Recent studies of hyperon polarization in heavy-ion collisions

Outline:

- Introduction
- Previous data on polarization in HIC
- Global polarization: Λ, Ξ, Ω
- Local polarization along beam direction
- Summary and future studies

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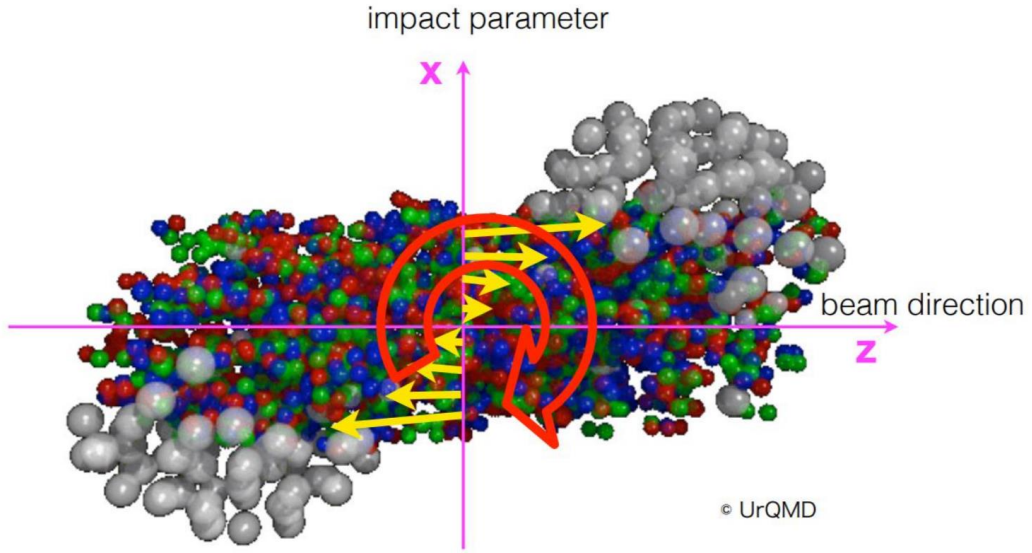
Heavy-ion collisions

Quark-gluon matter:

- Lifetime ~ 10 fermi/c ~ 3×10^{-23}s
- Energy density ~ up to tens of GeV/ϕм^3
- Size ~ a few femtometers
- Magnetic field ~ 10^{14} T
- Temperature ~ 300 MeV



S. A. Voloshin, arXiv:nucl-th/0410089.
Z.-T. Liang and X.-N. Wang, PRL 94 (2005) 102301

- In non-central collisions orbital angular momentum of order $10^3\hbar$

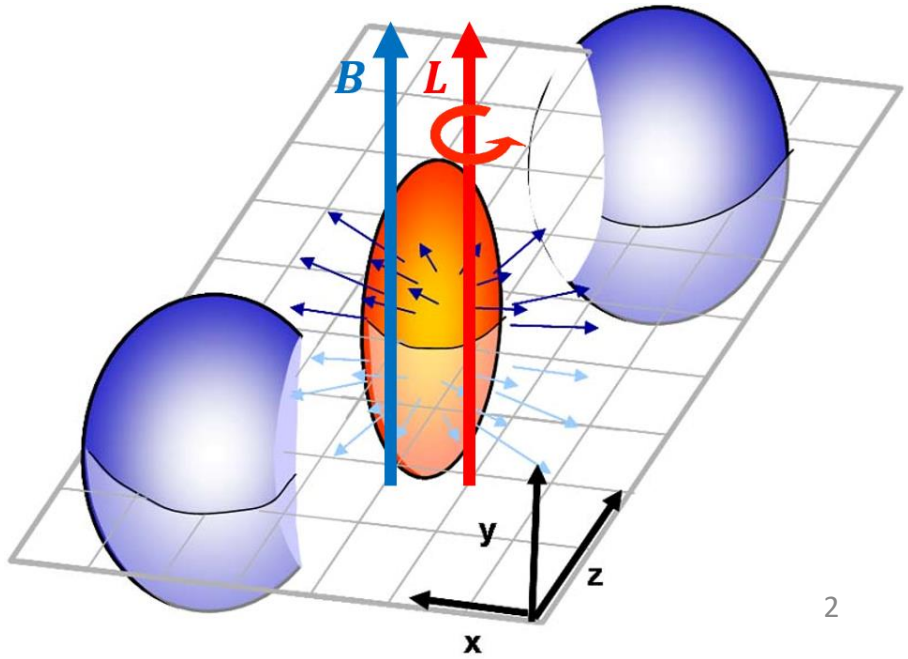
$$\hat{\rho} = \frac{1}{Z}\exp\left[\frac{1}{T}\left(-\hat{H} + \nu\hat{Q} + \hat{\mu}\cdot B + \omega\cdot\hat{J}\right)\right]$$

$-\hat{H}/T$ energy

$\hat{\mu}\cdot B/T$ magnetic field

$\nu\hat{Q}/T$ charge

$\omega\cdot\hat{J}/T$ **rotation**

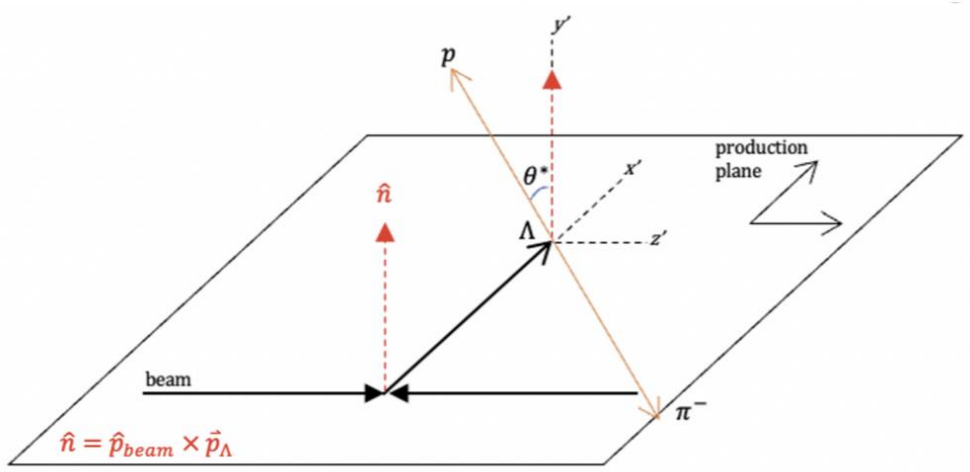


Vorticity:

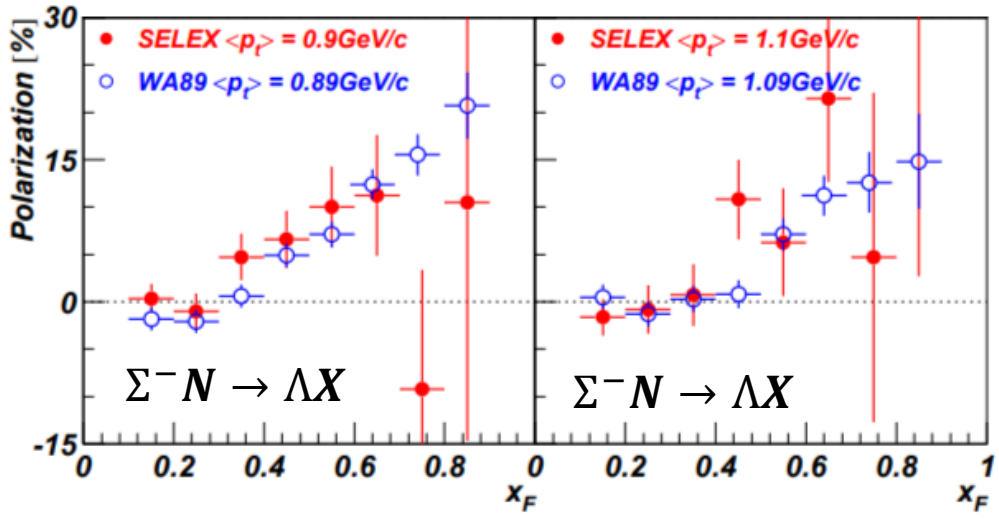
$\boldsymbol{\omega} = \frac{1}{2}\nabla\times\boldsymbol{v}$, where v – collective velocity

Transverse polarization of hyperons

- Parity is violated in weak decays
  - The emission direction of daughter baryons follows the hyperon spin
- In unpolarized pp, pA collisions, hyperon polarization was observed
  - Polarization is perpendicular to the hyperon production plane
- Angular distribution of daughter particles:
  $\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H |\vec{P}| \cdot \widehat{p_b^*}\right)$,
  - α_H - hyperon decay asymmetry parameter
  - $\widehat{p_b^*}$ - momentum of the daughter baryon in the hyperon rest frame
  - $\vec{P}$ - **hyperon polarization**
- $|\vec{P}|$ grows with x_F from zero to tens of percent

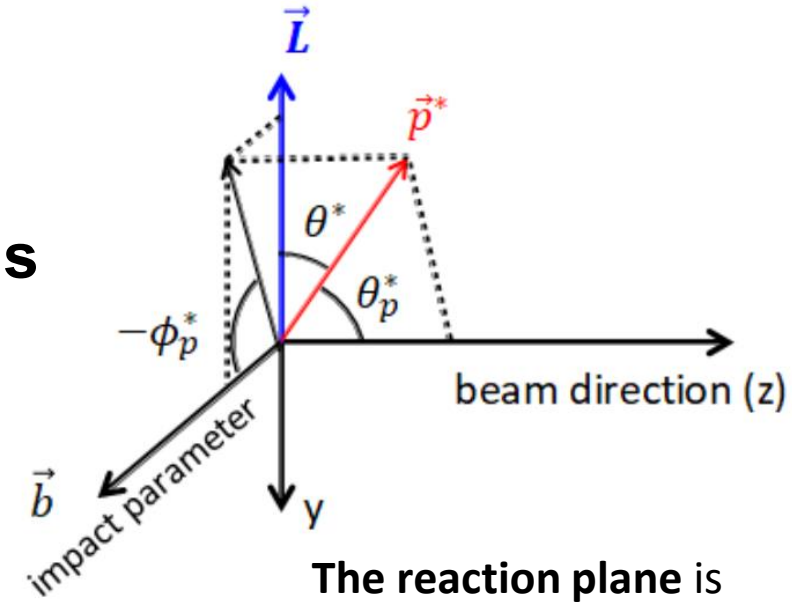


arXiv:0706.3660v1 [hep-ex]

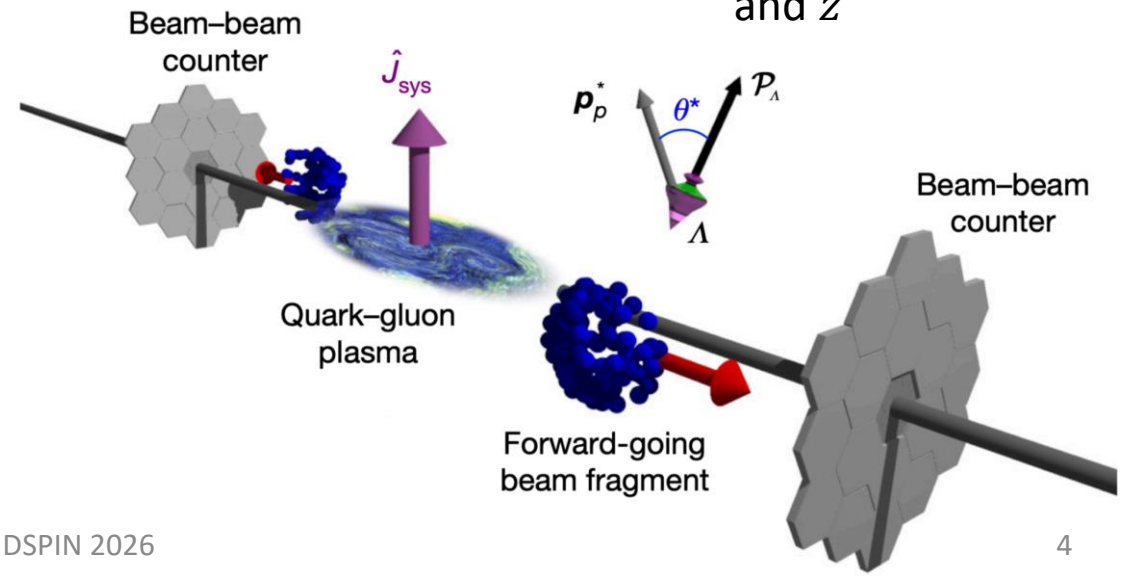


Global polarization of hyperons

- **Global** polarization of hyperons**:**
  - Polarization along **the orbital angular momentum axis**
  - Measured relative to **the reaction plane (RP)**
  - Convenient to work with **azimuthal angles**
- $P_H = \frac{8}{\pi \alpha_H} \langle \sin(\psi_{RP} - \varphi_b^*) \rangle$
  - ψ_{RP} - reaction-plane angle
- Non-zero global polarization
  - "Observable" of the vorticity
  - $\mathbf{P} \approx \frac{(s+1)}{3} \frac{(\boldsymbol{\omega} + \mu \boldsymbol{B}/s)}{T}$ s – spin, μ – magnetic moment
  - $P \approx \omega/(2T)$ for s=1/2



