Overview of Recent Numerical Studies of Spin Polarization

Cong Yi (易聪)

Central China Normal University (CCNU)

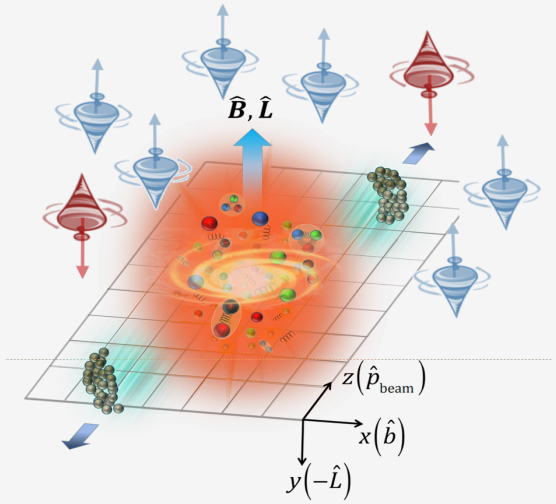
The 10th International Conference on Chirality, Vorticity and Magnetic Fields in Quantum Matter
Chirality 2026 • Zhuhai • November 16–20, 2026

Outline

- **Global polarization**
  thermal vorticity · hadronic stage · hypernuclei · a few GeV · new mechanisms
- **Local polarization**
  P_z & P_y · P_x · vortex rings · helicity
- **Other perspectives**
  machine learning (Bayesian inference, PINNs) · initial spin fluctuations
- **Summary and outlook**

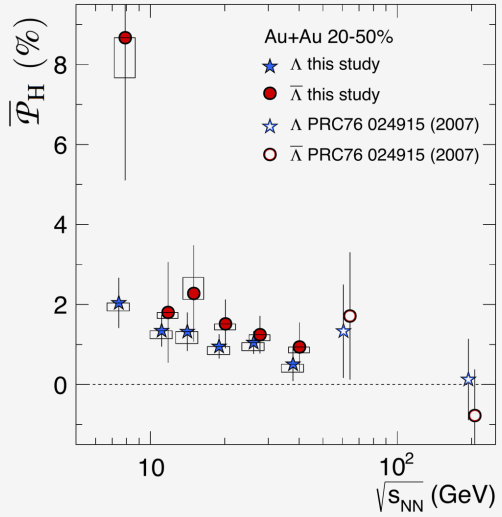
Global spin polarization

➢ Spin–orbit coupling



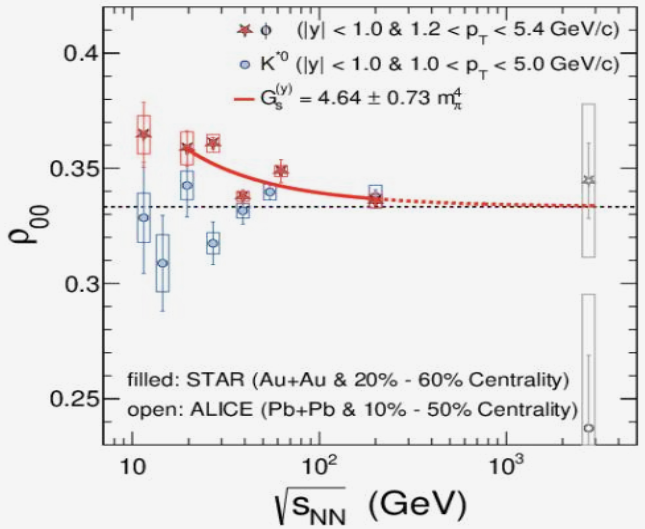
Liang, Wang, PRL 94, 102301 (2005)
Liang, Wang, PLB 629, 20 (2005)

➢ Global Λ polarization



STAR, Nature 548, 62 (2017)
Becattini et al., Ann. Phys. 338, 32 (2013)
Karpenko, Becattini, EPJC(2017)

➢ Global spin alignment



STAR, Nature 614, 244 (2023)
Sheng et al., PRL 131, 042304 (2023)

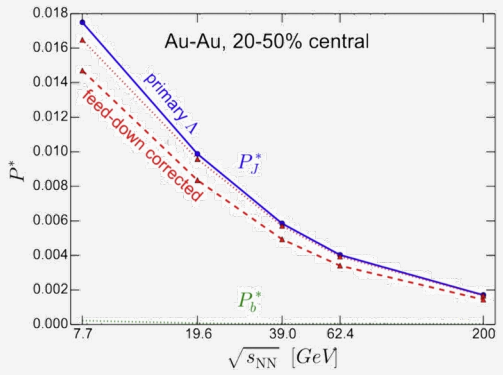
Xin-Li Sheng, Nov 16, 15:30–16:00

- Orbital angular momentum → spin: global Λ polarization and ϕ/K*0 spin alignment
- This talk: focus on studies of hyperon spin polarization

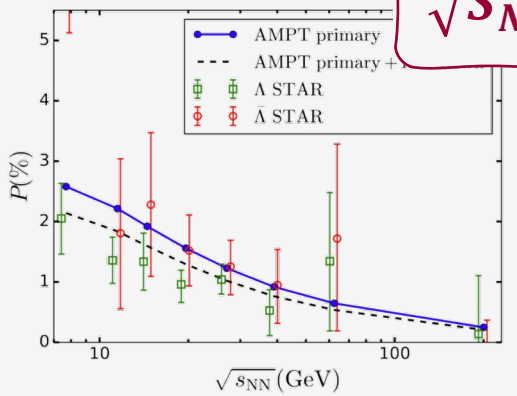
My apologies for the many valuable developments I cannot cover in this talk.

Global polarization from thermal vorticity

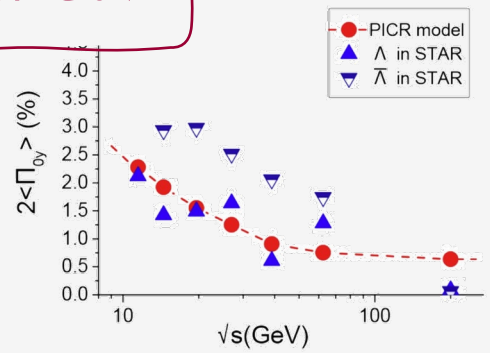
$\sqrt{s_{NN}} > 7.7$ GeV



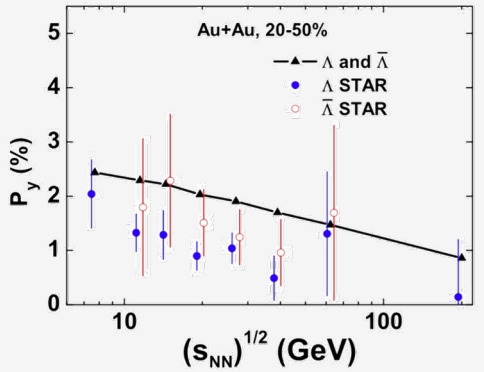
Karpenko, Becattini, EPJC(2017)



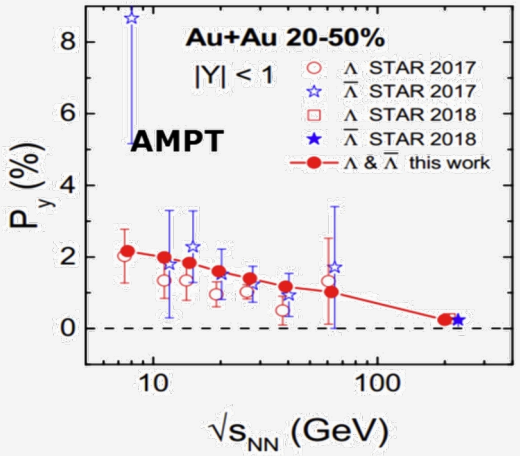
Li, Pang, Wang, Xia, PRC(2017)



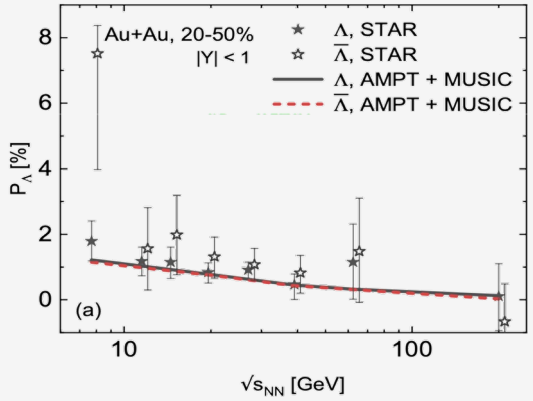
Xie, Wang, Csernai, PRC(2017)



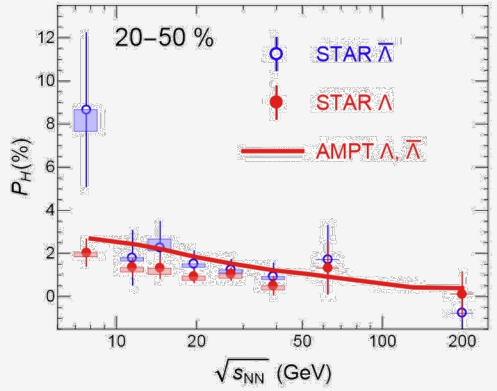
Sun, Ko, PRC(2017)



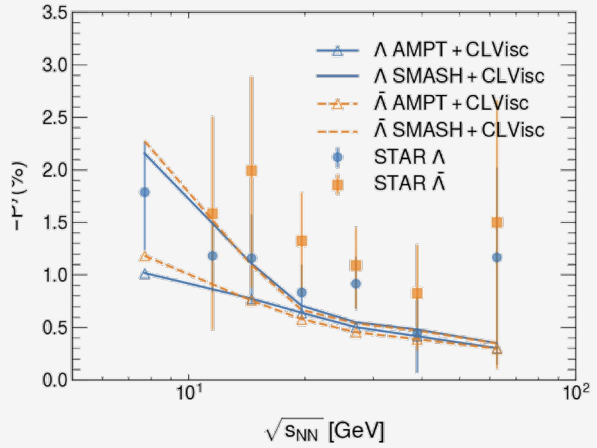
Wei, Deng, Huang, PRC(2019)



Fu, Xu, Huang, Song, PRC (2021)



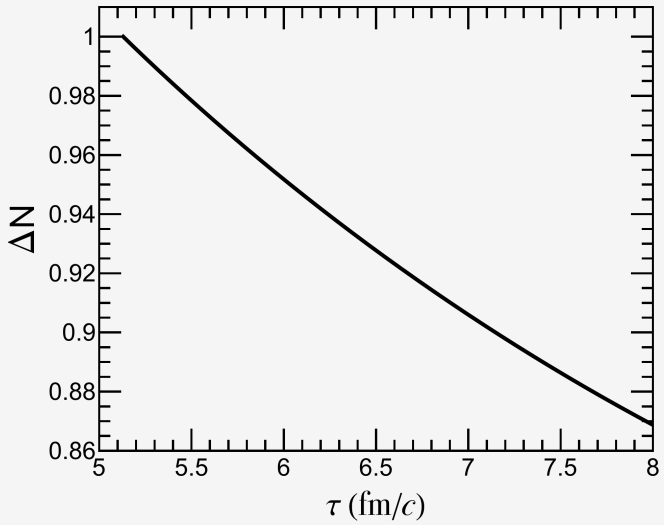
Shi, Li, Liao, PLB(2018)



Wu, CY, Qin, Pu, PRC(2022)

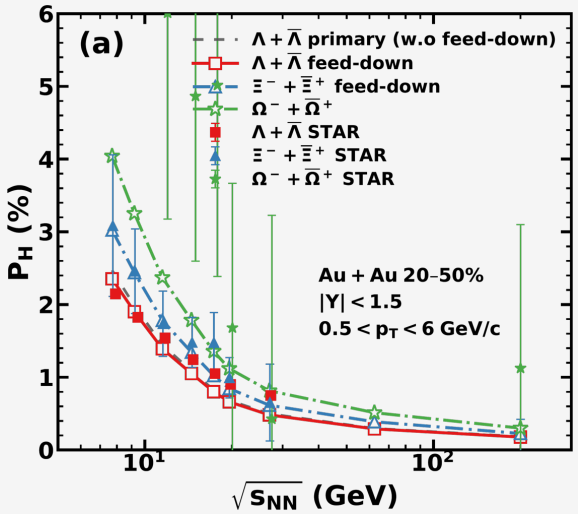
Effect of hadronic rescattering and feed-down

➢ Hadronic rescattering



Sung, Ko, Lee, PLB 858, 139004 (2024);
PRC 113, 014908 (2026)

➢ Feed-down (hydro)



Li, CY, Wu, Pu, Qin, arXiv:2606.10341 (2026)

Gen-Hui Li, Nov 18, 14:40–15:00

Decay spin kinematics + statistical model for the particle yield.

Feed-down:
Becattini et al., PRC 95, 054902 (2017)
Karpenko, Becattini, EPJC 77, 213 (2017)
Li et al., PRC 96, 054908 (2017)
Xia et al., PRC 100, 014913 (2019)
Becattini, Cao, Speranza, EPJC 79, 741 (2019)
Li et al., PLB 827, 136971 (2022)

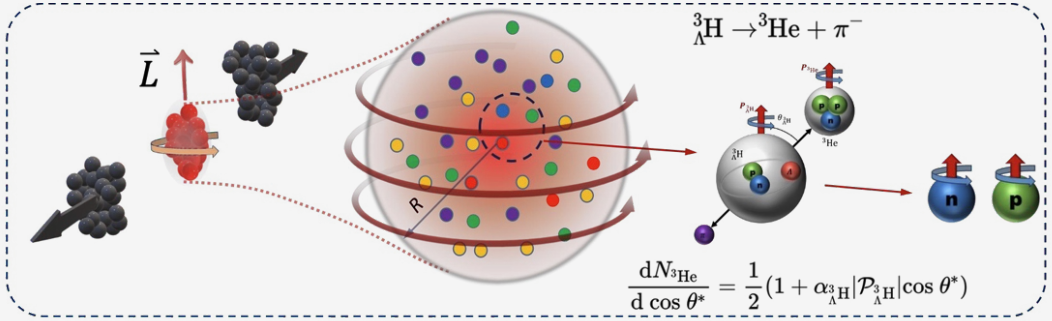
Recent experimental measurements:
STAR, arXiv:2611.03044 (2026)
STAR, arXiv:2611.03237 (2026)

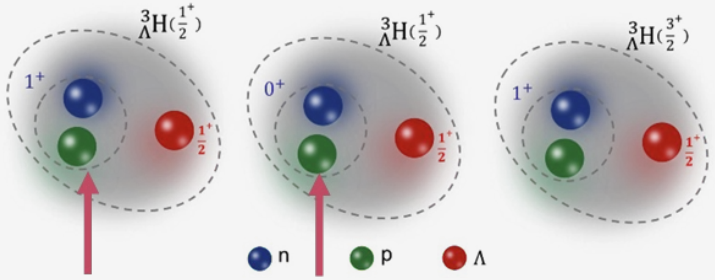
- Λ–π rescattering: primary P_Λ reduced by ≈10% at 7.7 GeV
- Feed-down: P_Λ decreases, P_Ξ increases → $P_\Omega > P_\Xi \gtrsim P_\Lambda$
- P_Ω below STAR central values: s-quark spin correlations?

