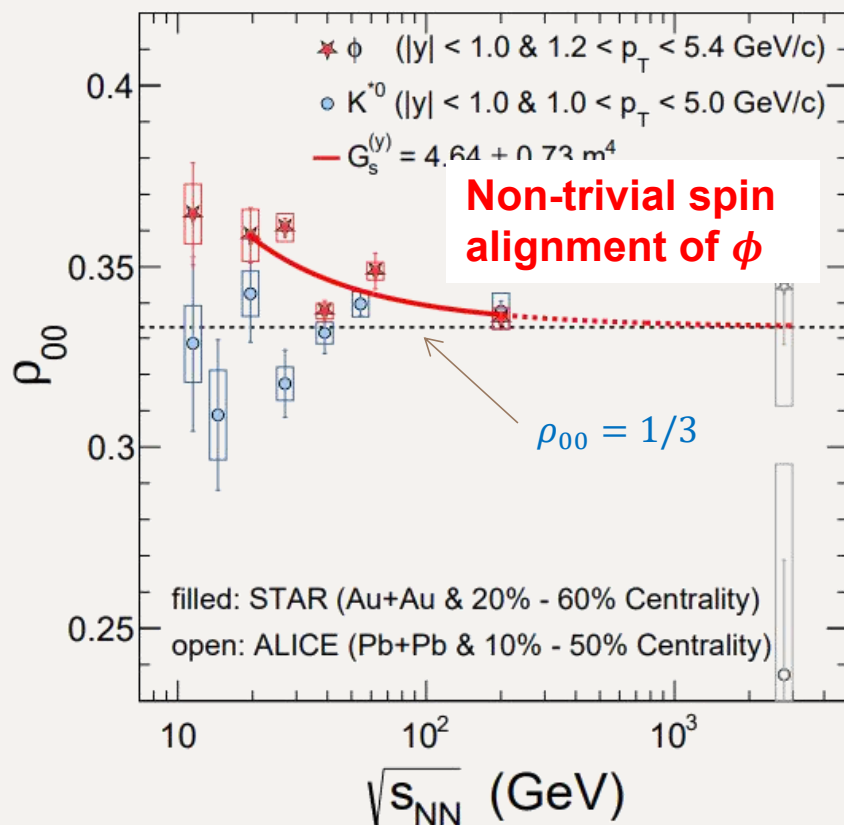


短程自旋关联
($\lesssim$ 介子尺寸)

长程或短程
自旋关联
(取决于超子
距离)



- 沿整体角动量方向的介子自旋排列



红线: 强场涨落模型理论预测

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

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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

Yu-Gang Ma, Jin-Hui Chen, Chen-Sheng Zhou, et al.

Nature 614, 244–248 (2023) | Cite this article

3084 Accesses | 8 Citations | 165 Altmetric | Metrics

STAR, Nature 614, 244 (2023)



Strong p-wave decay

(自旋 $\rightarrow$ 轨道角动量)

介子静止系中, 衰变产物动量角分布

$$\frac{dN}{d\theta^*} \propto 1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta^*$$

ρ_{00} : spin alignment

θ^* : Polar angle of daughter particle's momentum

- 夸克-介子模型有效拉氏量，强相互作用由标量与矢量介子传递

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

矢量 ϕ 介子场可以由部分子分布函数的 $s - \bar{s}$ 不对称性，或者奇异夸克流的涨落产生

- Kadanoff-Baym方程 $\rightarrow$ 矢量介子的自旋玻尔兹曼方程 $\rightarrow$ 近似求解

$$\rho_{00} \approx \frac{1}{3} - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_1 \left[\frac{1}{3} \mathbf{B}'_\phi \cdot \mathbf{B}'_\phi - (\epsilon_0 \cdot \mathbf{B}'_\phi)^2 \right] - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_2 \left[\frac{1}{3} \mathbf{E}'_\phi \cdot \mathbf{E}'_\phi - (\epsilon_0 \cdot \mathbf{E}'_\phi)^2 \right]$$

静止系中矢量 ϕ 介子场涨落的各向异性

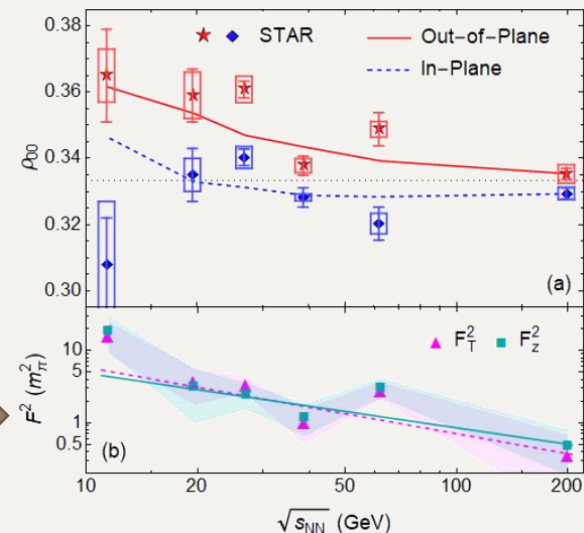
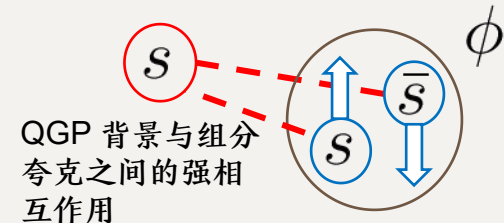
- 整体拟合实验得到碰撞质心系中的横向与纵向涨落 $\rightarrow$

L. P. Csernai, J. I. Kapusta, T. Wellwe, PRC 99, 2 (2019)

XLS, L. Oliva, Q. Wang, PRD 101, 9 (2020)

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

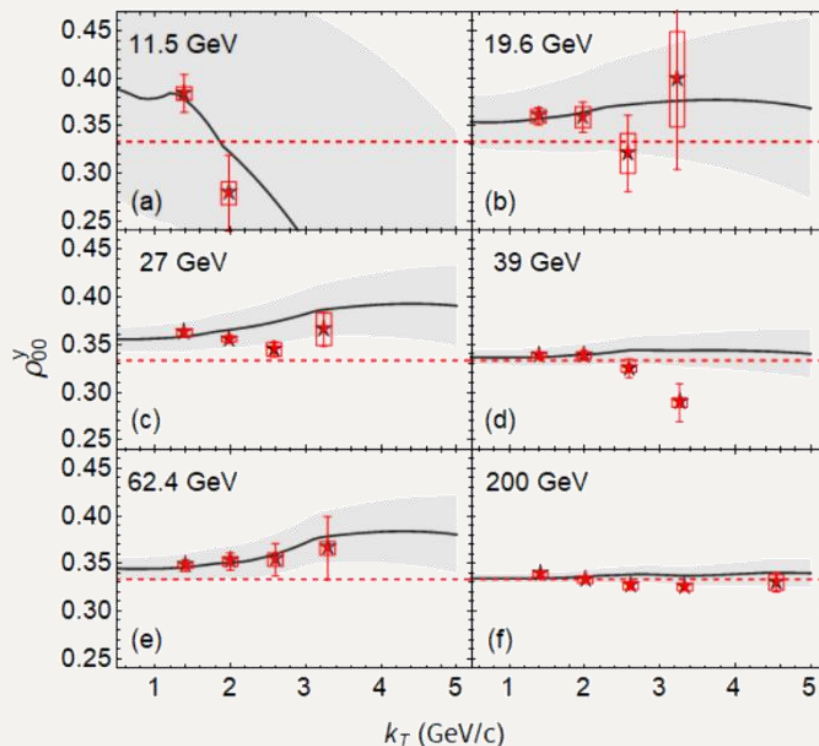
$$\begin{pmatrix} \frac{\omega + \rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega - \rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \boxed{\phi} \end{pmatrix}$$