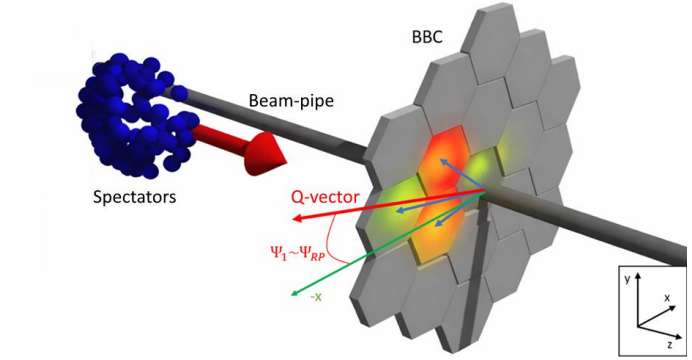
The reaction plane is defined by the vectors $\vec{b}$ and $\vec{z}$



How to measure polarization?

$$P_H = \frac{8}{\pi \alpha_H} \langle \sin(\boldsymbol{\psi_{RP}} - \boldsymbol{\varphi_b^*}) \rangle$$

Event plane angle



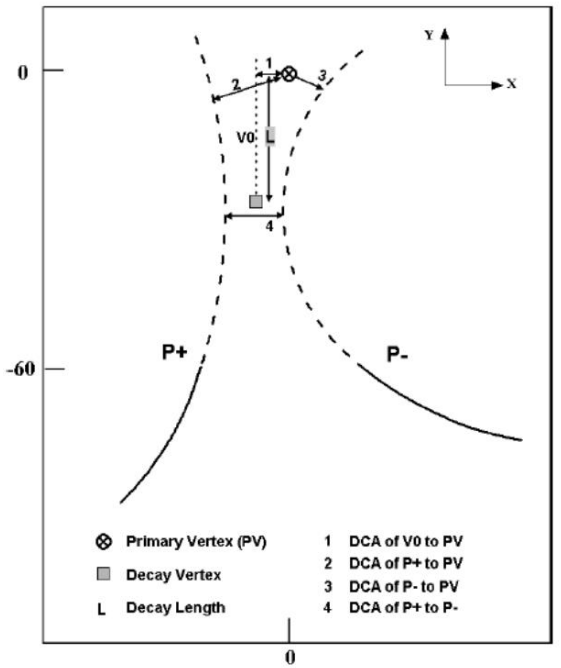
$$\Psi_n = \frac{1}{n} \tan^{-1} \left(\frac{\sum w_i \sin(n\varphi_i)}{\sum w_i \cos(n\varphi_i)} \right)$$

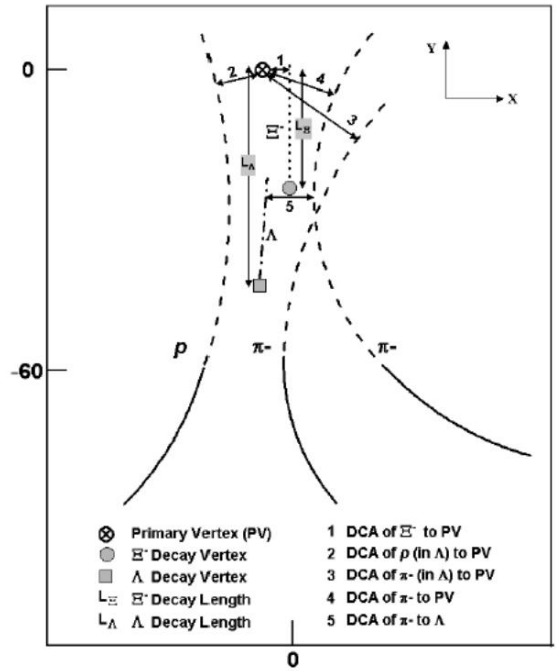
$$\Psi_1 \sim \Psi_{ReactionPlane}$$

EventPlane instead of RP:

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle sin(\psi_1 - \varphi_p^*) \rangle}{Res(\psi_1)}$$