Quark spin correlations:
Lv et al., PRD 109, 114003 (2024)
Zhang et al., PRD 110, 074019 (2024)
Lv et al., arXiv:2603.15135 (2026)

Global polarization of hypertriton

➢ Hypertriton spin from its polarization



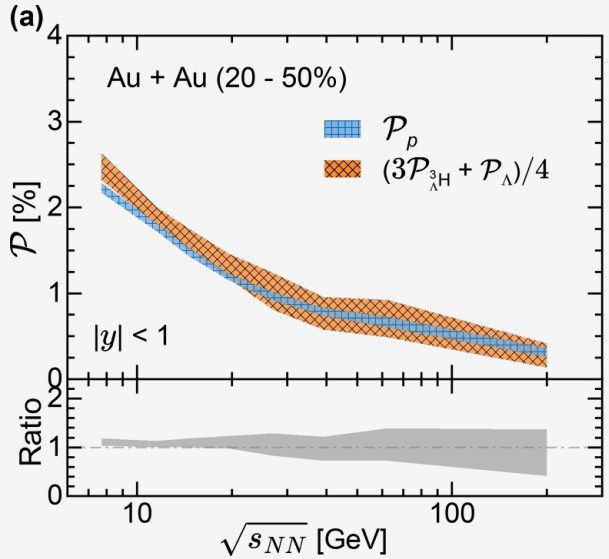


J^π	Structure	Decay mode	$dN/(\sin\theta^* d\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1 - \frac{1}{2.58}\alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	$^3_\Lambda\mathrm{H}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

Sun, Liu, Zheng, Chen, Ko, Ma, PRL 134, 022301 (2025)

➢ Different internal spin structures of $^3_\Lambda$H predict different $P_{^3\Lambda H}$ → its spin can be determined

➢ Hypernuclei → proton polarization



Liu et al., PRR 8, 033057 (2026)

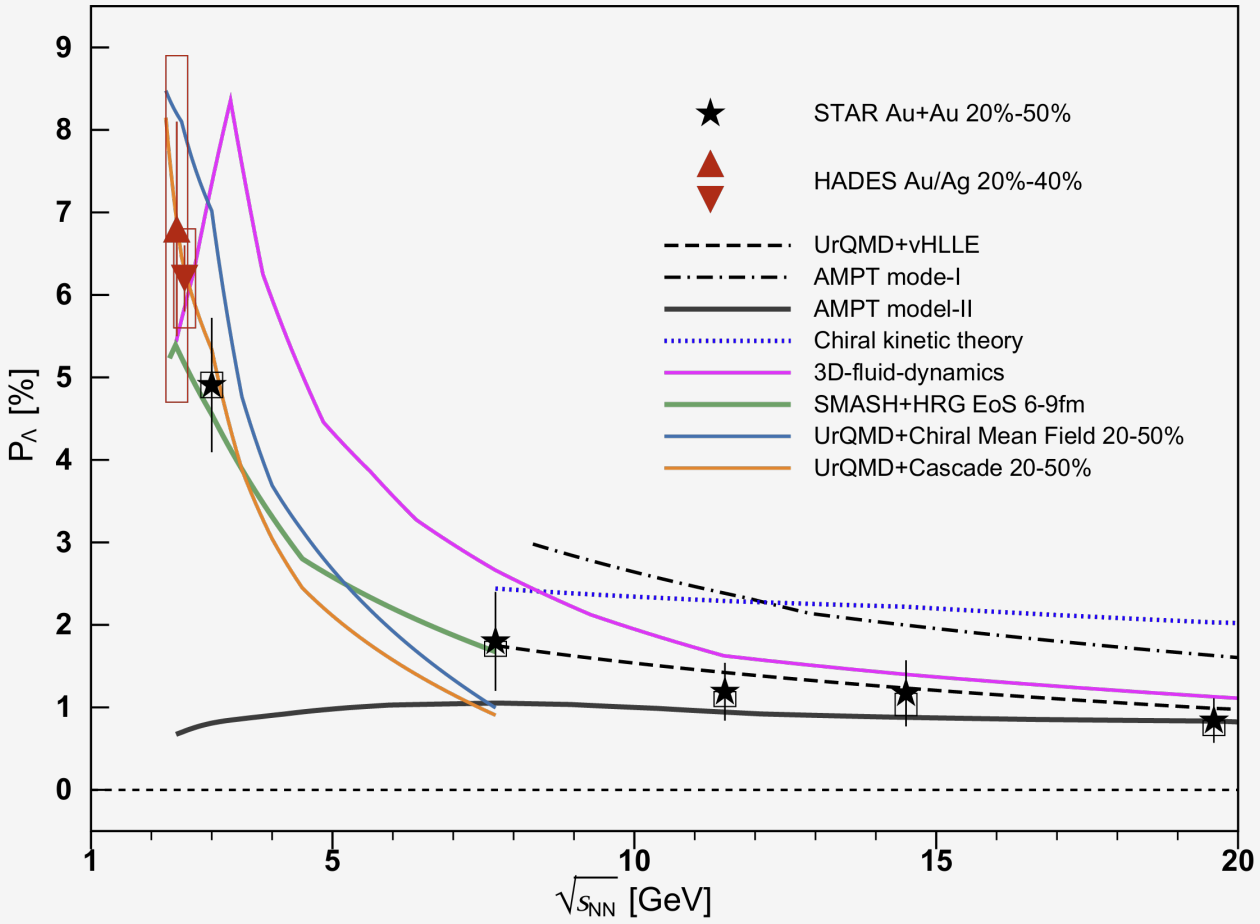
➢ $P_p \approx (3P_{^3\Lambda H} + P_\Lambda)/4$: hypernuclei give access to proton polarization

Kai-Jia Sun, Nov 17, 12:00–12:30

Also see: Liu, Sun, Steinheimer, Chen, Ma, Bleicher, arXiv:2610.35310 (2026)

Global polarization at low energies

➢ Equilibrium (thermal-vorticity) picture



HIAF white paper (in preparation)

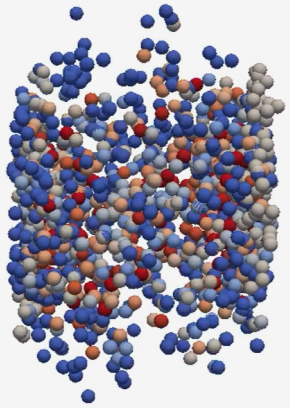
AMPT: Guo, Liao et al., PRC 104, L041902 (2021)
UrQMD + vHLLE: Karpenko, Becattini, EPJC 77, 213 (2017)
Chiral kinetic theory: Sun, Ko, PRC 96, 024906 (2017)
3FD: Ivanov, PRC 103, L031903 (2021)
SMASH: CY, Pu, Pang, Qin, Wang, arXiv:2603.27521 (2026)
UrQMD: Liu et al., arXiv:2606.13333 (2026)

Also see:
Deng, Huang, PRC 93, 064907 (2016)
Akridge, Gallimore, Morales, Liao, PRC(2025)
Xu, APS Open Sci. 1, L000035 (2026)

- Vorticity picture still valid at a few GeV?
- Will P_Λ keep rising with decreasing energy? Where is the turning point?

Thermal vorticity from SMASH

➢ SMASH



- Hydro may no longer apply at a few GeV
- Elastic, resonances and strings; all hadrons up to 2.35 GeV

Weil et al., PRC 94, 054905 (2016)

➢ From particles to polarization

1 Coarse-graining

$$T^{\mu\nu}(\tau, x, y, \eta_s) = \frac{1}{\Delta V} \left\langle \sum_i \frac{p_i^\mu p_i^\nu}{p_i^0} \right\rangle$$

$$T^\mu{}_\nu \, u^\nu = \varepsilon \, u^\mu, \qquad N_B = J_B^\mu \, u_\mu$$

2 Equation of state

$$(\varepsilon, N_B) \rightarrow T, \qquad \beta^\mu = u^\mu / T$$

3 Thermal vorticity

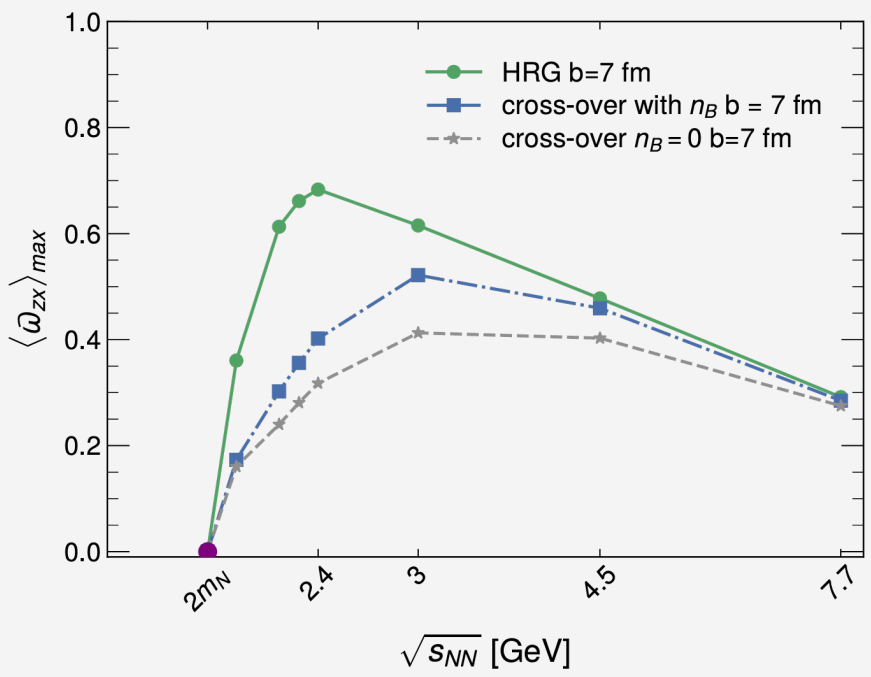
$$\varpi_{\mathrm{T}} = \frac{1}{2} \left(\nabla \beta_t + \partial_t \boldsymbol{\beta} \right), \qquad \varpi_{\mathrm{S}} = \frac{1}{2} \nabla \times \boldsymbol{\beta}$$

4 Polarization

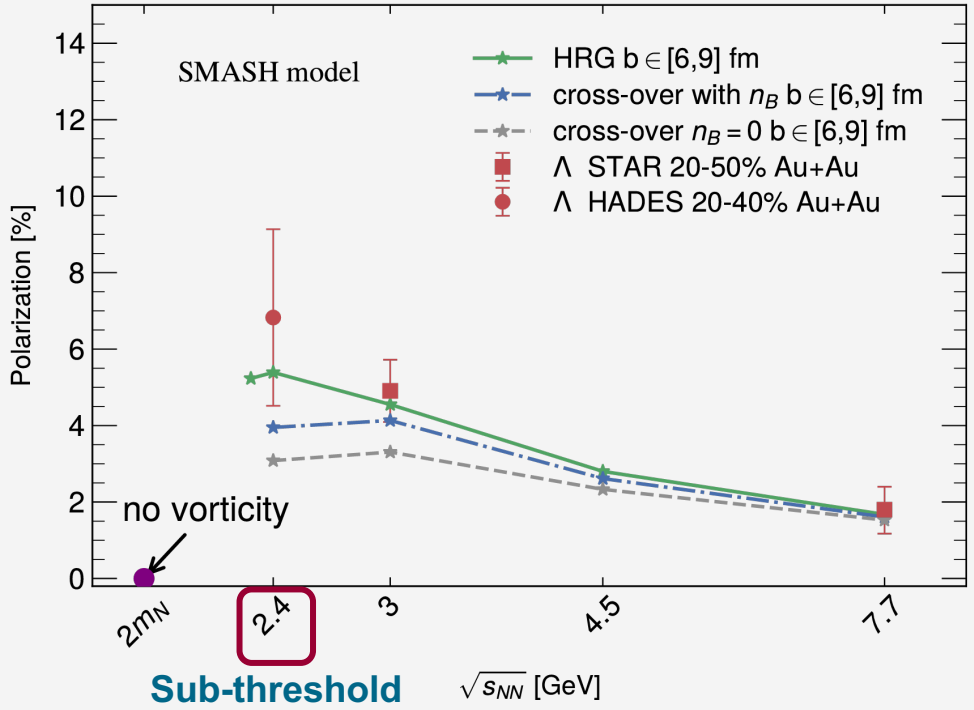
$$\mathbf{P}_{\mathrm{H}} = \frac{S+1}{3} \left[\frac{E}{m} \varpi_{\mathrm{S}}(x) + \frac{\mathbf{p}}{m} \times \varpi_{\mathrm{T}}(x) - \frac{\mathbf{p} \cdot \varpi_{\mathrm{S}}(x)}{m(E+m)} \mathbf{p} \right]$$

Global polarization at a few GeV

➢ Thermal vorticity



➢ Global Polarization



CY, Pu, Pang, Qin, Wang, arXiv:2603.27521 (2026)

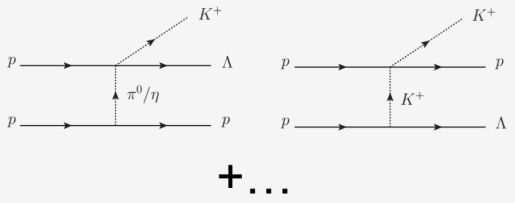
- Global polarization at a few GeV may still be **driven by vorticity**
- Can polarization **probe the EoS**?

Non-equilibrium approach: spin from NN scattering

➢ Spin-dependent production NN → NΛK

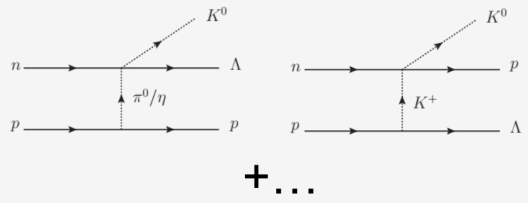
$NN \to N\Lambda K$ cross section

$pp \to p\Lambda K^+$ (7 diagrams)



+…

$pn \to p\Lambda K^0$ (12 diagrams)



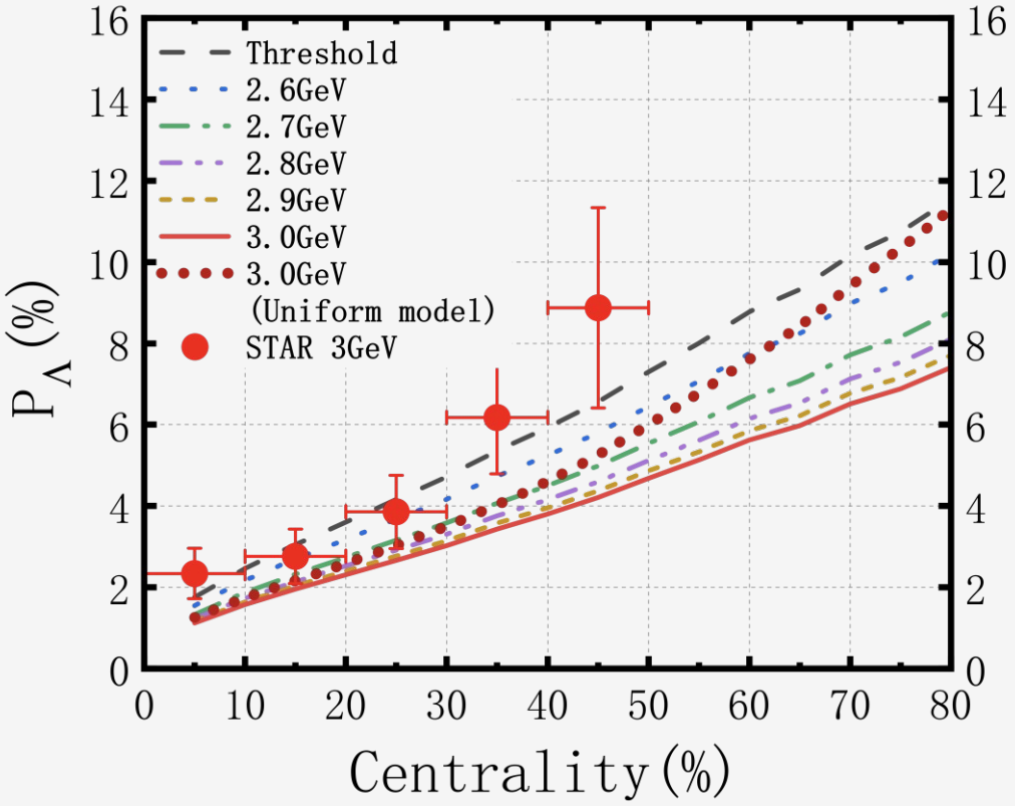
+…

➢ Polarization is generated in elementary scattering, without assuming local equilibrium

Liang, Wang, PRL 94, 102301 (2005);
Gao et al., PRC 77, 044902 (2008)

Beyond equilibrium: microscopic spin generation

➢ P_Λ vs. centrality for NN → NΛK



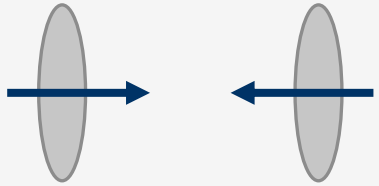
Yiliang Yin, Nov 18, 15:00–15:20

Rescattering matters at a few GeV

➢ Longer overlap at low energies

7.7 GeV

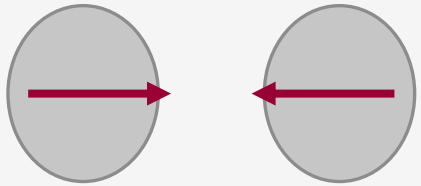
γ = 4.1



t_{pass} = 3.3 fm/c

2.4 GeV

γ = 1.3



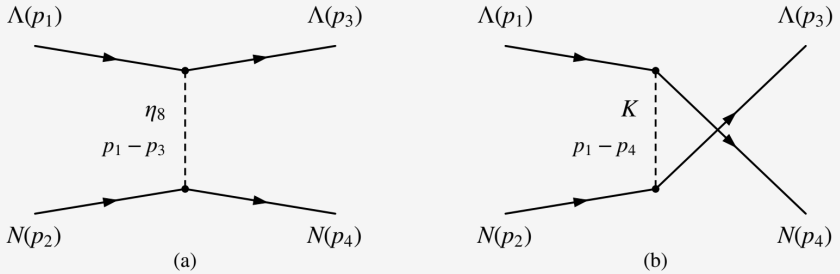
t_{pass} = 16.3 fm/c

$$t_{\rm pass} \simeq \frac{2R_{\rm Au}}{\gamma\beta}\,, \qquad R_{\rm Au} \approx 6.5 \text{ fm}$$

