Measurements of global and local spin polarization of hyperons in Au+Au collisions at RHIC

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Outline

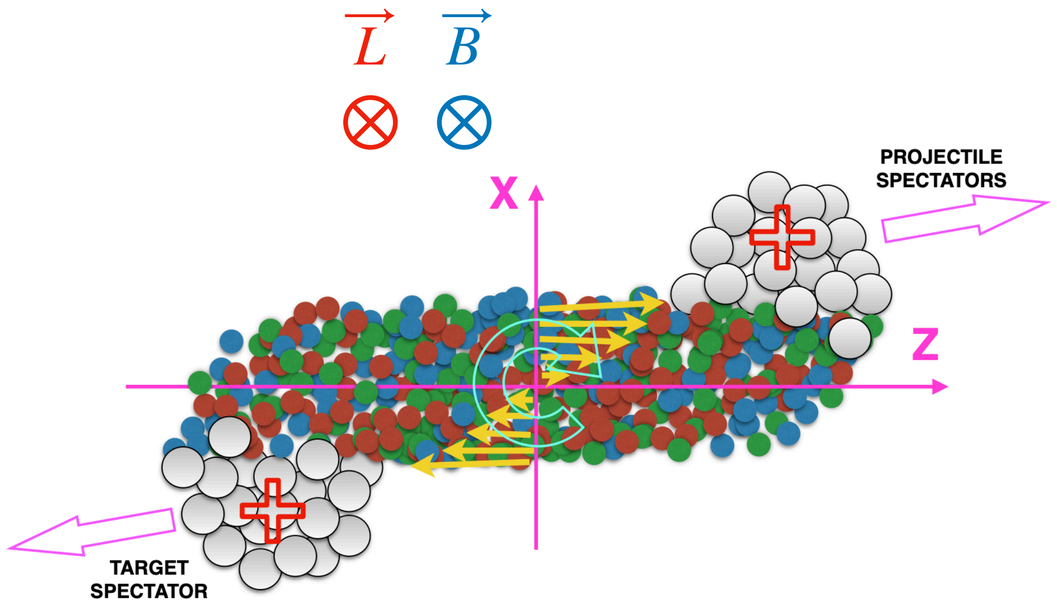
- Introduction

- Results from BES-II
  - ✦ Global polarization: Λ, Ξ, Ω hyperons
  - ✦ Local polarization: Λ hyperons, baryonic spin hall effect

- Summary

Introduction

Non-central heavy ion collisions



Z. Liang, X. Wang, Phys. Rev. Lett 94, 102301 (2005)
Y. Jiang, Z. Lin et al, Phys. Rev. C 94, 044910 (2016)
F. Becattini, I. Karpenko et al, Phys. Rev. C 95, 054902 (2017)
T. Niida, S. A. Voloshin, Int. J. Mod. Phys. E 33, 2430010 (2024)

① A Large Orbital Angular Momentum imparted into the system

$$\vec{L} = \vec{r} \times \vec{p} \sim bA\sqrt{s_{\mathrm{NN}}} \sim 10^5\ \hbar$$

- Vorticity along orbital angular momentum

$$\vec{\omega} = \frac{1}{2}\nabla \times \vec{v}, \quad \omega_y = \frac{1}{2}(\nabla \times v)_y \approx \frac{1}{2}\frac{dv_z}{dx}$$

- Spin-orbit coupling leads to spin polarization of final-state particle

$$\omega \approx k_B T(P_\Lambda + P_{\overline{\Lambda}})/\hbar$$

② A strong initial magnetic field (B) is expected

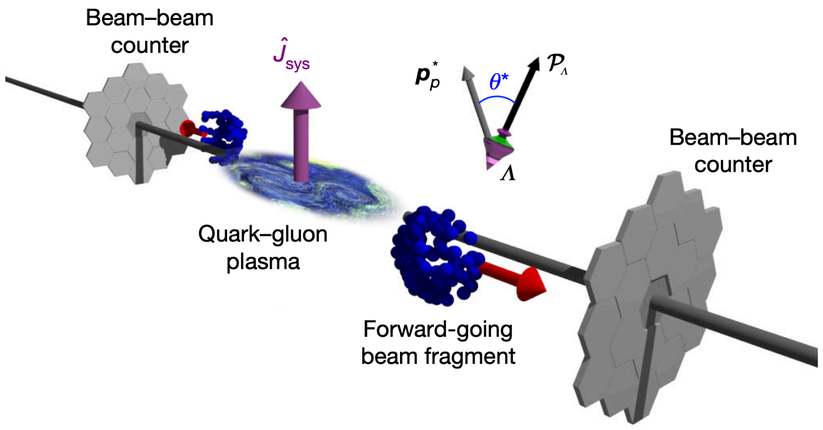
$$B \sim e/m_\pi^2 \sim 10^{14}\ \mathrm{T}$$

- Strong B-field can lead to splitting of Λ, $\overline{\Lambda}$ global polarization

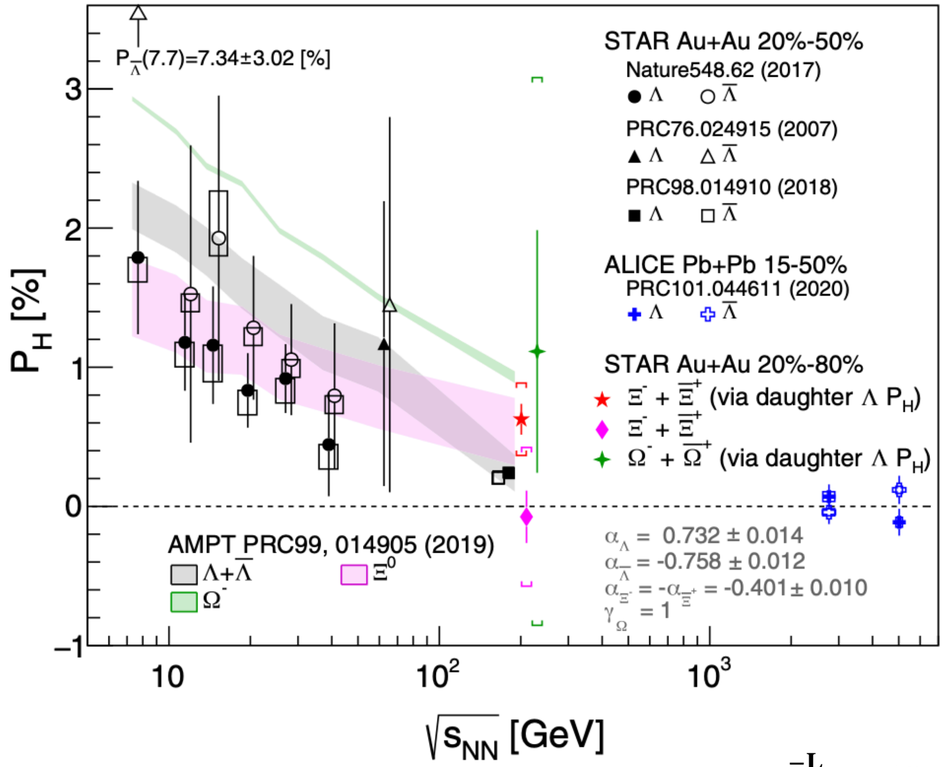
$$P_{\overline{\Lambda}} - P_\Lambda \approx \frac{2|\mu_\Lambda|B}{T}$$