Hyperon reconstruction



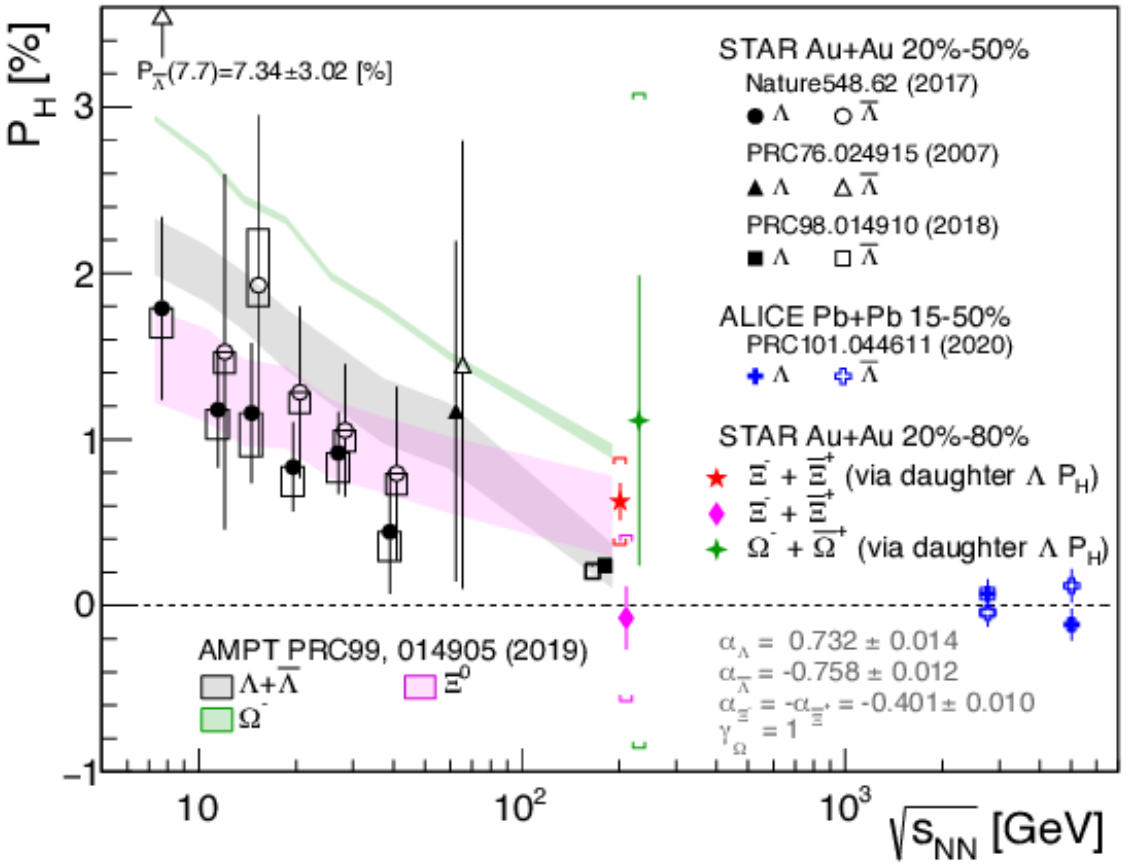


1. Daughter particle identification
2. Analysis of decay topology

World data: experiment

- P_Λ measured in STAR for $\sqrt{s_{NN}}$ = 3-200 GeV, in ALICE for $\sqrt{s_{NN}}$=2.76 and 5.02 TeV
  - First results were consistent with zero
  - Global polarization decreases with increasing collision energy
  - A difference is observed in the global polarization of P_{Λ^0} and $P_{\bar{\Lambda}^0}$
- First measurements of P_Ξ and P_Ω at $\sqrt{s_{NN}}$ = 200 GeV in 2021
- At $\sqrt{s_{NN}}$ = 200 GeV $P_{\Lambda^0+\bar{\Lambda}^0}$ and $P_{\Xi^-+\bar{\Xi}^+}$ agree within uncertainties

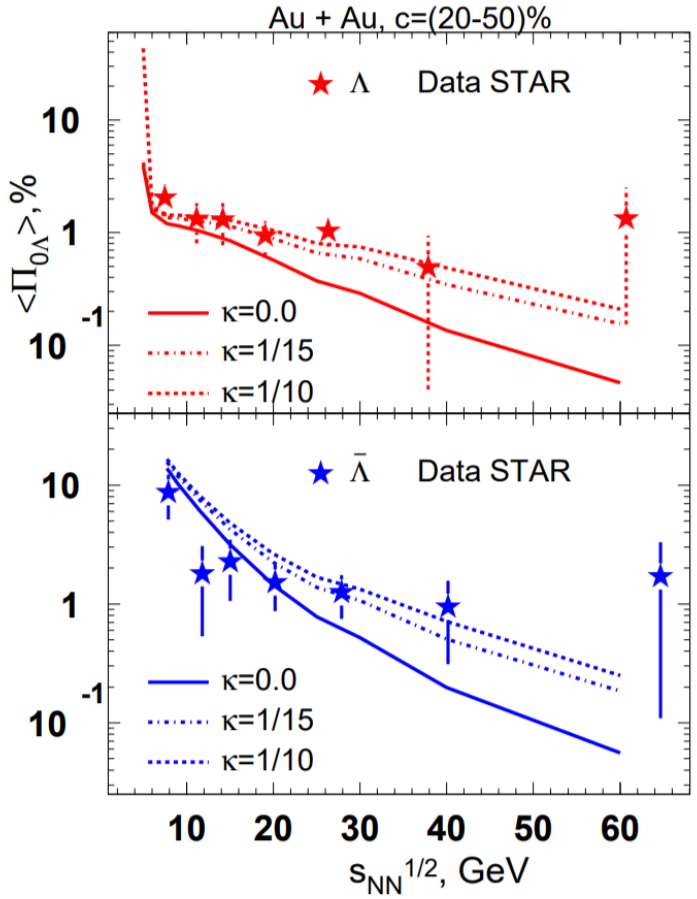
PRL 126, 162301 (2021)



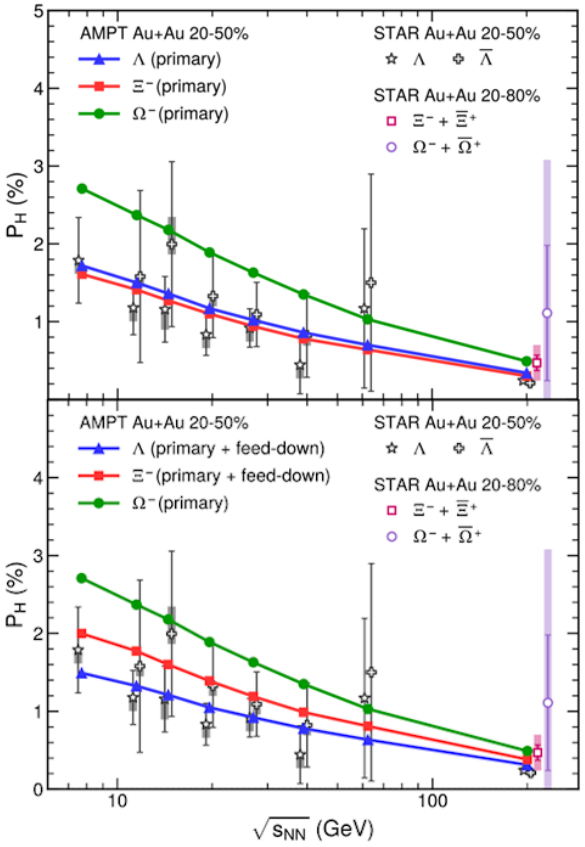
World data: theory

- Sources of P_{Λ^0} and $P_{\bar{\Lambda}^0}$ difference:
  - Magnetic field of the QGP [1]
  - Different freeze-out characteristics [2]
  - Gravitational anomaly [3]
  - Baryon-meson interaction [4]
  - Polarization of heavier hyperons: Only ~40% of Λ hyperons are produced directly in the collision [5]
- Different predictions for the ratio P_Ξ and P_Λ [6]
  - P_Ξ is also sensitive to the effects above
  - ~80% Ξ hyperons are produced directly in the collision
- P_Ξ and P_Ω can be measured via daughter Λ: $P_\Lambda = C_{\Xi\Lambda} P_\Xi$ ($C_{\Xi\Lambda}$~0.932; $C_{\Omega\Lambda}$~1)

[3] PRC 97, 041902 (2018)