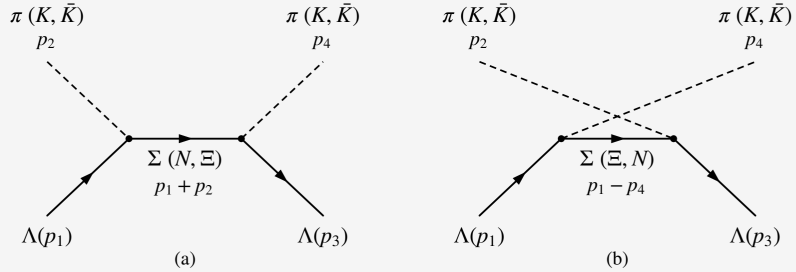
≈ 5× longer overlap at 2.4 GeV

➢ Spin-dependent Λ + X scattering

Λ+N



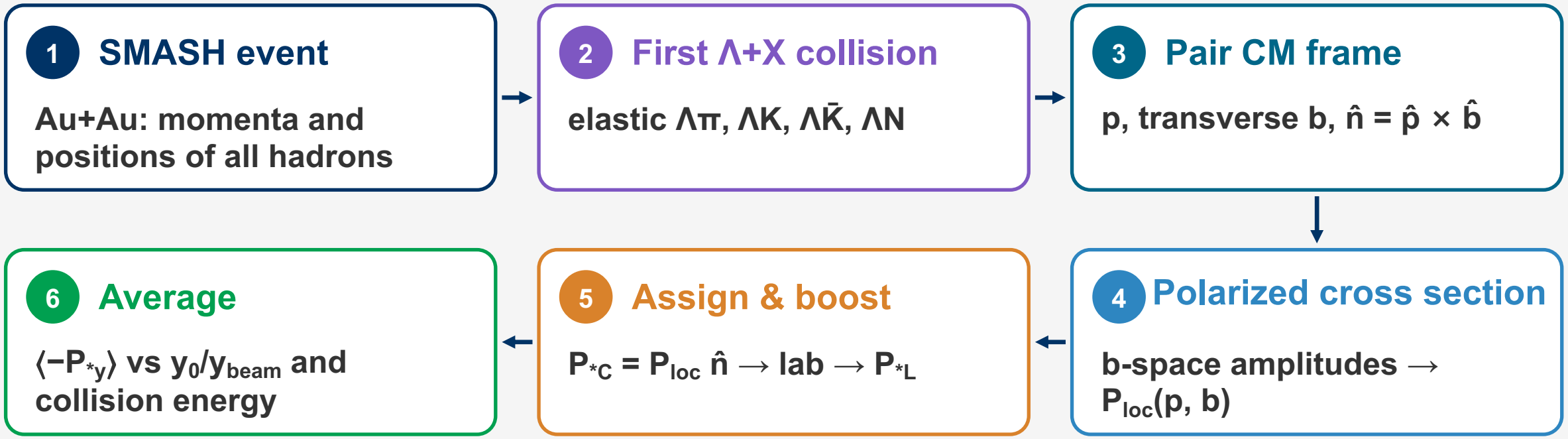
Λ+π/K



➢ Longer crossing time → more Λ rescattering with nucleons from both nuclei

Chiral EFT + SMASH: CY et al., in preparation

Embedding in SMASH

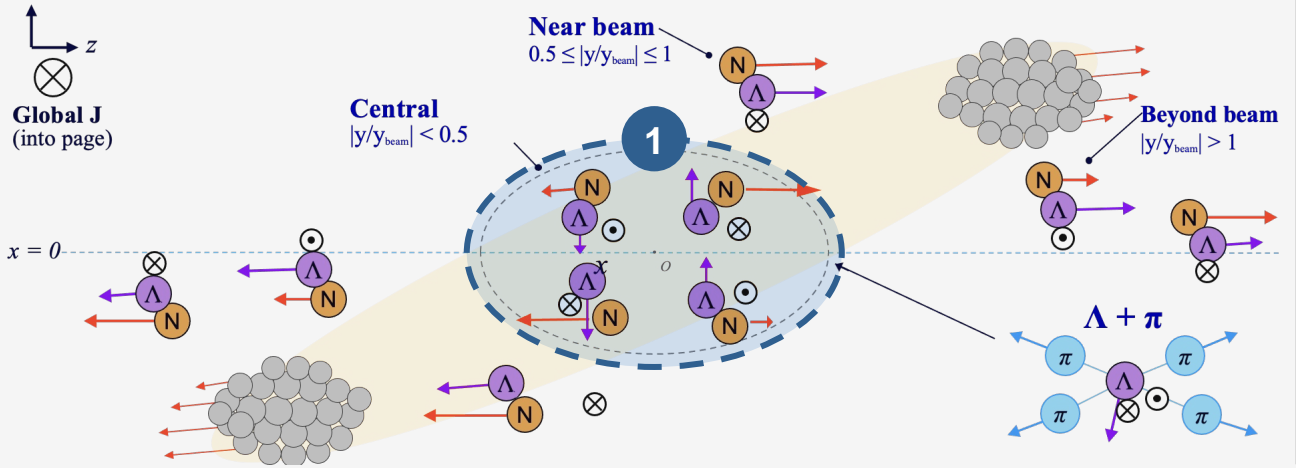


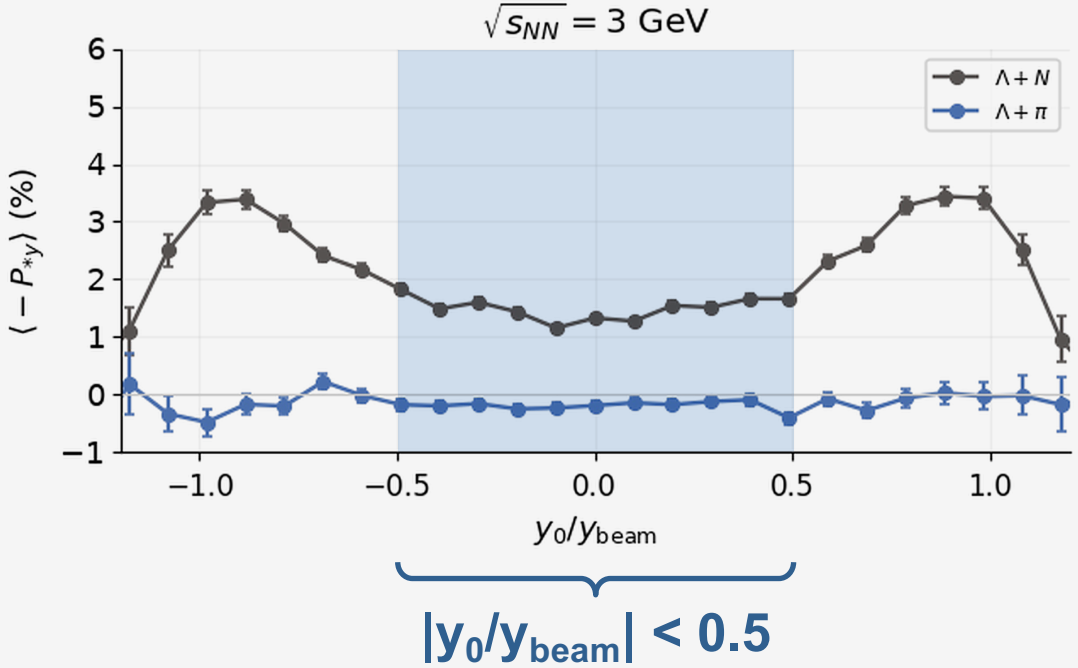
- **Model assignment:** $P_{loc}(p, b)$ is given to the recorded outgoing Λ momentum
- So far only the **first** Λ+X collision of each Λ is evaluated

Chiral EFT + SMASH: CY et al., in preparation

Rescattering-induced polarization at 3 GeV

➢ Unpolarized Λ + spin-dependent Λ+N, Λ+π scattering





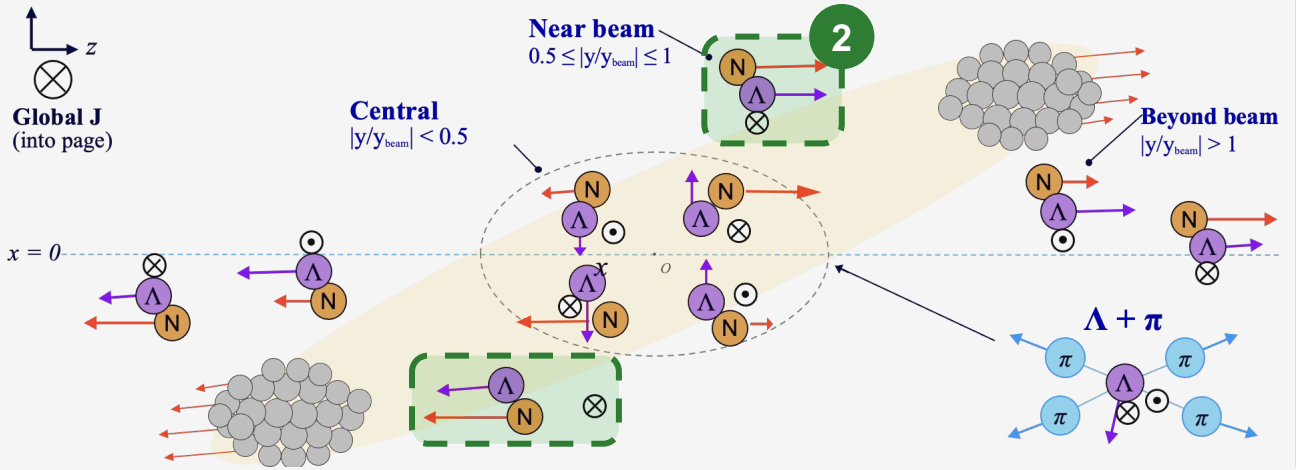
1 Central region

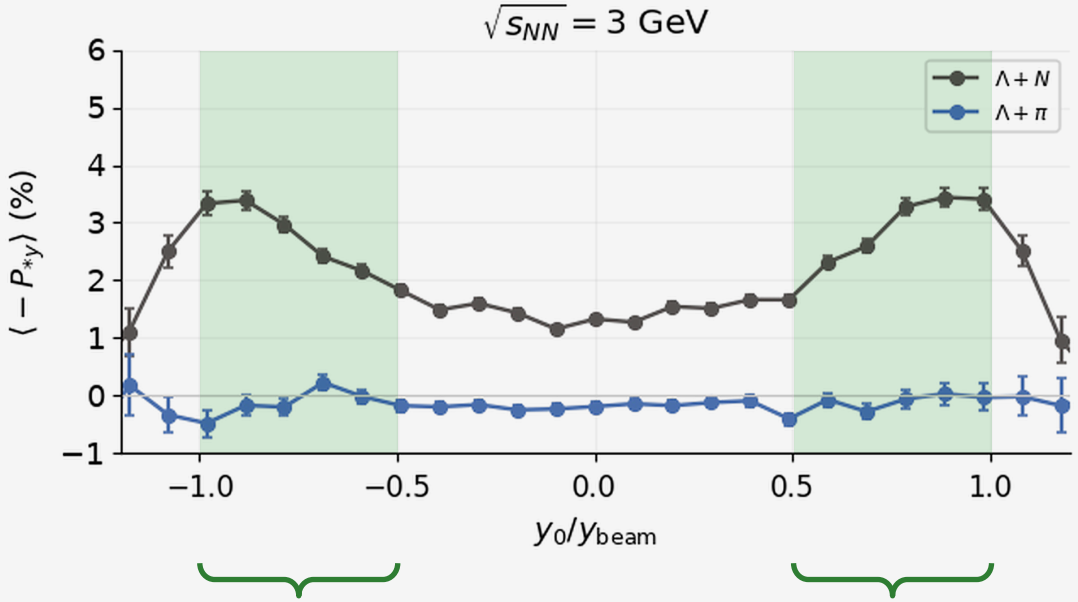
- Λ scatters with nucleons from **both nuclei**
- Local L of opposite signs partly cancel → **small polarization**

Chiral EFT + SMASH: Au+Au, b = 7 fm; first Λ+X elastic scattering, $0 \le p_T \le 3$ GeV/c; CY et al., in preparation

Rescattering-induced polarization at 3 GeV

➢ Unpolarized Λ + spin-dependent Λ+N, Λ+π scattering





2 Near beam rapidity

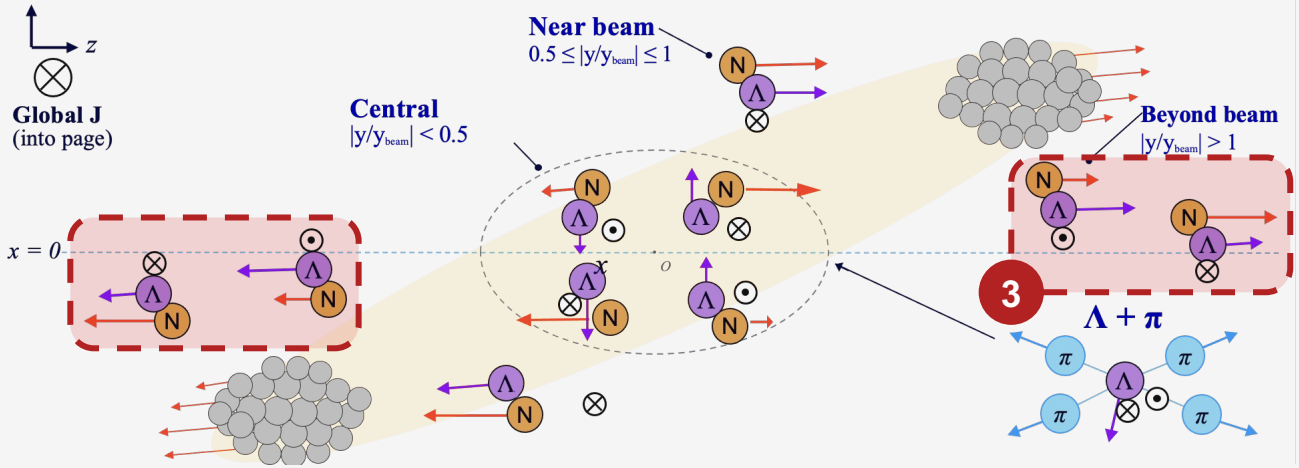
$0.5 \le |y_0/y_{beam}| \le 1$

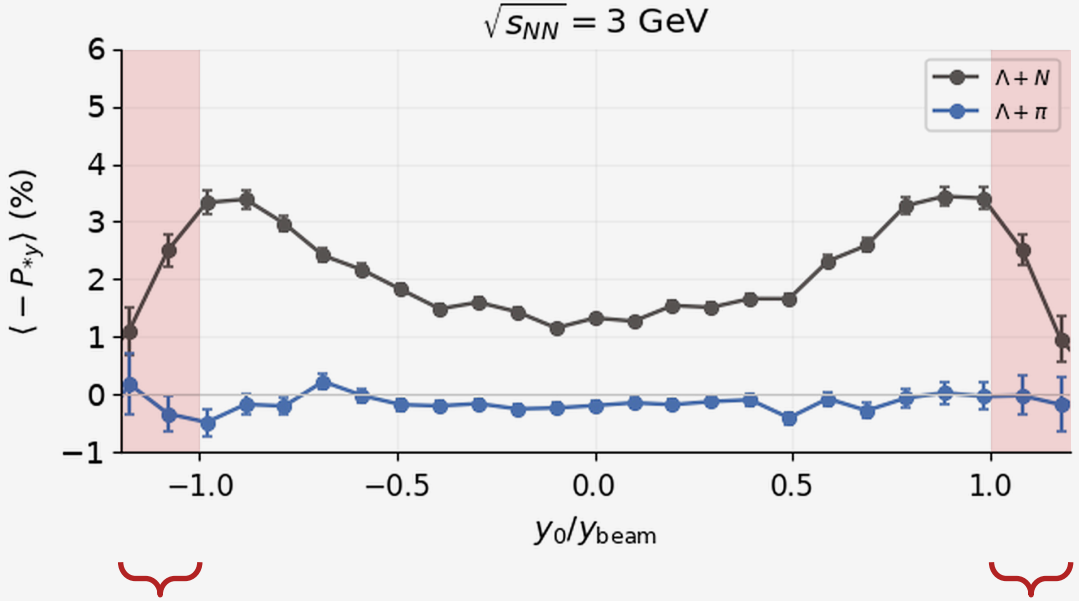
- Λ is less disturbed by the other nucleus
- More ordered orbital motion → polarization rises

Chiral EFT + SMASH: Au+Au, b = 7 fm; first Λ+X elastic scattering, $0 \le p_T \le 3$ GeV/c; CY et al., in preparation