③ Study spin dynamics and QGP medium properties in heavy ion collisions

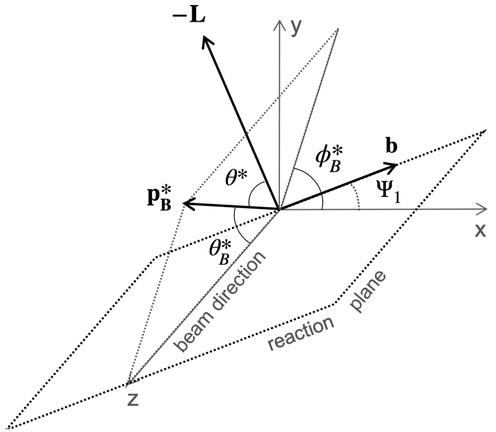
Hyperons global polarization



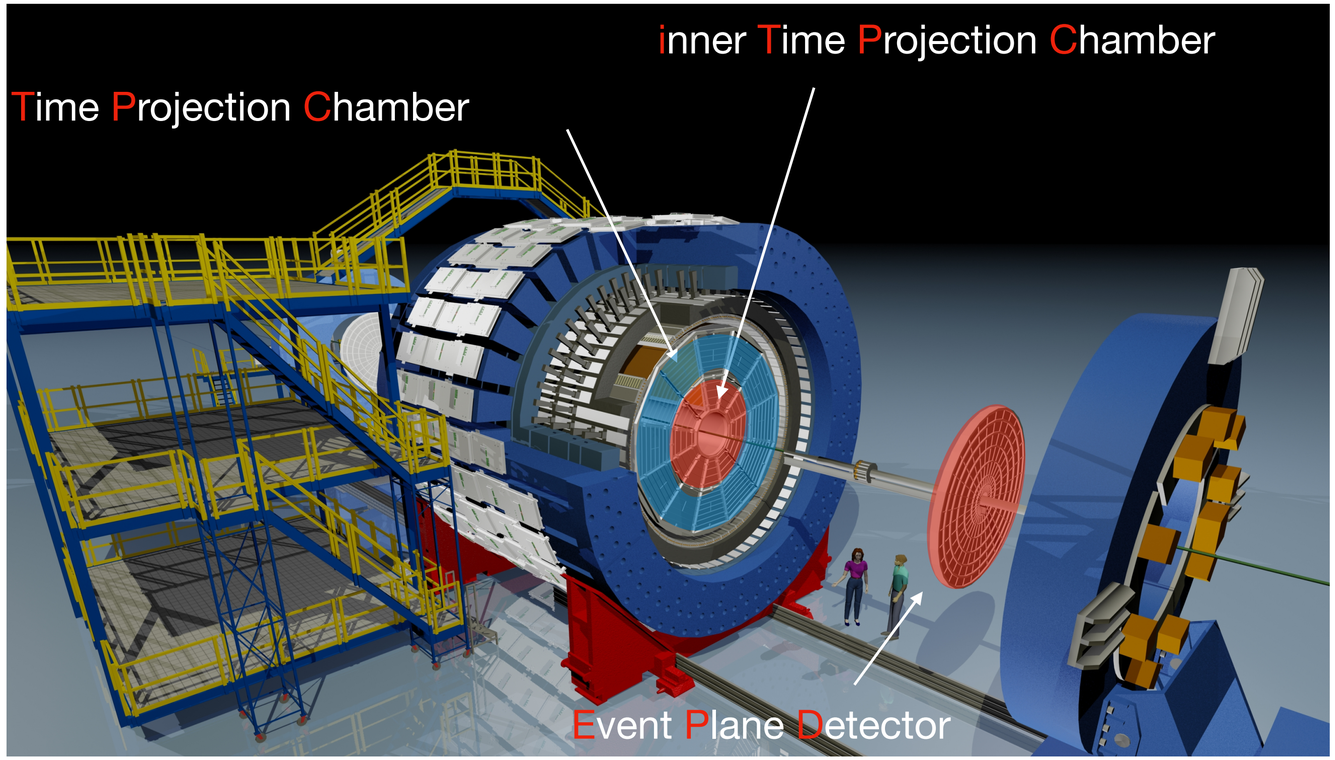
STAR, Phys. Rev. C 76, 024915 (2007)
STAR, Nature 548, 62–65 (2017)
STAR, Phys. Rev. Lett. 126, 162301 (2021)