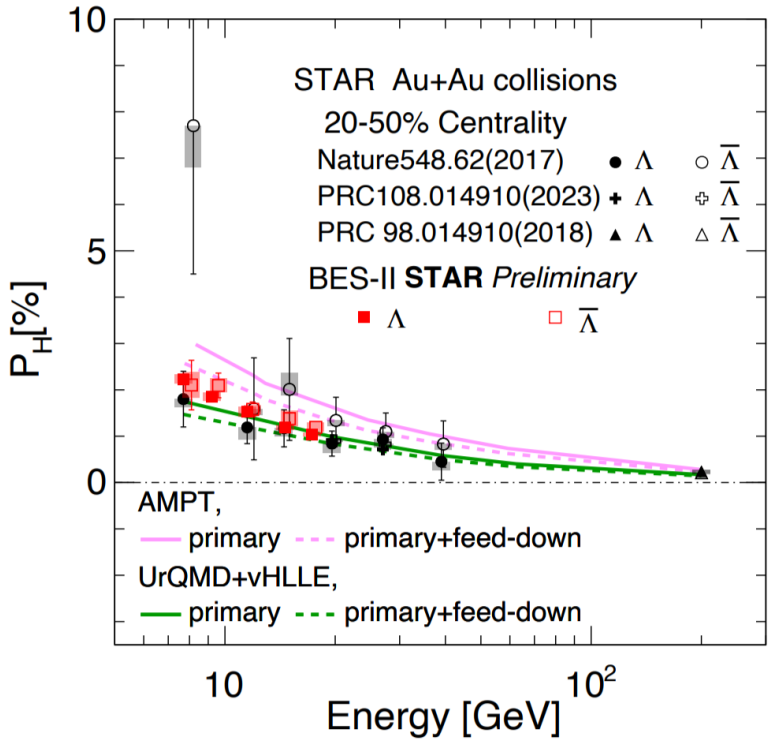


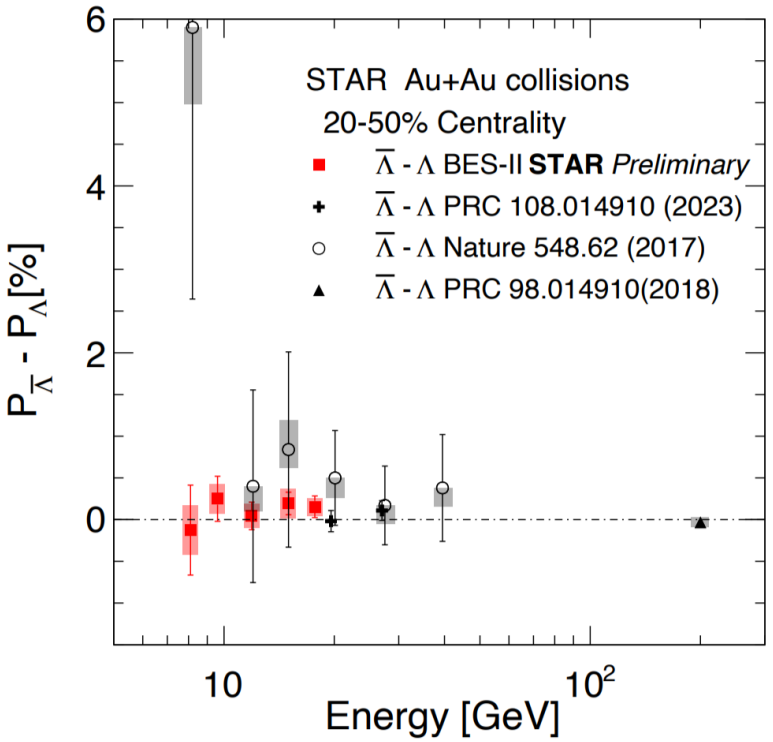
[6] PLB 827, 136971 (2018)



[1] PRC 95, 054902 (2017)
[2] PLB 803 (2020) 135298
[4] PRC 99, 021901 (2019)
[5] PRC 100, 014913 (2019)

Recent results on Λ global polarization

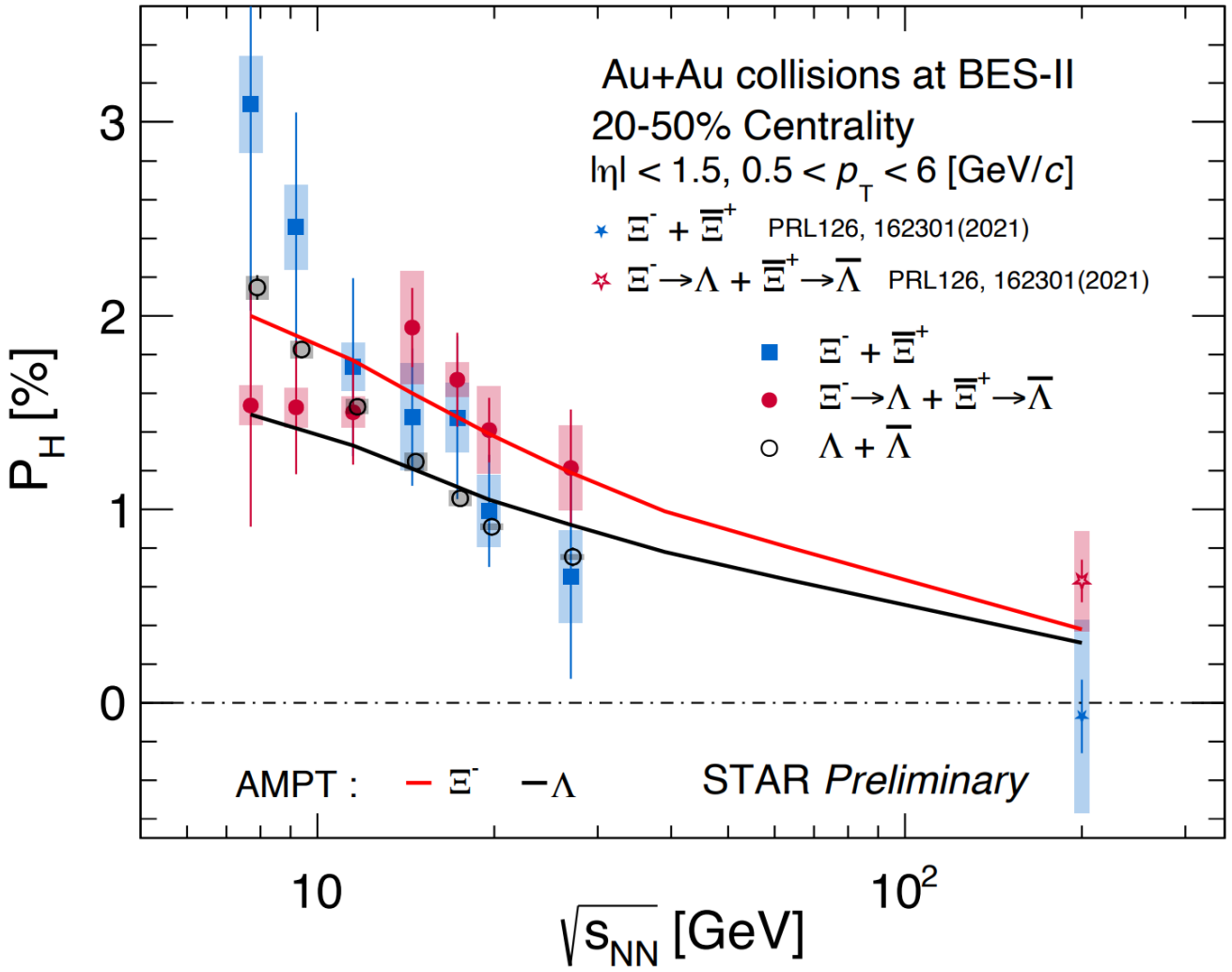




- BES-II upgrades in detectors and higher statistics
  Significant improvement in precision, consistent dependence with BES-I
- No obvious splitting between Λ and $\bar{\Lambda}$ global polarization with high precision
- Upper limit on late stage magnetic field: $B \lesssim 10^{13}$T (95% confidence level)
  - "Naive" limit – there is still many other possible effects and different contributions