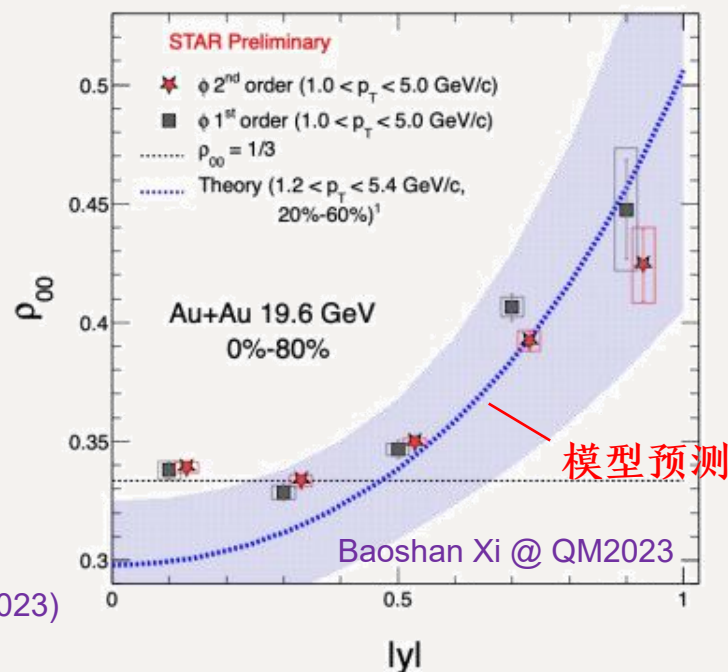
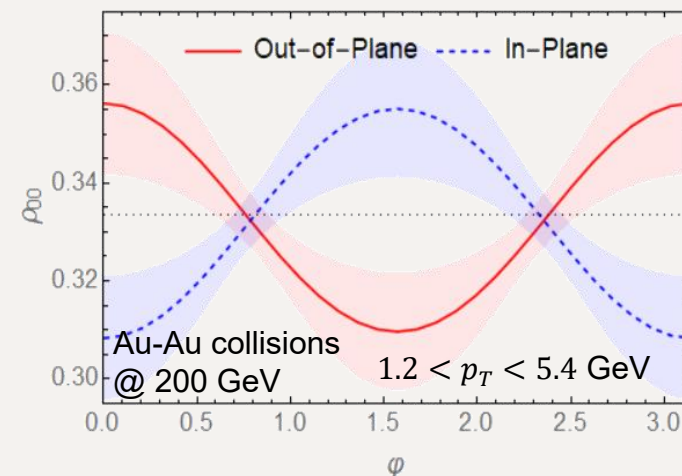
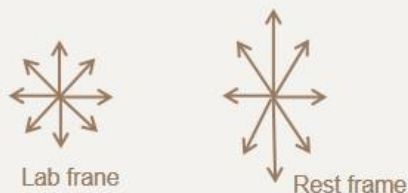
ϕ 介子自旋排列



- 模型预测：自旋排列对动量的依赖



- 主要因素：介子相对QGP导致的各向异性



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

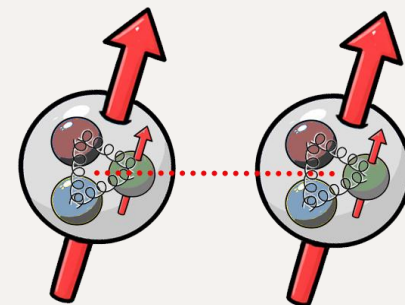
XLS, S. Pu, Q. Wang, PRC 108, 054902 (2023).

- 两粒子自旋关联的定义

$$C_{12}^{\mu\nu}(p_1, p_2) \equiv \langle P_1^\mu(x_1, p_1) P_2^\nu(x_2, p_2) \rangle \quad 4 \times 4 \text{ Lorentz tensor}$$

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

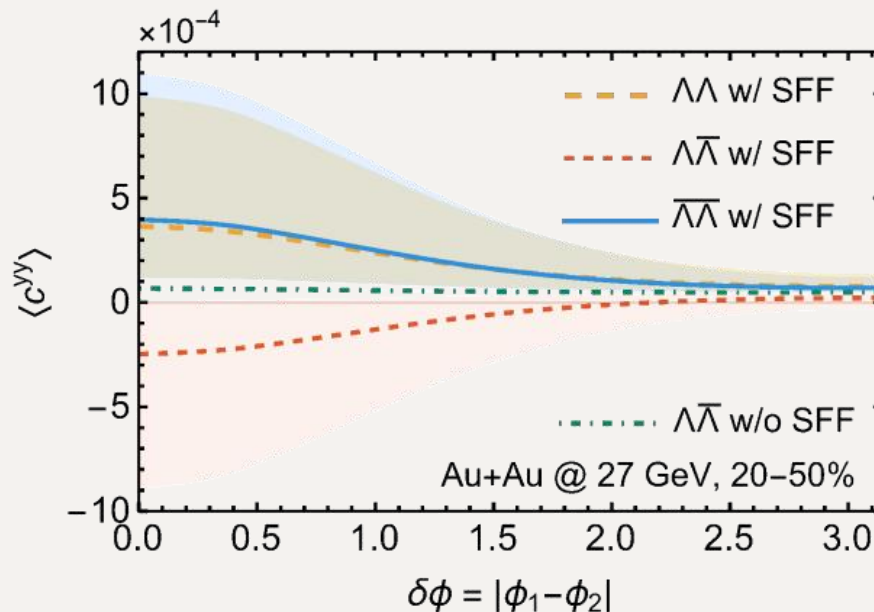
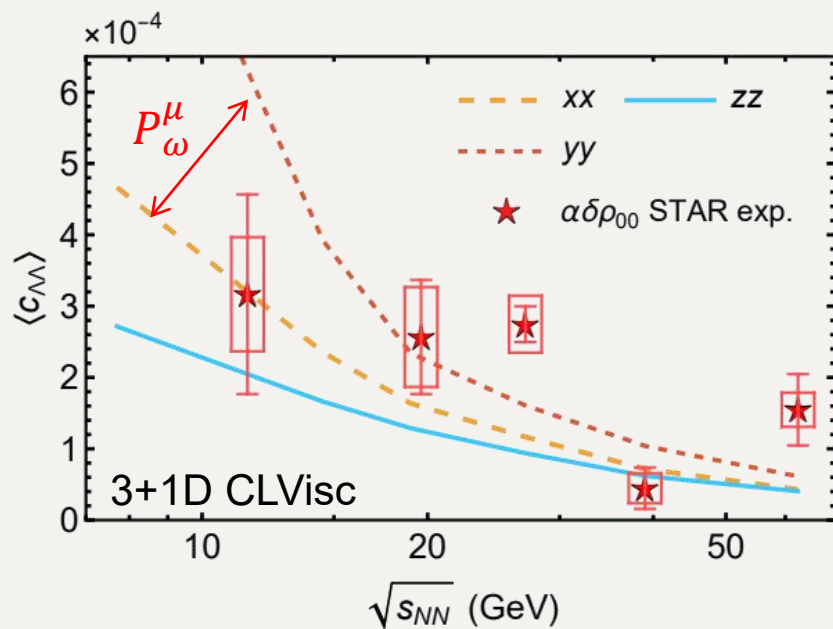
Correlation between spins in two particle's respective rest frames