Rescattering-induced polarization at 3 GeV

➢ Unpolarized Λ + spin-dependent Λ+N, Λ+π scattering





3 Beyond beam rapidity

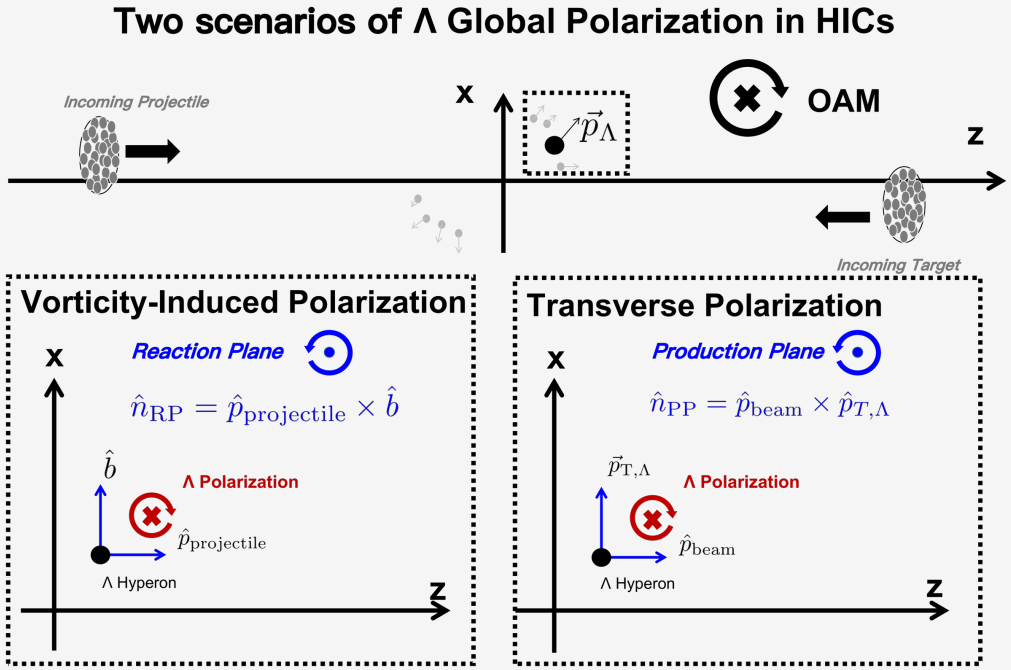
$|y_0/y_{beam}| > 1$

- Λ overtakes the spectators
- Local L reverses → polarization drops

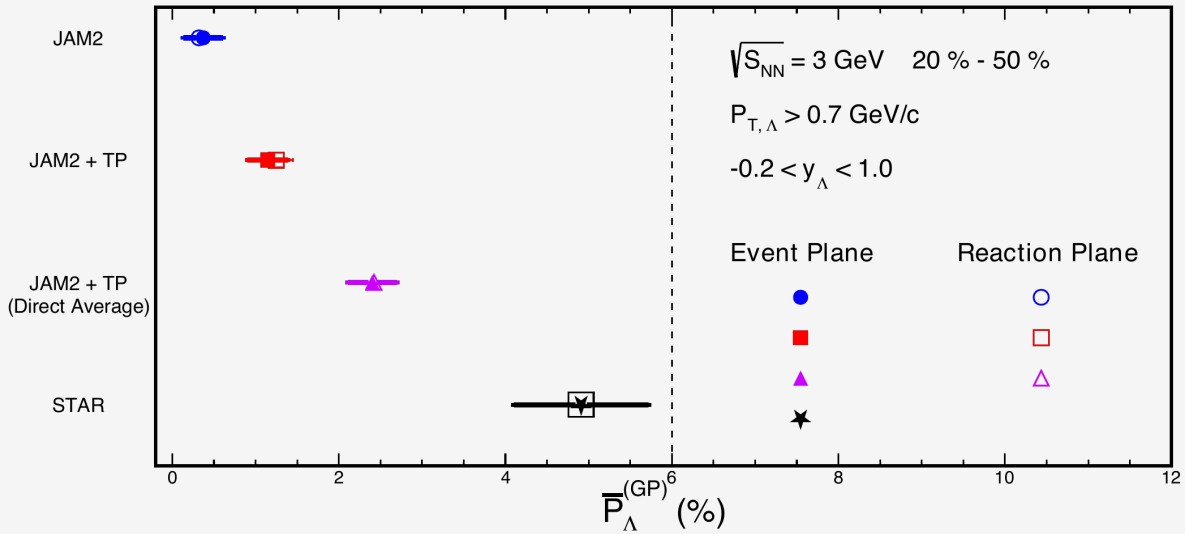
Chiral EFT + SMASH: Au+Au, b = 7 fm; first Λ+X elastic scattering, $0 \le p_T \le 3$ GeV/c; CY et al., in preparation

Directed flow and transverse polarization

➢ Vorticity and transverse polarization



➢ v_1 + TP at 3 GeV



TP + v_1 ≈ 23 ± 6% of the STAR signal

Liu, Tu, PRD 113, 114051 (2026)

- v_1 biases the production plane → transverse polarization contributes to global P_Λ
- Independent of vorticity, but still linked to angular momentum
- $\bar{\Lambda}$: transverse polarization ≈ 0 → the contribution of this mechanism may vanish

Outline

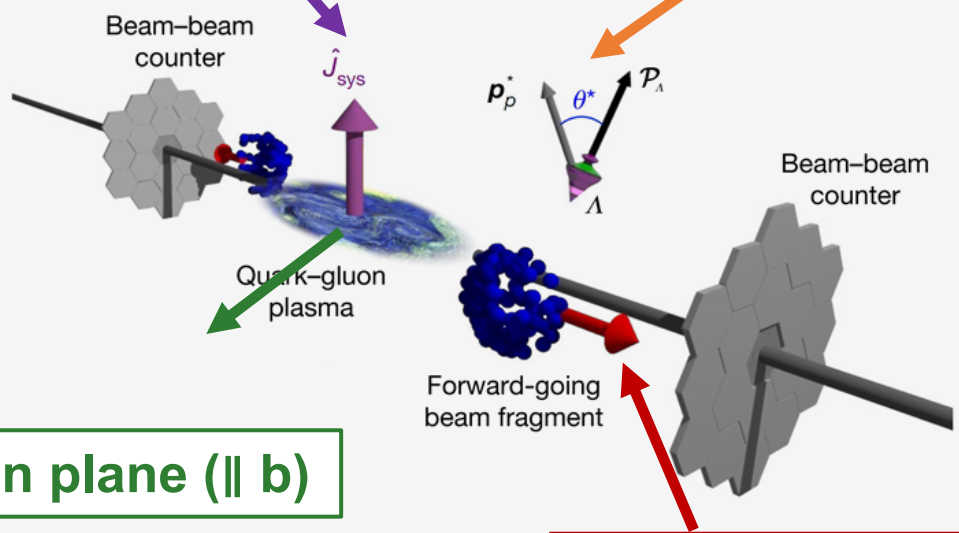
- **Global polarization**
  thermal vorticity · hadronic stage · hypernuclei · a few GeV · new mechanisms
- **Local polarization**
  P_z & P_y · P_x · vortex rings · helicity
- **Other perspectives**
  machine learning (Bayesian inference, PINNs) · initial spin fluctuations
- **Summary and outlook**

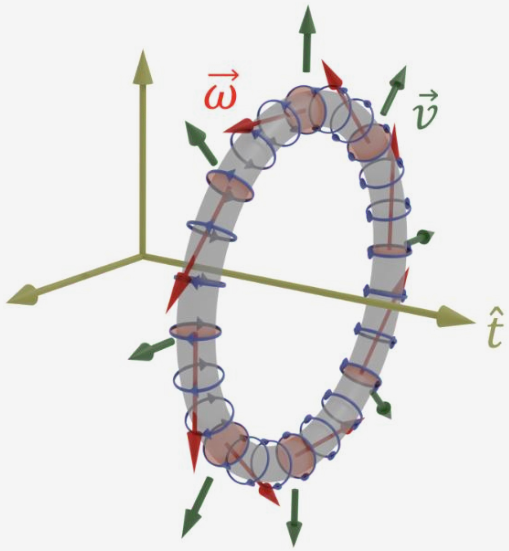
Local polarization: spin quantization axes

P_y: out of plane (∥ J)

Helicity: along p

Ring: along the vortex ring





$$\mathcal{R}_\Lambda^{\hat{t}} = \left\langle \frac{\mathbf{P}_\Lambda \cdot (\hat{t} \times \mathbf{p}_\Lambda)}{|\hat{t} \times \mathbf{p}_\Lambda|} \right\rangle$$

t̂ = jet axis

P_x: in plane (∥ b)

P_z: beam direction

P_y: Liang, Wang, PRL 94, 102301 (2005); STAR, Nature 548, 62 (2017); Becattini, Karpenko, PRL 120, 012302 (2018)

P_z: STAR, PRL 123, 132301 (2019); Becattini, Karpenko, PRL 120, 012302 (2018)

P_x: Karpenko, Becattini, EPJC 77, 213 (2017); Arslan et al., PRC 113, 034920 (2026)

Helicity: Becattini et al., PLB 822, 136706 (2021); Gao, PRD 104, 076016 (2021

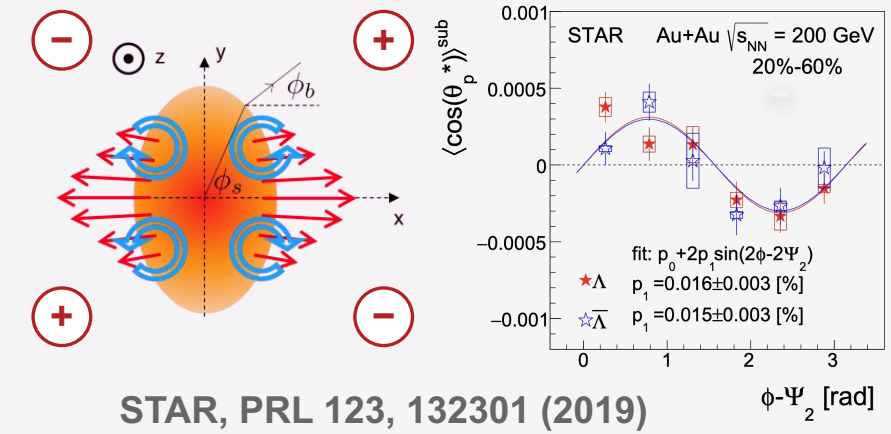
Ring: Lisa et al., PRC 104, L011901 (2021); Serenone et al., PLB 820, 136500 (2021); Ribeiro et al., PRC 109, 014905 (2024); Chinellato et al., PRC 110, 054908 (2024)

Local polarization: the sign puzzle

➢ Experiment (STAR)

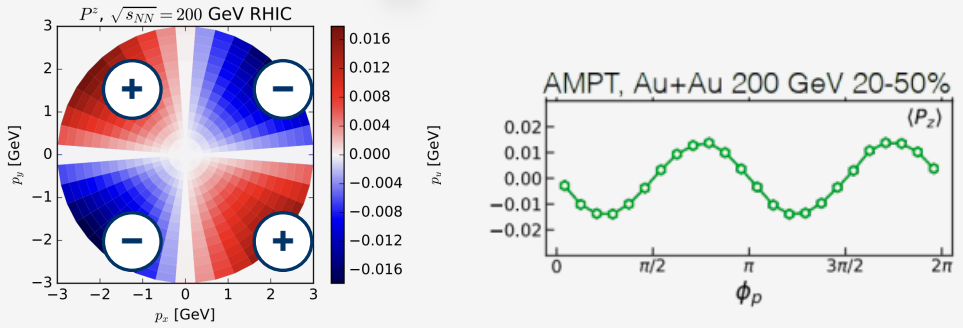
➢ Thermal vorticity (hydro / AMPT)

P_z



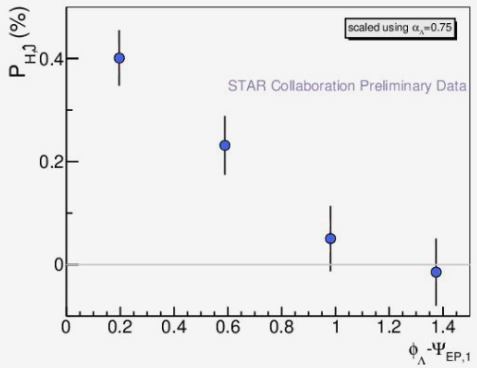
STAR, PRL 123, 132301 (2019)

≠ opposite sign



Becattini, Karpenko, PRL 120, 012302 (2018);
Xia, Li, Tang, Wang, PRC 98, 024905 (2018)

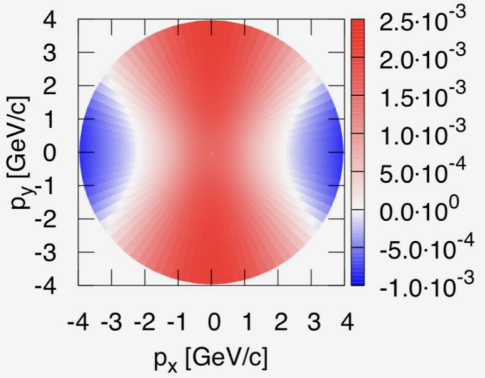
P_y



Niida (STAR), NPA 982, 511 (2019)

in-plane > out-of-plane

≠ opposite trend



Becattini et al., EPJC 75, 406 (2015)

out-of-plane > in-plane

Theoretical approaches to spin polarization

➢ Spin polarization from the axial current

Modified Cooper–Frye prescription at freeze-out:

$$\mathcal{S}^{\mu}(\mathbf{p}) = \frac{\int d\Sigma \cdot p\, \mathcal{J}_5^{\mu}(p, X)}{2m_{\Lambda} \int d\Sigma \cdot \mathcal{N}(p, X)}$$

Karpenko, Becattini, EPJC 77, 213 (2017); Fang, Pang, Wang, Wang, PRC 94, 024904 (2016)

➢ Microscopic descriptions

- ➢ Statistical quantum field theory and quantum kinetic theory
- ➢ Kubo formulas and effective theories

Contributions from many groups:
Becattini, Rischke, Florkowski, Xin-Nian Wang, Zuo-Tang Liang, Peng-fei Zhuang, Qun Wang, Shi Pu, Mei Huang, Feng Li, Xu-Guang Huang, Li Yan, Yin Yi, Huichao Song, Defu Hou, Jianhua Gao, Shu Lin, Shuai Liu, …

Polarization induced by different sources

➢ Spin polarization at local equilibrium

$$\mathcal{S}^\mu(\mathbf{p}) = \mathcal{S}^\mu_{\rm thermal} + \mathcal{S}^\mu_{\rm shear} + \mathcal{S}^\mu_{\rm accT} + \mathcal{S}^\mu_{\rm chemical} + \mathcal{S}^\mu_{\rm EB}$$

$$\mathcal{S}^\mu_{\rm thermal}(\mathbf{p}) = \frac{\hbar}{8m_\Lambda N}\int d\Sigma^\sigma p_\sigma\, f_V^{(0)}(1-f_V^{(0)})\,\epsilon^{\mu\nu\alpha\beta}p_\nu\partial_\alpha\frac{u_\beta}{T},$$

$$\mathcal{S}^\mu_{\rm shear}(\mathbf{p}) = -\frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p\, f_V^{(0)}(1-f_V^{(0)})\,\frac{\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta}{(u\cdot p)T}\,\frac{1}{2}\,p^\sigma\left[(\partial_\sigma u_\nu+\partial_\nu u_\sigma)-u_\sigma Du_\nu\right],$$

$$\mathcal{S}^\mu_{\rm accT}(\mathbf{p}) = -\frac{\hbar}{8m_\Lambda N}\int d\Sigma\cdot p\, f_V^{(0)}(1-f_V^{(0)})\,\frac{1}{T}\,\epsilon^{\mu\nu\alpha\beta}p_\nu u_\alpha\left(Du_\beta-\frac{1}{T}\partial_\beta T\right),$$

$$\mathcal{S}^\mu_{\rm chemical}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p\, f_V^{(0)}(1-f_V^{(0)})\,\frac{1}{(u\cdot p)}\,\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\partial_\nu\frac{\mu}{T},$$

$$\mathcal{S}^\mu_{\rm EB}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p\, f_V^{(0)}(1-f_V^{(0)})\left(\frac{1}{(u\cdot p)T}\,\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta E_\nu+\frac{B^\mu}{T}\right).$$

Thermal vorticity

Shear-induced polarization (SIP)

Fluid acceleration

Spin Hall effect (SHE)

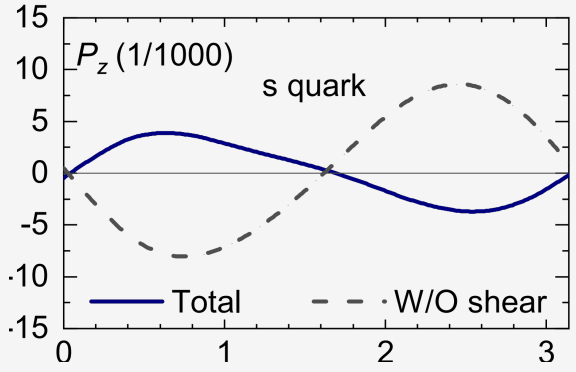
Electromagnetic fields

Liu, Yin, PRD 104, 054043 (2021)
Becattini, Buzzegoli, Palermo, PLB 820, 136519 (2021)
Liu, Yin, JHEP 07, 188 (2021)

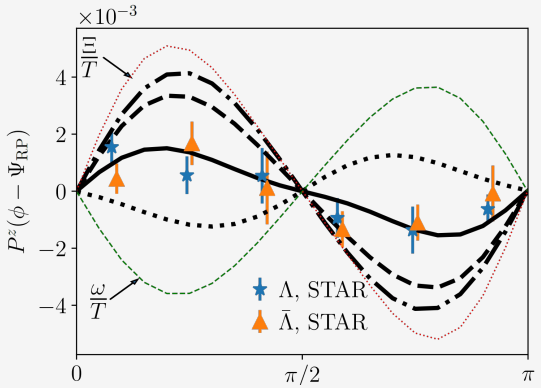
Hidaka, Pu, Yang, PRD 97, 016004 (2018)
CY, Pu, Yang, PRC 104, 064901 (2021)

Shear-induced polarization (SIP): P_z

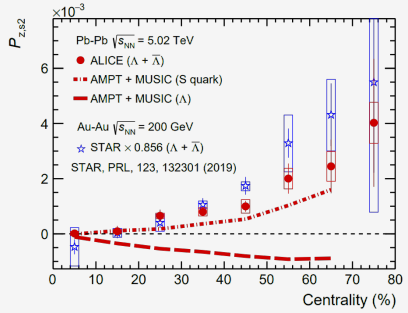
➢ Thermal vorticity + thermal shear



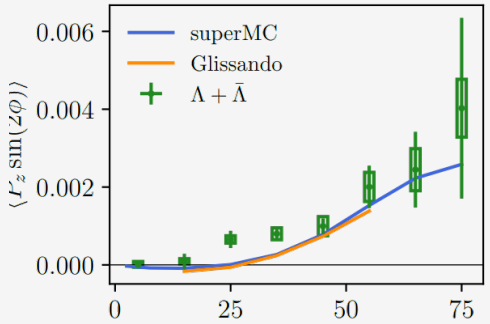
Fu et al., PRL 127, 142301 (2021)