Ref: T. Fu (STAR), SPIN2025; STAR, arXiv:2606.10341; STAR, PRC 108, 014910 (2023)

Recent results on Ξ global polarization

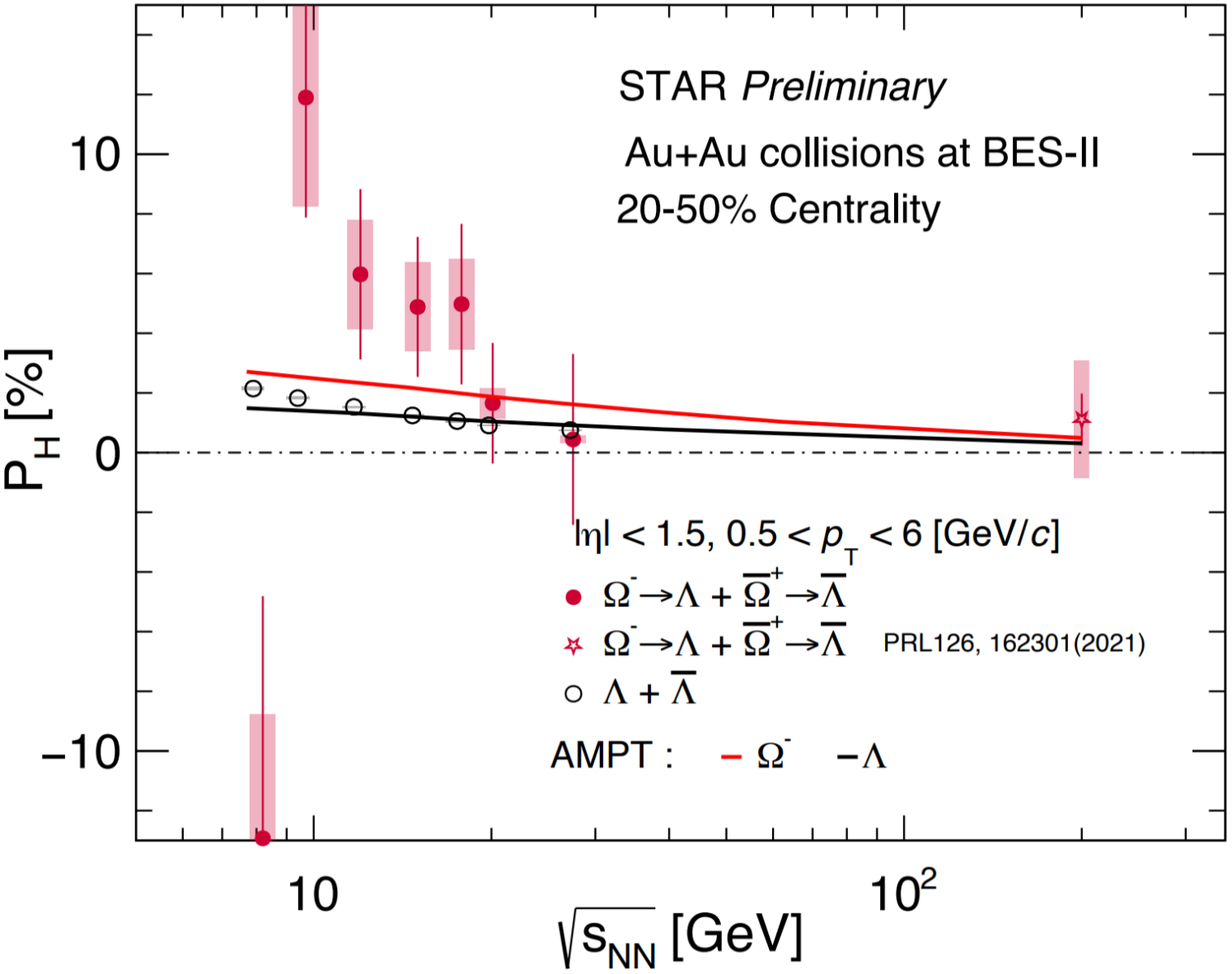


- Significant non-zero signal of Ξ global polarization observed
- Decreasing with increase in collision energy
- Consistent between direct (via φ^*_Λ) and indirect ($P_\Lambda = C_{\Xi\Lambda} P_\Xi$) measurements
- No significant difference between Λ and Ξ global polarization
  - While $P_\Xi \sim P_\Lambda$ is expected from pure spin transfer from vorticity, there is possible difference due to different freeze-out properties

Z.-T. Liang and X.-N. Wang, PRL 94, 102301 (2005)
Hui Li et al., PLB 827, 136971(2022)

Ref: X. Gou (STAR), QM2025 poster; T. Fu (STAR), SPIN2025; STAR, arXiv:2606.10341

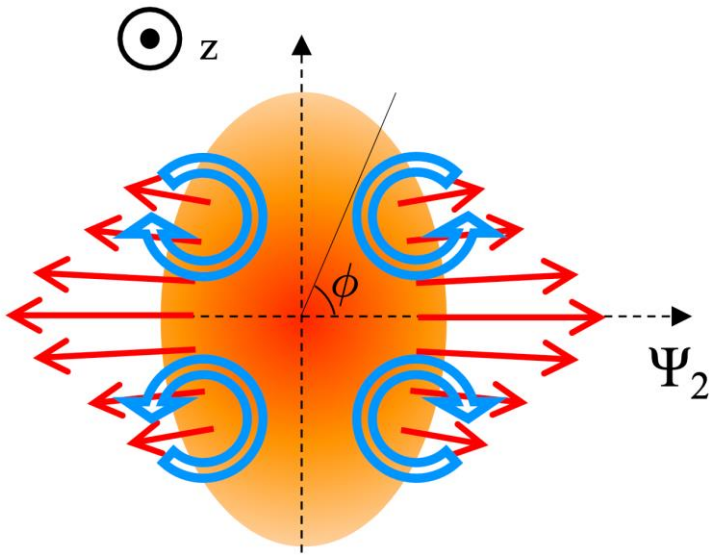
Recent results on Ω global polarization



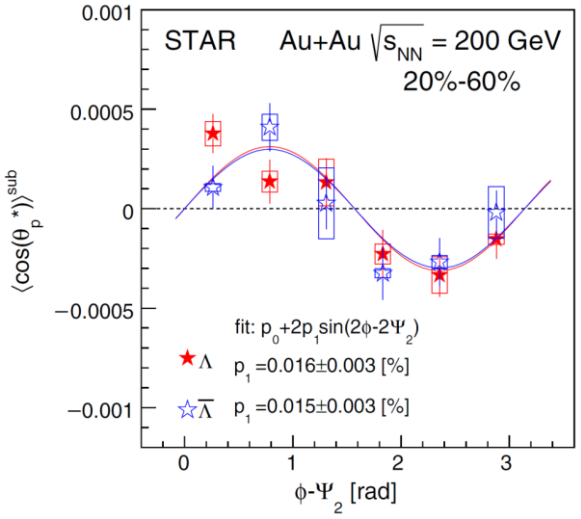
- Ω global polarization seems to decrease with increase in collision energy
- A hint of larger Ω global polarization than Λ at lower energies
  - Theory expects larger global polarization of Ω
  - $P_\Omega \sim \frac{5}{3} P_\Lambda$