- Λ 超子自旋由 s 夸克自旋给出

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

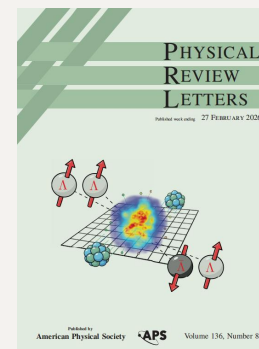
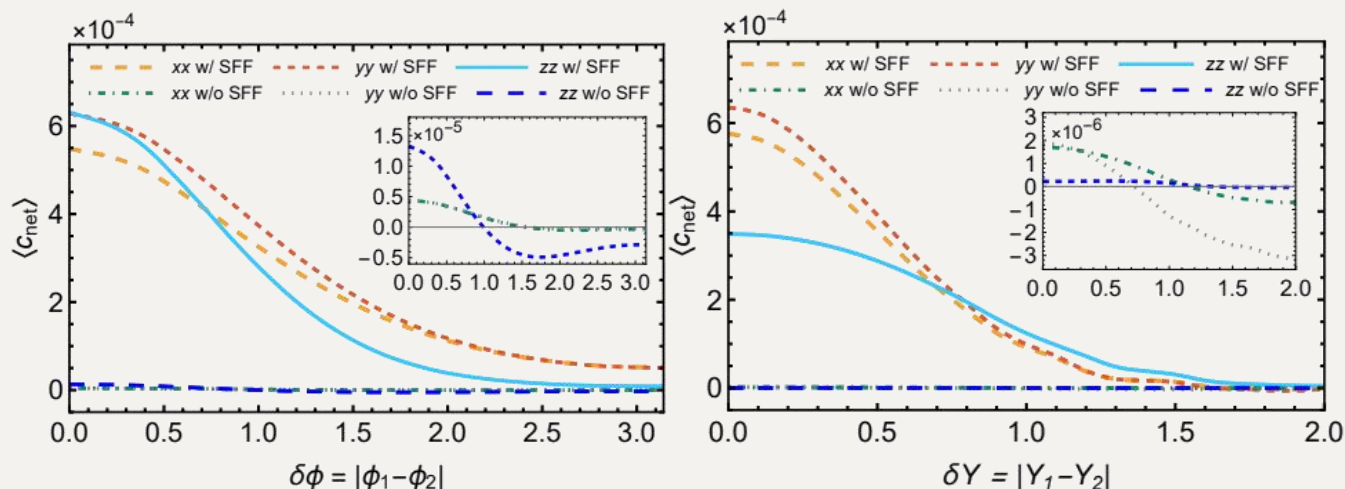
$$P_{s/\bar{s}}^\mu(x, p) = \underbrace{P_\omega^\mu + P_{\text{shear}}^\mu + P_{\text{SHE}}^\mu}_{\text{流体力学效应}} + \boxed{P_\phi^\mu} \quad \begin{array}{l} \text{Strong force field} \\ \text{(涨落由 } \phi \text{ 自旋排列拟合} \\ \text{得到)} \end{array}$$



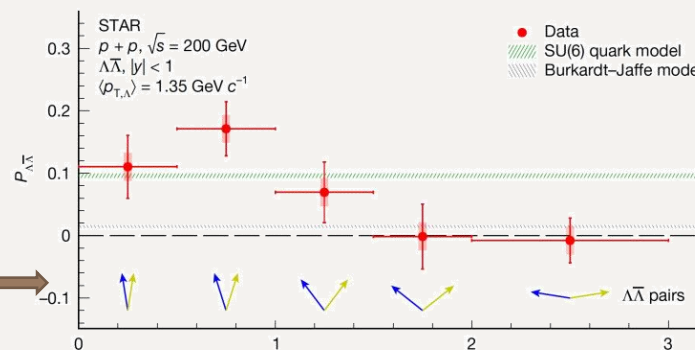
- Net spin correlation:
difference between “same-sign” and “opposite-sign” pairs

$$c_{\text{net}}^{ab} \equiv \frac{1}{2}(c_{\Lambda\Lambda}^{ab} + c_{\bar{\Lambda}\bar{\Lambda}}^{ab}) - c_{\Lambda\bar{\Lambda}}^{ab}$$

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



- 自旋关联量级很小 ($\sim 10^{-4}$)
- 流体力学效应被抑制了1-2个数量级
- 在大 $\delta\phi$ 或 δY 趋于零 (短程关联)
- $\Lambda\bar{\Lambda}$ 自旋关联在RHIC质子-质子碰撞中被观测到



STAR, Nature 650, 44-45 (2026) $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$

轻核（氧核）碰撞中的自旋？

能否通过自旋来判断原子核形状？

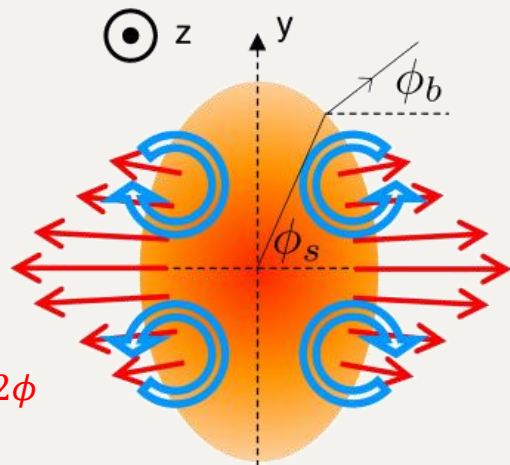
- 横平面内膨胀的各向异性



- 涡旋的四极结构

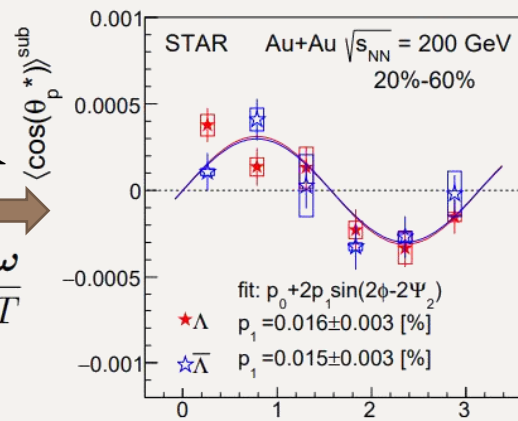


- 沿束流方向的极化 $\propto \sin 2\phi$



自旋轨道耦合

$$\mathbf{P} \simeq \frac{S+1}{3} \frac{\omega}{T}$$



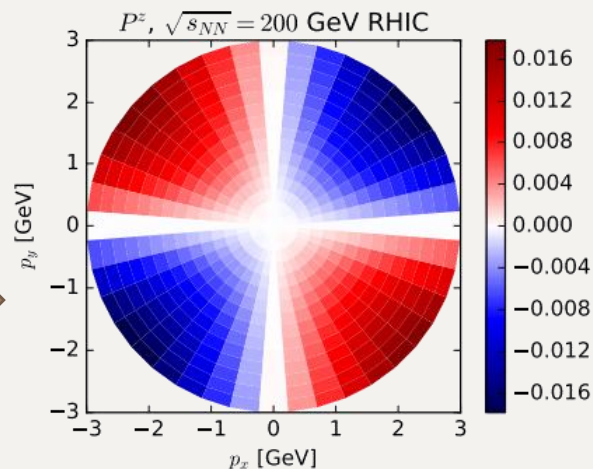
- 自旋极化的Cooper-Frye 公式

$$P^\mu(p) = -\frac{1}{8m} \epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma d\Sigma_\lambda p^\lambda \varpi_{\rho\sigma} n_F (1 - n_F)}{\int_\Sigma d\Sigma_\lambda p^\lambda n_F}$$

局域自旋极化的
“Spin sign puzzle”



3+1维
耗散流体



STAR, Nucl. Phys. A 982, 511 (2019); Phys.Rev.Lett. 123 (2019) 13, 132301.

