Review of polarization in heavy ion collisions at STAR

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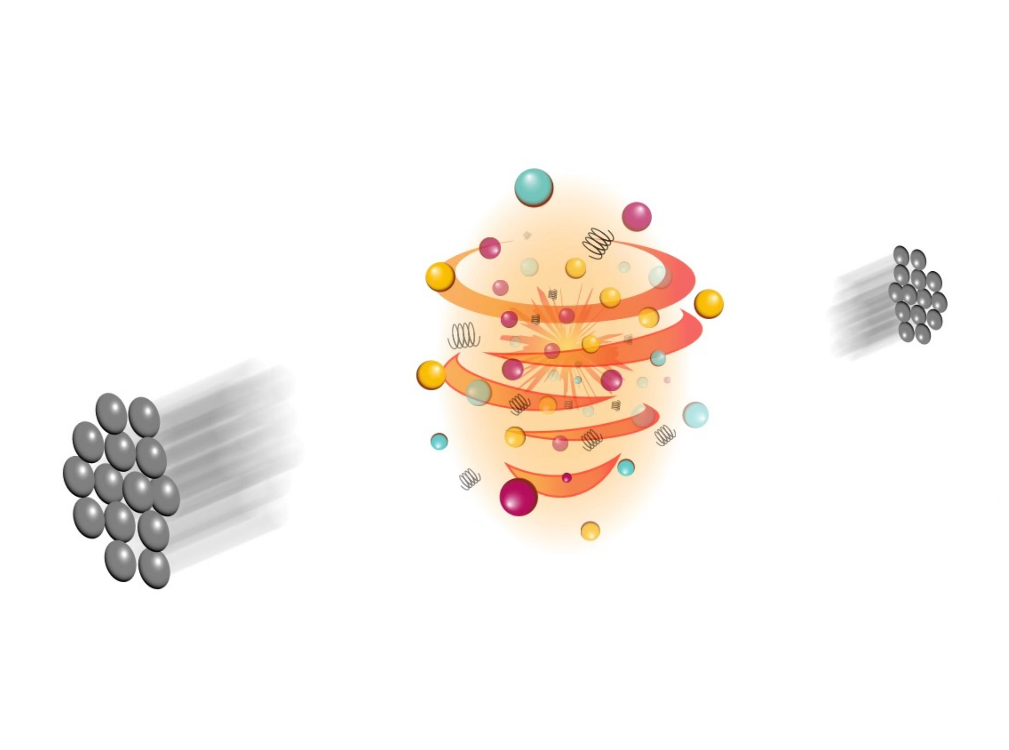
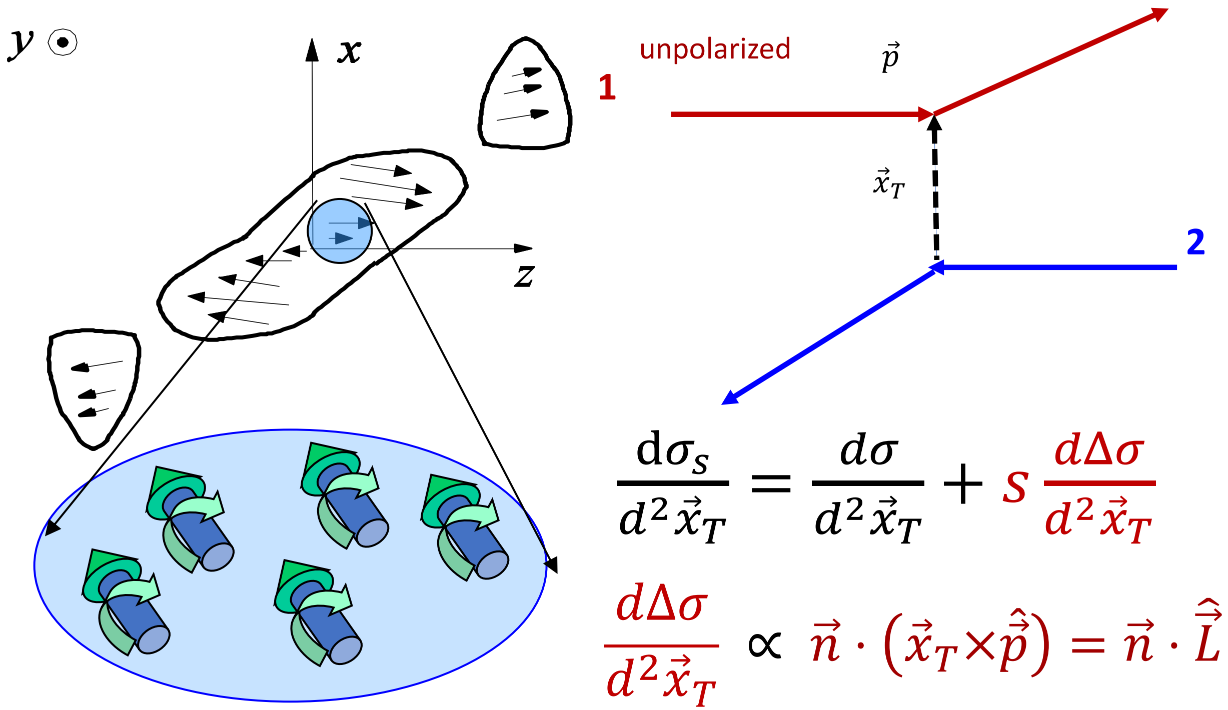
"The 1st Conference on Strong-Interaction Spin Physics"

Qingdao, 2026/7/26-31

New phenomenon: global pol. in HIC

Liang and Wang Phys. Rev. Lett. **94**, 102301 (2005); Phys. Lett. B **629**, 20 (2025)





$$\frac{d\sigma_s}{d^2\vec{x}_T} = \frac{d\sigma}{d^2\vec{x}_T} + s\,\frac{d\Delta\sigma}{d^2\vec{x}_T}$$

$$\frac{d\Delta\sigma}{d^2\vec{x}_T} \propto \vec{n}\cdot(\vec{x}_T\times\hat{\vec{p}}) = \vec{n}\cdot\hat{\vec{L}}$$

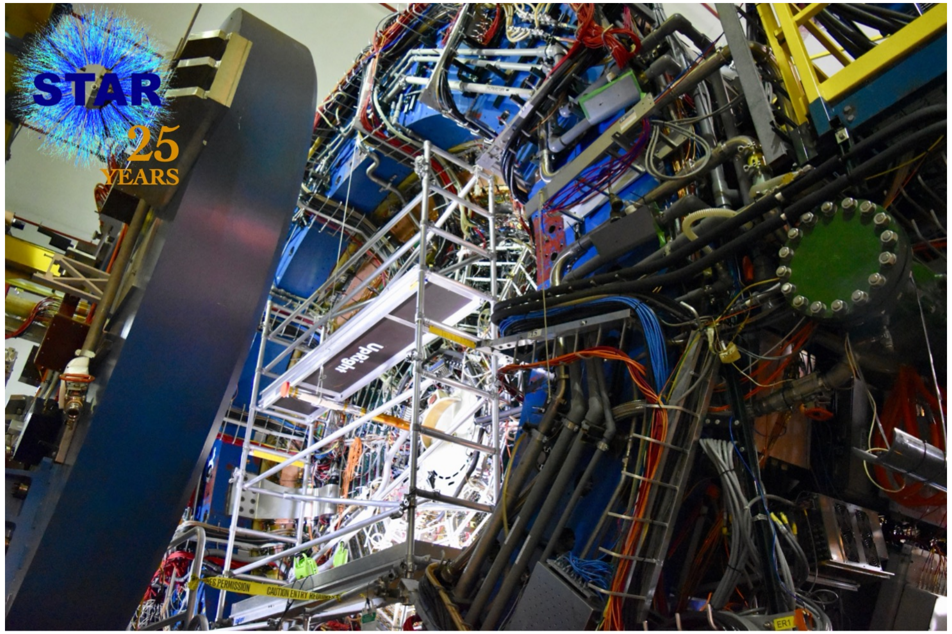
- Produced partons are shown to have large local relative OAM in noncentral heavy-ion collisions.
- Parton scattering with given relative OAM is shown to polarize quarks along the same direction due to spin-orbit coupling.
- Such global quark polarization has many measurable consequences in high-energy heavy-ion collisions.

Measurable consequences of Λ polarization

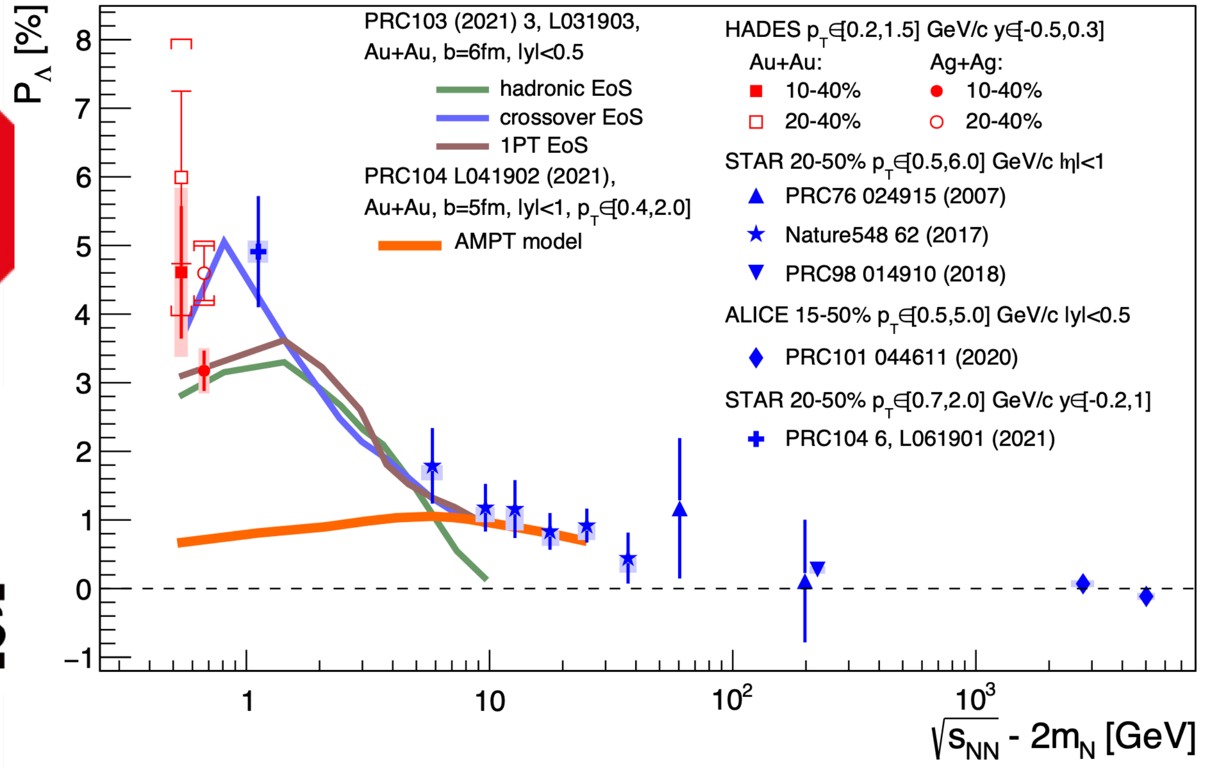
- The idea has yielded an active 20-year collective efforts in experimental and theoretical side.

Liang and Wang, PRL (2005) Inspire 693, STAR Col., Nature (2017) Inspire 1081

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1+\alpha_H|\mathcal{P}_H|\cos\theta^*\right) \qquad \overline{\mathcal{P}}_H \equiv \langle \mathcal{P}_H \cdot \hat{J}_{sys}\rangle = \frac{8}{\pi\alpha_H}\frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{sys}}\right)\right\rangle}{R_{EP}^{(1)}}$$