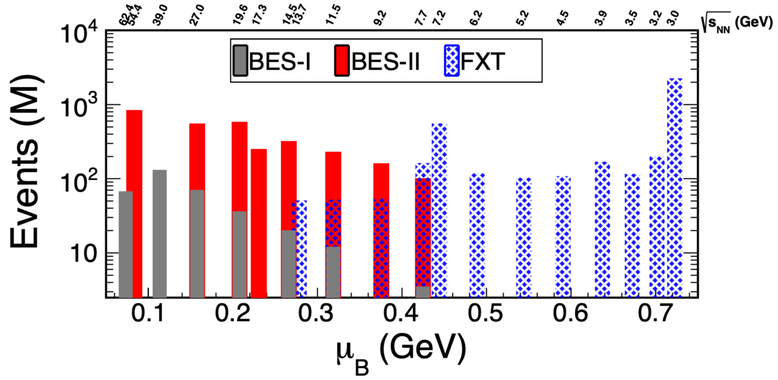


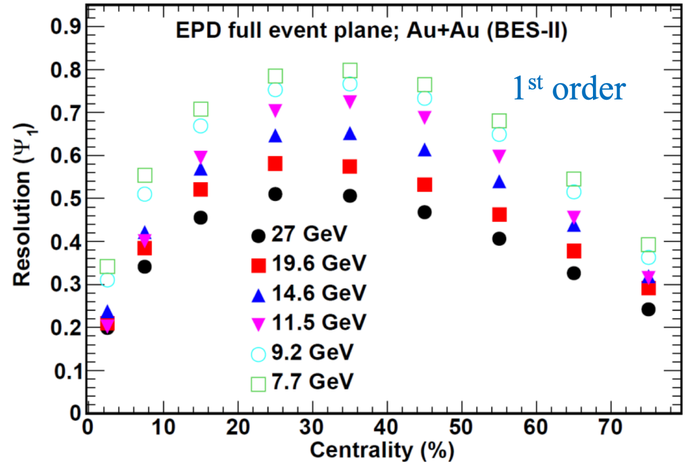
- Hyperons weak-decay leads to "self-analyzing" frame
  - ✦Decayed products in hyperon rest frame is $\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \overrightarrow{P_H^*} \cdot \hat{p_B^*})$
  - ✦Experiment observable is $P_H = \frac{8}{\pi \alpha_H R_1} < sin(\Psi_1 - \phi_B^*) >$



STAR detector





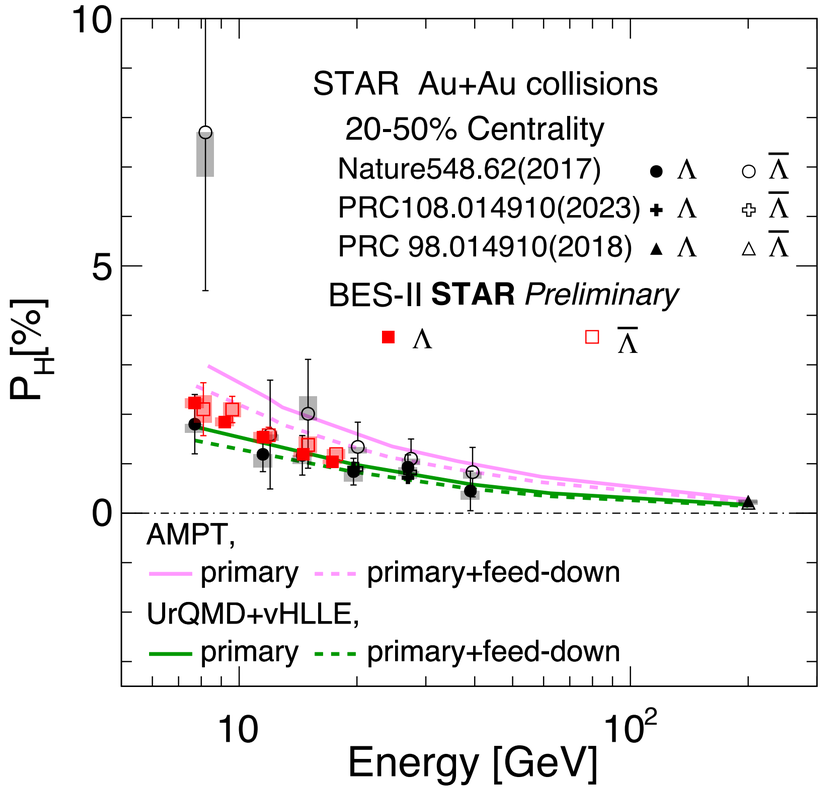


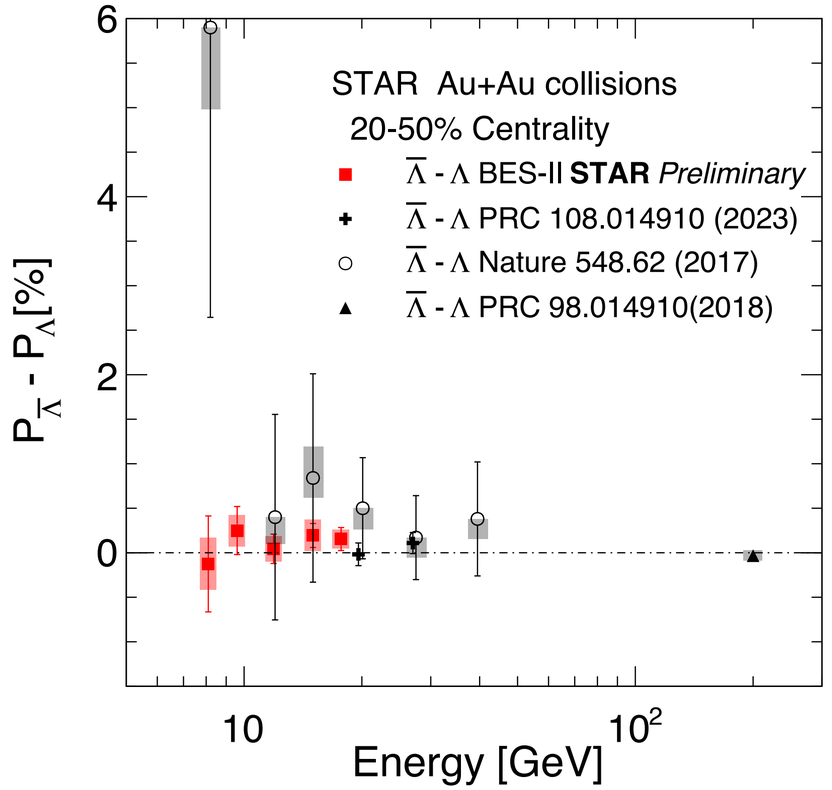
- STAR detector with Beam Energy Scan II (BES-II) upgrades:
  - ✦ (inner) Time Projection Chamber: Tracking, Centrality, Particle identification, Event plane (Ψ_2)
  - ✦ Event plane detector: Event plane (Ψ_1)
- BES-II: Opportunity to study hyperons spin polarization over a wide energy range

  $\mu_B \sim$: 760 - 156 MeV, $\sqrt{s_{NN}} =$ 3.0 - 27 GeV

Result I: Λ, $\overline{\Lambda}$ hyperons global polarization

Additional new energy:
9.2, 17.3 GeV





Tong Fu, Poster No.709

$\alpha_\Lambda = 0.732 \pm 0.014$

$$(P_{\overline{\Lambda}} - P_\Lambda) \approx \frac{2|\mu_\Lambda|B}{T}$$

$T = 150$ MeV

$\mu_\Lambda = -1.93 \times 10^{-14}$ MeV/T

Caveat: splitting can arise from sources: different freeze-out[1]