F. Becattini, I. Karpenko, Phys.Rev.Lett. 120 (2018) 1, 012302

F. Becattini, M. Buzzegoli, G. Inghirami, I. Karpenko, and A. Palermo, Phys. Rev. Lett. 127, 272302 (2021).

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

- Shear-induced polarization $\xi_{\mu\nu} = \frac{1}{2} (\partial_\mu \beta_\nu + \partial_\nu \beta_\mu)$

$$S_{\text{shear}}^\mu(p) \left\{ \begin{array}{l} -\frac{1}{4mN_p} \epsilon^{\mu\rho\sigma\tau} p_\tau \int_\Sigma d\Sigma \cdot p n_F(1-n_F) \frac{\hat{t}_\rho}{\hat{t} \cdot p} \xi_{\sigma\lambda} p^\lambda \\ -\frac{1}{4mN_p} \epsilon^{\mu\rho\sigma\tau} p_\tau \int_\Sigma d\Sigma \cdot p n_F(1-n_F) \frac{u_\rho}{u \cdot p} \xi_{\sigma\lambda} p^\lambda \\ -\frac{1}{4mN_p} \epsilon^{\mu\rho\sigma\tau} p_\tau \int_\Sigma d\Sigma \cdot p n_F(1-n_F) \frac{n_\rho}{n \cdot p} \xi_{\sigma\lambda} p^\lambda \end{array} \right.$$

F. Becattini, M. Buzzegoli, A. Palermo, Phys.Lett.B 820 (2021) 136519

S. Liu, Y. Yin, JHEP 07 (2021) 188

Y.-C. Liu, X.-G. Huang, Sci.China Phys.Mech.Astron. 65 (2022) 7, 272011;

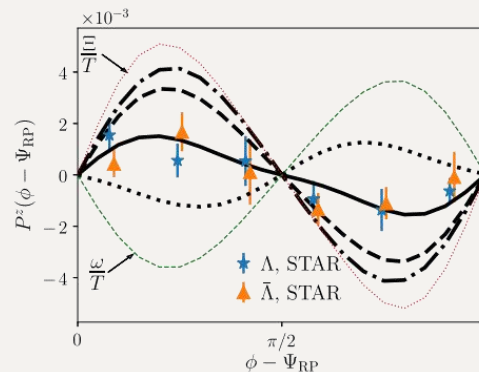
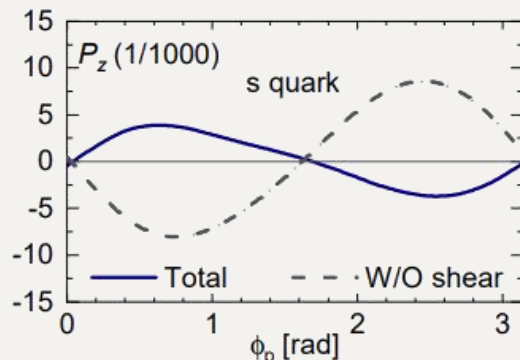
- 结合其他假设，可以较好地解释局域极化：

“Strange memory” scenario - using quark mass instead of hyperon mass

Isothermal local equilibrium - neglecting T-gradient

B. Fu, S. Liu, L. Pang, H. Song, Y. Yin, Phys. Rev. Lett. 127, 142301 (2021)

F. Becattini, M. Buzzegoli, G. Inghirami, I. Karpenko, and A. Palermo, Phys. Rev. Lett. 127, 272302 (2021).



流体压强的各向异性

三阶傅里叶系数

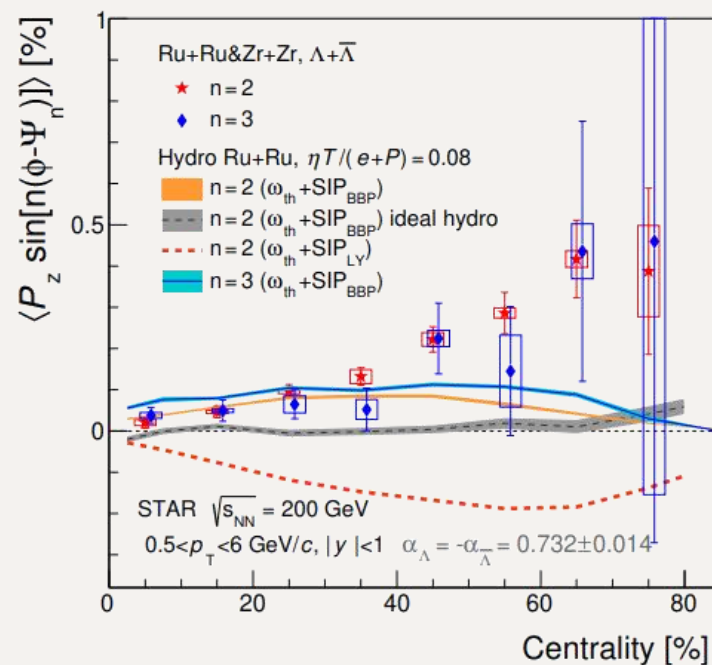
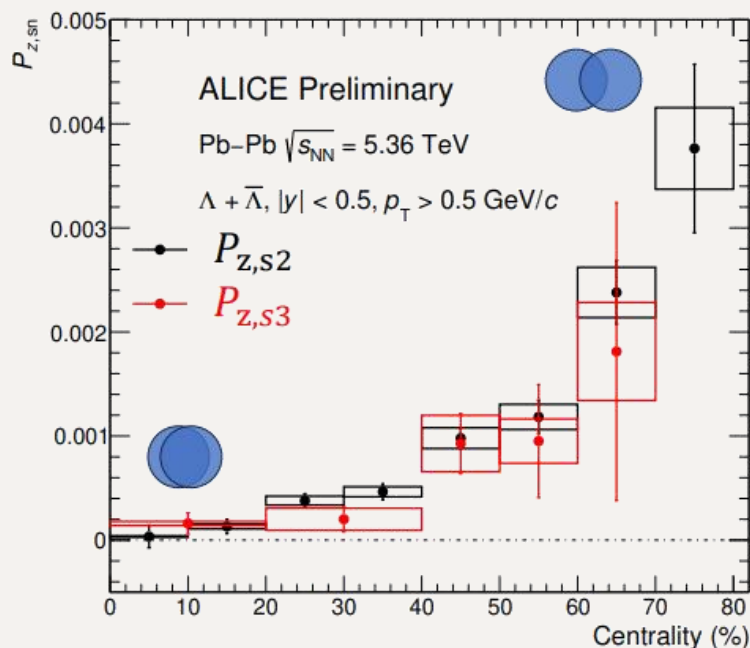
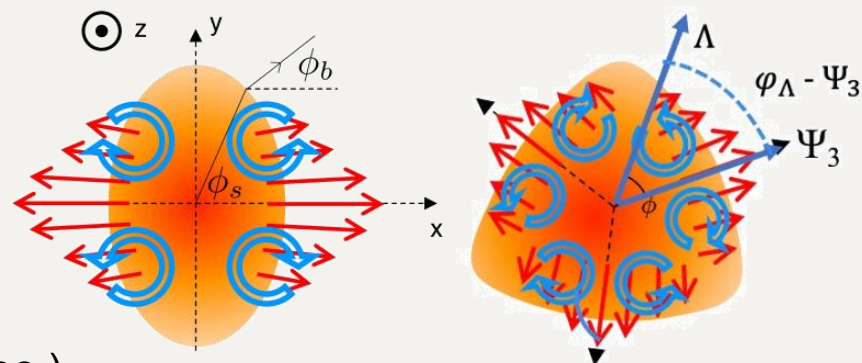