Ref: X. Gou (STAR), QM2025 poster; T. Fu (STAR), SPIN2025; STAR, arXiv:2606.10341

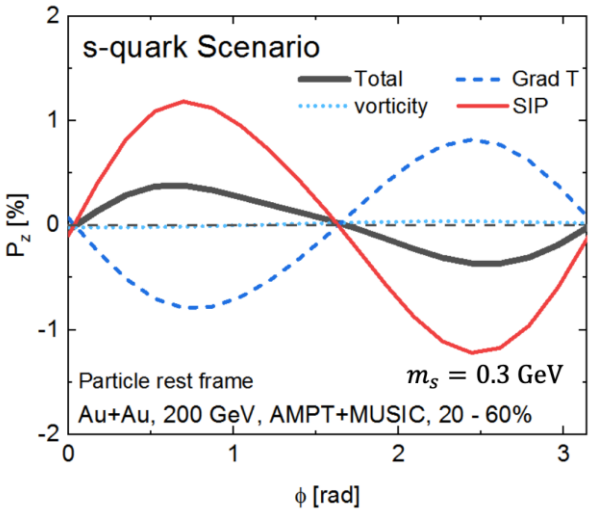
Local polarization: along the beam direction



Geometry: flow → beam vorticity



Observation — STAR, Au+Au 200 GeV



Model (AMPT+MUSIC)

$$P_Z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \left\langle (\cos\theta_p^*)^2 \right\rangle}$$

- Anisotropic (elliptic) flow generates vorticity along the beam → beam-direction polarization P_z, modulating with azimuth
- Observable (2nd harmonic): $P_{2,z} = \langle P_z \cdot \sin(2(\varphi_H - \Psi_2)) \rangle / Res_2$
- STAR (Au+Au 200 GeV): clear sin(2φ) modulation, $p_1 \approx 0.016\%$
- Correct sign requires the thermal-shear term: $P_z \sim \nabla T \oplus$ Shear

Ref: STAR, PRL 123, 132301 (2019) & PRL 131, 202301 (2023); model: F. Becattini et al., PRL 127 (2021); S. Liu et al., PRL 125 (2020)

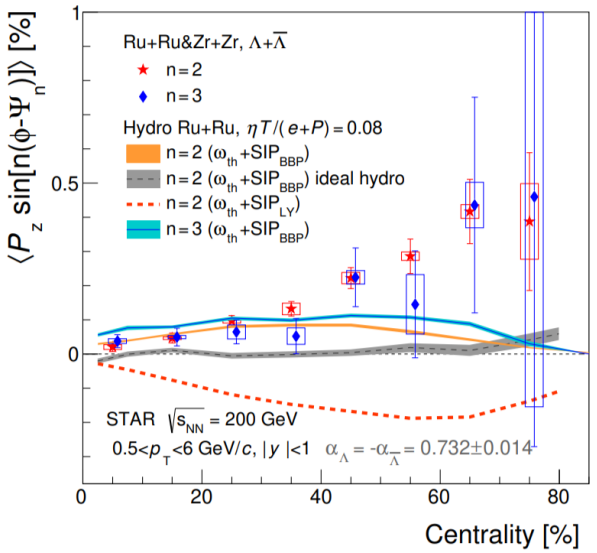
P_z — recent results

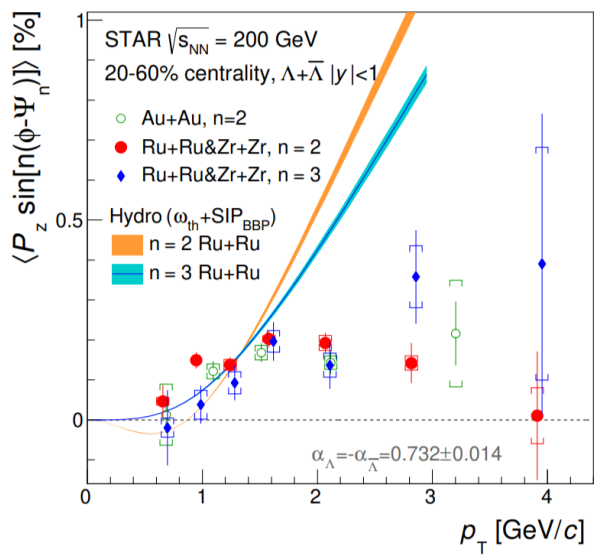
- STAR — isobar Ru+Ru / Zr+Zr at 200 GeV
  - P_z relative to 2nd AND 3rd-order event planes; first observation driven by triangular flow
  - weak system-size dependence
- ALICE — Pb+Pb, Run 3, 5.36 TeV
  - positive sin modulation vs 2nd & 3rd order; first 3rd-order at the LHC
  - sensitive to bulk viscosity (its inclusion flips the predicted sign)

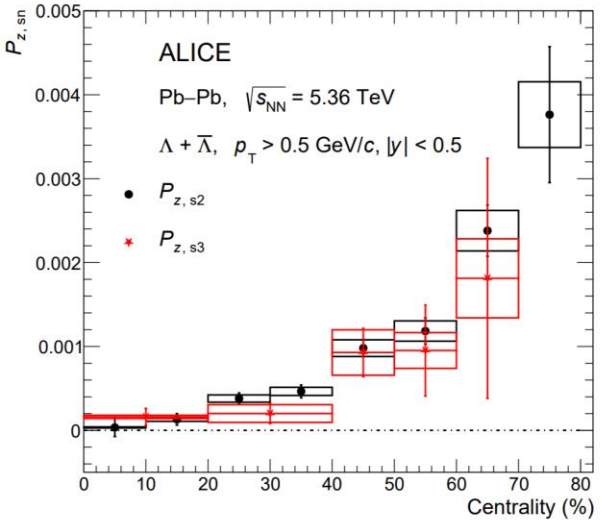
→ Positive P_z modulation from RHIC (200 GeV) to LH (5.36 TeV), growing with p_T and centrality