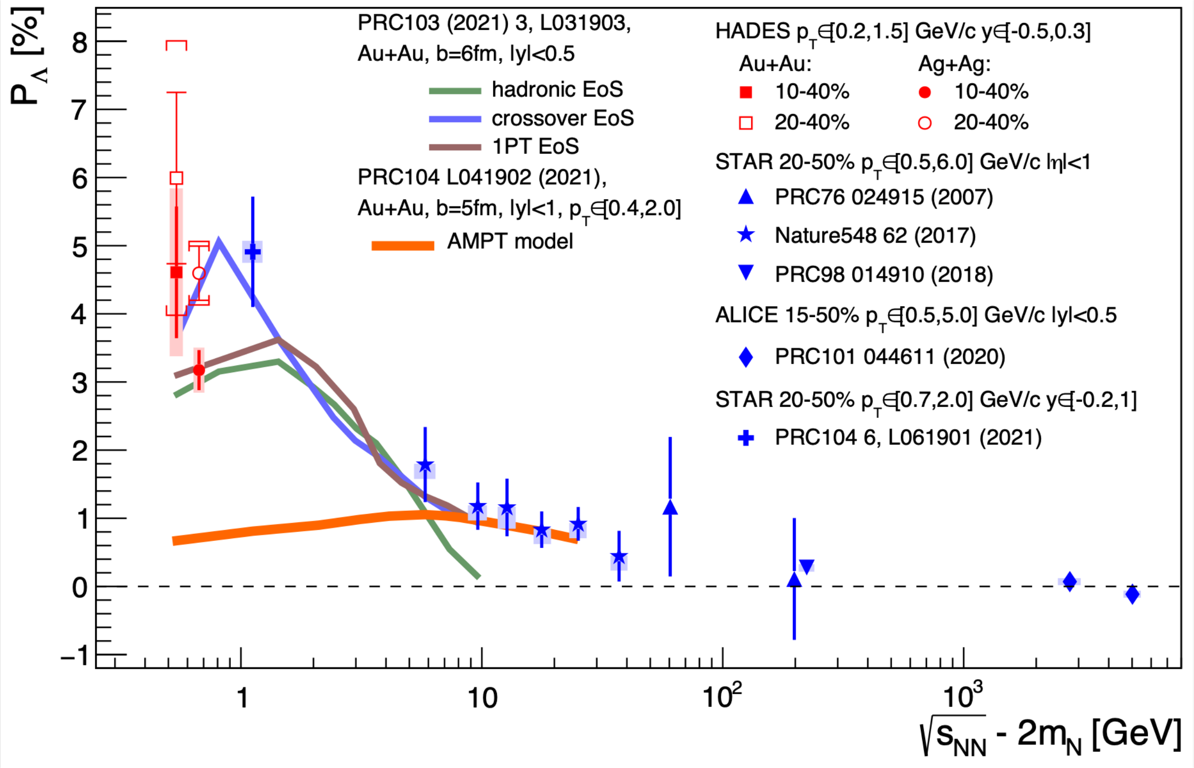
HADES

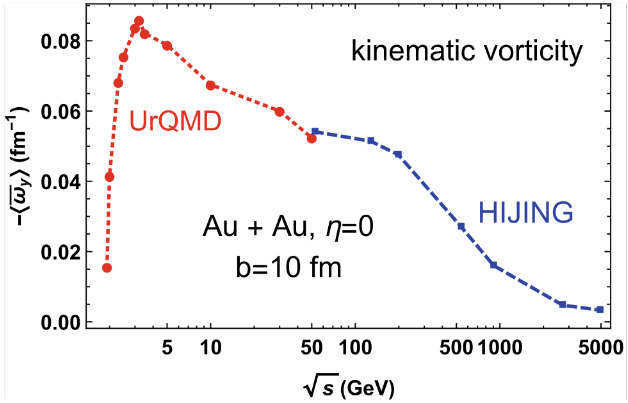


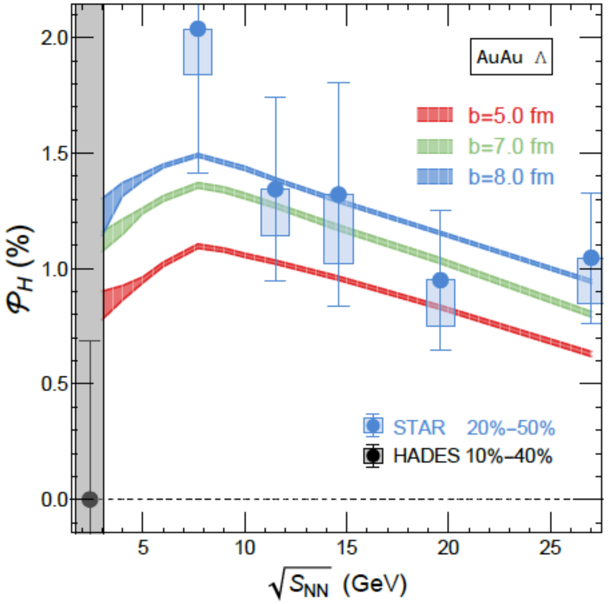
A collection of data show global polarization in broad energy range, and identify the most vortical fluid ever created.

Λ polarization: energy dept. or independent

HADES Col. Phys. Lett. B **835**, 137506 (2022)





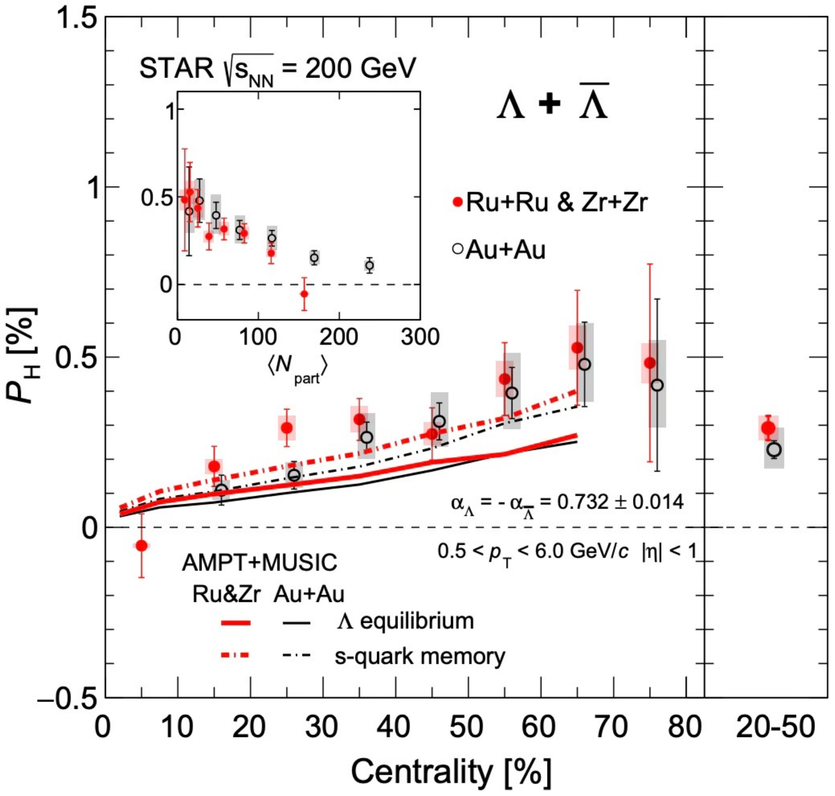


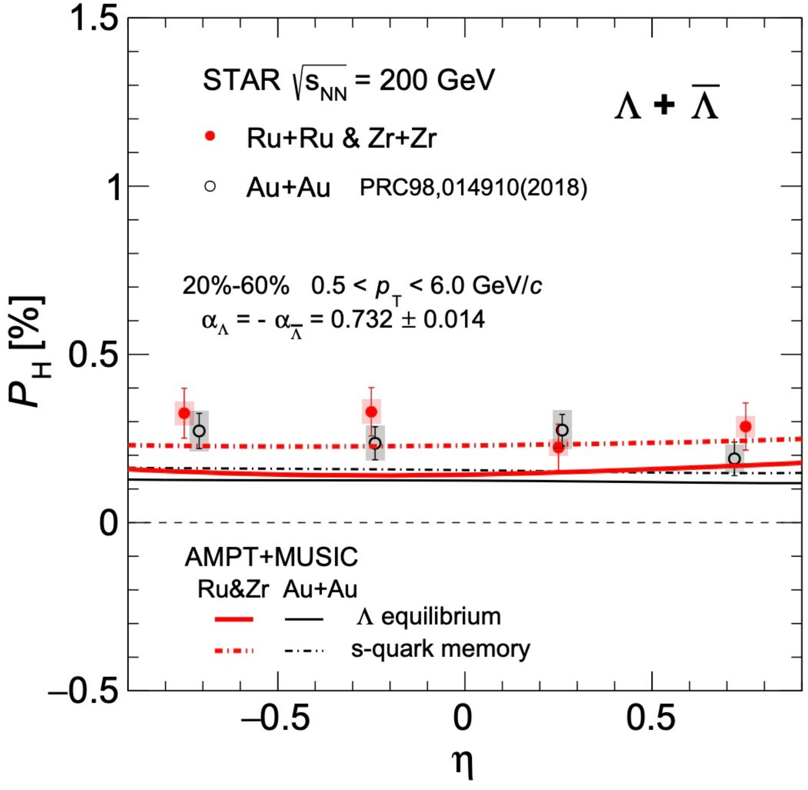
Deng, Huang, Ma, Zhang Phys. Rev. C **101**, 064908 (2020)
Guo, Liao, Wang, Xing, Zhang Phys. Rev. C **104**, L041902 (2021)
Wu, Yi, Qin, Pu, Phys. Rev. C **105**, 064909 (2022)
(HADES data, Springer Proc. Phys. 250, 435 (2020))
…

- Lambda polarization at 1-10 GeV presents strong energy dependence, which was described by the fluid dynamics, while transport model AMPT described the BES-I data was lower than data at 1 GeV.
- How to understand the underlying physics, is there any turn over point at lower energies?

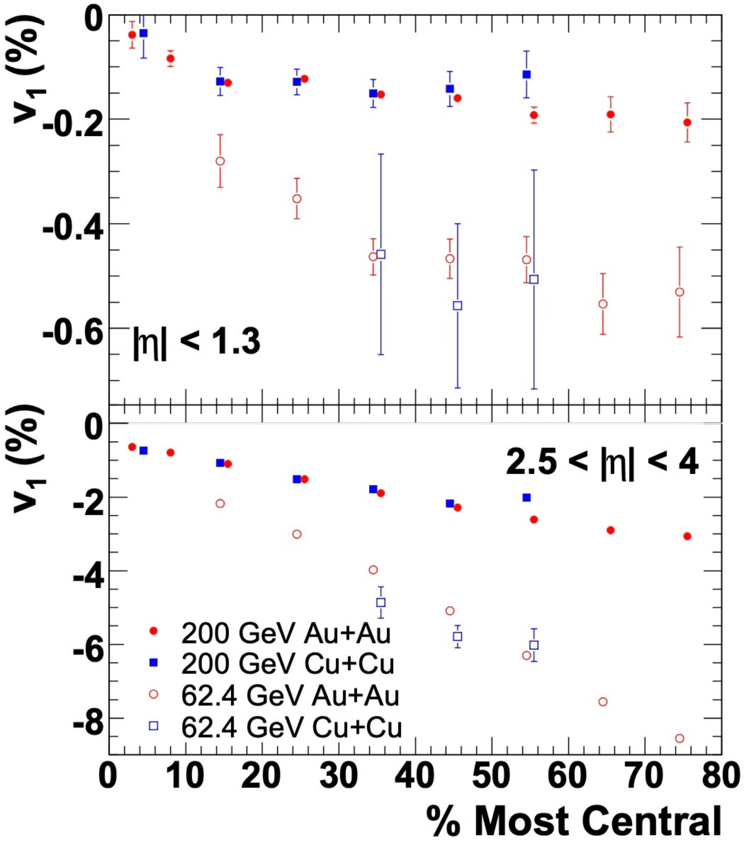
Λ polarization: system size dept. or independent

STAR Col., Phys. Lett. B **870**, 139891 (2025)



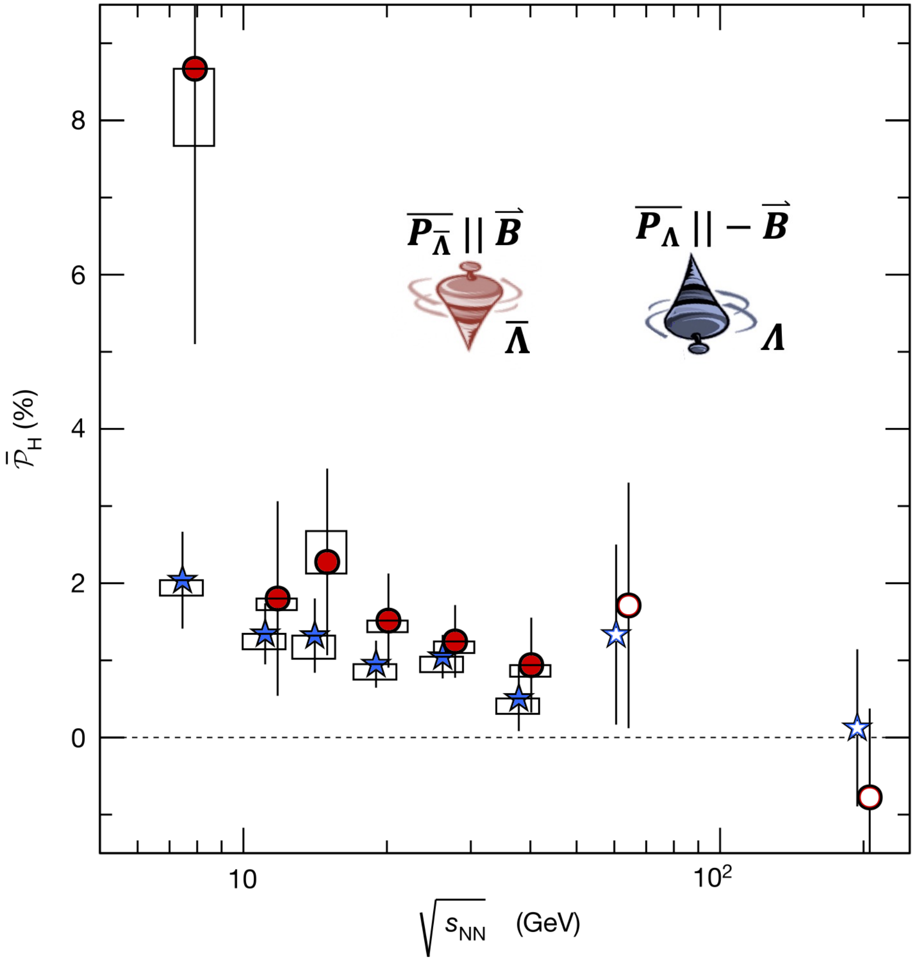


STAR Col., Phys. Rev. Lett. **101**, 252301 (2008)