- Λ 超子沿束流方向极化的三阶傅里叶系数

└ Triangular flow originating from initial geometry

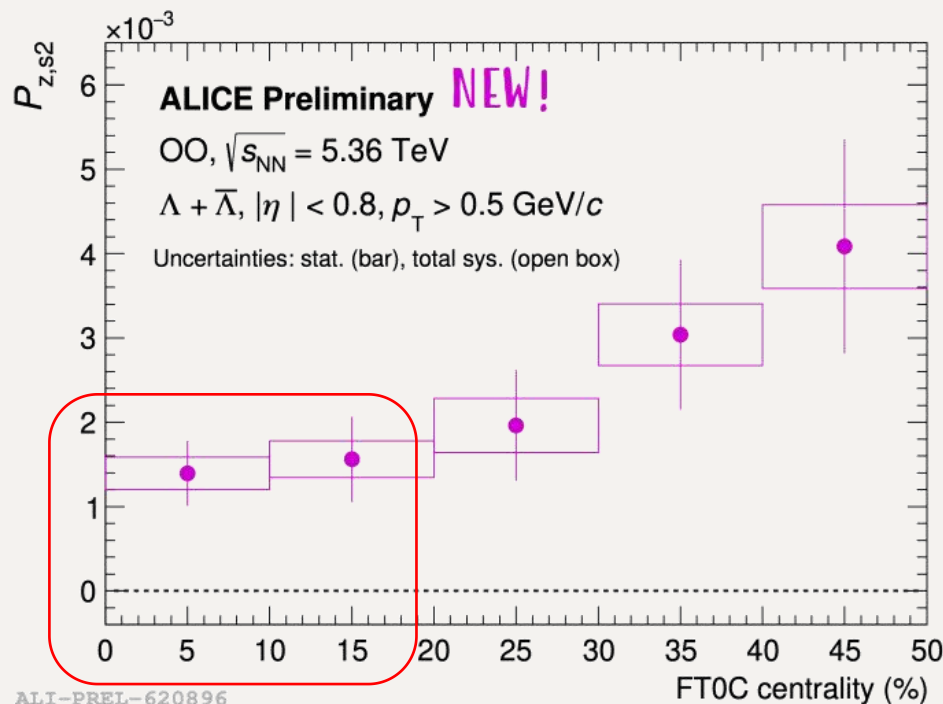
$$P_{z,sn} \propto \varepsilon_n$$

- Au-Au or Pb-Pb: $P_{z,s2} \approx P_{z,s3}$
Ru+Ru: $P_{z,s2} \approx P_{z,s3}$ (exp.) $P_{z,s2} < P_{z,s3}$ (theo.)

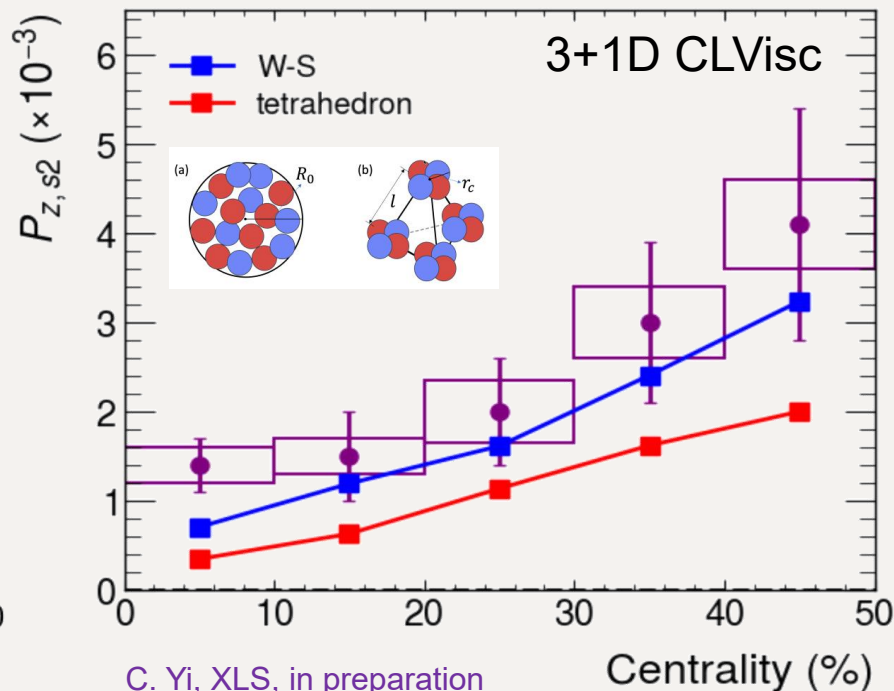


氧氧碰撞中的局域极化

- 中心碰撞区，局域极化大于零 $\longrightarrow$ 原子核形状导致
- Woods-Saxon 分布产生了更大的 P_z ，更接近实验结果
- 四面体结构可能使得 $P_{z,s3}/P_{z,s2} > 1$? (数值计算正在进行中)



Chiara de Martin @ Rencontres de Moriond 2026



C. Yi, XLS, in preparation

Fig. for nucleon structures: X.-L. Zhao, Z.-W. Lin, Y. Zhou, C. Zhang, G.-L. Ma, PLB 874, 140254 (2026)

- 氧氧碰撞中的夸克自旋

➡ 矢量介子自旋排列或超子自旋关联?

$$\rho_{00}^y \approx \frac{1}{3} + \frac{2}{9} \langle P_q^x P_{\bar{q}}^x + P_q^z P_{\bar{q}}^z - 2P_q^y P_{\bar{q}}^y \rangle$$

$$\text{Re} \rho_{1,-1}^y \approx \frac{1}{3} \langle P_q^z P_{\bar{q}}^z - P_q^x P_{\bar{q}}^x \rangle$$

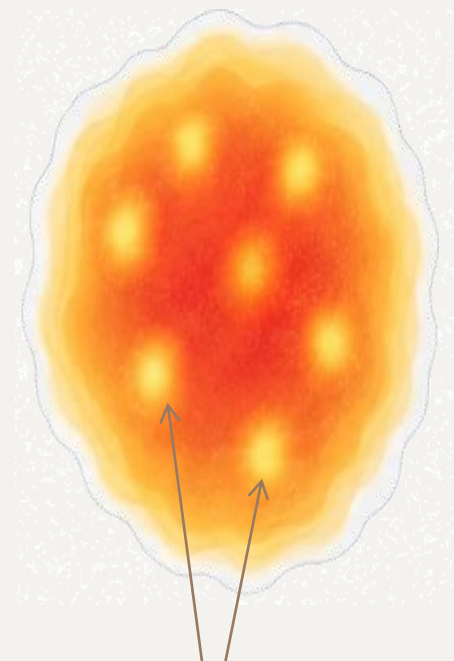
$$\text{Im} \rho_{1,-1}^y \approx -\frac{1}{3} \langle P_q^z P_{\bar{q}}^x + P_q^x P_{\bar{q}}^z \rangle$$

$$\text{Re}(\rho_{10}^y - \rho_{-1,0}^y) \approx \frac{\sqrt{2}}{3} \langle P_q^y P_{\bar{q}}^z + P_q^z P_{\bar{q}}^y \rangle$$

$$\text{Im}(\rho_{10}^y - \rho_{-1,0}^y) \approx -\frac{\sqrt{2}}{3} \langle P_q^y P_{\bar{q}}^x + P_q^x P_{\bar{q}}^y \rangle$$

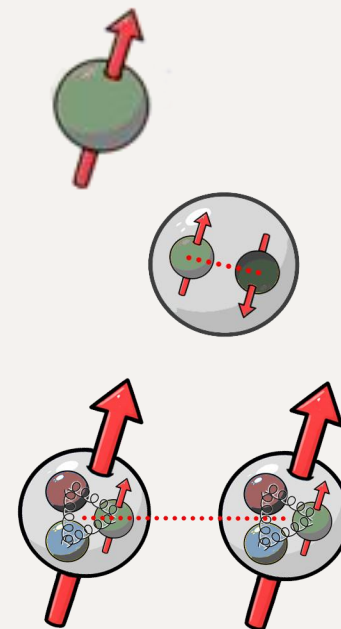
$$\langle P_\Lambda P_\Lambda \rangle = \langle P_s P_s \rangle + \mathcal{O}[(P_q)^4]$$

- 初始核的 α 集团在QGP中产生更强的hot spot 结构
 - 更强的能量密度涨落
 - 比金金碰撞中更明显的自旋关联或自旋排列?
 - 数值模拟正在进行中
- 火球几何与尺寸的影响?