- Global polarization of Λ, $\overline{\Lambda}$ shows energy dependence
- Uncertainty reduced by a factor of ~9

- No splitting between P_Λ and $P_{\overline{\Lambda}}$ within uncertainty
- Upper limit of late-stage magnetic field

$$B \lesssim 10^{13}\ \mathrm{T} \qquad (95\%\ \text{confidence level})$$

[1] O. Vitiuk, L. V. Bravina et al, Phys. Lett. B 803, 135298 (2020)

Result II: Ξ hyperons global polarization

Hyperon	Decay channel	Spin
Λ (uds)	$\Lambda \to p + \pi^-$	1/2
$\Xi^-(dss)$	$\Xi^- \to \Lambda + \pi^-$	1/2

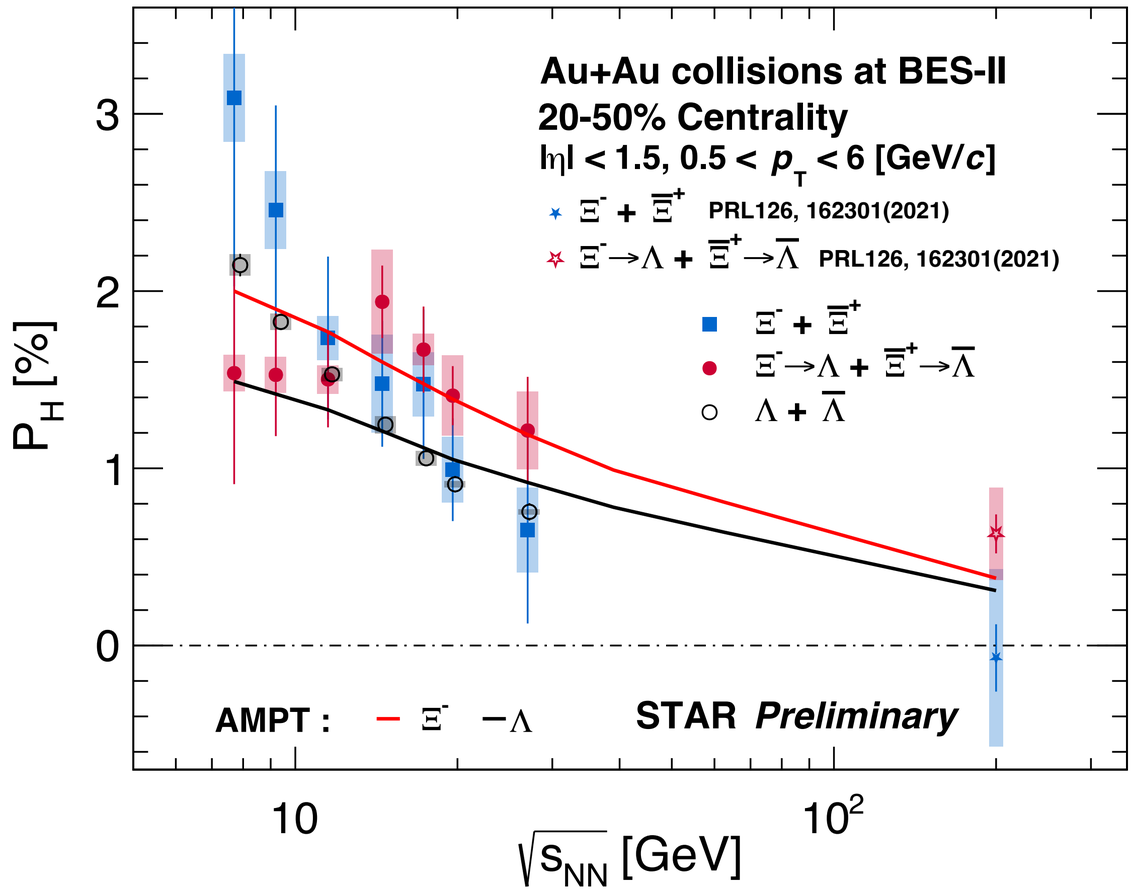
$\alpha_\Lambda = 0.732 \pm 0.014$

$\alpha_\Xi = -0.401 \pm 0.010$

New at QM 2025

P_Ξ measurements in BES-II

Model calculation:
H. Li, X. Xia et al
Phys. Lett. B 827, 136971 (2022)



Xingrui Gou, Poster No.708

Methods:

- Daughter Λ angle distribution in Ξ rest frame
- Daughter Λ polarization with spin transfer factor

  $\boldsymbol{P}^*_\Lambda = C_{\Xi^-\Lambda}\boldsymbol{P}^*_\Xi$, $C_{\Xi^-\Lambda} = 0.944$
- P_Ξ from two methods are consistent within uncertainty

- First measurement of $\Xi^- + \overline{\Xi}^+$ global polarization in BES-II energy
  - Data suggests energy dependence of $\Xi^- + \overline{\Xi}^+$ global polarization
  - No significant difference between Λ and Ξ global polarization

