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中国科学院近代物理研究所
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Measurements of global and local spin polarization of Λ and $\bar{\Lambda}$ in Au+Au collisions from the RHIC Beam Energy Scan

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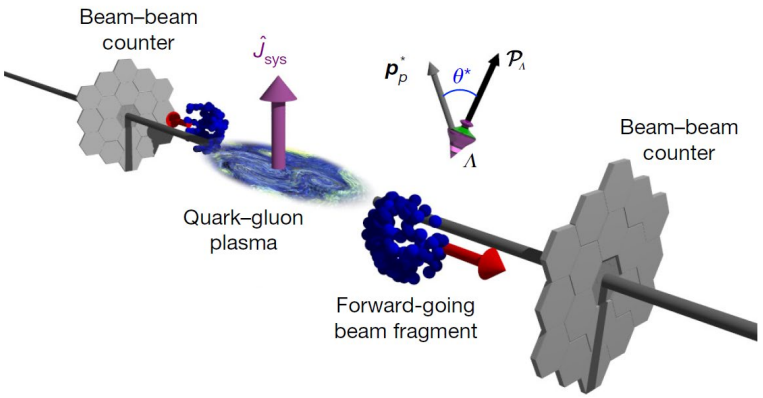
Outline

- Introduction
- STAR Detector at RHIC
- Results and Discussions:
  - Energy Dependence of Global Polarization:
  - Energy Dependence of Local Polarization (in-plane and out-of-plane)
  - First Study of Baryonic Spin Hall Effect
- Summary

Introduction

Global Spin Polarization



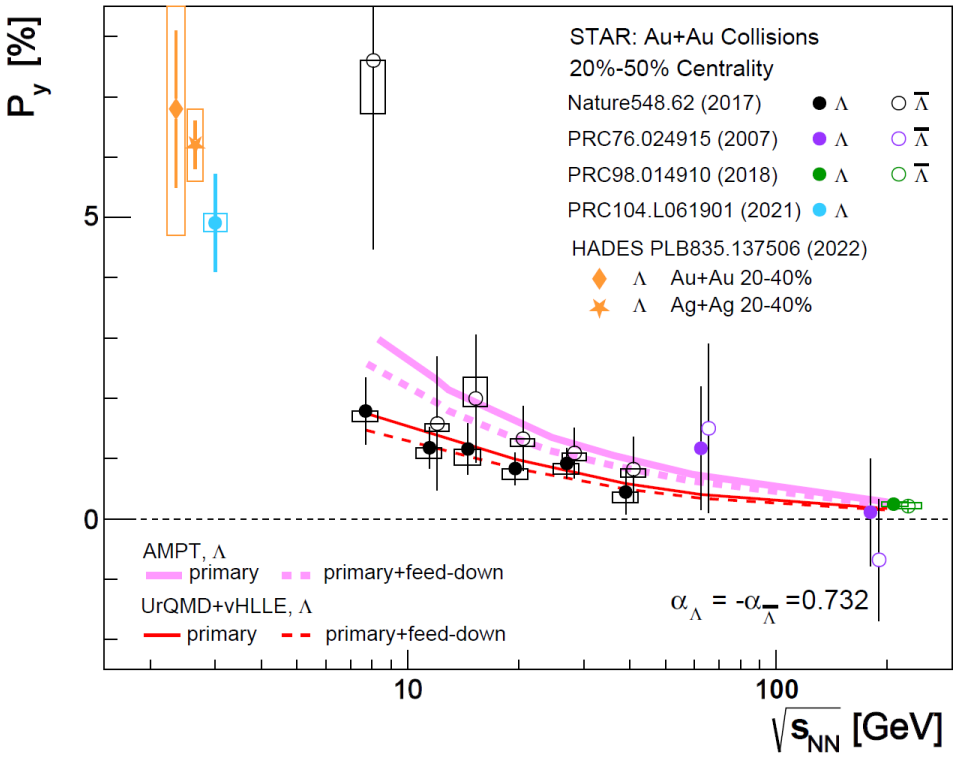
STAR Collaboration, Nature 548 (62) (2017)