Hot spots

- 夸克或超子自旋极化
 - 涡旋场或shear-stress导致
 - 局域极化与初始的横向几何形状相关
- 矢量介子自旋排列
 - 夸克短程关联的各向异性
 - 强相互作用场的涨落导致（矢量介子场或胶子场）
- 超子自旋关联
 - 可以区分自旋关联的产生机制
- 氧氧碰撞中的自旋极化或关联，可能为研究氧原子核形状提供新的实验信号



Thanks for your attention!

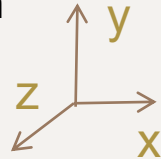
Backup

Quark spin correlation



- Local polarization

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



- Spin correlation in quantization direction

$\uparrow\uparrow$

$$\rho_{00}^y < \frac{1}{3}$$

$$(\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \quad \rho_{00}^y > \frac{1}{3}$$

- Spin correlation in transverse direction

$$\rightarrow\rightarrow = \frac{1}{2}(\uparrow\uparrow + \downarrow\downarrow) + \frac{1}{\sqrt{2}} \left[\frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow) \right] \quad \begin{cases} S_y = +1 & 1/4 \\ S_y = 0 & 1/2 \\ S_y = -1 & 1/4 \end{cases} \quad \begin{cases} \rho_{00}^y > \frac{1}{3} & \langle P_q^x P_{\bar{q}}^x \rangle > 0 \\ & \langle P_q^y P_{\bar{q}}^y \rangle = 0 \end{cases}$$

$$\frac{1}{\sqrt{2}}(\rightarrow\leftarrow + \leftarrow\rightarrow) = \frac{1}{\sqrt{2}}(\uparrow\uparrow - \downarrow\downarrow) \quad \begin{cases} S_y = +1 & 1/2 \\ S_y = 0 & 0 \\ S_y = -1 & 1/2 \end{cases} \quad \rho_{00}^y < \frac{1}{3}$$

- Spin alignment $\longleftrightarrow$ Anisotropy of spin correlation

$$\rho_{00} = \frac{1}{3} + \frac{4}{9} \left[\frac{1}{2} \langle \mathbf{P}_q^T \cdot \mathbf{P}_{\bar{q}}^T \rangle - \langle P_q^L P_{\bar{q}}^L \rangle \right]$$

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 $\begin{cases} \text{Significant } q\bar{q} \text{ spin correlation} \\ \text{No spin alignment} \end{cases}$

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

Non-relativistic

- Kadanoff-Baym equation $\longrightarrow$ Matrix-form Boltzmann equation

$$k \cdot \partial_x f_{\lambda_1 \lambda_2}^V(x, \mathbf{k}) = \frac{1}{8} [\epsilon_\mu^*(\lambda_1, \mathbf{k}) \epsilon_\nu(\lambda_2, \mathbf{k}) C_{\text{coal}}^{\mu\nu}(x, \mathbf{k}) - f_{\lambda_1 \lambda_2}^V(x, \mathbf{k}) C_{\text{diss}}(x, \mathbf{k})]$$

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)

$$C_{\text{coal}}^{\mu\nu}(x, \mathbf{k}) = \int \frac{d^3 \mathbf{p}'}{(2\pi\hbar)^2} \frac{1}{E_{\mathbf{p}'}^{\bar{q}} E_{\mathbf{k}-\mathbf{p}'}^q} \delta(E_{\mathbf{k}}^V - E_{\mathbf{p}'}^{\bar{q}} - E_{\mathbf{k}-\mathbf{p}'}^q) \times \text{Tr} \{ \Gamma^\nu (p' \cdot \gamma - m_{\bar{q}}) [1 + \gamma_5 \gamma \cdot P^{\bar{q}}(x, \mathbf{p}')] \times \Gamma^\mu [(k - p') \cdot \gamma + m_q] [1 + \gamma_5 \gamma \cdot P^q(x, \mathbf{k} - \mathbf{p}')] \} \times f_{\bar{q}}(x, \mathbf{p}') f_q(x, \mathbf{k} - \mathbf{p}'),$$

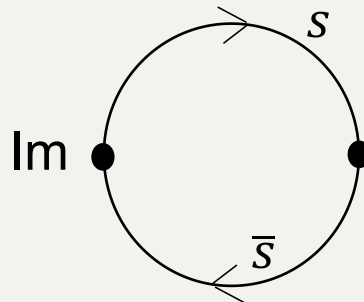
Energy conservation

$q\bar{q}V$
vertex

Polarizations of
quark/antiquark

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

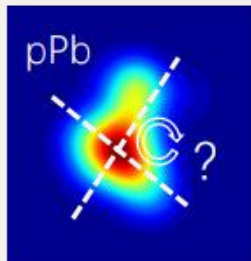
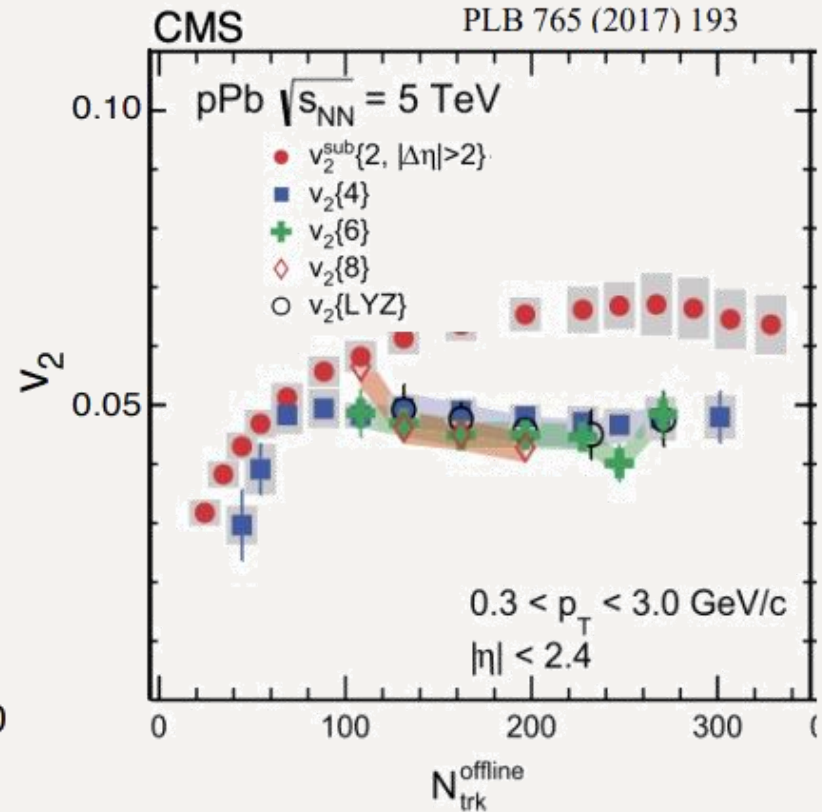
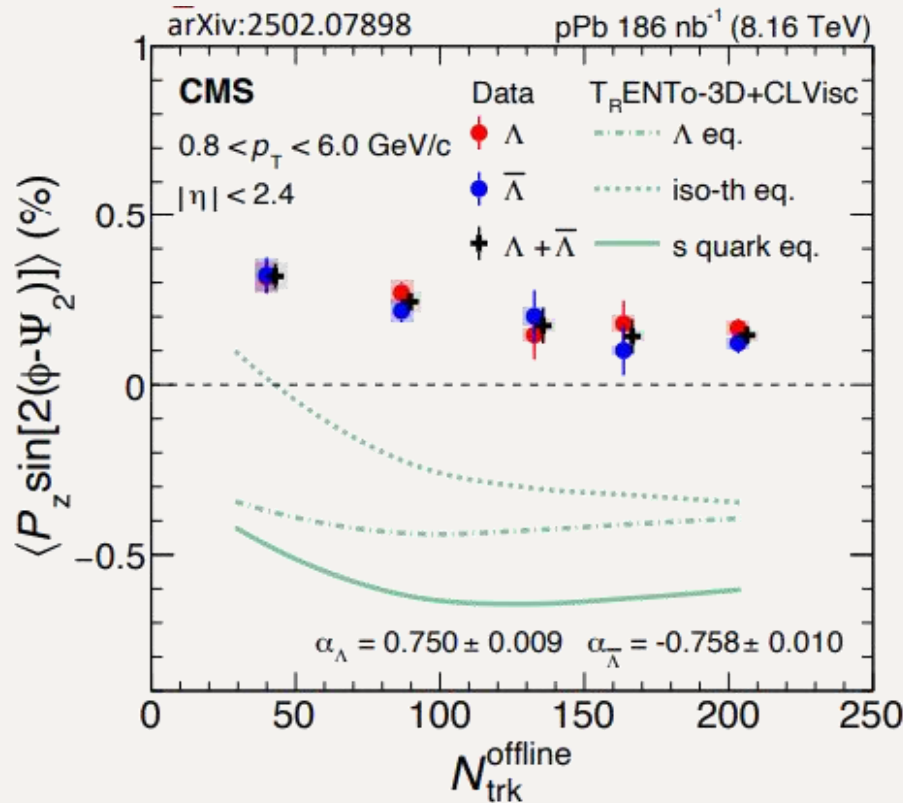
- Cutting rule:**
Probability of
 $s + \bar{s} \rightarrow \phi$ is
related to