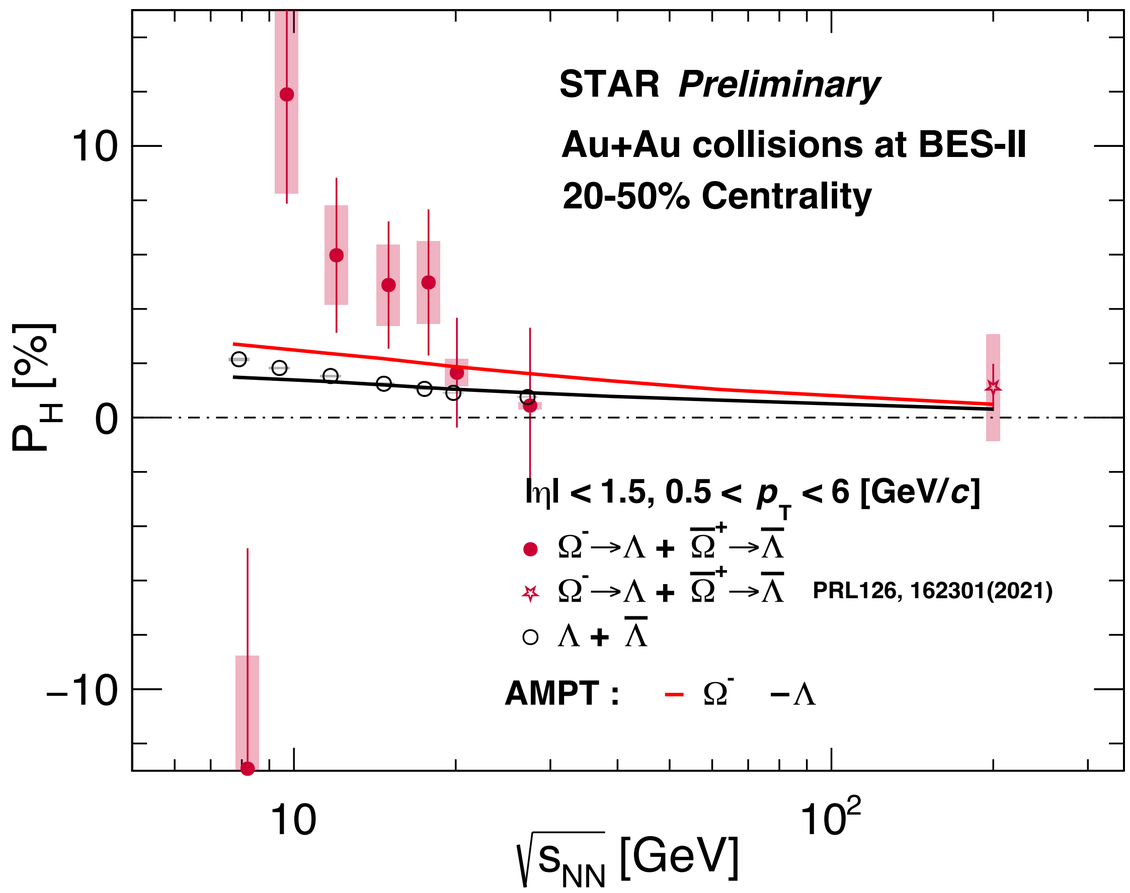
Result III: Ω hyperons global polarization

Hyperon	Decay channel	Spin
Λ (uds)	$\Lambda \to p + \pi^-$	1/2
$\Omega^-(sss)$	$\Omega^- \to \Lambda + K^-$	3/2

New at QM 2025

P_Ω measurements in BES-II

Model calculation:
H. Li, X. Xia et al
Phys. Lett. B 827, 136971 (2022)



Xingrui Gou, Poster No.708

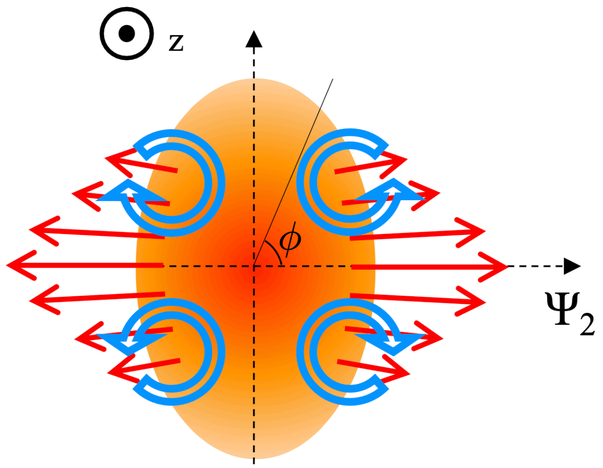
Method:

- Daughter Λ polarization with spin transfer factor

$$P_\Lambda^* = C_{\Omega\text{-}\Lambda} P_\Omega^*, \; C_{\Omega\text{-}\Lambda} \approx 1.0$$

- First measurement of $\Omega^- + \overline{\Omega}^+$ global polarization in BES-II energy
  - Data suggests the hint of energy dependence of $\Omega^- + \overline{\Omega}^+$ global polarization
  - Hint of larger global polarization of Ω than Λ hyperon

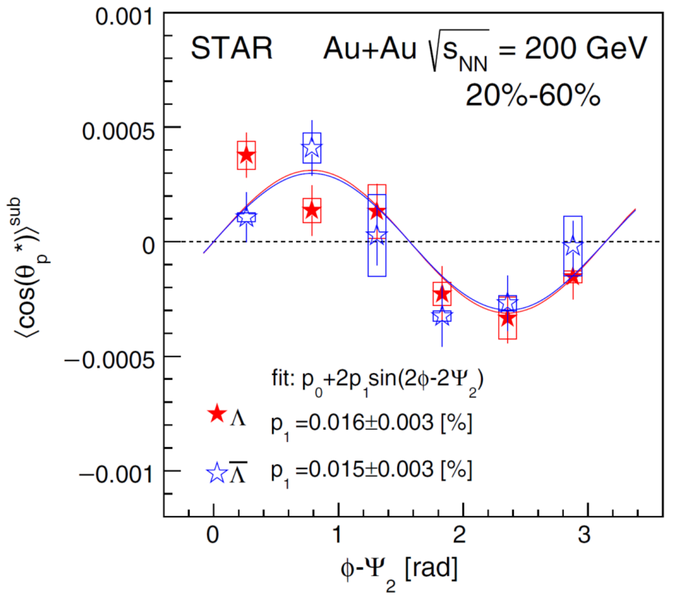
Hyperons local polarization



- Anisotropic flow leads to vorticity along the beam direction.
- Experimental observable is $P_z = \frac{1}{A_z}\frac{3 < cos\theta_B^* >}{\alpha_H}$
- For polarization induced by n-th harmonic flow:
  - Observable is $P_{n,z} = \frac{< P_z sin(n(\phi_H - \Psi_n)) >}{R_n}$

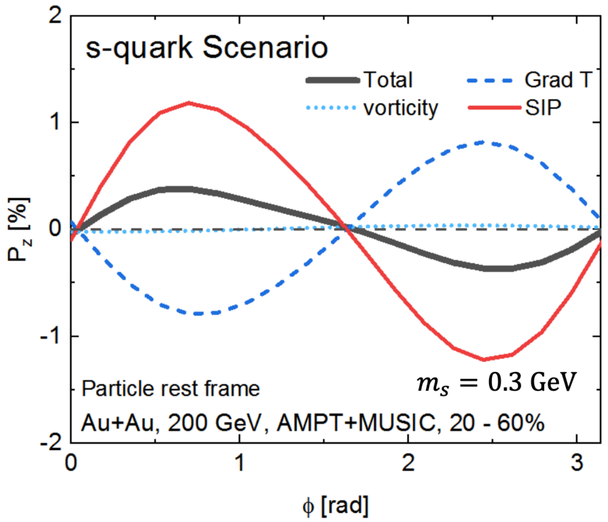
α_H	weak decay parameter	Ψ_n	n-th order event plane (EP)
P_z	hyperon polarization	R_n	n-th order EP resolution
A_z	acceptance factor	ϕ_H	azimuthal angle of hyperon