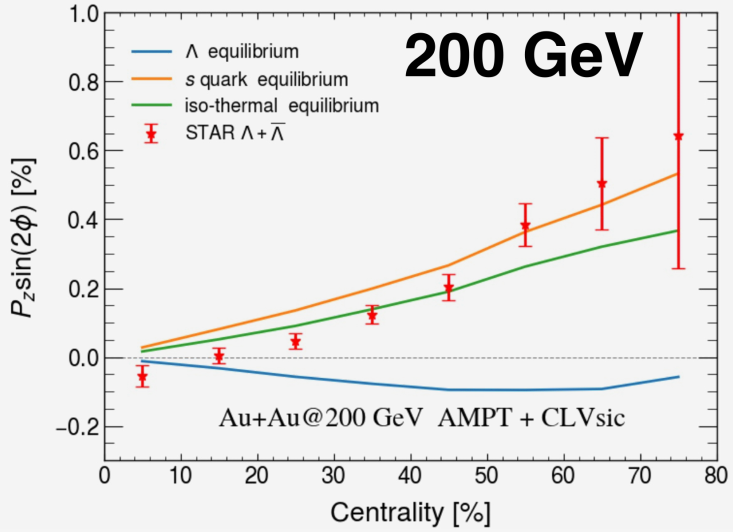
Becattini et al., PRL 127, 272302 (2021)



ALICE, PRL 128, 172005 (2022)



Palermo et al., EPJC 84, 920 (2024)



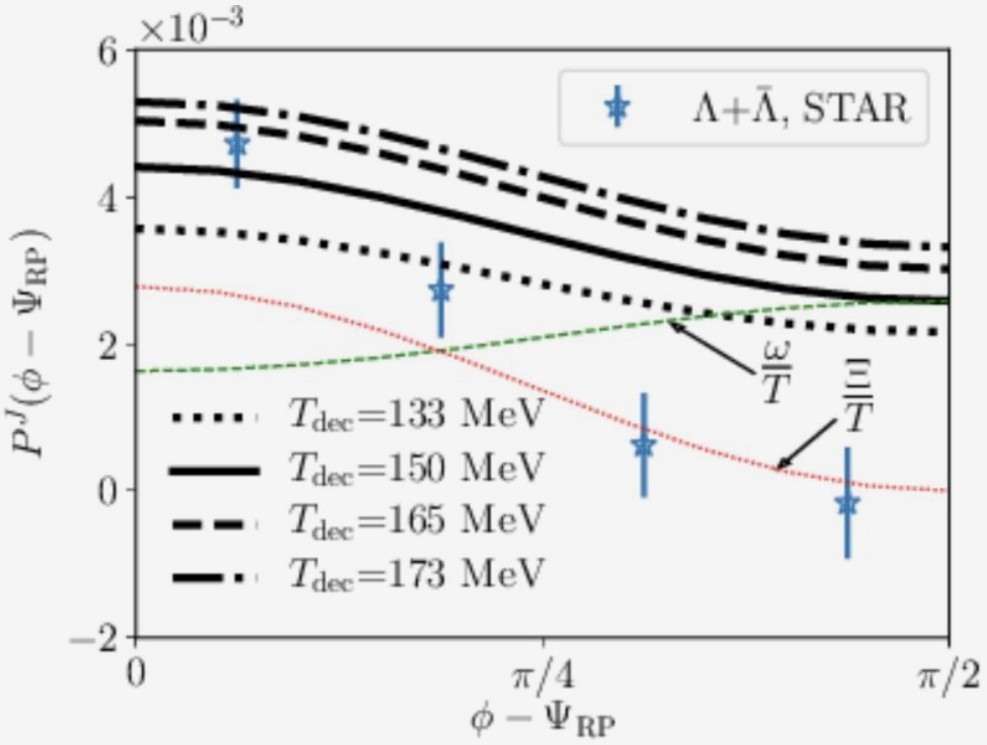
CY, Pu, Yang, PRC 104, 064901 (2021);
Wu, CY, Qin, Pu, PRC 105, 064909 (2022)

- With SIP the sign of P_z is reproduced at RHIC and LHC
- Quantitative result depends on freeze-out (T_{frz}, Λ vs. s-quark)

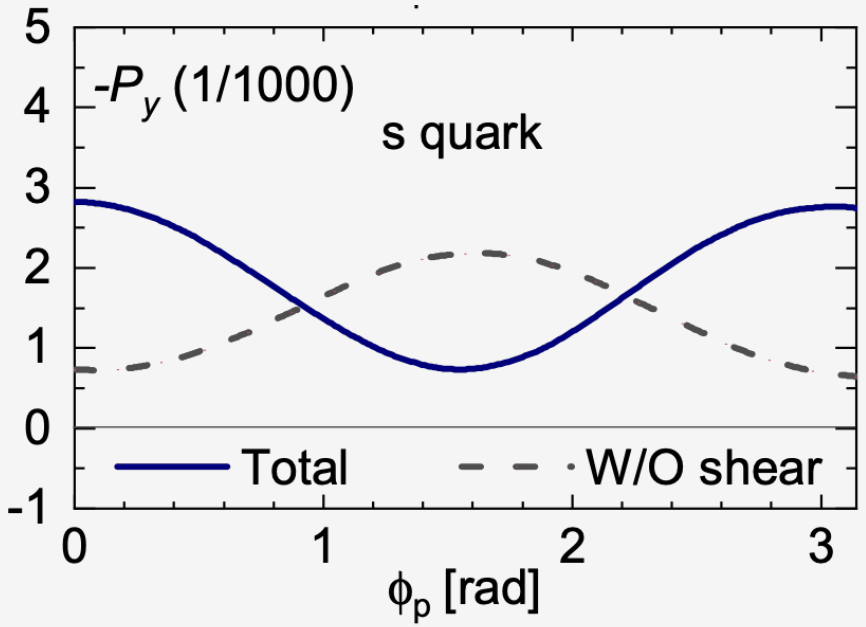
Also see: Ryu, Jupic, Shen, PRC 104, 054908 (2021);
Fu, Pang, Song, Yin, PRC 113, L041901 (2026);
Alzhrani, Ryu, Shen, PRC 106, 014905 (2022)

SIP and the azimuthal dependence of P_y

- $P_J(\varphi)$ along the angular momentum



Becattini, Buzzegoli, Inghirami, Karpenko, Palermo, PRL 127, 272302 (2021)



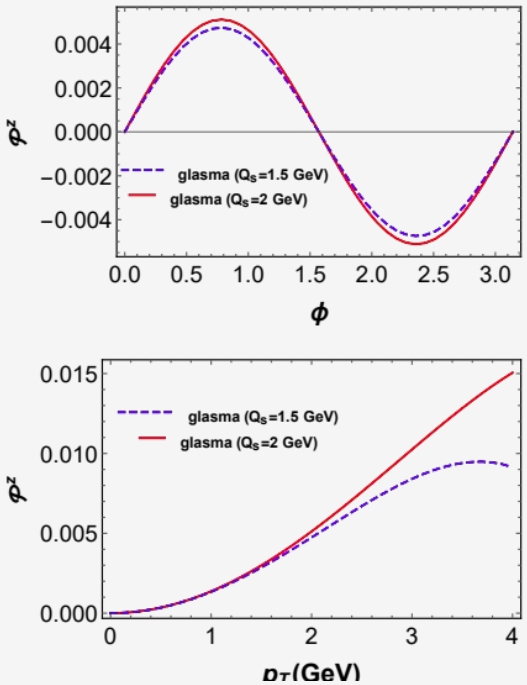
Fu, Liu, Pang, Song, Yin, PRL 127, 142301 (2021)

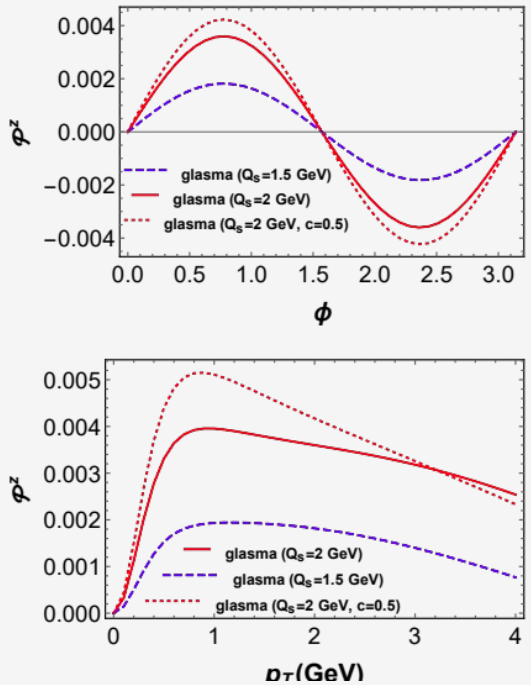
SIP: both P_z and P_y puzzles resolved qualitatively

Local polarization from color fields

- **Glasma: P^z of quarks at $y_p = 0$**

Schwinger-type **Quasi-equilibrium**





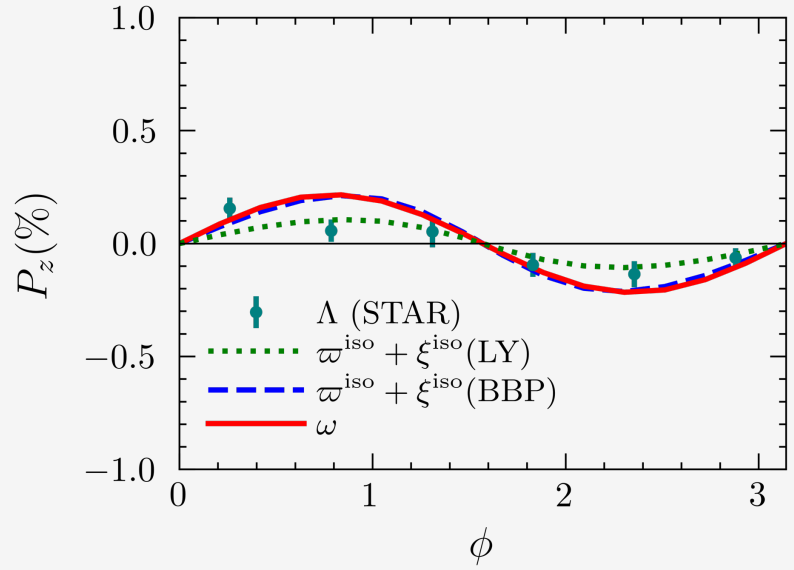
- Color-field correlators + anisotropic quark flow (chromo-spin Hall effect) → **local quark polarization**
- Glasma: $P^z \propto$ **sin 2φ**; sign and size (~0.1–1%) consistent with data
- QGP core gives the **opposite sign** → total depends on corona vs. core
- **Coherent gluon fields**: a new polarization source, no spin equilibrium needed

Sung, Müller, Yang, J. Subatomic Part. Cosmol. 5, 100311 (2026)

Di-Lun Yang, Nov 20, 09:30–10:00

Numerical spin hydrodynamics

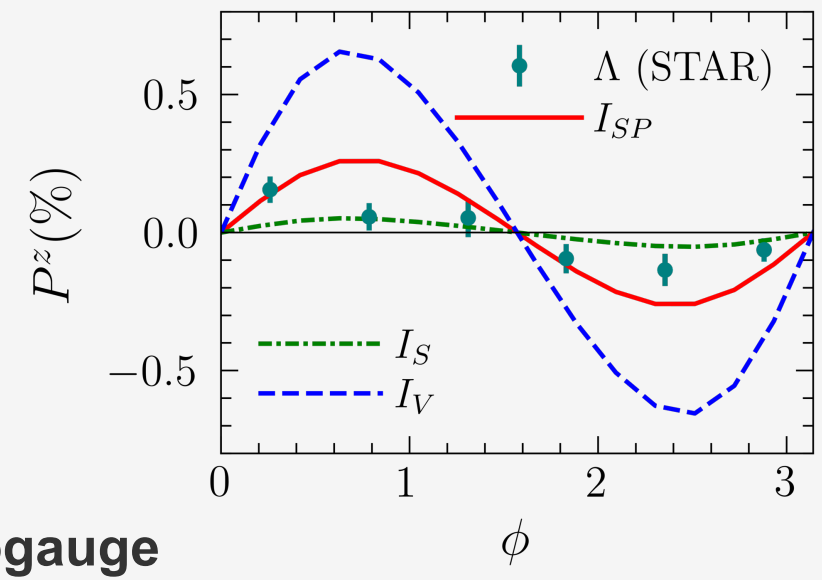
➢ Perfect spin hydrodynamics



Singh, Ryblewski, Florkowski, PRC 111, 024907 (2025)

Wojciech Florkowski, Nov 20, 08:30–09:00

➢ Dissipative spin hydrodynamics



Sapna, Singh, Wagner, PRC 112, 054902 (2025)

David Wagner, Nov 18, 10:55–11:15

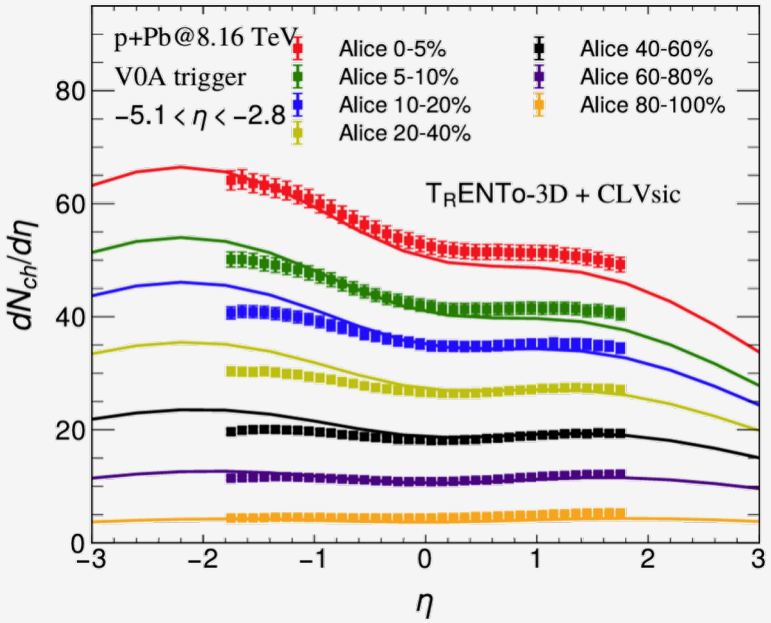
GLW pseudogauge

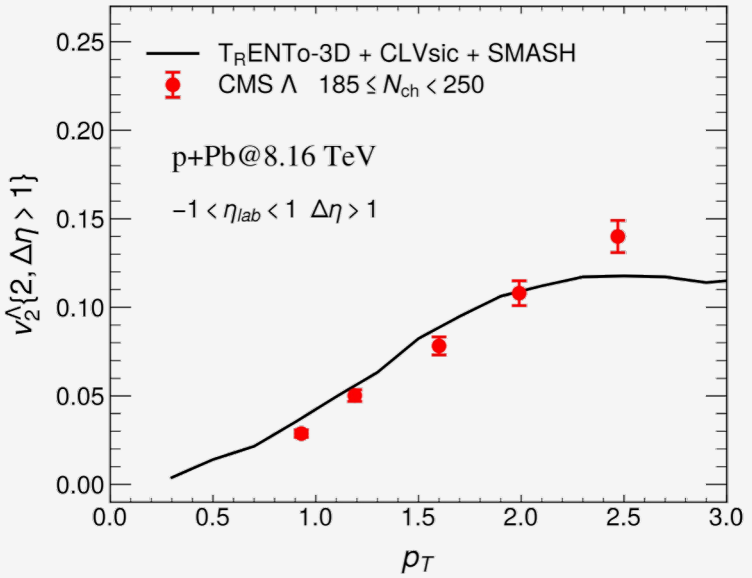
- 6 spin components on a 3+1D background; **sensitive to the spin initialization time**
- 11 coupled spin variables: **finite spin relaxation** and spin shear

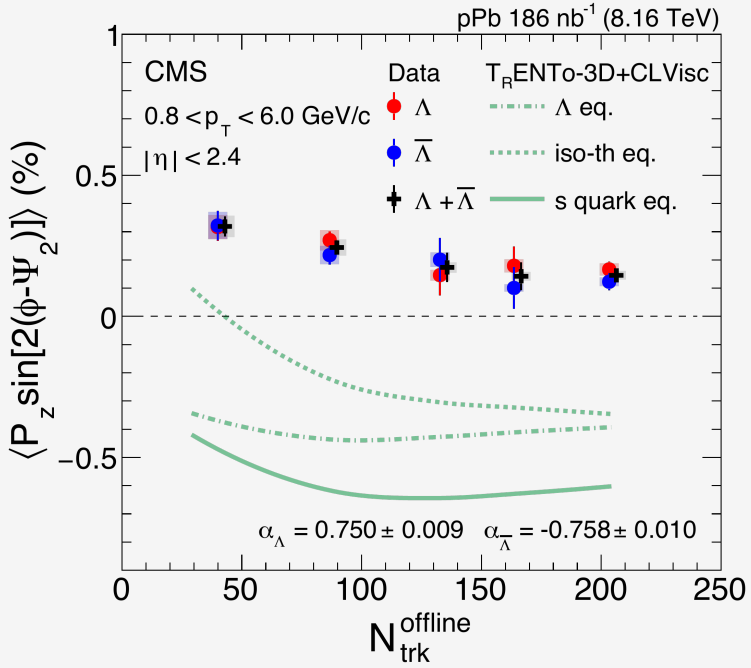
- Both: spin evolves on a 3+1D hydro background (small polarization, no back-reaction)

Local polarization in small systems

➢ CMS p+Pb, 8.16 TeV





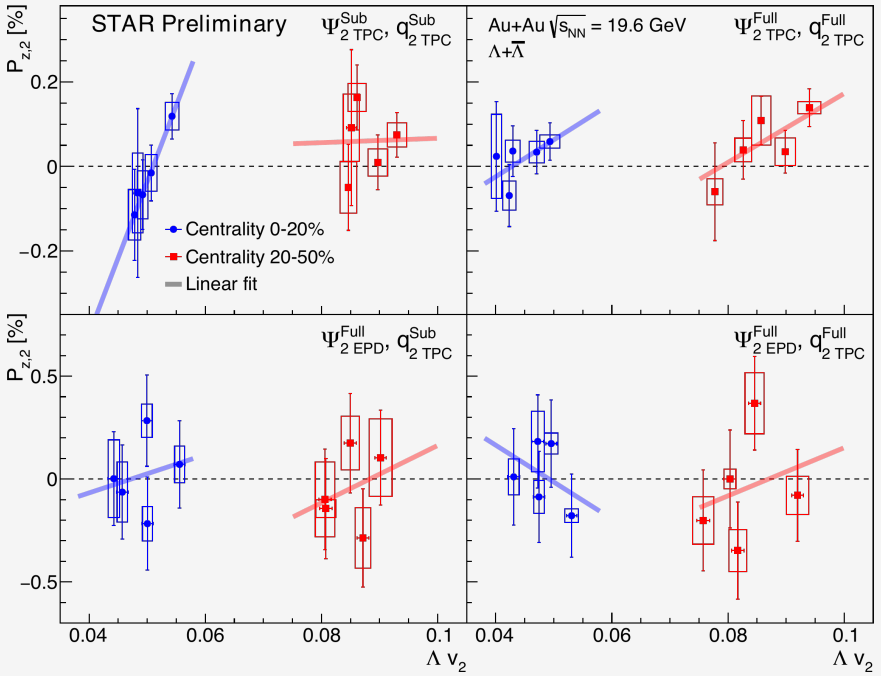


CMS, PRL 135, 132301 (2025);
CY, Wu, Zhu, Pu, Qin, PRC 111, 044901 (2025)

- ➢ p+Pb: hydro (all freeze-out scenarios) gives the opposite sign to CMS data
- ➢ What is the sign of P^2_z in O+O collisions?