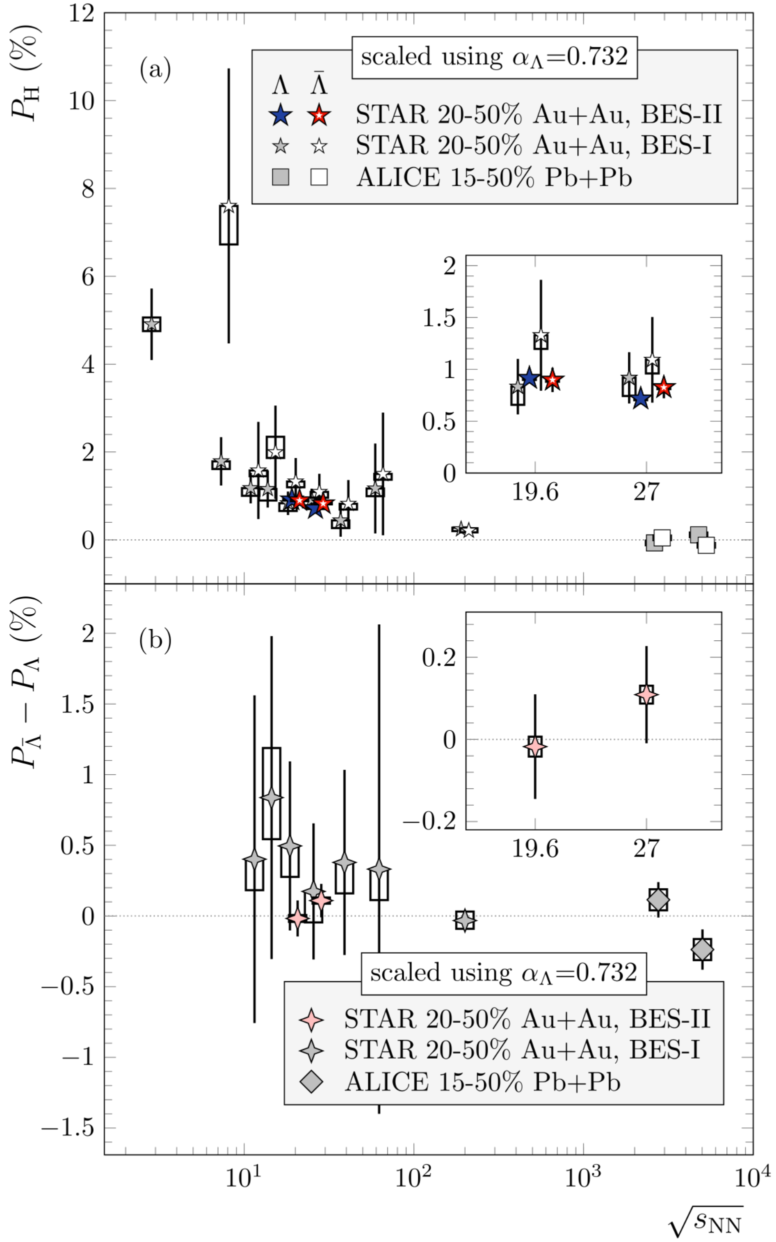


- System size independence?
- Both polarization and directed flow show system size independence
  - physics or coincidence?

Measurable consequences of Λ polarization splitting



$$|B| \approx \frac{T_s |P_{\bar{\Lambda}} - P_{\Lambda}|}{2|\mu_{\Lambda}|}$$



STAR Col. Nature **548**, 62 (2017);
STAR Col., Phys. Rev. C **108**, 014910 (2023)

- High statistics BES-II data, 19.6 and 27 GeV
  - -0.018 ± 0.127 (stat.) ± 0.024 (syst.)

    $B < 9.4 \times 10^{12}$ T
  - 0.109 ± 0.118 (stat.) ± 0.022 (syst.)

    $B < 1.4 \times 10^{13}$ T

Λ polarization splitting: B-field vs. meson?

Csernai, Kapusta, Welle, Phys. Rev. C **99**, 021901(R) (2019)

- Interactions of baryons with mesons can result in a splitting of the polarization of Lambdas in high energy heavy ion collisions.

$$H^V_{\text{spin-orbit}} = \frac{g_{V\Lambda}}{2m_\Lambda^2}\frac{1}{r}\frac{\partial V_0}{\partial r}\boldsymbol{S}\cdot\boldsymbol{L}, \qquad (5) \qquad\qquad H^\sigma_{\text{spin-orbit}} = \frac{g_{\sigma\Lambda}}{2m_\Lambda^2}\boldsymbol{S}\cdot\boldsymbol{\nabla}\sigma\times\boldsymbol{p}, \qquad (6)$$

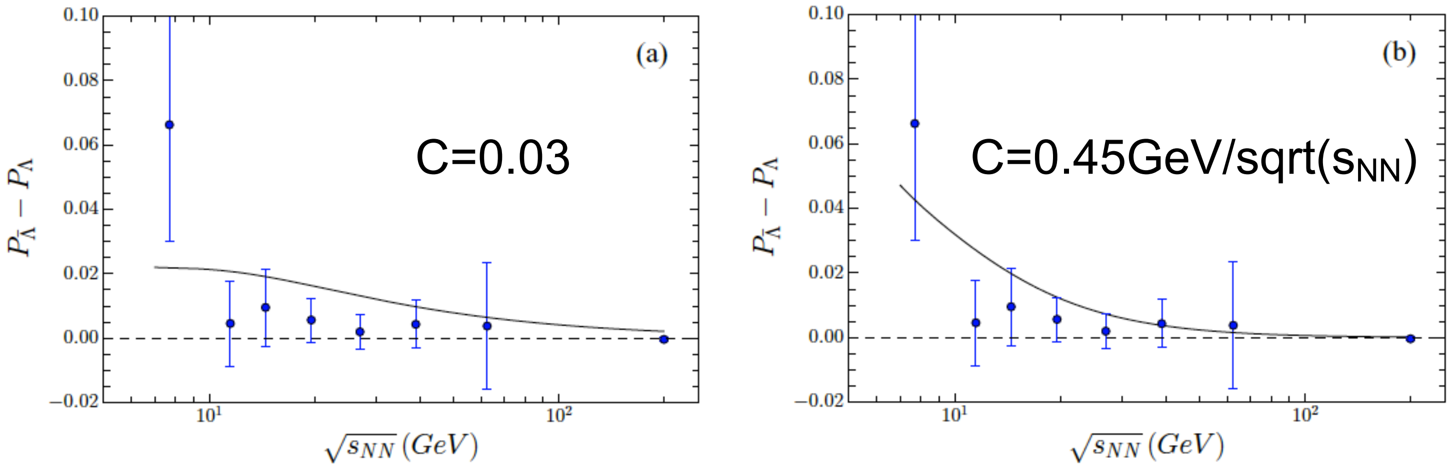
‘It is the phi meson which is the primary origin of the polarization difference, which should be no surprise because of the matching of the strange quark spin content of these hadrons.’

- The interaction is orders of magnitude larger than the one arising from electromagnetic fields.

$$B = \frac{eb\sigma_E}{8\pi t^2}\exp(-b^2\sigma_E/4t), \qquad Py\sim 10^{-6}$$

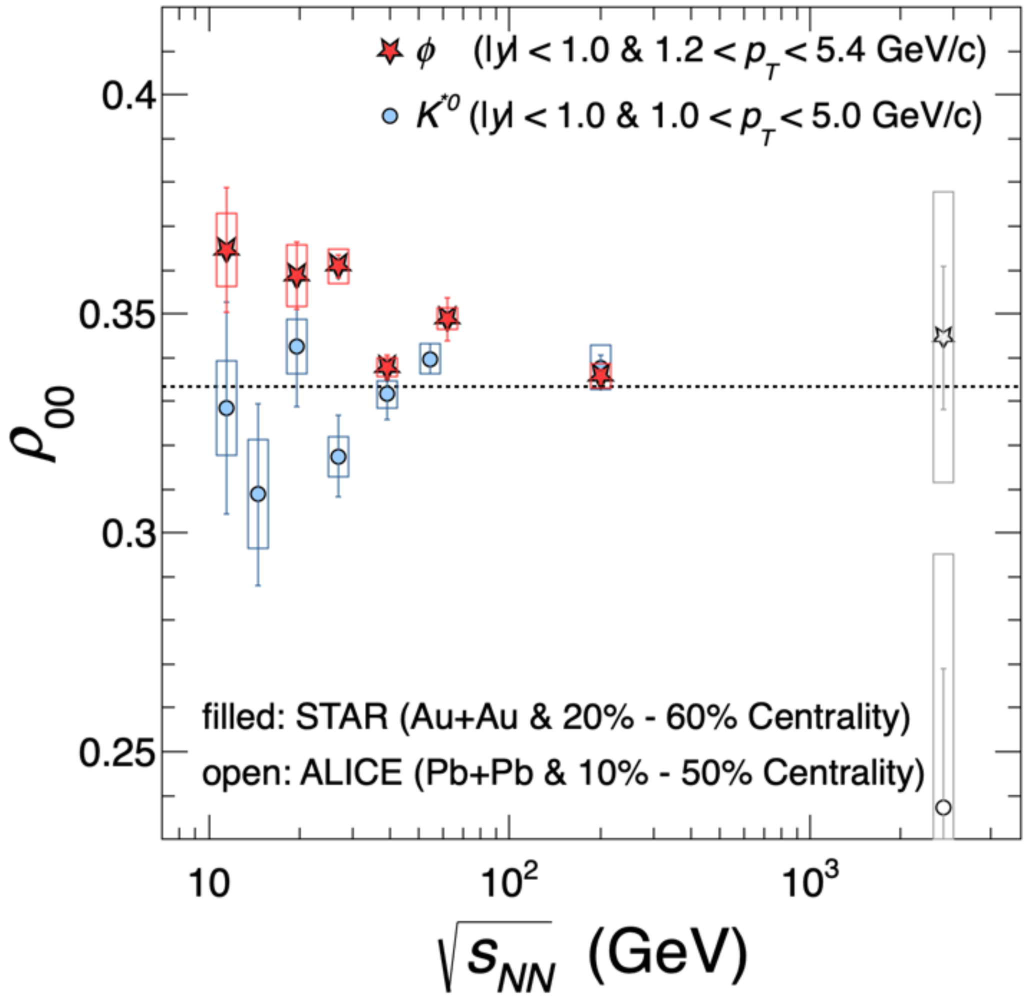
$$P_{\bar\Lambda} - P_\Lambda = C\left(\frac{n_B(t_{ch})}{0.15/\text{fm}^3}\right)\left(\frac{140\ \text{MeV}}{T(t_{ch})}\right).$$

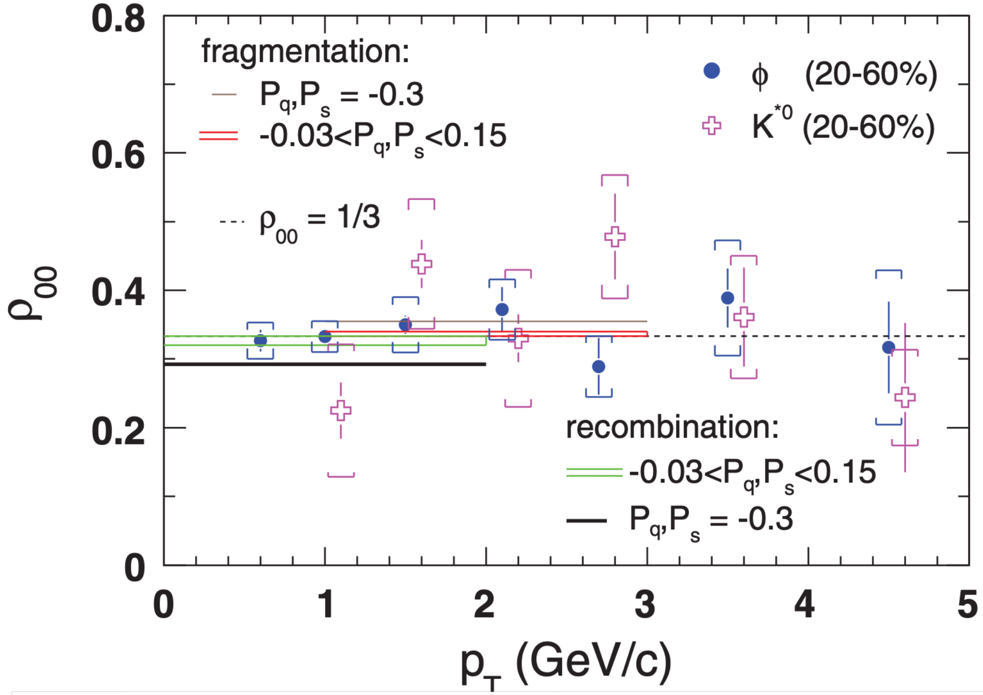
‘The results are sensitive to the space-time evolution of the baryon current.’