Quark's full propagator

$$\begin{aligned} & \text{Free} \quad \text{First order} \quad \text{Higher orders...} \\ & \xrightarrow{s} + \xrightarrow{\phi} + \xrightarrow{K^{*+}} + \xrightarrow{K^{*-}} + \dots \\ & \propto (\gamma \cdot p + m)(1 + \gamma_5 \gamma \cdot P_q) \end{aligned}$$

Experiment results



- Quadrupole structure of vorticity?
- Not consistent with trend of v_2
- Not consistent with hydro calculation

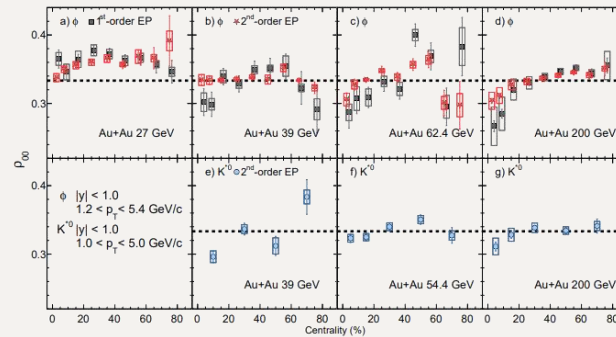
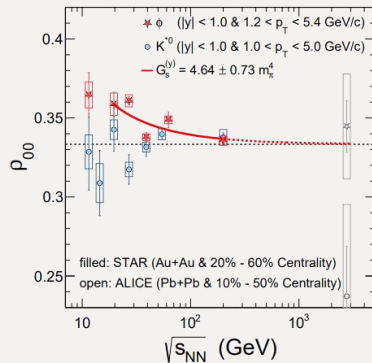
C. Yi, X.-Y. Wu, J. Zhu, S. Pu, G.-Y. Qin, Phys.Rev.C 111, 044901 (2025)

Experiment results



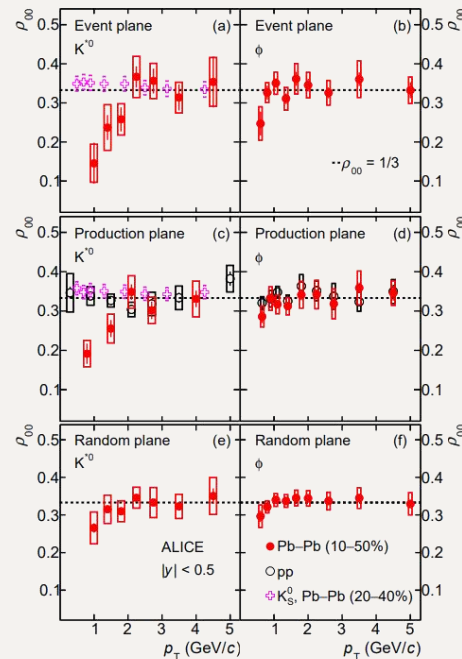
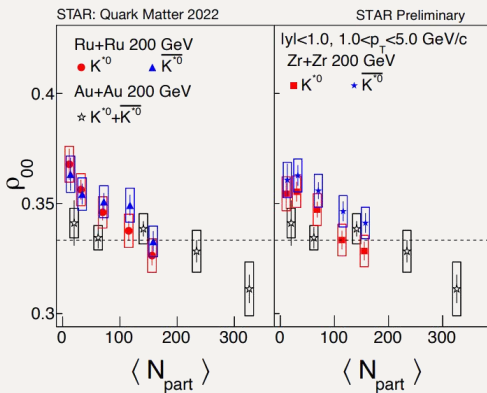
• ϕ and K^{*0} @ RHIC

STAR, Nature 614, 244 (2023)



• K^{*0} @ RHIC Isobar

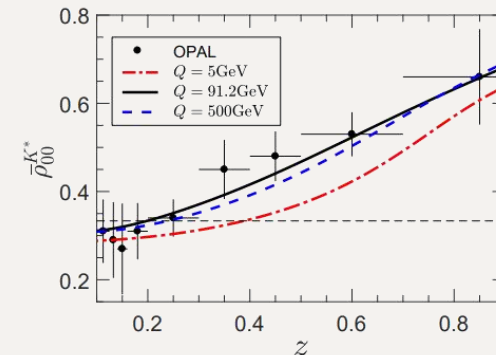
STAR Preliminary @ QM2022



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)



Meson spin alignment
varies across different
colliding systems

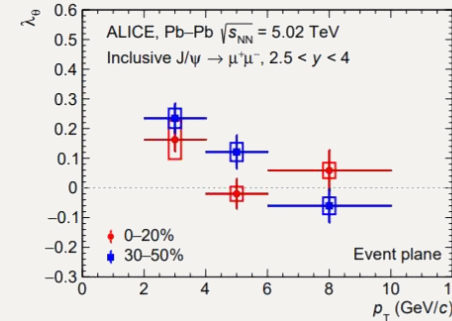
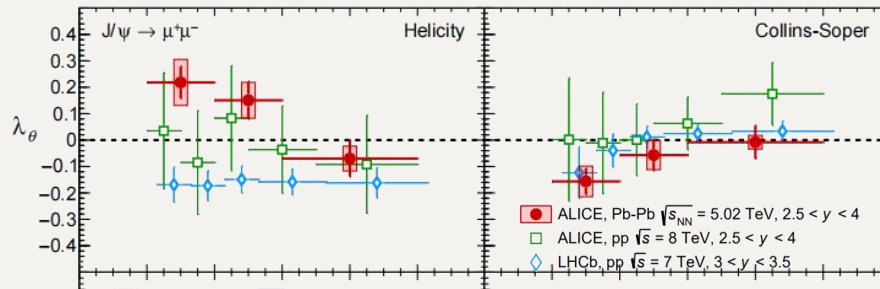
ϕ and K^{*0} @ LHC