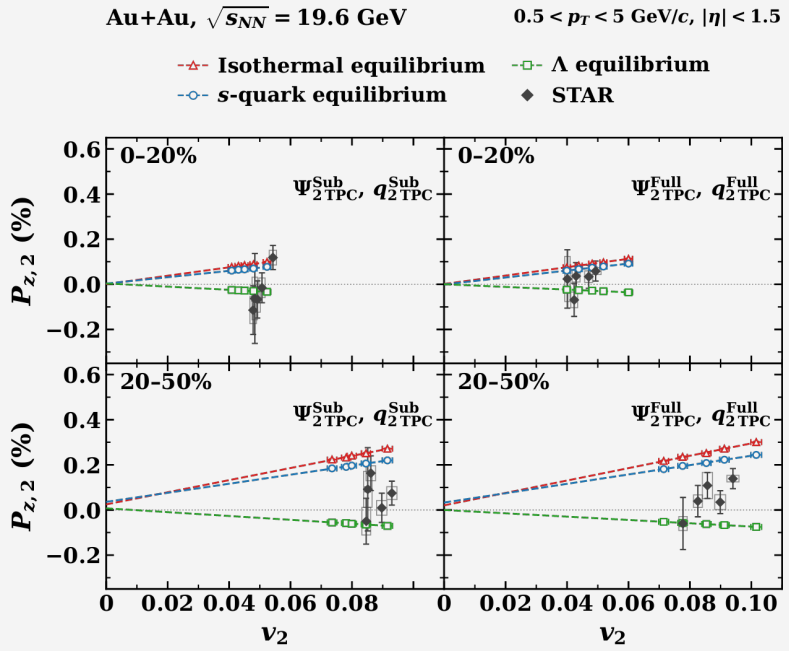
Event-shape engineering of P_z

➢ STAR Au+Au, 19.6 GeV



Kondo (STAR), J. Subatomic Part. Cosmol. 6, 100494 (2026)

➢ Hydrodynamics (preliminary)

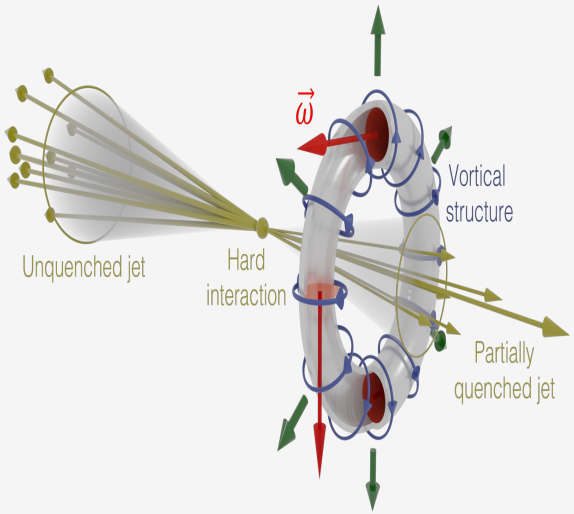


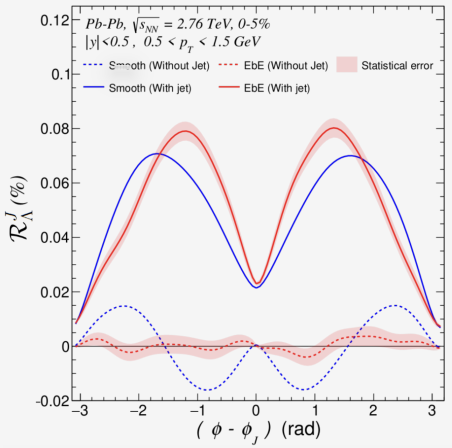
Gen-Hui Li, Nov 18, 14:40–15:00

- A weak positive correlation is observed
- Hydrodynamic results are consistent with data within uncertainties
- The Pz is induced by flow at 19.6 GeV Au+Au collisions

Jet-induced vortex rings and P_z

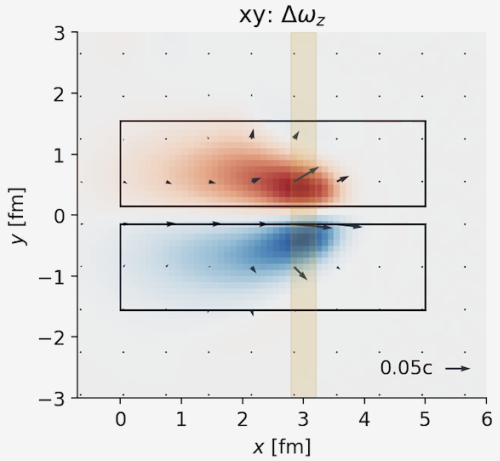
➢ Jet-induced vortex ring



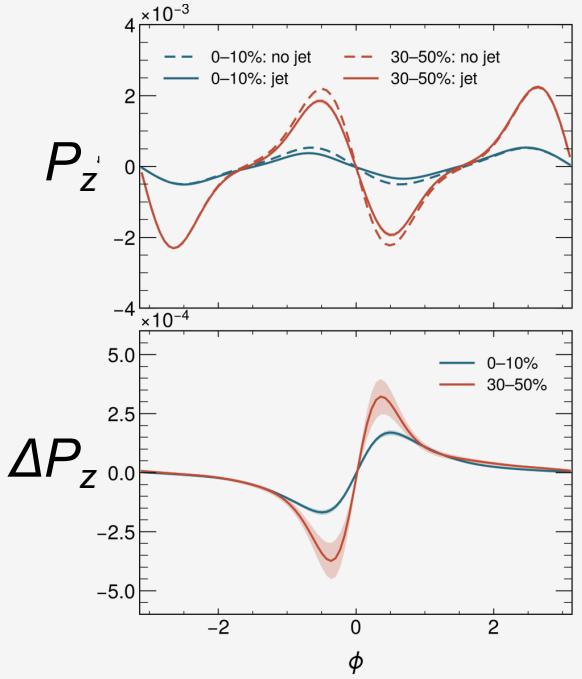


Serenone et al., PLB 820, 136500 (2021)

➢ Jet-induced P_z in Pb+Pb collisions



$\Delta\omega_z$, transverse plane (0–10%)



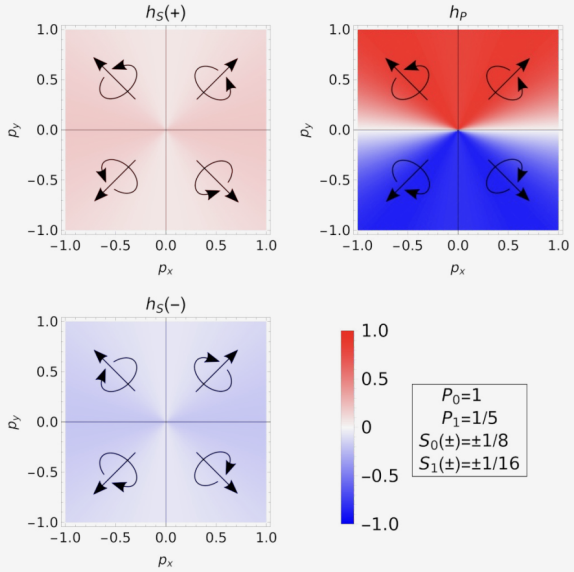
thermal-vorticity contribution only
CY et al., in preparation

- Jet energy deposition drives a vortex ring (smoke ring) around the jet axis
- $\Delta P_z(\Delta\varphi) \approx a_1 \sin\Delta\varphi$; sine modulation in γ–jet events tests the ring

Ribeiro et al., PRC 109, 014905 (2024); p+A rings: Lisa et al., PRC 104, L011901 (2021); Chinellato et al., PRC 110, 054908 (2024)

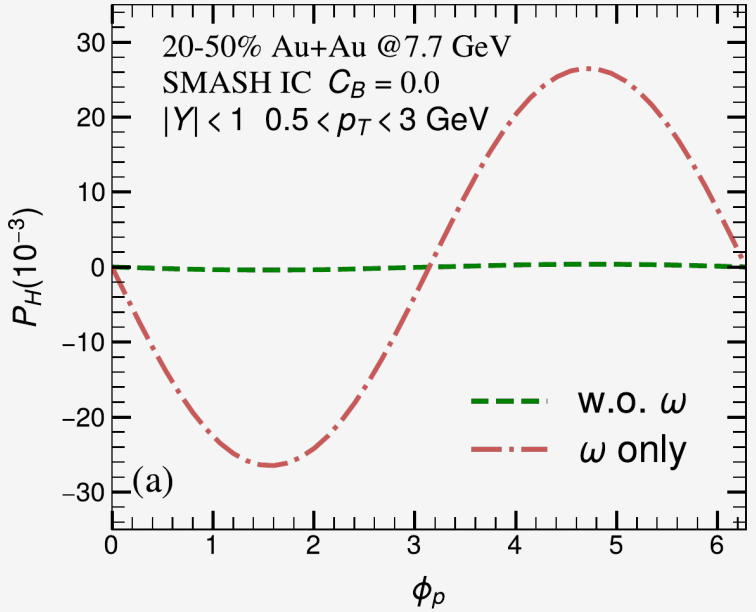
Helicity polarization

➢ Local helicity (spin ∥ p)



Becattini, Buzzegoli, Palermo, Prokhorov, PLB 822, 136706 (2021)

➢ 7.7 GeV: kinetic vorticity



CY, Wu, Yang, Gao, Pu, Qin, PRC 109, L011901 (2024)

- ➢ Spin projected on the particle momentum: no reaction plane needed
- ➢ At 7.7 GeV the pattern is dominated by kinetic vorticity (≈10× other sources)
- ➢ Helicity correlations: a probe of local parity-odd fluctuations

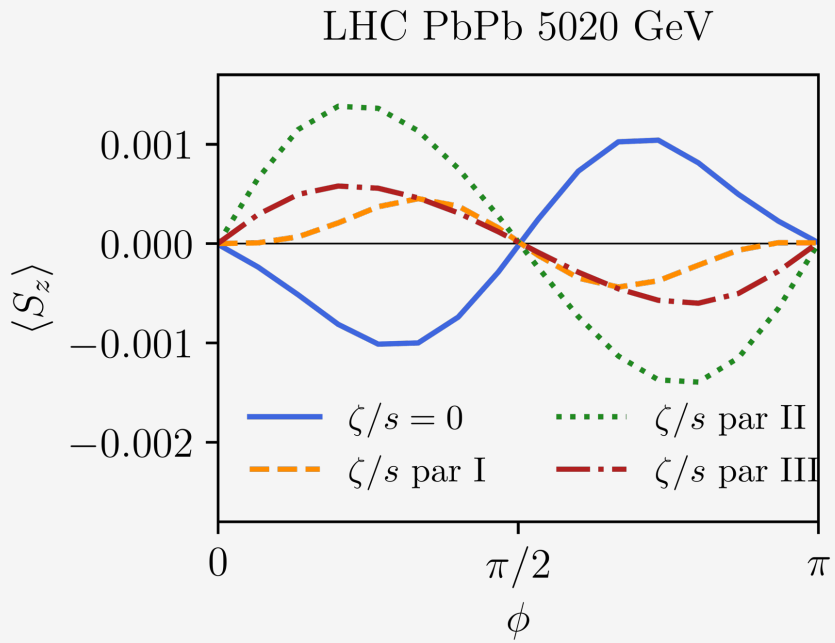
Gao, PRD 104, 076016 (2021); CY, Pu, Gao, Yang, PRC 105, 044911 (2022)

Outline

- **Global polarization**
  thermal vorticity · hadronic stage · hypernuclei · a few GeV · new mechanisms
- **Local polarization**
  P_z & P_y · P_x · vortex rings · helicity
- **Other perspectives**
  machine learning (Bayesian inference, PINNs) · initial spin fluctuations
- **Summary and outlook**

Polarization and transport properties

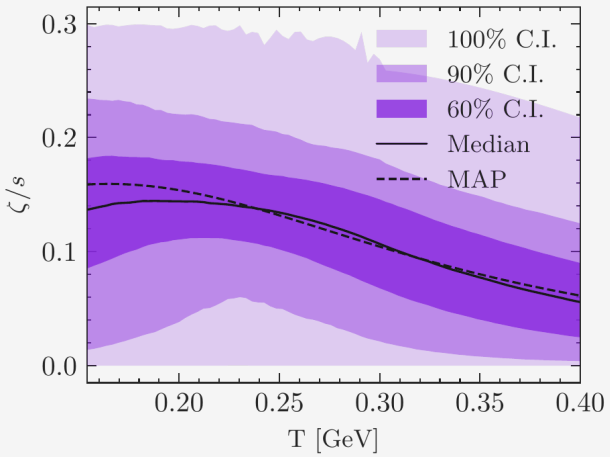
➢ Sensitivity to bulk viscosity



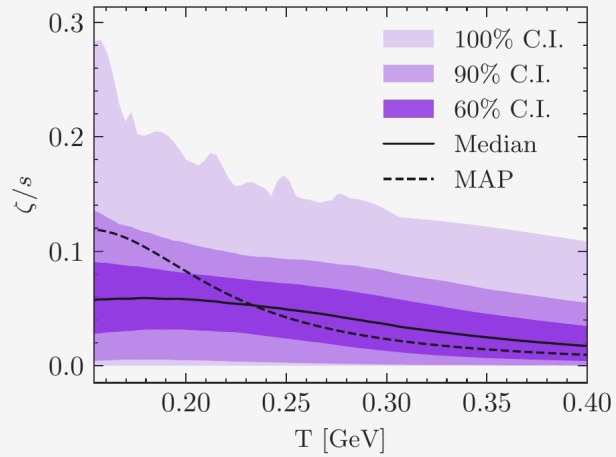
Palermo, Grossi, Karpenko, Becattini, EPJC 84, 920 (2024)

➢ Bayesian analysis with / without P_z

With longitudinal polarization



Without longitudinal polarization



Singh, Grossi, Becattini, arXiv:2605.29383 (2026)

- Local polarization is sensitive to ζ/s (η/s has a minor effect)
- Bayesian inference (Gaussian-process emulator): adding P_z shifts ζ/s upward (not yet significant)

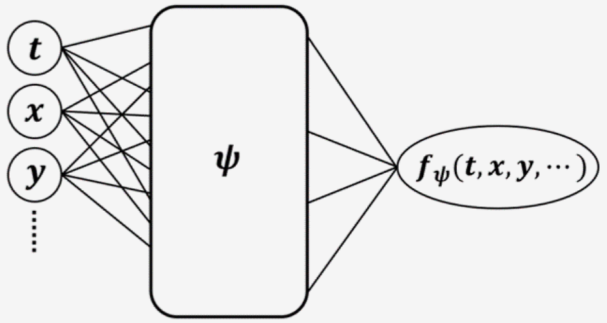
PINNs for dissipative spin hydrodynamics

➢ Physics-informed neural network (PINN)