Observation



- Observation of sine modulation in $P_{2,z}$

Model



- Need shear term to capture correct sign in $P_{2,z}$

Polarization ~ $\nabla T \oplus$ Shear

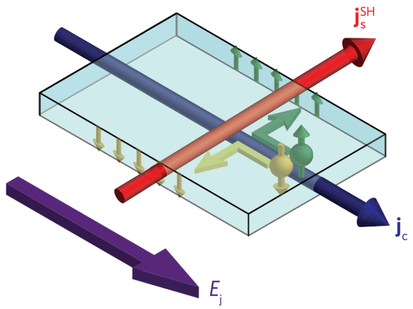
STAR,
Phys. Rev. Lett. 123, 132301 (2019)
Phys. Rev. Lett. 131, 202301 (2023)

S. Liu et al, Phys. Rev. Lett. 125, 062301 (2020)
F. Becattini et al, Phys. Rev. Lett. 127, 272302 (2021)
Y. Yin, RHIC AGS, 2024

Baryonic spin hall effect

Spin hall effect

$\overrightarrow{P} \propto \vec{p} \times \overrightarrow{E}$

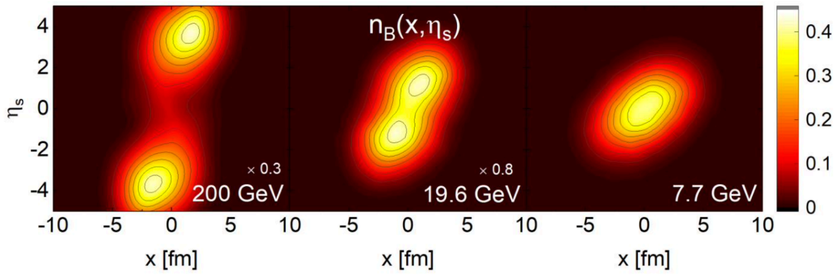


Condensed matter

Baryonic Spin hall effect

$\overrightarrow{P} \propto -\vec{p} \times (q_B \nabla \mu_B)$

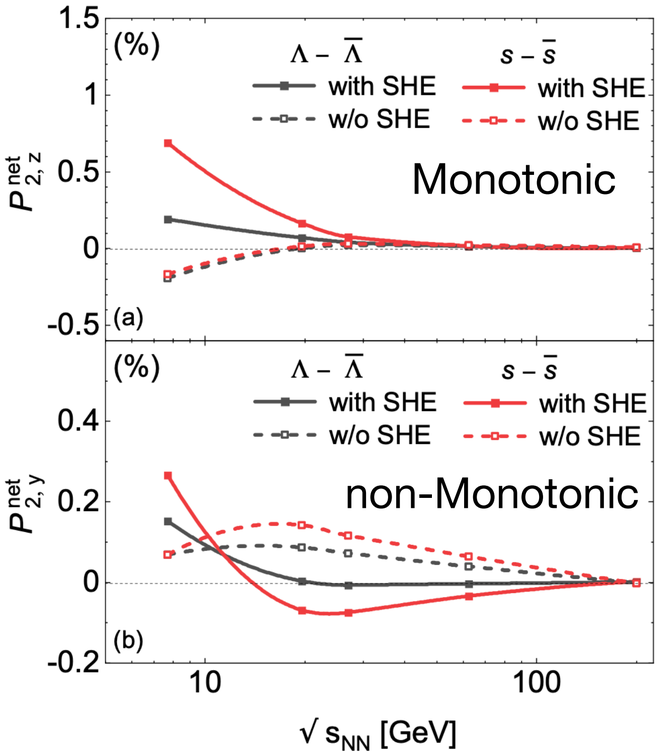
Baryon density in Longitudinal-plane (x, η)



QCD matter

Polarization ~ $\nabla T \oplus$ Shear $\oplus \nabla \mu_B$

Prediction: $\Lambda - \overline{\Lambda}$



S. Meyer, Y. Chen et al, Nature materials 16, 977-981 (2017)
B. Fu, S. Liu et al, Phys. Rev. Lett. 127, 142301 (2021)
S. Liu, Y. Yin, Phys. Rev. D 104, 054043 (2021)
B. Fu, L. Pang et al, arXiv:2201.12970v1

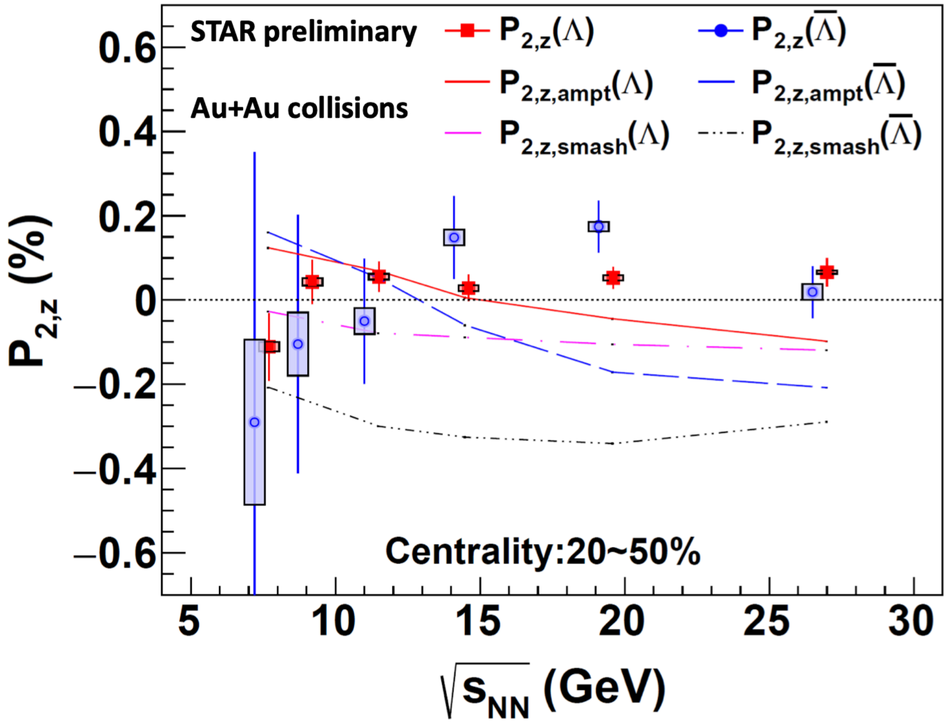
- Observables for baryonic SHE

$P^{net}_{2,z} = < P^{net}_z(\Delta\phi) sin(2\Delta\phi) >$, $P^{net}_{2,y} = < P^{net}_y(\Delta\phi) cos(2\Delta\phi) >$, where $P^{net}_{z,y} = P_{z,y}(\Lambda) - P_{z,y}(\overline{\Lambda})$