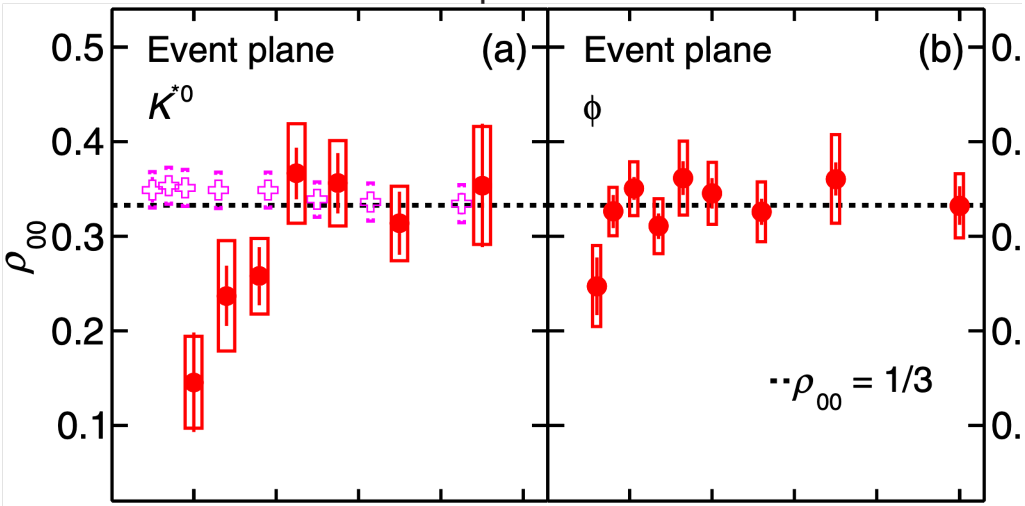


Measurable consequences of vector meson spin alignment

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



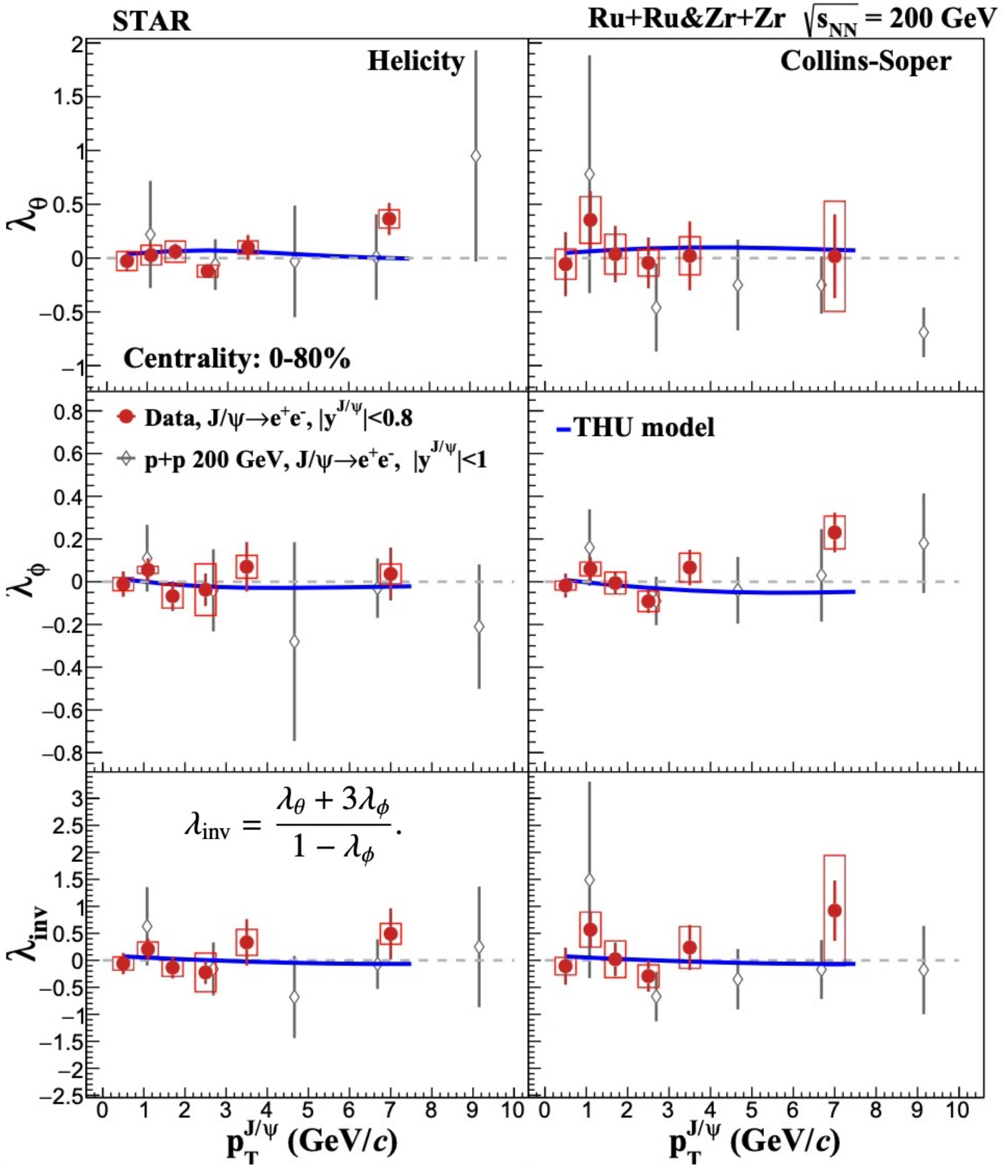




STAR Col. Nature **614**, 244 (2023), Phys. Rev. C **77**, 061902(R) (2008); ALICE Col. Phys. Rev. Lett. **125**, 012301 (2020) …

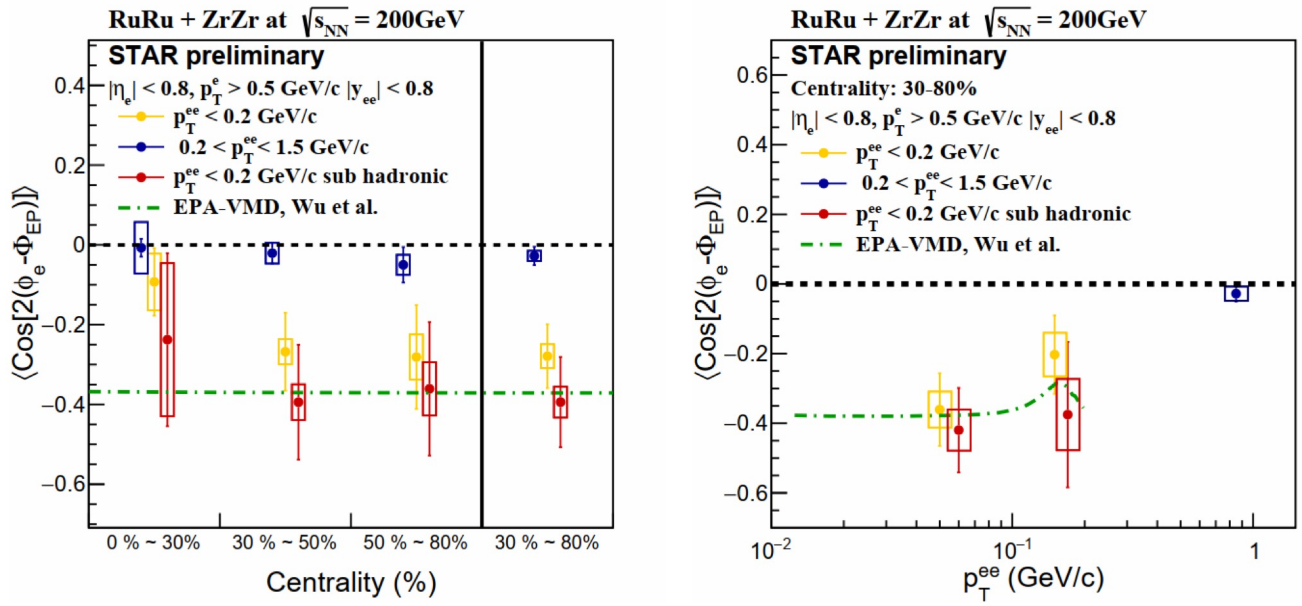
Spin alignment of charm mesons

STAR Col., arXiv:2604.07005

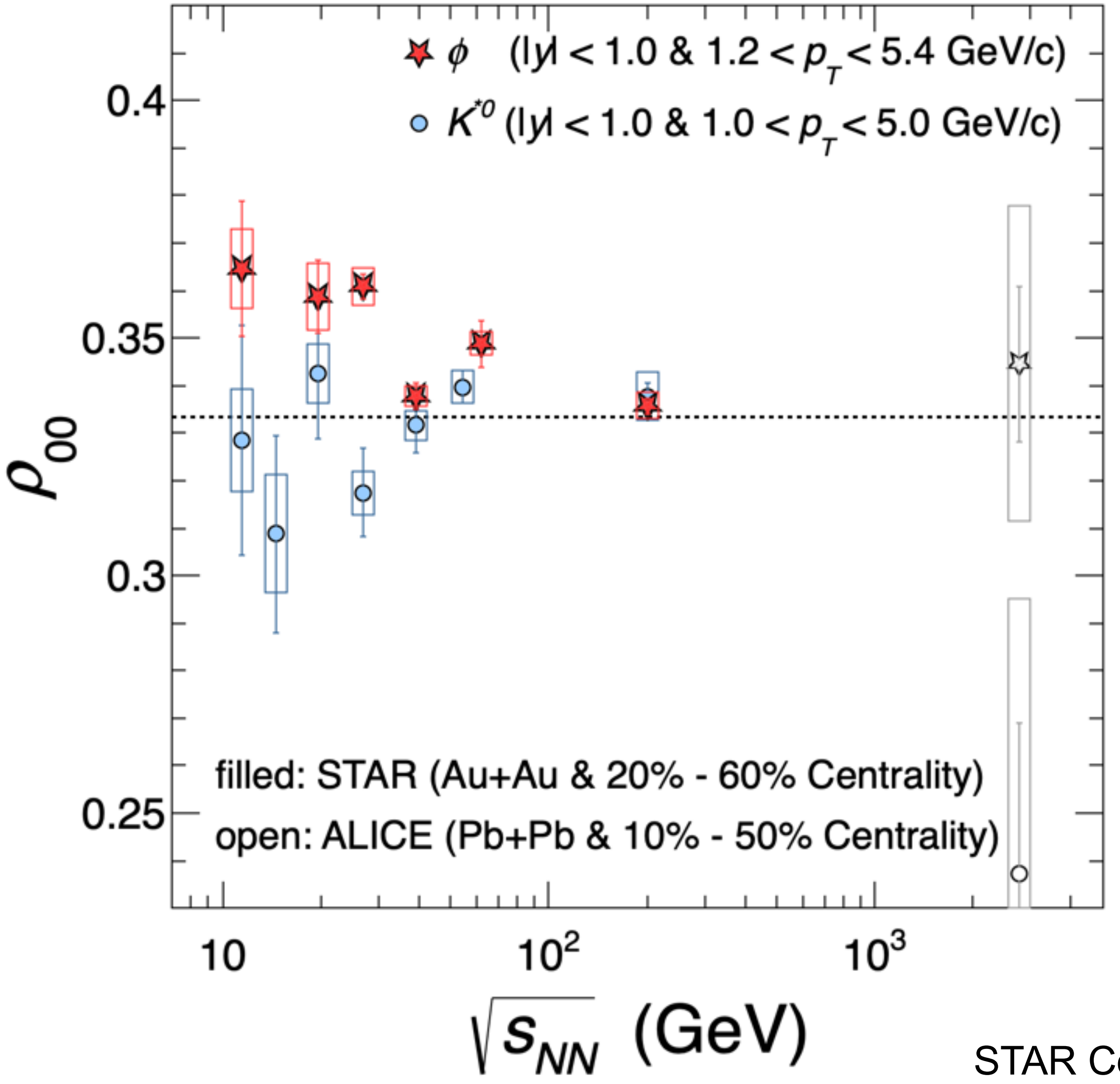


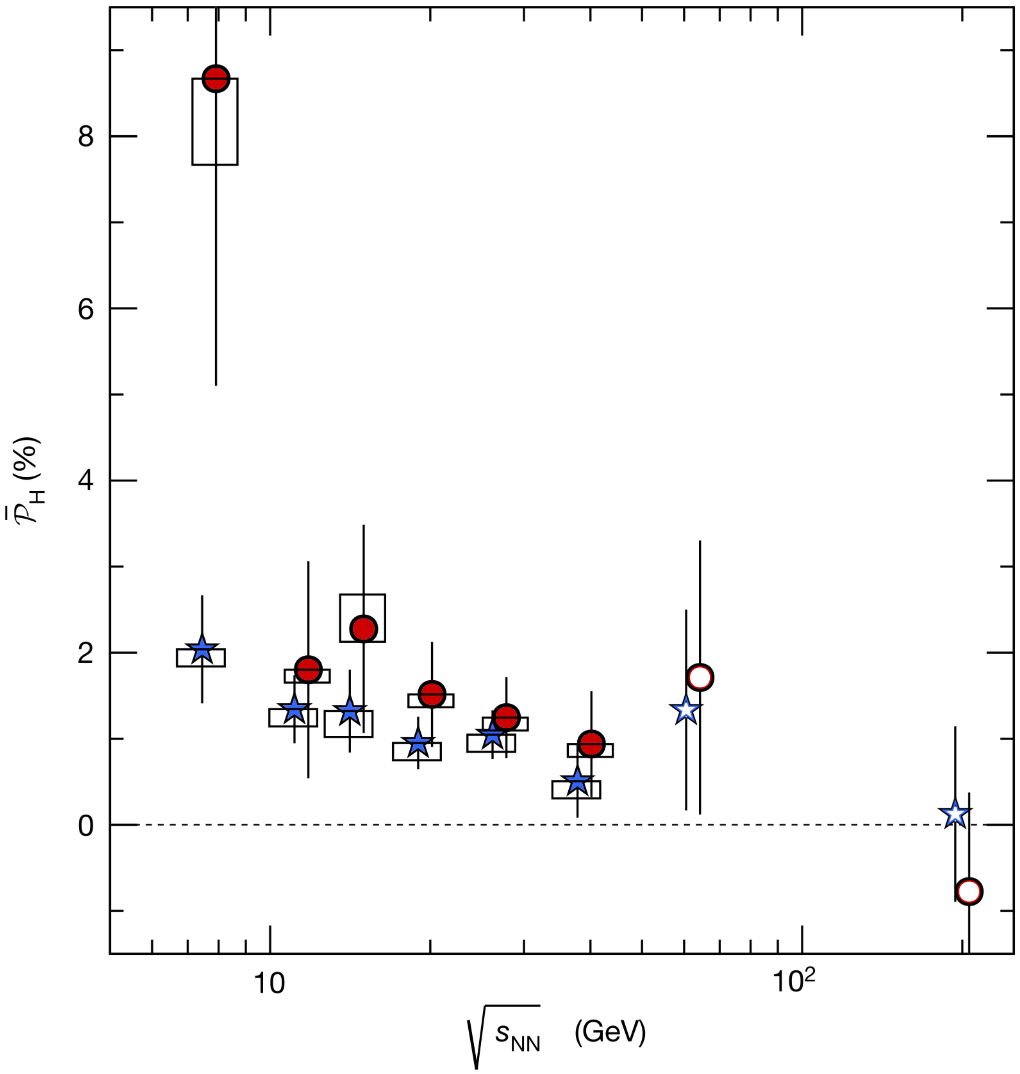
- STAR measured the J/Psi polarization in HIC and pp collisions
  -Polarization are consistent with zero within uncertainties.
  -Results in A+A collisions and p+p collisions are similar.
- From hadronic interaction to photon-induced dominant
  Photon induced J/Psi present evidence of decay anisotropy
  -accessing impact parameter direction with photon-induced process

Kaiyang Wang, QM25



Large φ-meson alignment vs. Small Λ pol.