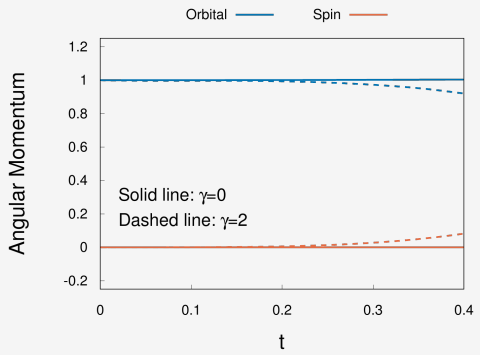
Loss = PDE residuals + initial/boundary conditions + angular-momentum conservation

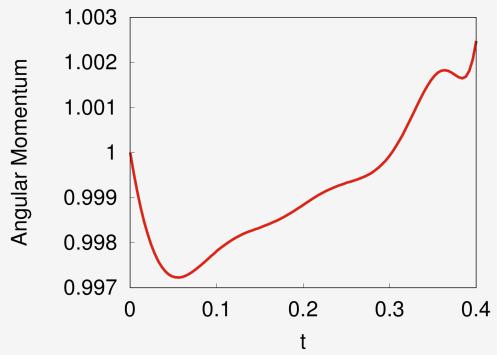
Solution of partial differential equation

$$(t, x, y, \cdots) \quad \mapsto \quad f(t, x, y, \cdots) \quad \approx$$



A neural network parametrized by trainable parameters ψ





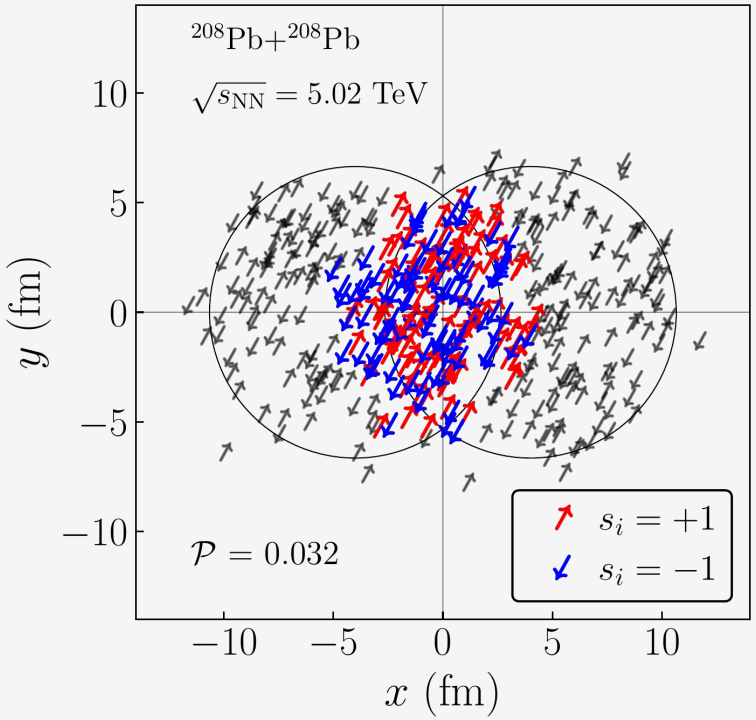
Matsuda, Hattori, Murase, arXiv:2512.17971 (2025)

Hidefumi Matsuda, Nov 18, 15:50–16:10

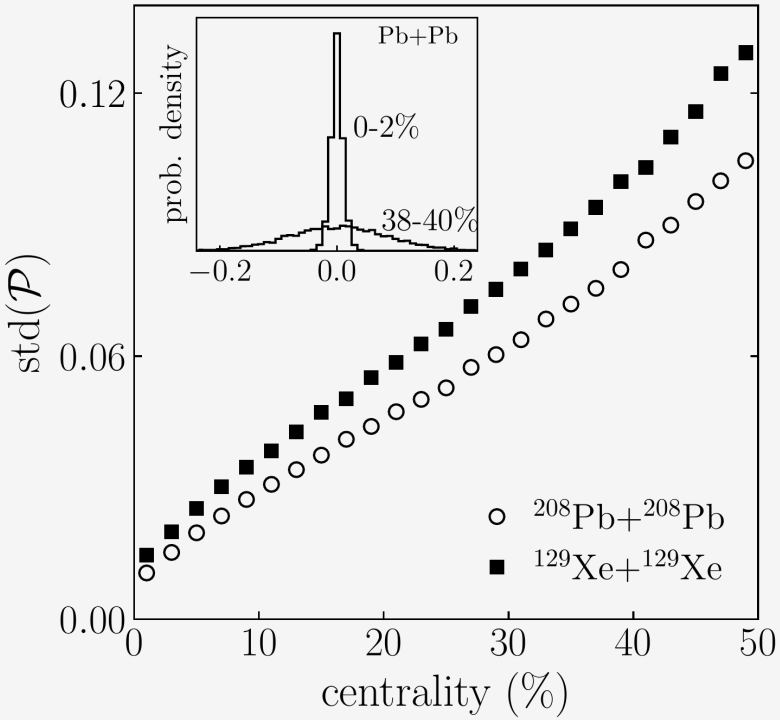
- **Axisymmetric (t, r) benchmark with five fields**
- **Total angular momentum conserved; nonlinear spin–orbit conversion captured**
- **Next: full 3+1D event-by-event simulations**

Initial spin fluctuations

- **Random nucleon spins in Pb+Pb**



- **Event-by-event spread vs. centrality**



Giacalone, Speranza, arXiv:2502.13102 (2025)

- **Zero ensemble mean, nonzero event-by-event spin: testable with two-particle spin correlations, if it survives the evolution**

Summary and outlook

➢ Global polarization

- Thermal vorticity describes P_Λ; hadronic evolution and feed-down modify it
- A few GeV: non-equilibrium sources (NN production, rescattering, v_1 + TP)

➢ Local polarization

- SIP qualitatively resolves the P_z and P_y sign puzzles
- P_x, vortex rings, helicity and color fields: complementary probes

➢ Other perspectives

- Bayesian analysis: P_z constrain ζ/s
- PINNs: simulate 3+1D spin hydrodynamics event by event.
- Initial spin fluctuations: do they survive into spin correlations?

➢ Open questions

- Non-equilibrium sources at a few GeV; where is the turning point?
- Pz in the small system?
- Spin dependent initial condition?

Thanks for your attention!

➢ Post-QM2027 Satellite Workshop @CCNU March 29–31, 2027

C3NT Workshop: Post-QM2027 Satellite Workshop on Spin Polarization and Chirality in Nuclear Collisions

Mar 28 – 31, 2027
Central China Center for Nuclear Theory
Asia/Shanghai timezone

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Central China Center for Nuclear Theory 华中核理论中心

Post-QM2027 Satellite Workshop on Spin Polarization and Chirality in Nuclear Collisions

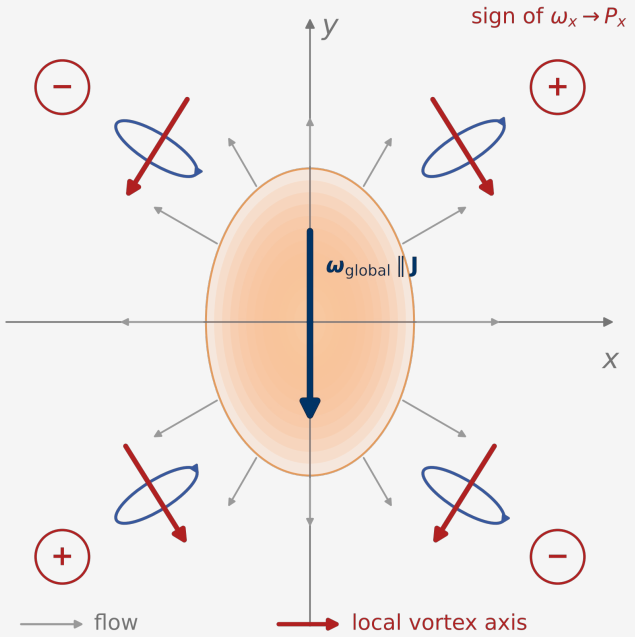
We are pleased to announce that the **post-QM2027 Satellite Workshop on Spin Polarization and Chirality in Nuclear Collisions** will be held at **C3NT** on **March 29–31, 2027**, with **onsite registration on March 28, 2027**. This workshop will bring together theorists and experimentalists from around the world to discuss recent advances in spin polarization, chiral phenomena, and related topics in nuclear collisions.

https://indico.pnp.ustc.edu.cn/event/6218/

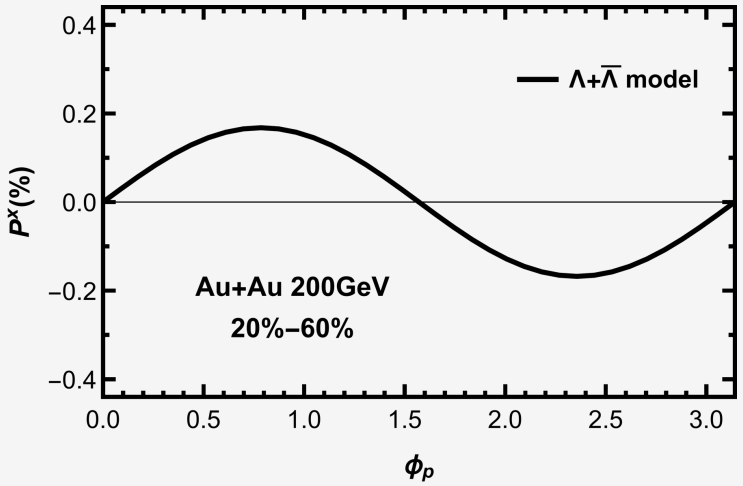
Backup

In-plane polarization P_x

➢ Vortex picture

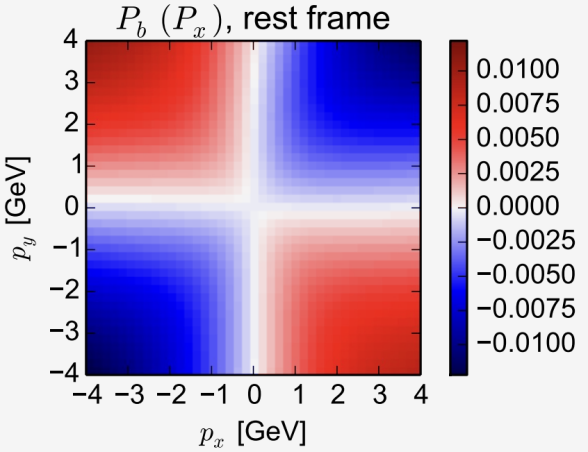


➢ Blast wave



Arslan et al., PRC 113, 034920 (2026)

➢ Hydro (rest frame)



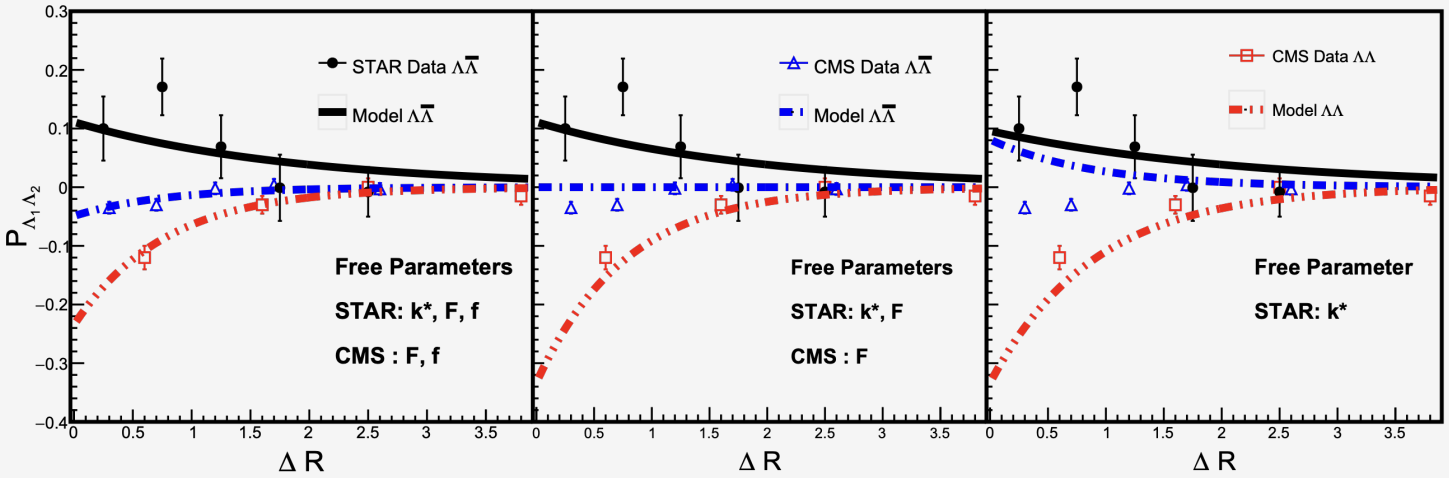
Karpenko, Becattini, EPJC 77, 213 (2017)

- Transverse expansion **tilts the vortex lines** ∥ J
- $\omega_x \propto xy$ (+ − + −) → $P_x \propto \sin 2\varphi$

- $P_x \propto \sin 2\varphi$ like P_z, **not yet measured**
- Blast wave and hydro give **opposite signs** (large ∇T term in hydro)

Spin entanglement and quark spin correlations

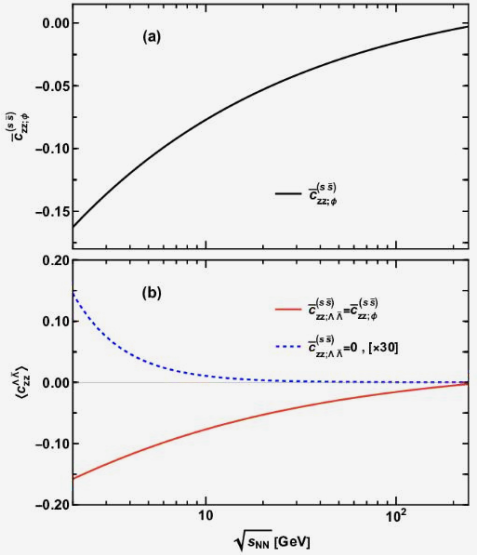
➢ Vacuum entanglement + decoherence



Liu, Tu, arXiv:2606.17240 (2026)

- s s̄ pairs pulled from the QCD vacuum inherit its quantum numbers → born **spin-entangled**
- String breaking acts as an environment → **decoherence**
- Describes the STAR and CMS ΛΛ̄, ΛΛ data

➢ Quark spin correlations



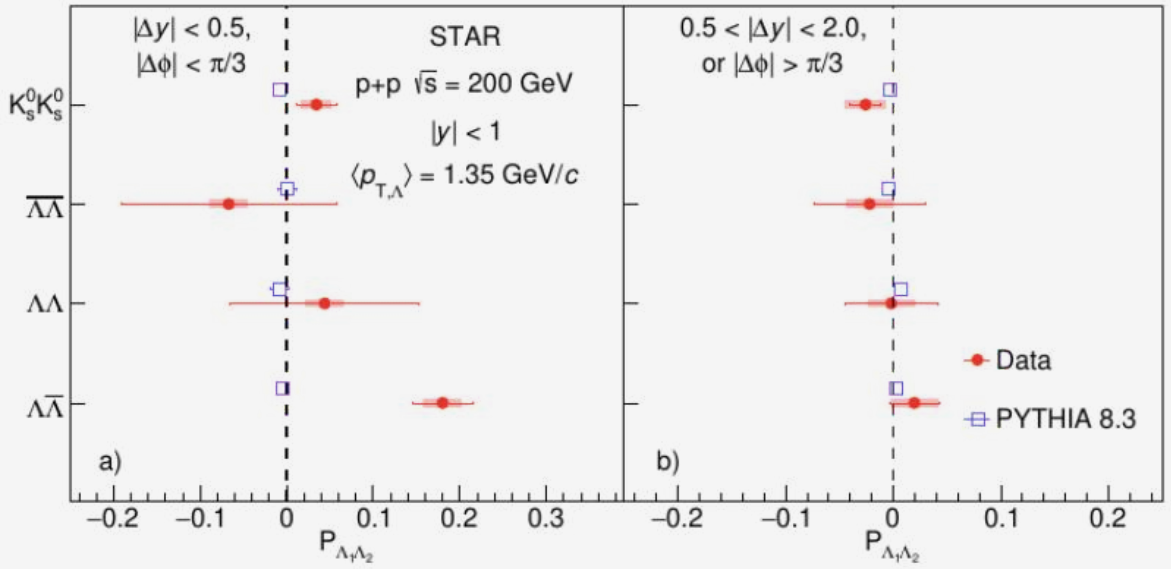
Lv, Yu, Liang, Wang, Wang, PRD 109, 114003 (2024)

- s–s̄ short range correlation from ϕ -meson ρ_{00}
- ΛΛ̄: extreme cases differ in **sign and size** → probe long-range s–s̄ correlations

Also see, Zhang et al., PRD 110, 074019 (2024)
Lv et al., arXiv:2603.15135 (2026);