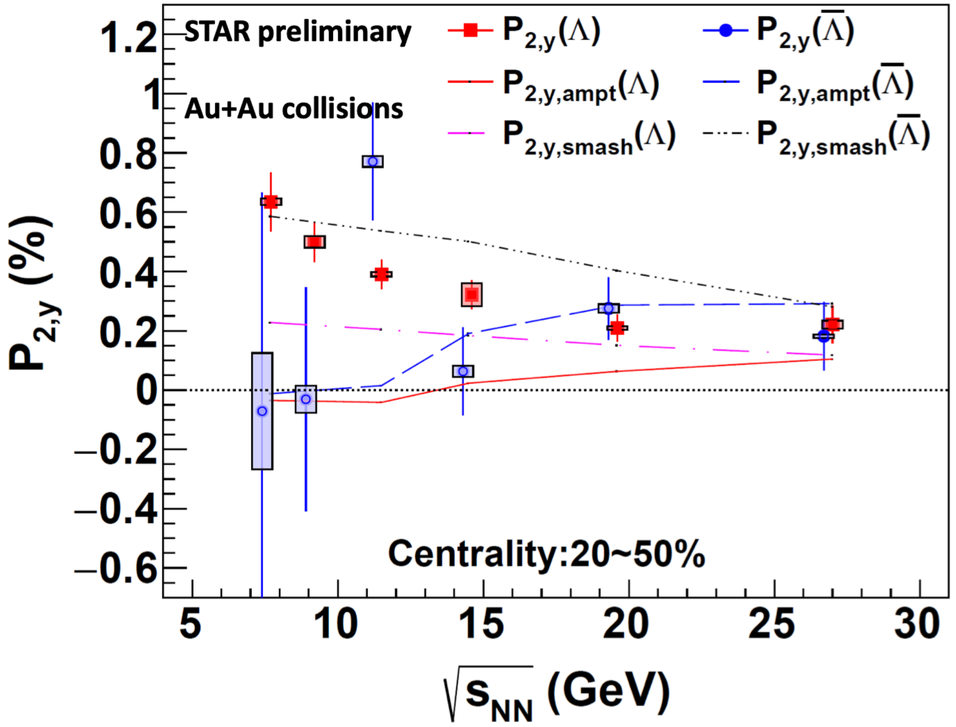
Result IV: Λ hyperons local polarization

Qiang Hu,
Poster No.932

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



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



$$P_y = \frac{8}{\pi \alpha_\Lambda R_1} \langle \sin(\Psi_1 - \phi_p^*) \rangle$$

$$P_z = \frac{3}{\alpha_\Lambda} \frac{\langle \cos \theta_p^* \rangle}{\langle (\cos \theta_p^*)^2 \rangle}$$

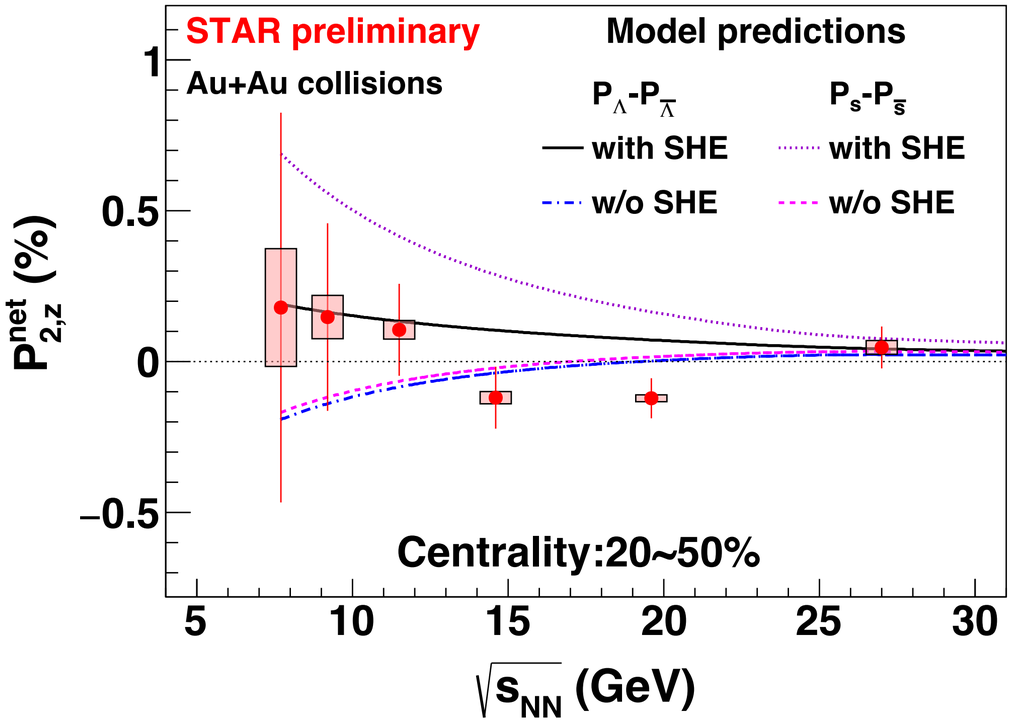
- $P_{2,z}$: No strong collision energy dependence of Λ $P_{2,z}$
- $P_{2,y}$: Monotonic increase with decrease energy (for Λ)
- Models can not simultaneously explain $P_{2,z}$ and $P_{2,y}$

Model calculation:
X. Wu, C. Yi et al,
Phys. Rev. C 105, 064909 (2022)