STAR Col. Nature **548**, 62 (2017), Nature **614**, 244 (2023)

Large φ-meson alignment vs. Small Λ pol. (cont.)

Liang, Chirality 2023

$$\left|\rho_{00}^{V}-\frac{1}{3}\right| \gg P_{\Lambda}^{2} \sim P_{q}^{2}$$

$$\rho_{00}^{V}-\frac{1}{3} \sim \langle P_q P_{\bar{q}} \rangle$$

The STAR data show that: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$ $\quad \langle P_q P_{\bar{q}} \rangle \gg \langle P_q \rangle \langle P_{\bar{q}} \rangle$

By studying P_H, we study the average of quark polarization P_q;
by studying ρ_{00}^{V}, we study the correlation between P_q and $P_{\bar{q}}$.

How to separate long range or local correlations

$$C_{NN}^{H_i\bar{H}_j} \equiv \frac{N_{H_i\bar{H}_j}^{\uparrow\uparrow}+N_{H_i\bar{H}_j}^{\downarrow\downarrow}-N_{H_i\bar{H}_j}^{\uparrow\downarrow}-N_{H_i\bar{H}_j}^{\downarrow\uparrow}}{N_{H_i\bar{H}_j}^{\uparrow\uparrow}+N_{H_i\bar{H}_j}^{\downarrow\downarrow}+N_{H_i\bar{H}_j}^{\uparrow\downarrow}+N_{H_i\bar{H}_j}^{\downarrow\uparrow}}$$

sensitive to the long range correlation

$$\rho_{10}^{V}=\frac{P_{qz}(1+P_{\bar{q}y})+(1+P_{qy})P_{\bar{q}z}-iP_{qx}(1+P_{\bar{q}y})-i(1+P_{qy})P_{\bar{q}x}}{\sqrt{2}(3+\vec{P}_q\cdot\vec{P}_{\bar{q}})}$$

$$\rho_{0-1}^{V}=\frac{P_{qz}(1-P_{\bar{q}y})+(1-P_{qy})P_{\bar{q}z}-iP_{qx}(1-P_{\bar{q}y})-i(1-P_{qy})P_{\bar{q}x}}{\sqrt{2}(3+\vec{P}_q\cdot\vec{P}_{\bar{q}})}$$

$$\rho_{1-1}^{V}=\frac{P_{qz}P_{\bar{q}z}-P_{qx}P_{\bar{q}x}+i(P_{qx}P_{\bar{q}y}+P_{qy}P_{\bar{q}x})}{3+\vec{P}_q\cdot\vec{P}_{\bar{q}}}$$

They should be sensitive to the local correlations.

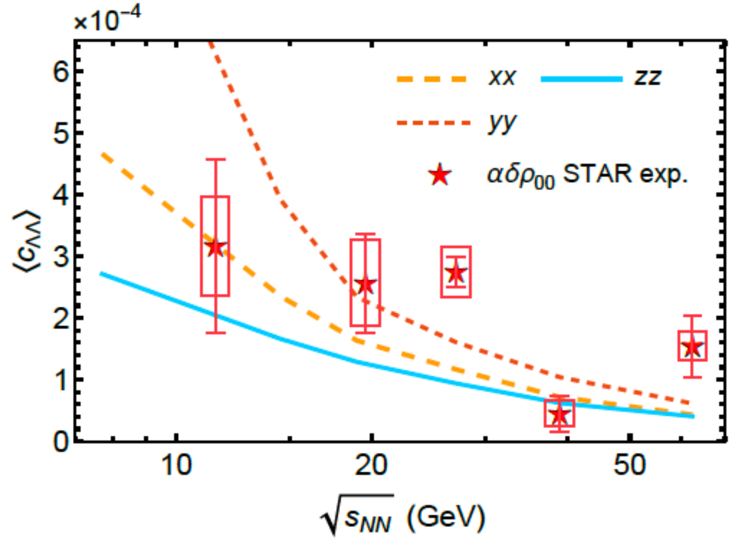
Spin-spin correlation

Lv, Yu, Liang, Wang, Wang, PRD **109**, 114003 (2024); Zhang, Lv, Yu, Liang, PRD **110**, 074019 (2024)

Sheng, Wu, Rischke, Wang, Phys. Rev. Lett. **136**, 082301 (2026)…

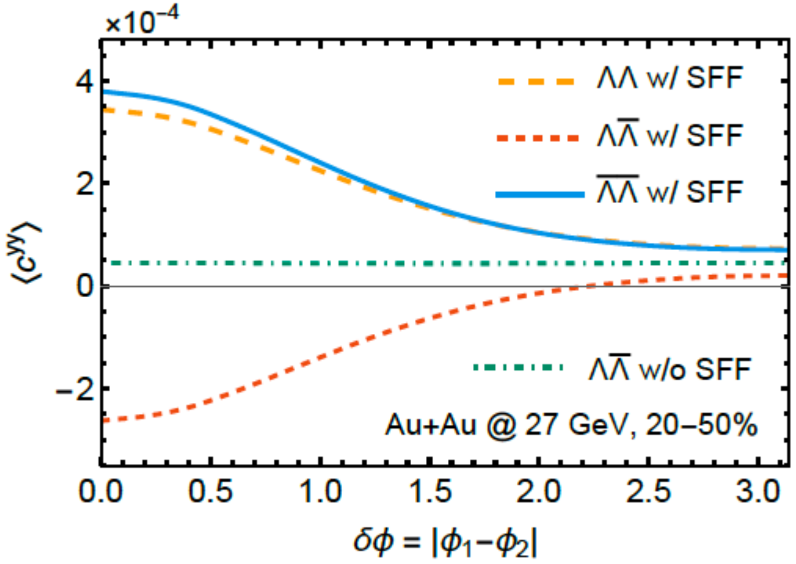
$$C_{12}^{\mu\nu}(p_1,p_2) \equiv \langle P_1^\mu(x_1,p_1) P_2^\nu(x_2,p_2)\rangle \ , \qquad (1)$$

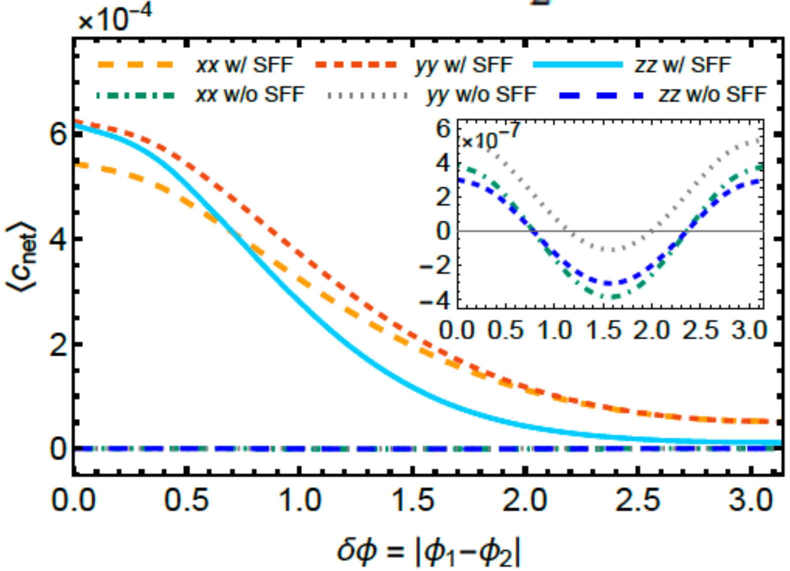
$$C_{12}^{\mu\nu}(p_1,p_2) = \frac{1}{N_{\text{event}}} \sum_{\text{event}} \times \frac{\int d\Sigma(x_1)\cdot p_1 \int d\Sigma(x_2)\cdot p_2\, P_1^\mu\, P_2^\nu\, f_1\, f_2}{\left[\int d\Sigma(x_1)\cdot p_1\, f_1\right]\left[\int d\Sigma(x_2)\cdot p_2\, f_2\right]} \qquad (8)$$

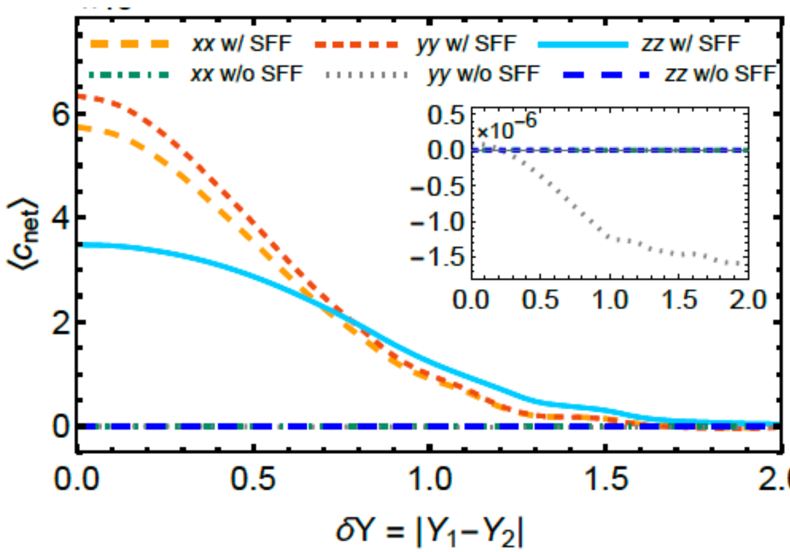


‘A key unique feature of the hyperon spin correlation caused by the SFF is that the spin correlation of ΛΛ and anti-Λanti-Λ has the opposite sign as the Λanti-Λ spin correlation.’

$$c_{\text{net}}^{ab} \equiv \frac{1}{2}\left(c_{\Lambda\Lambda}^{ab} + c_{\bar\Lambda\bar\Lambda}^{ab}\right) - c_{\Lambda\bar\Lambda}^{ab} \ , \qquad (12)$$