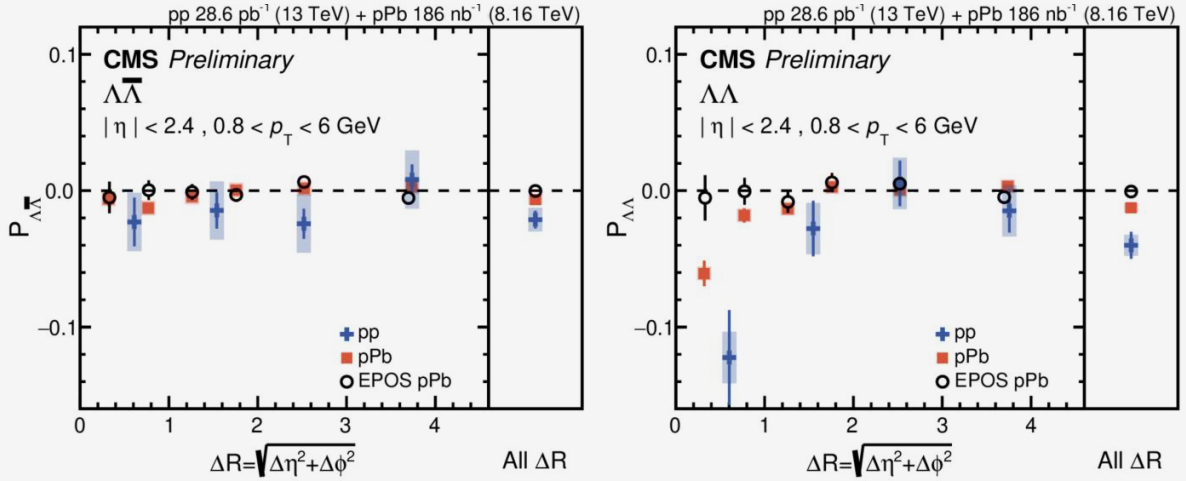
Λ hyperon spin correlations: measurements

➢ STAR: p+p, 200 GeV



STAR, Nature 650, 65 (2026)

➢ CMS: pp & pPb (preliminary)



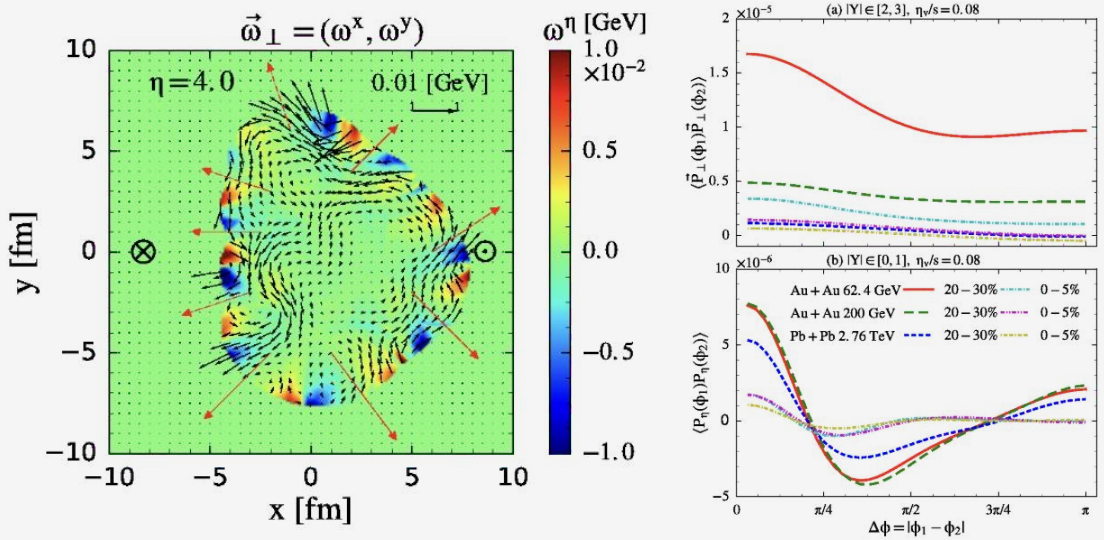
CMS-PAS-HIN-26-002 (2026): pp 13 TeV, pPb 8.16 TeV

Zhenyu Chen, Nov 16, 09:00–09:30

- STAR: short-range ΛΛ̄ P = 18 ± 4% (4.4σ), long range ≈ 0 → spin-entangled s s̄ pairs, decoherence with separation
- CMS: ΛΛ and Λ̄Λ̄ negative at small ΔR, ΛΛ̄ ≈ 0 — differs from STAR (√s dependence?)

Hyperon spin correlations in heavy-ion collisions

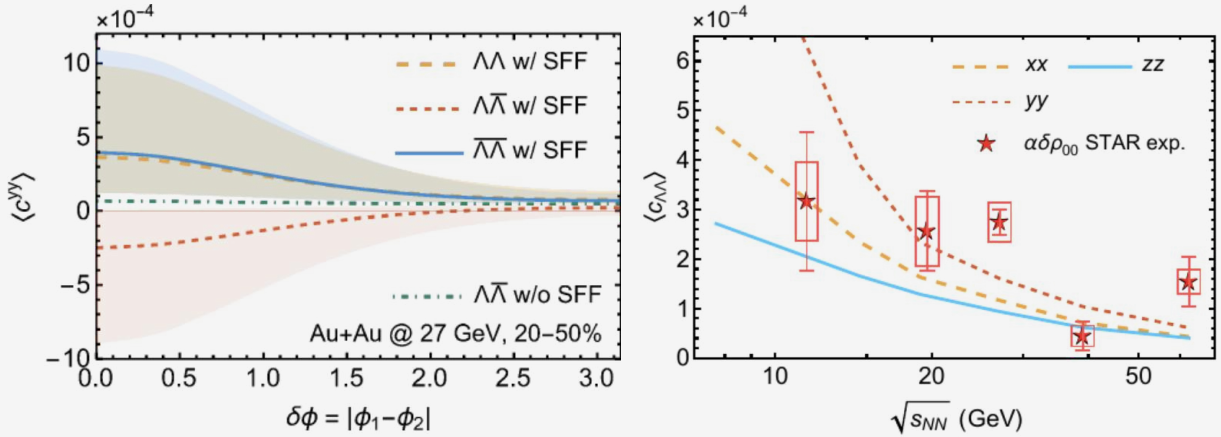
➢ Vortical fluid (CLVisc + AMPT)



Pang, Petersen, Wang, Wang, PRL 117, 192301 (2016)

- Transverse: cos Δϕ + offset ← circular vorticity around the beam + global polarization
- Longitudinal: vortex pairs from the radial flow of hot spots

➢ Strong-force-field fluctuations

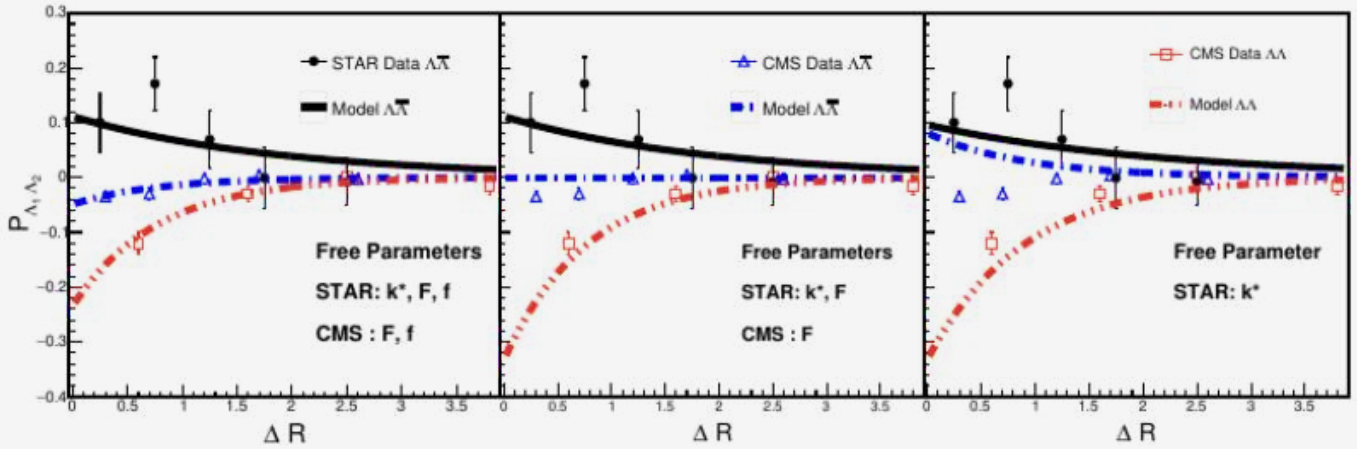


Sheng, Wu, Rischke, Wang, PRL 136, 082301 (2026)

- ϕ -field fluctuations fitted to ϕ -meson ρ_{00}: $\Lambda\bar{\Lambda} < 0$, while $\Lambda\Lambda$, $\bar{\Lambda}\bar{\Lambda} > 0$
- Net spin correlation separates strong-force fields from hydro effects

Spin entanglement and quark spin correlations

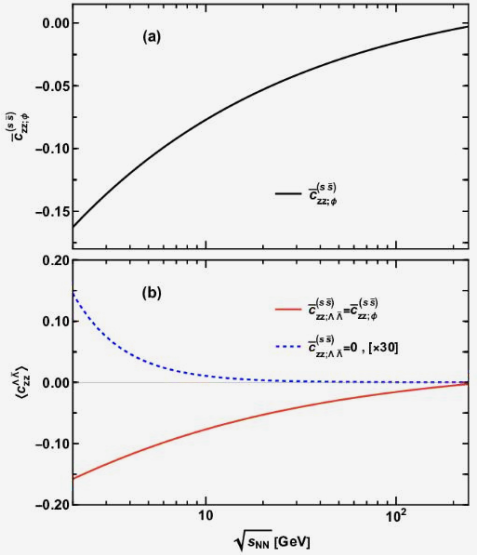
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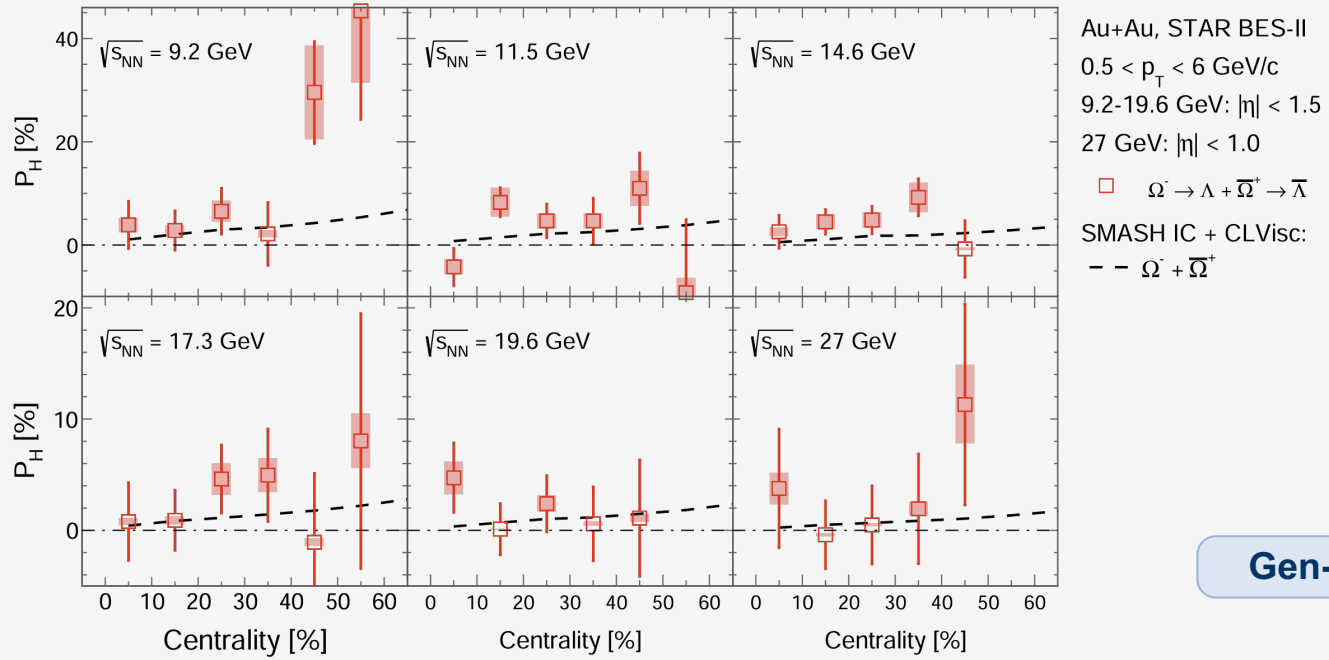
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Ω polarization: centrality dependence

- P_Ω vs. centrality: STAR BES-II data and hydrodynamics (SMASH IC + CLVisc)



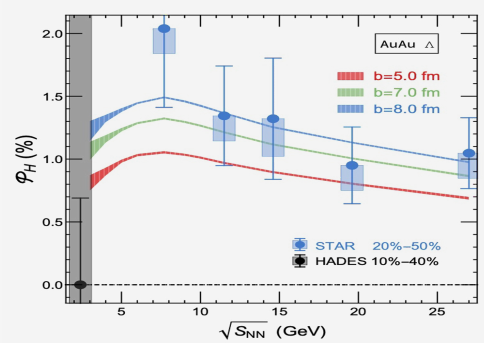
Gen-Hui Li, Nov 18, 14:40–15:00

Data: STAR, arXiv:2611.03044 (2026); SMASH IC + CLVisc: Li, CY, Wu, Pu, Qin, arXiv:2606.10341 (2026)

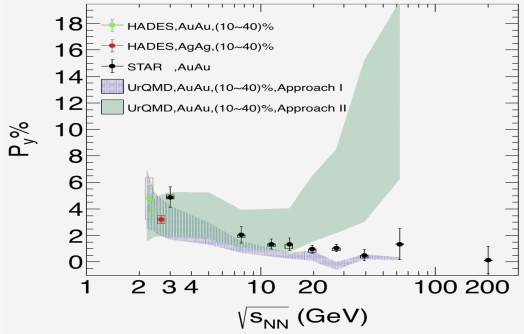
- Energy dependence: hydro P_Ω lies **below the STAR central values**
- Centrality dependence: same tendency, but the **experimental uncertainties are still large**
- **s-quark spin correlations**? Not conclusive yet → more precise measurements needed

Global polarization at low energies

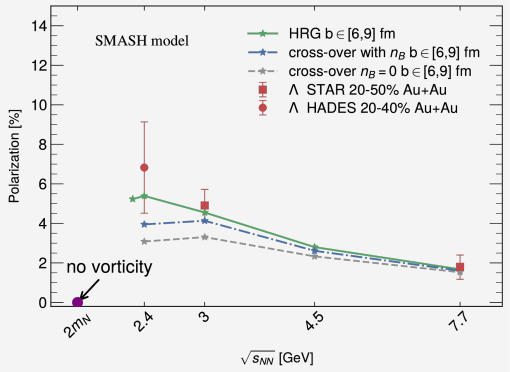
➢ Equilibrium (thermal-vorticity) picture



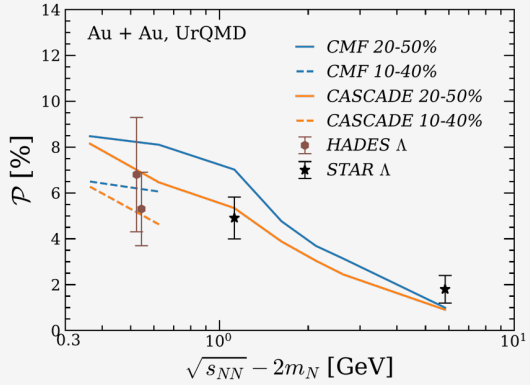
Guo, Liao, et al.,
PRC 104, L041902 (2021)



Deng, Huang, PRC 2016,
PRC 2020, PLB 2022

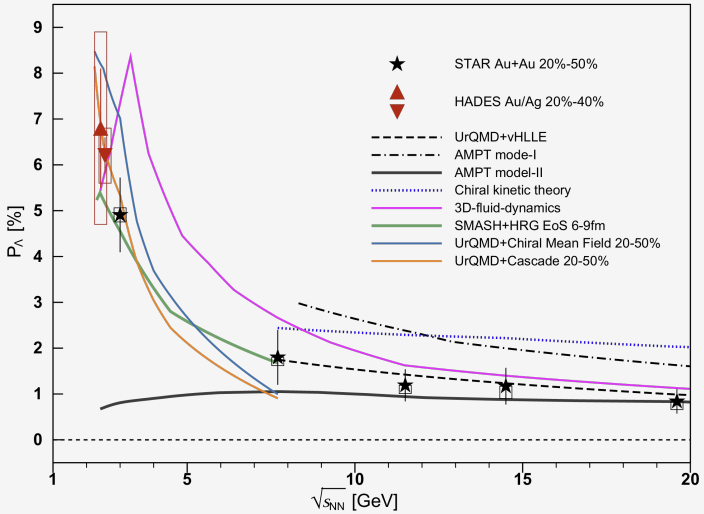


CY, Pu, Pang, Qin, Wang,
arXiv:2603.27521 (2026)



Liu, Steinheimer, Sun, Chen, Ma,
Bleicher, arXiv:2606.13333 (2026)

➢ Experimental results



HIAF white paper in preparation
HADES, PLB 835, 137506 (2022); Ivanov, PRC 103, L031903 (2021)
Xu, APS Open Sci. 1, L000035 (2026)

- With a baryon-rich EoS, thermal vorticity still describes P_Λ down to 2.4 GeV
- Will P_Λ keep rising with decreasing energy? Where is the turning point?