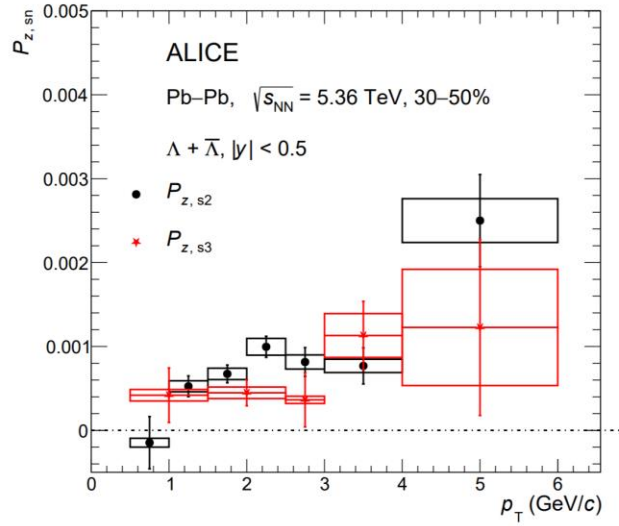
→ 2nd- and 3rd-harmonic P_z are comparable — local vorticity follows both elliptic and triangular flow

⇒ Sign captured only with the thermal-shear term (SIP); vorticity-only gives the wrong sign





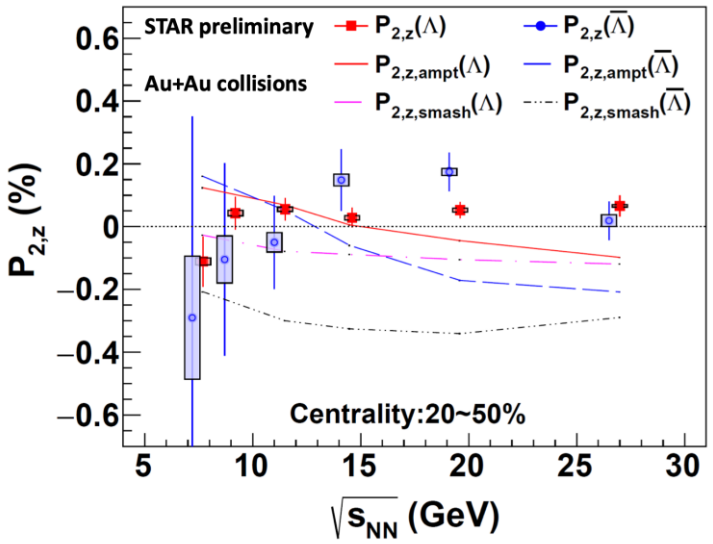




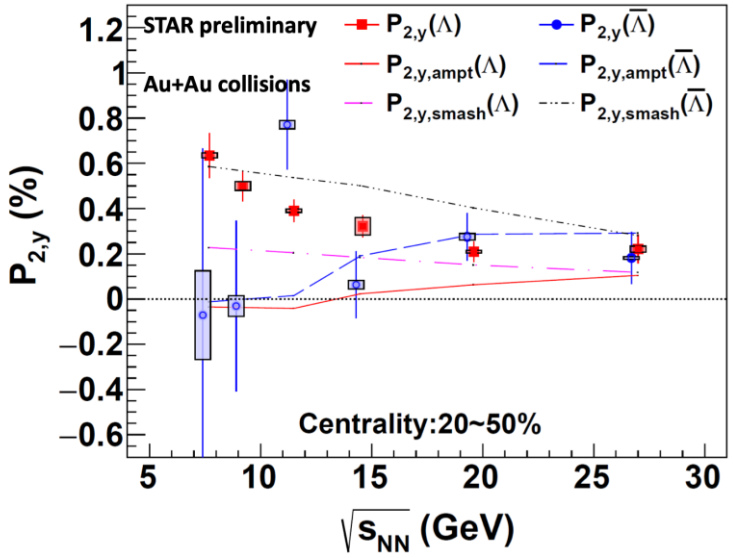
Ref: STAR, arXiv:2303.09074 (PRL); ALICE, arXiv:2606.18070; ALICE, PRL 128, 172005 (2022)

Local polarization of Λ: energy dependence

$P_{2,z} = \langle P_z \sin(2\Delta\varphi) \rangle$



$P_{2,y} = \langle P_y \cos(2\Delta\varphi) \rangle$



- BES-II (Au+Au, 20–50%): $P_{2,z}$ and $P_{2,y}$ of Λ and Λ̄ vs $\sqrt{s_{NN}}$
- $P_{2,z}$: no strong collision-energy dependence
- $P_{2,y}$: monotonic increase toward lower energy (for Λ)
- No transport model (AMPT, SMASH) describes $P_{2,z}$ and $P_{2,y}$ simultaneously

→ Simultaneous $P_{2,z}$ and $P_{2,y}$ remain an unmet constraint for all current models

Ref: STAR preliminary — Qiang Hu, QM2025 poster No. 932; model: X. Wu, C. Yi et al., Phys. Rev. C 105, 064909 (2022)

Summary

Global polarization (STAR BES-II, $\sqrt{s_{NN}}$ = 7.7–27 GeV)

- Λ, Ξ, Ω global polarization measured; first BES-II energy dependence of Ξ and Ω; hierarchy $P_\Omega \gtrsim P_\Xi \approx P_\Lambda$ → common spin–vorticity coupling
- No significant Λ – Λ̄ splitting (>5× improved precision) → upper limit on the QGP magnetic field
- Fix-target data would be available soon

Local polarization (P_z along the beam)

- Positive sin(2ϕ) modulation from RHIC isobars (200 GeV) to ALICE (5.36 TeV); 3rd-harmonic P_z seen for the first time
- Sign reproduced only with the thermal-shear term (SIP)
- BES-II scan: $P_{2,z}$ ≈ flat, $P_{2,y}$ rises toward low energy; need model reproduction

What's next?

1. **Low energies, small system and bigger rapidity.** System size and energy scan (need of small system measurements d+d, alpha+alpha, C+C, O+O, Ne+Ne, etc). STAR covers large systems at midrapidity for 3-40 GeV, while at lower energies significant difference in polarization is expected at higher rapidity

2. A consistent treatment of feed-down. A large fraction of measured Λ come from decays of heavier hyperons (Σ^0, Σ*, Ξ, Ω) that carry their own polarization and shift the primary-Λ signal; correcting it

3. Toward a 3D map of the QGP vorticity. Measure the radial component P_x (along the impact parameter) alongside P_y (global, along L) and P_z (beam) to reconstruct the full vorticity field and test hydrodynamic predictions of its spatial structure.

4. Global, multi-differential confrontation with theory. Fit all observables together — global P_H (Λ, Ξ, Ω), $P_{2,z}$, $P_{2,y}$ and particle–antiparticle differences — to disentangle the competing mechanisms: thermal vorticity, thermal shear (SIP), freeze-out characteristics, magnetic field