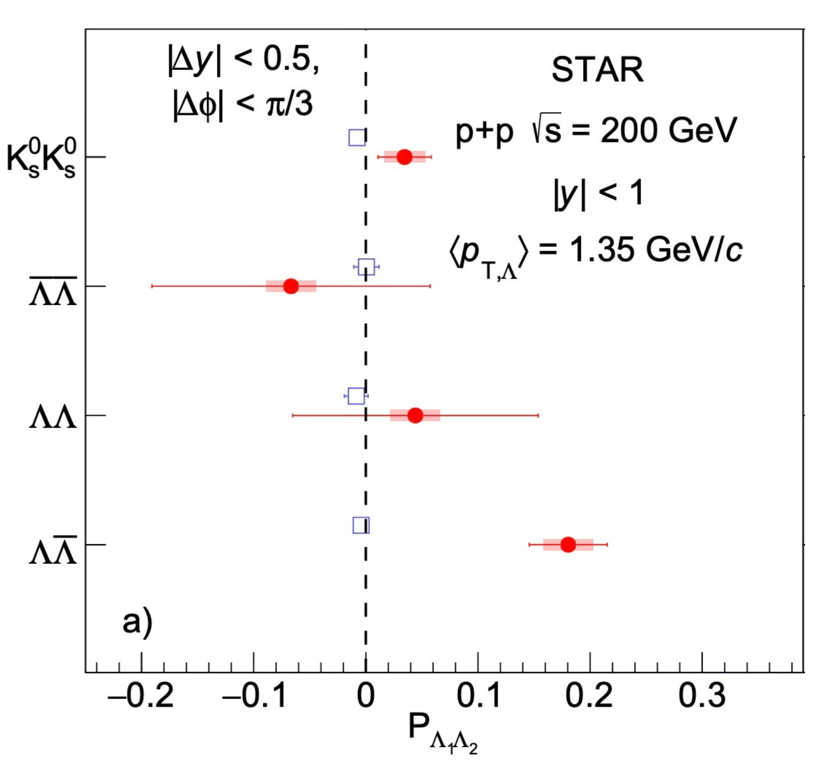


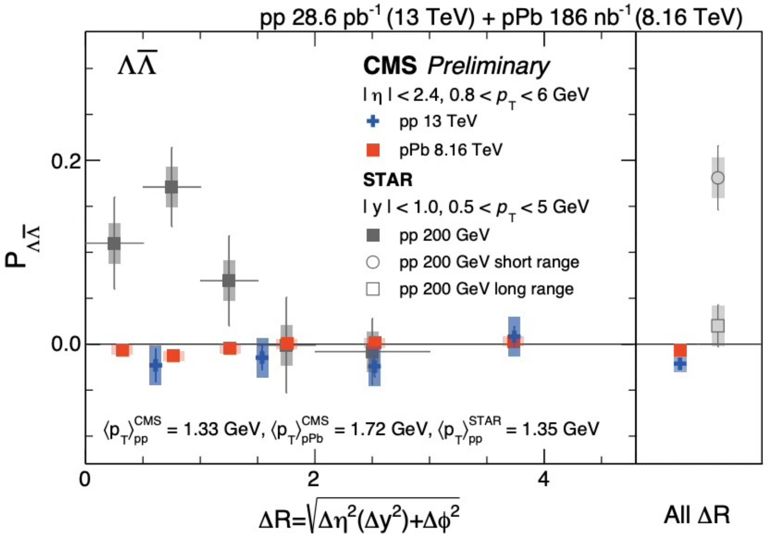


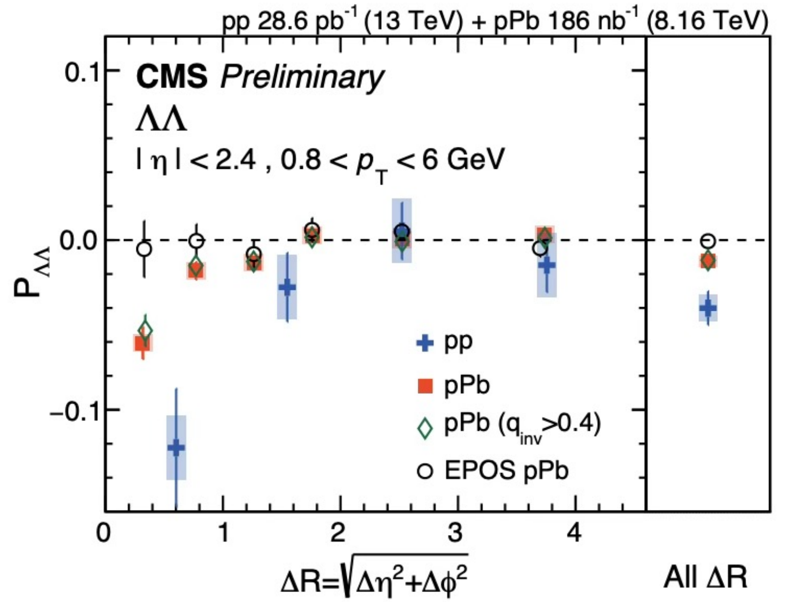
Measure the spin-spin correlation

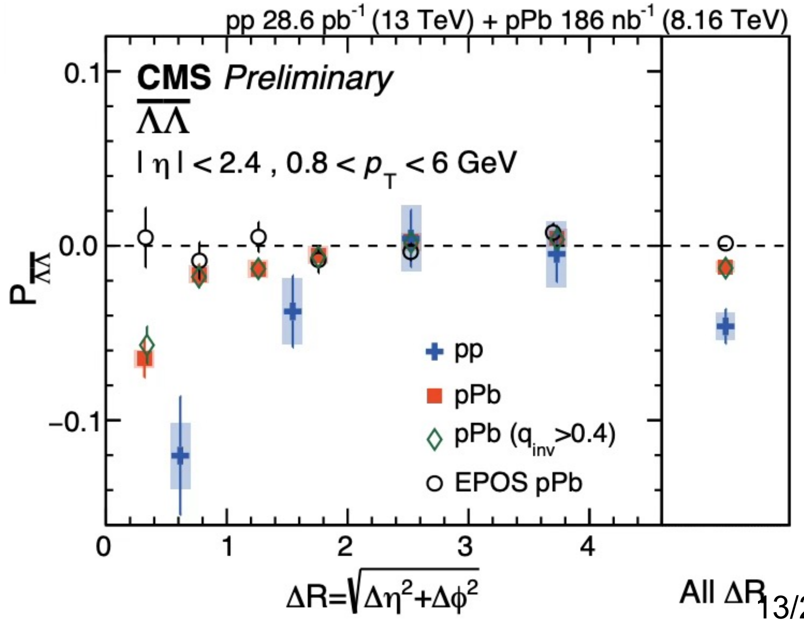
$$\frac{dN}{d\cos(\theta^*)} \sim 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)$$

Jieke Wang DIS 2026





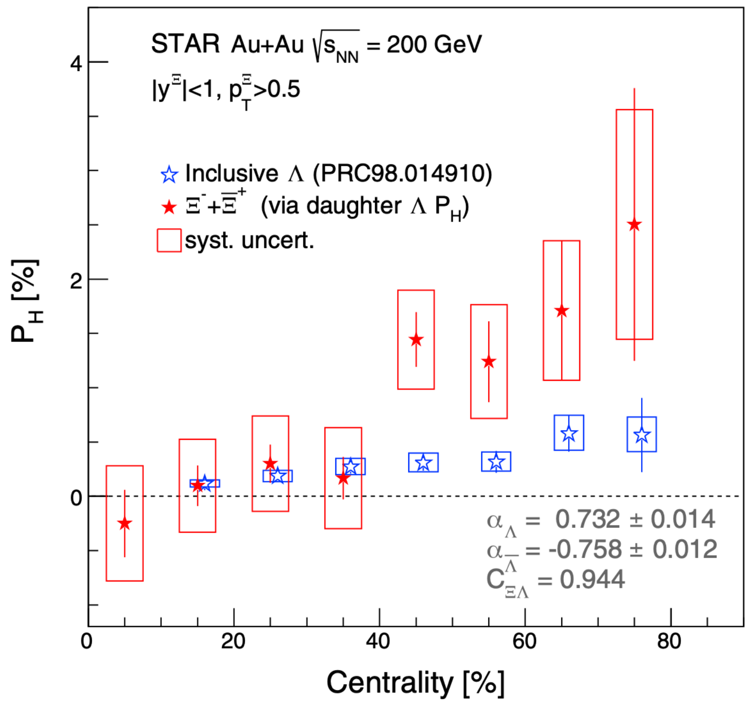


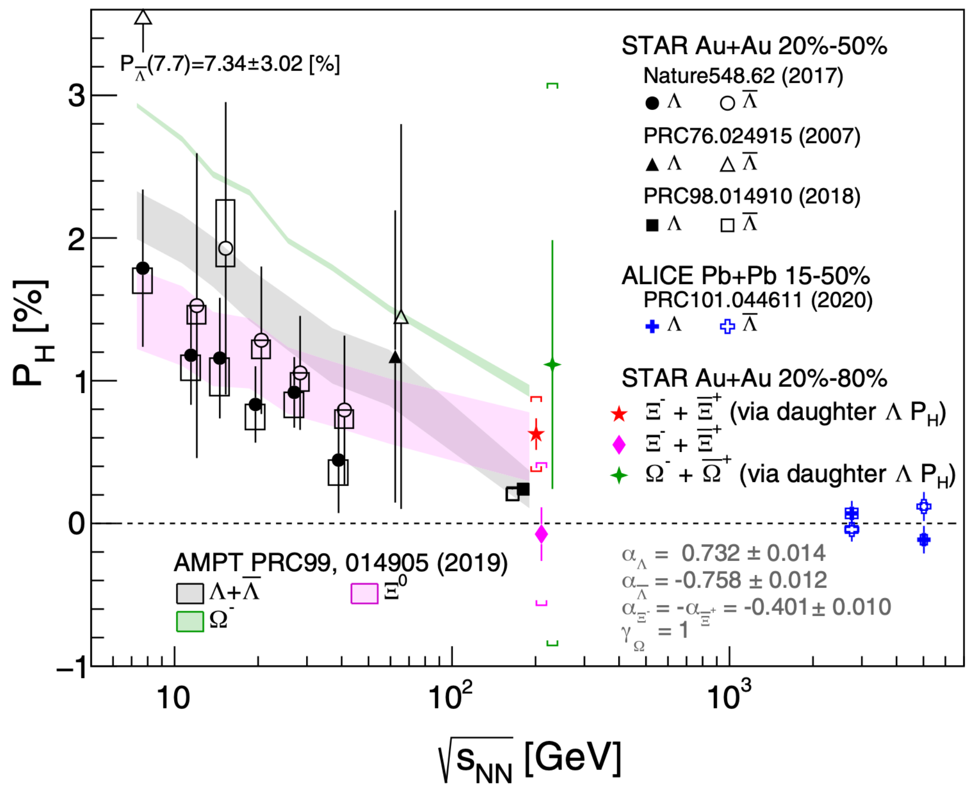


- Lambda spin correlation has been measured in small systems.
  - p+p 200 GeV: $P_{OS}>0$, $P_{SS}\sim 0$
  - p+p 13 TeV and p+Pb 8.16 TeV: $P_{OS}\sim 0$, $P_{SS}<0$

Measurements of spin 3/2 baryon

STAR Col. Phys. Rev. Lett. **126**, 162301 (2021)





- Xi data confirm the global polarization picture based on the system fluid vorticity

- New data agree with AMPT model prediction

- spin ½

$$\mathbf{P}^*_\Lambda = \frac{(\alpha_\Xi + \mathbf{P}^*_\Xi \cdot \hat{\boldsymbol{p}}^*_\Lambda)\hat{\boldsymbol{p}}^*_\Lambda + \beta_\Xi \mathbf{P}^*_\Xi \times \hat{\boldsymbol{p}}^*_\Lambda + \gamma_\Xi \hat{\boldsymbol{p}}^*_\Lambda \times (\mathbf{P}^*_\Xi \times \hat{\boldsymbol{p}}^*_\Lambda)}{1 + \alpha_\Xi \mathbf{P}^*_\Xi \cdot \hat{\boldsymbol{p}}^*_\Lambda}$$

$$\mathbf{P}^*_\Lambda = C_{\Xi^-\Lambda}\mathbf{P}^*_\Xi = \frac{1}{3}(1+2\gamma_\Xi)\mathbf{P}^*_\Xi \qquad C_{\Xi^-\Lambda} = \frac{1}{3}(1+2\times 0.916) = +0.944$$

T.D. Lee and C.-N. Yang, Phys. Rev. **108**, 1645 (1957)

- spin 3/2

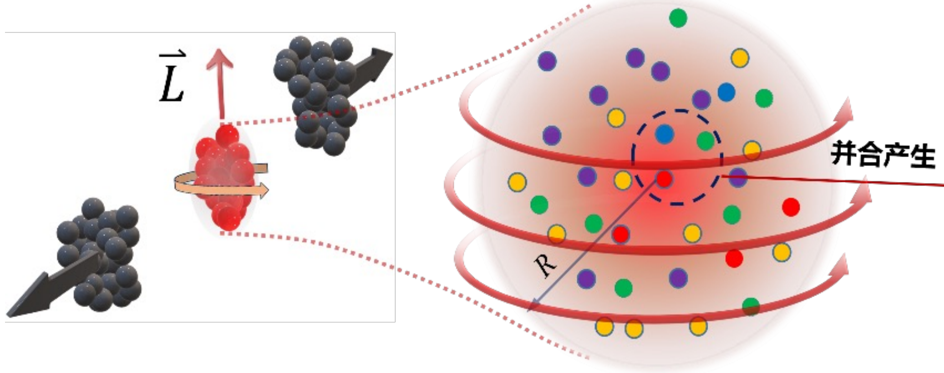
$$\boxed{\mathbf{P}^*_\Lambda = C_{\Omega^-\Lambda}\mathbf{P}^*_\Omega = \frac{1}{5}(1+4\gamma_\Omega)\mathbf{P}^*_\Omega}$$

$$C_{\Omega^-\Lambda} \approx 1 \qquad C_{\Omega^-\Lambda} \approx -0.6$$

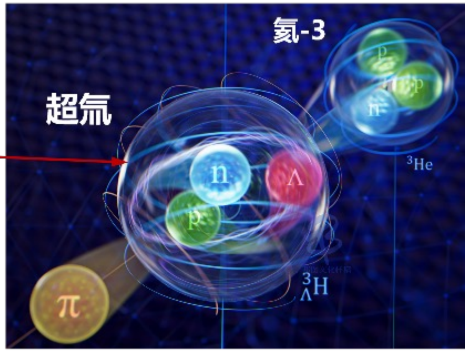
*different component?