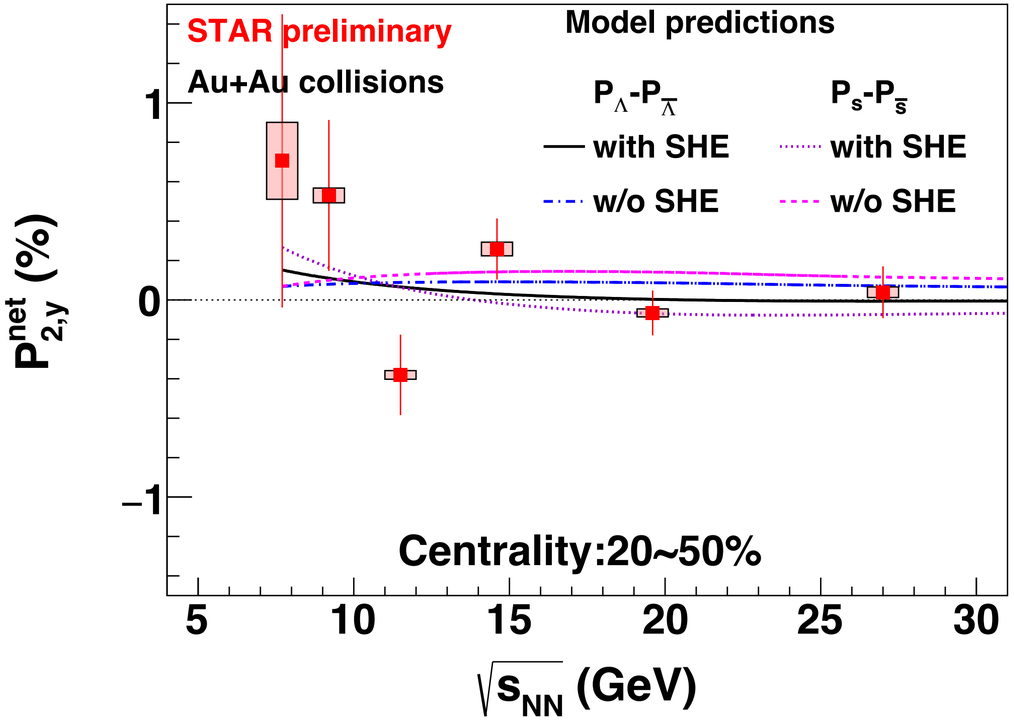
Result V: Probing baryonic spin hall effect

Qiang Hu,
Poster No.932

$$P_{2,z}^{\text{net}} = P_{2,z}^{\Lambda} - P_{2,z}^{\overline{\Lambda}}$$



$$P_{2,y}^{\text{net}} = P_{2,y}^{\Lambda} - P_{2,y}^{\overline{\Lambda}}$$



- First study of baryonic spin hall effect in heavy ion collision.
- Simultaneous model fit for $P_{2,z}$ and $P_{2,y}$ is required to help understand the energy dependence of local polarization and expected not-trivial contribution from SHE.

Model calculation:
B. Fu, L. Pang, et al
arXiv:2201.12970v1

Summary

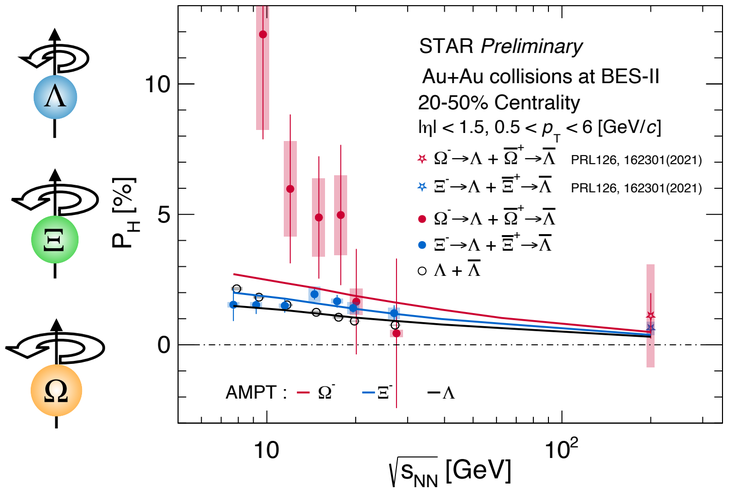
In BES-II at RHIC-STAR ($\sqrt{s_{NN}}$ = 7.7 - 27 GeV)

✅ Global polarization of Λ, Ξ, Ω hyperons are measured

① First measurement of non-zero global polarization for Ξ and Ω in BES-II

② Within uncertainty, no splitting is observed between Λ, $\overline{\Lambda}$ global polarization

③ Global polarization of Λ, Ξ, and Ω shows a similar beam energy dependence ($\mu_B \uparrow$, $P_H \uparrow$)

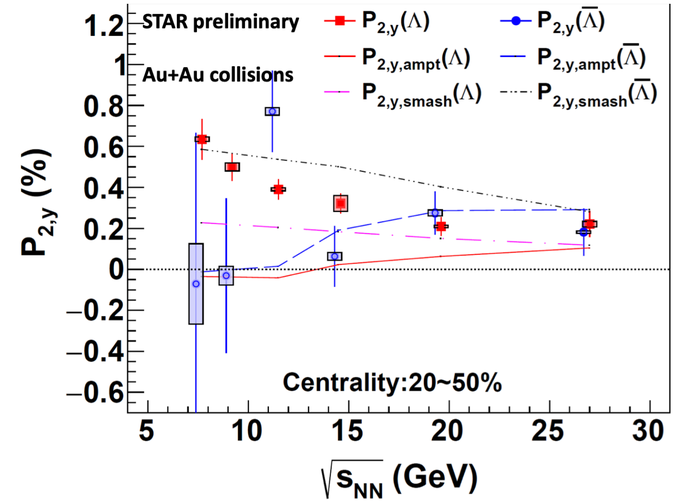


✅ Local polarization of Λ hyperons are measured

① First observation of energy dependence of Λ $P_{2,y}$ ($\mu_B \uparrow$, $P_H \uparrow$)

② No strong energy dependence of Λ hyperons $P_{2,z}$

③ First study of baryonic spin hall effect in heavy ion collision



Outlook

Global polarization of Λ from STAR Fixed-Target energies ($\sqrt{s_{NN}}$=3.0-7.7 GeV) is ongoing

Thanks for your attention!