ALICE, PRL 125,
012301 (2020)

Experiment results



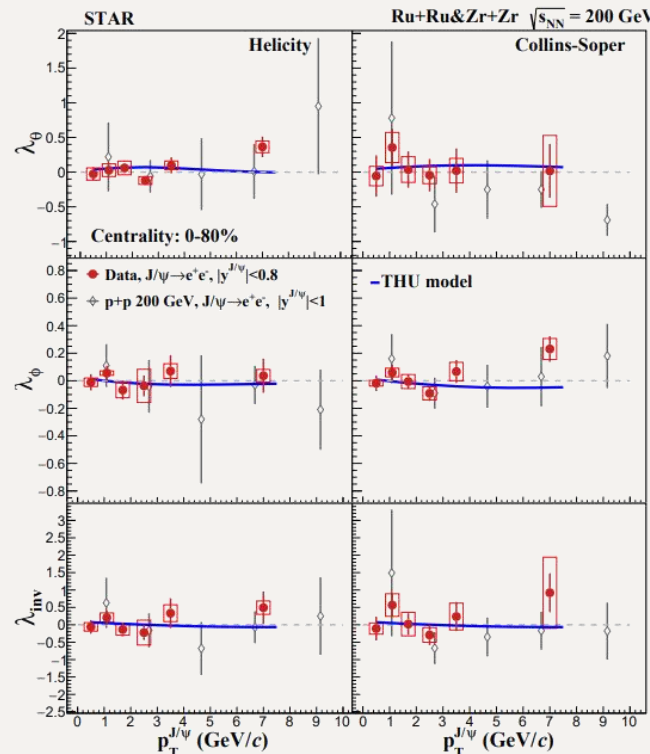
- Spin alignment of J/ψ @ LHC ALICE, PLB 815, 136146 (2021); PRL 131, 042303 (2023)



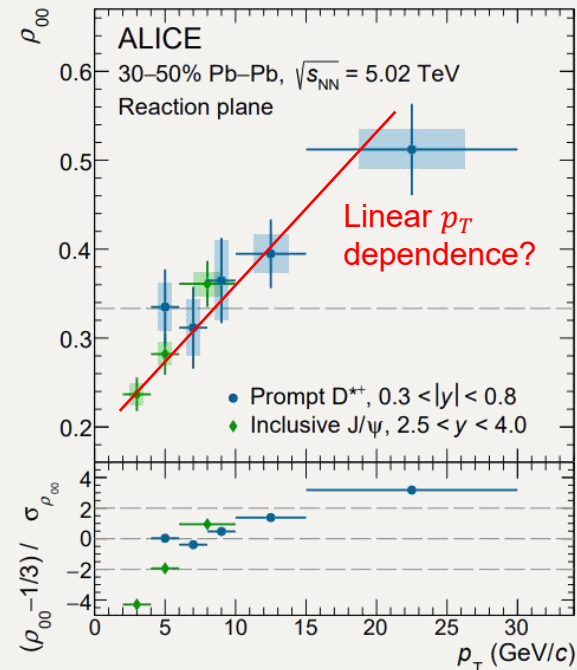
$$\rho_{00} < 1/3$$

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

STAR, arXiv:
2604.07005



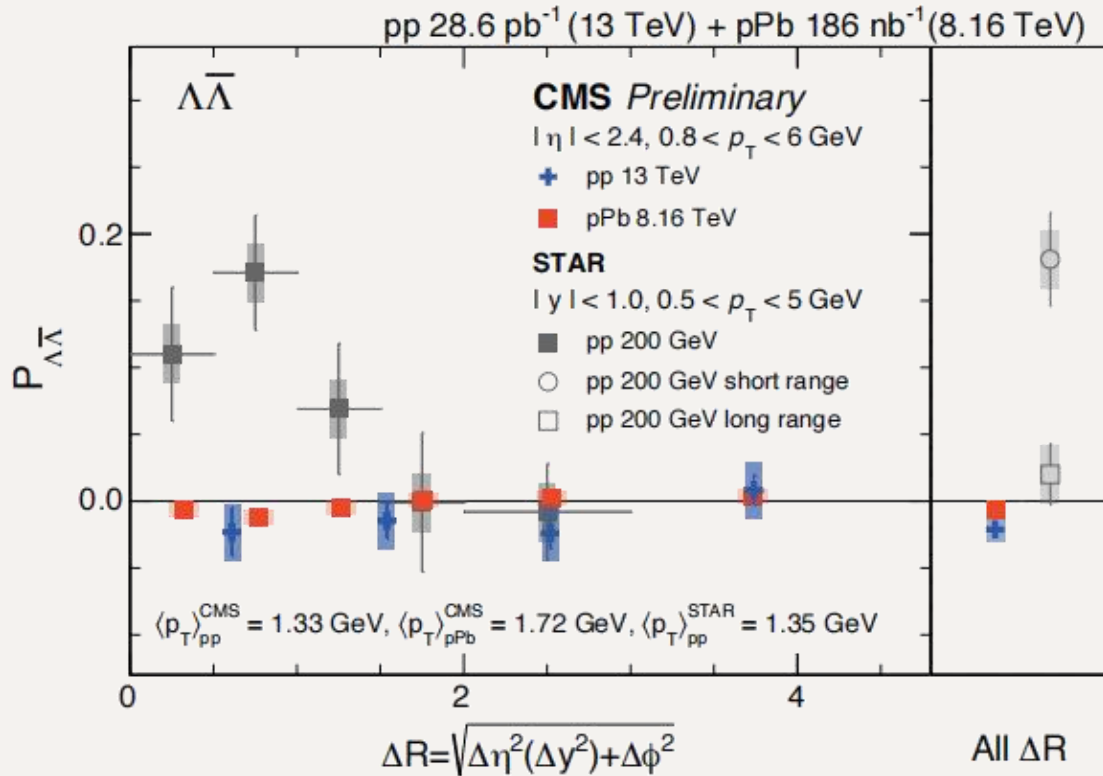
- Spin alignment of D^{*0} @ LHC



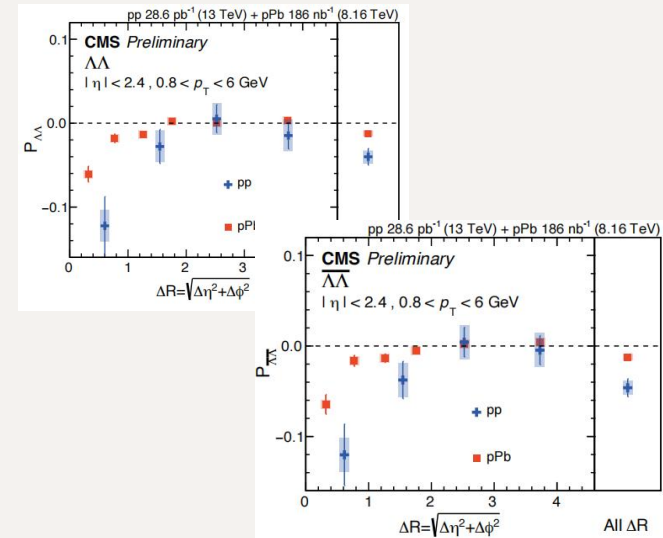
Experiment results



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



pp 13 TeV
pp 200 GeV
pPb 8.16 TeV



Jieke Wang @ DIS2026

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

Top-quark pair

- Spin density matrix of a top-quark pair

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

Polarization of $t, \bar{t}$

Spin correlation

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

- Measured through angular distribution

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

$t \rightarrow b + W$

Weak decay