Spin polarization of light cluster and correlation

Sun, Liu, Zheng, Chen, Ko and Ma, Phys. Rev. Lett. **134**, 022301 (2025), Phys. Rev. C **113**, 054906 (2026), Phys. Rev. Res. **8**, 033057 (2026)…

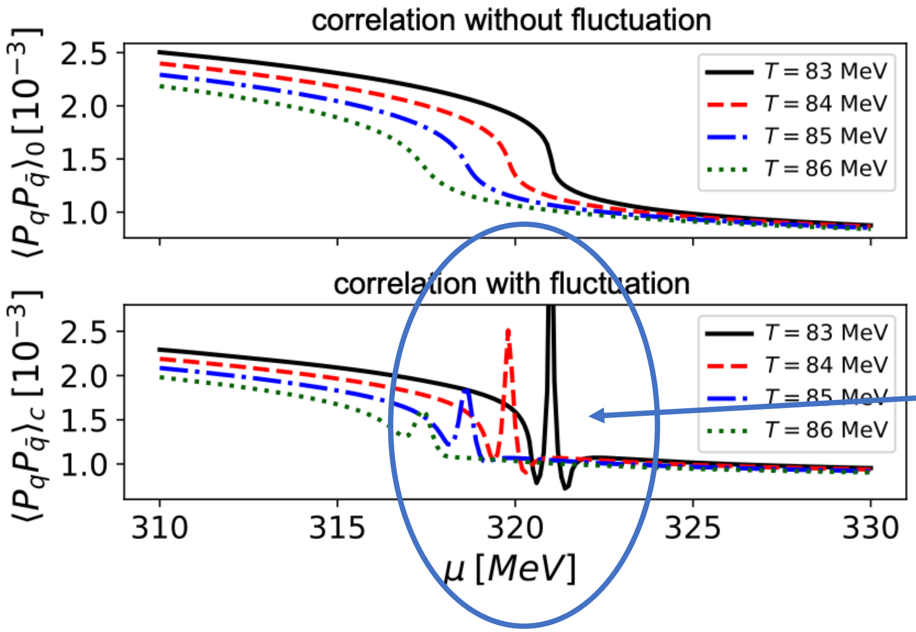


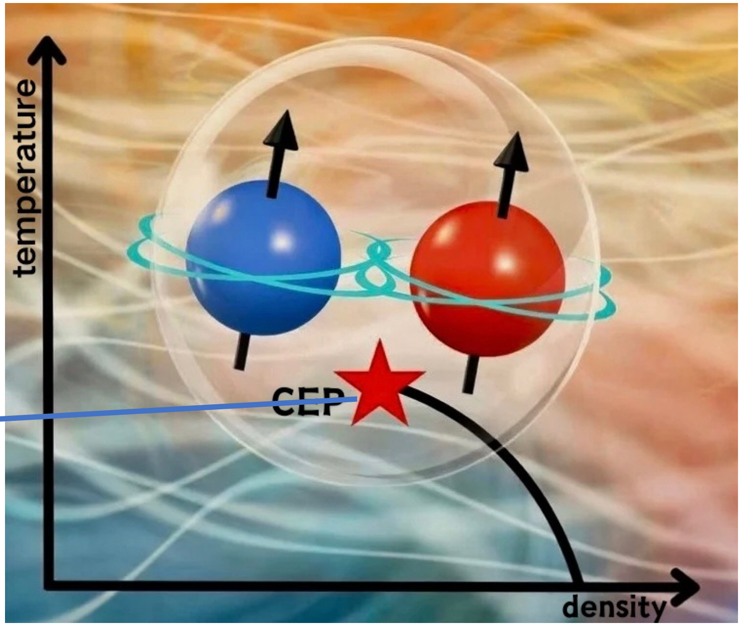
$${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$$



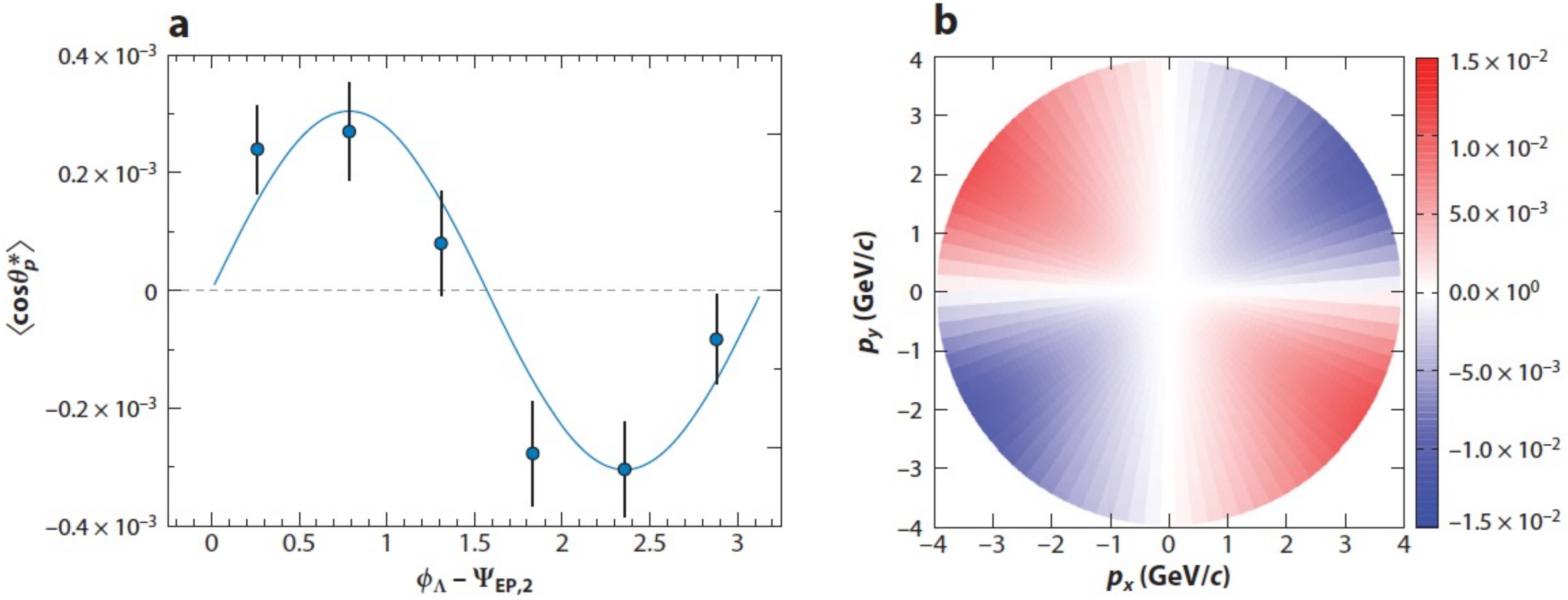
J^{π}	Structure	Decay mode	$dN/(\sin\theta^* d\theta^*)$
$\frac{1}{2}^{+}$	$\Lambda(\frac{1}{2}^{+}) - np(1^{+})$	${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{3}\mathrm{He}$	$\frac{1}{2}[1 - (1/2.58)\alpha_{\Lambda}\mathcal{P}_{\Lambda}\cos\theta^*]$
$\frac{1}{2}^{+}$	$\Lambda(\frac{1}{2}^{+}) - np(0^{+})$	${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{3}\mathrm{He}$	$\frac{1}{2}(1 + \alpha_{\Lambda}\mathcal{P}_{\Lambda}\cos\theta^*)$
$\frac{3}{2}^{+}$	$\Lambda(\frac{1}{2}^{+}) - np(1^{+})$	${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{3}\mathrm{He}$	$\frac{1}{2}\left(1 - \mathcal{P}_{\Lambda}^{2}(3\cos^2\theta^* - 1)\right)$
$\frac{1}{2}^{-}$	$\bar{\Lambda}(\frac{1}{2}^{-}) - \overline{np}(1^{+})$	${}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}} \rightarrow \pi^{+} + {}^{3}\overline{\mathrm{He}}$	$\frac{1}{2}[1 - (1/2.58)\alpha_{\bar{\Lambda}}\mathcal{P}_{\bar{\Lambda}}\cos\theta^*]$
$\frac{1}{2}^{-}$	$\bar{\Lambda}(\frac{1}{2}^{-}) - \overline{np}(0^{+})$	${}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}} \rightarrow \pi^{+} + {}^{3}\overline{\mathrm{He}}$	$\frac{1}{2}(1 + \alpha_{\bar{\Lambda}}\mathcal{P}_{\bar{\Lambda}}\cos\theta^*)$
$\frac{3}{2}^{-}$	$\bar{\Lambda}(\frac{1}{2}^{-}) - \overline{np}(1^{+})$	${}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}} \rightarrow \pi^{+} + {}^{3}\overline{\mathrm{He}}$	$\frac{1}{2}\left(1 - \mathcal{P}_{\bar{\Lambda}}^{2}(3\cos^2\theta^* - 1)\right)$

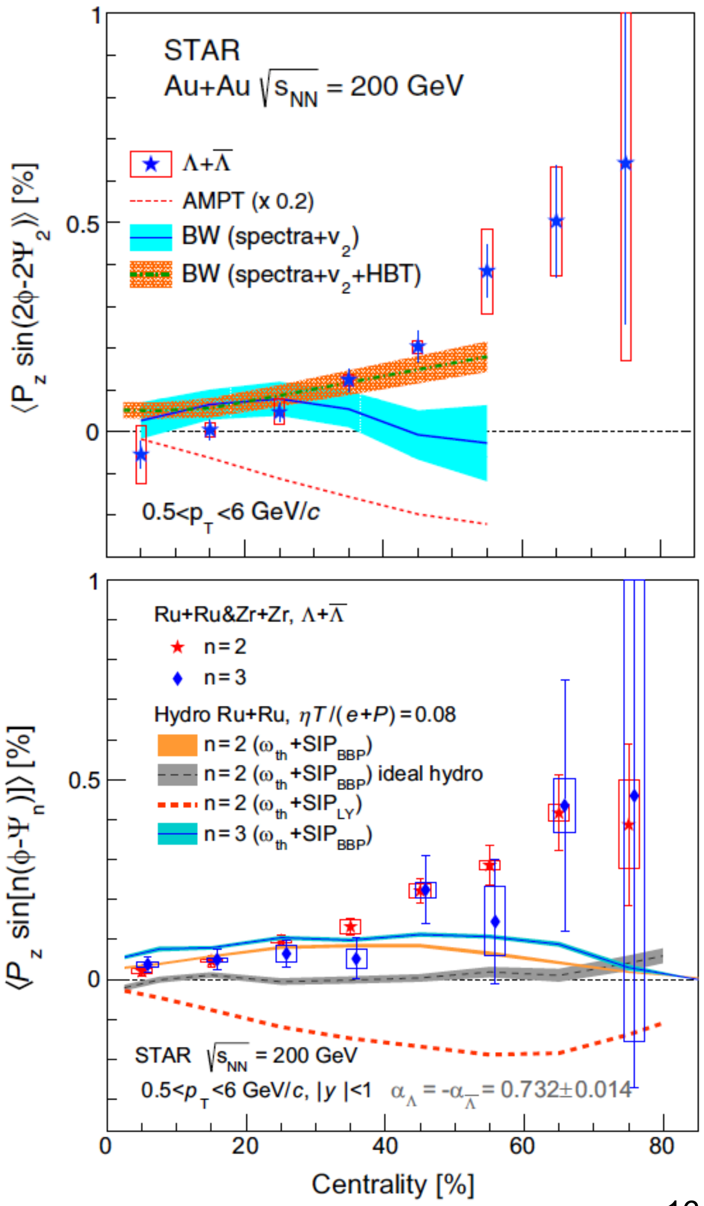
Chen, Fu, Huang and Ma, Phys. Rev. Lett. **135**, 032302 (2025)





Λ polarization along beam direction



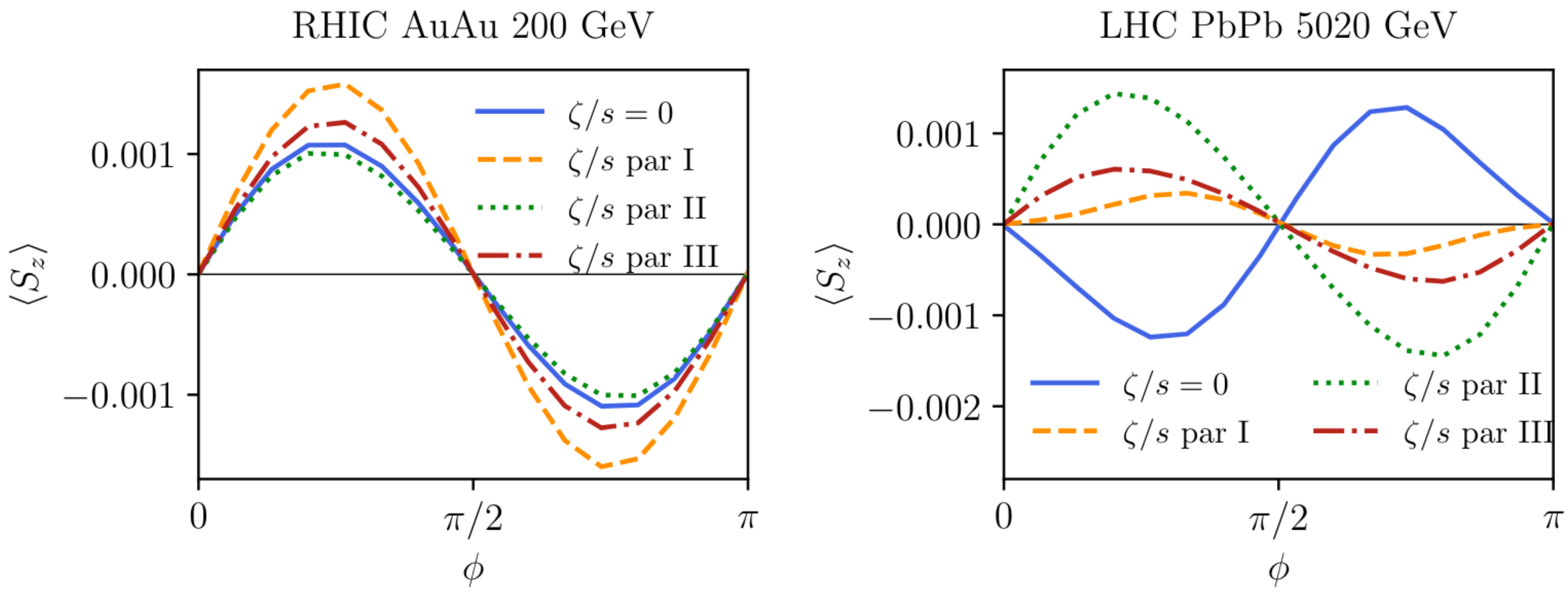


STAR Col., Phys. Rev. Lett. **123**, 132301 (2019), Phys. Rev. Lett. **131**, 202301 (2023),
ALICE Col., Phys. Rev. Lett. **128**, 172005 (2022), CMS Col., Phys. Rev. Lett. **135**, 132301 (2025).
Becattini, Lisa, Annu. Rev. Nucl. Part. Sci. 70, 395 (2020)…

- A quadrupole modulation of the polarization along the beam direction is observed. It is qualitatively consistent with the expectation from the vorticity component along the beam direction due to collective flow.
- ‘Spin sign puzzle’: data present a positive sine modulation, while hydrodynamics and transport model calculations predict a negative sign.

Polarization is sensitive to bulk viscosity

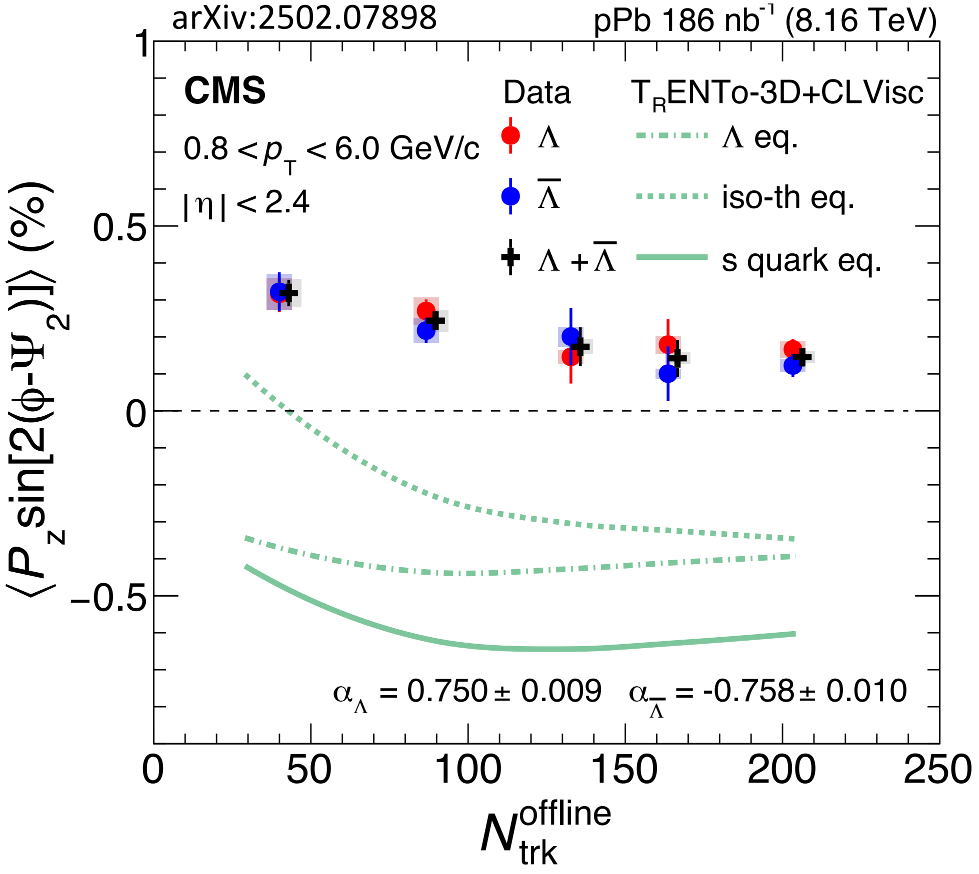
Palermo, Grosssi, Karpenko, Becattini, Eur. Phys. J. C **84**, 920 (2024)

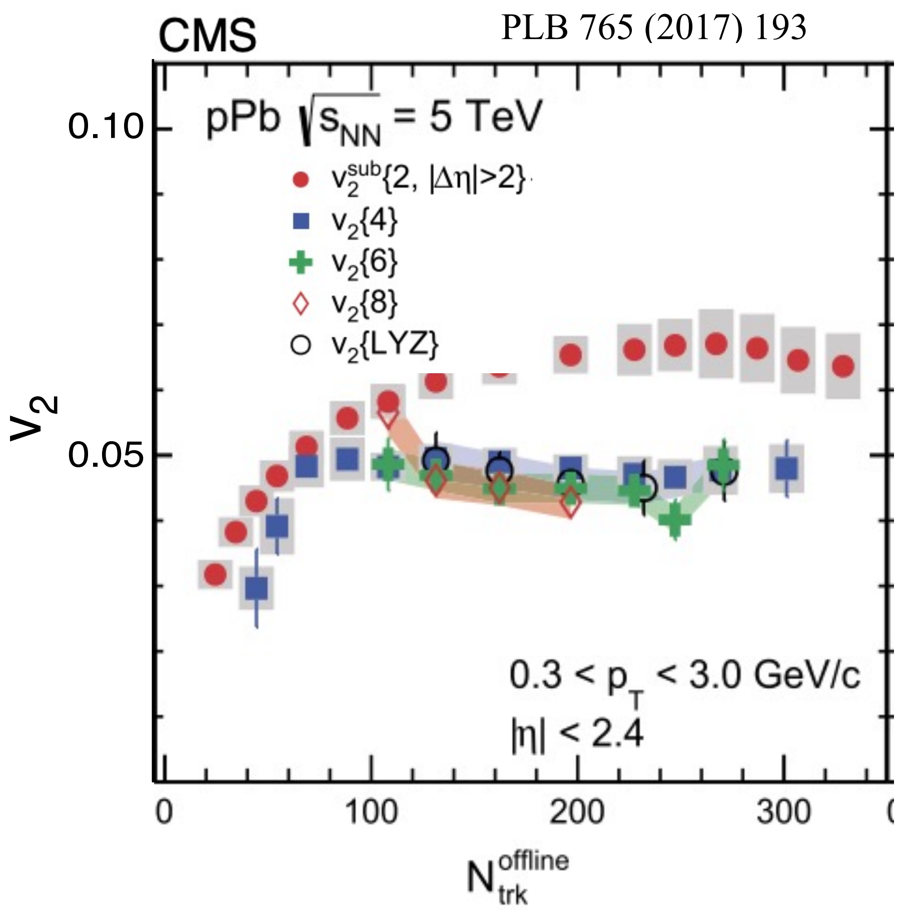


- The bulk viscosity significantly affects local polarization
- Once bulk viscosity is implemented, the sign of polarization is flipping in LHC energy (LHC more sensitive)
- Challenging to accurately extract the viscosity from <*Sz*>

Measurements at LHC energies

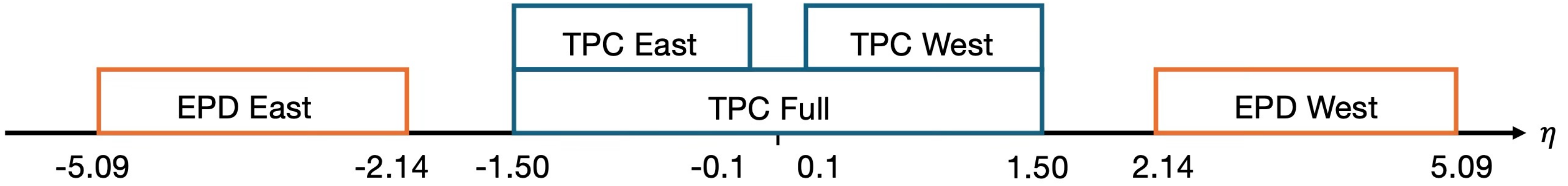
CMS Col. Phys. Rev. Lett. **135**, 132301 (2025)





- Local polarization was observed in small system. Hydro calculations is not consistent with data
- Polarization increases monotonically toward 0 multiplicity, not consistent with the trend of v_2.
- In large system, apply ESE to investigate any local polarization dependence? In small system, flow + initial state effect?

Local polarization with ESE



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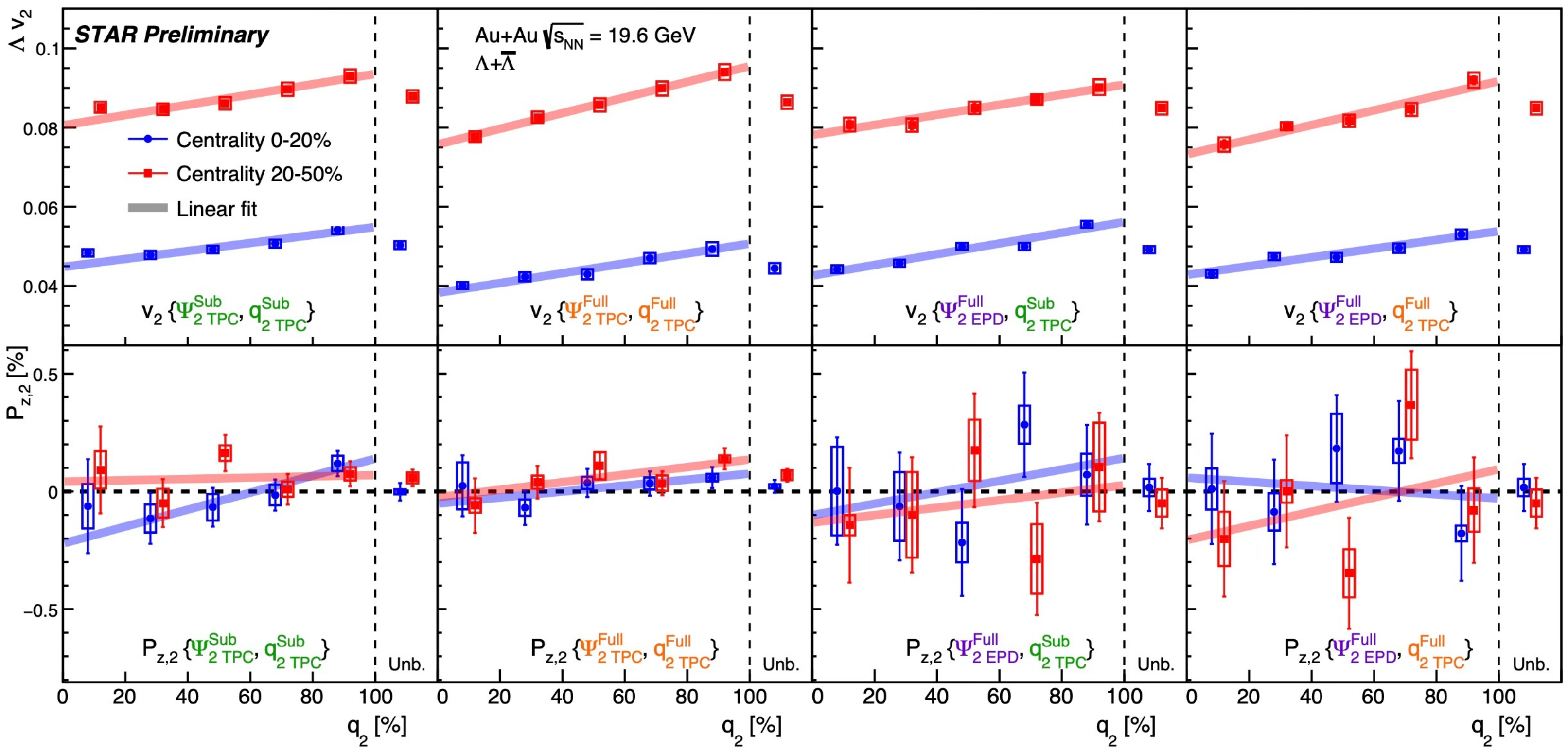


- Selecting different initial geometry and elliptic flow via event shape engineering at a given centrality.
- Making flow the only variable and study its relationship with local polarization.
- No significant v_2 dependence of $P_{z,2}$ in Au+Au 19.6 GeV has been observed.

Summary and Outlook

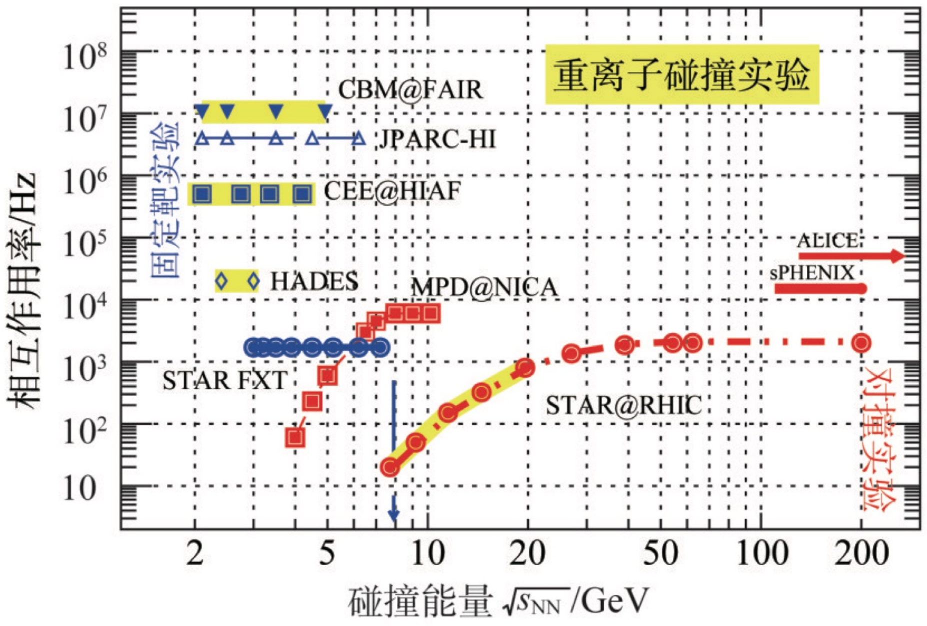
- Spin polarization opens a new avenue of heavy-ion collisions physics

- Global hyperon polarization is observed with the order of a few percent. It represents a measure of the average value of the global quark polarization in the system

- Global vector meson spin alignment is observed with a surprisingly large parttern for φ-meson. It represents a local fluctuation/correlation between quarks polarization

- Local polarization show a profound structure, which is sensitive to the fluctuation of vorticity and bulk properties

- Measurements of spin-spin correlations are progressing well, rich physics to be explored



Thank you for your attentions!