- ✓ **2005: prediction of the global polarization**
- ✓ **2017: observation of the Λ global polarization**

Z. –T. Liang and X. –N. Wang Phys. Rev. Lett. 94, 102301 (2005); erratum 96, 039901

$$P_y = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$

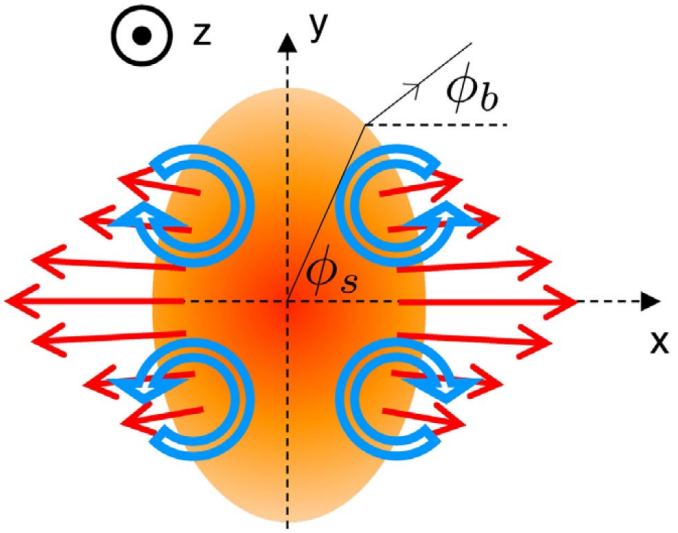
α_Λ: Λ's decay parameter
ψ_1: 1st order event-plane angle
ϕ_p^*: the azimuthal angle of the daughter proton in Λ rest frame

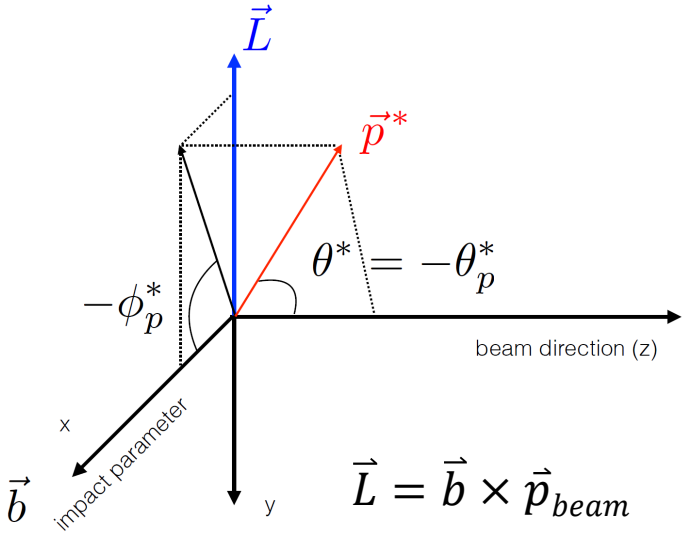


Sun Xu et al., Acta Phys. Sin. 72(7), 072401 (2023)

- **Significant energy dependence in Λ global polarization**
- **Help to understand the vortical nature of the QCD matter**
- **Hints of splitting between Λ and $\bar{\Lambda}$, expected from late-stage magnetic field sustained by the QGP**

Local Spin Polarization





- Elliptic flow (stronger flow in-plane than out-of-plane) is expected to generate a longitudinal component of polarization (P_z)

$$P_z = \frac{\langle \cos\theta_p^\star \rangle}{\alpha_H \langle (\cos\theta_p^\star)^2 \rangle}$$

$$P_y = \frac{8}{\pi\alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$

$\theta_p^\star$: polar angle

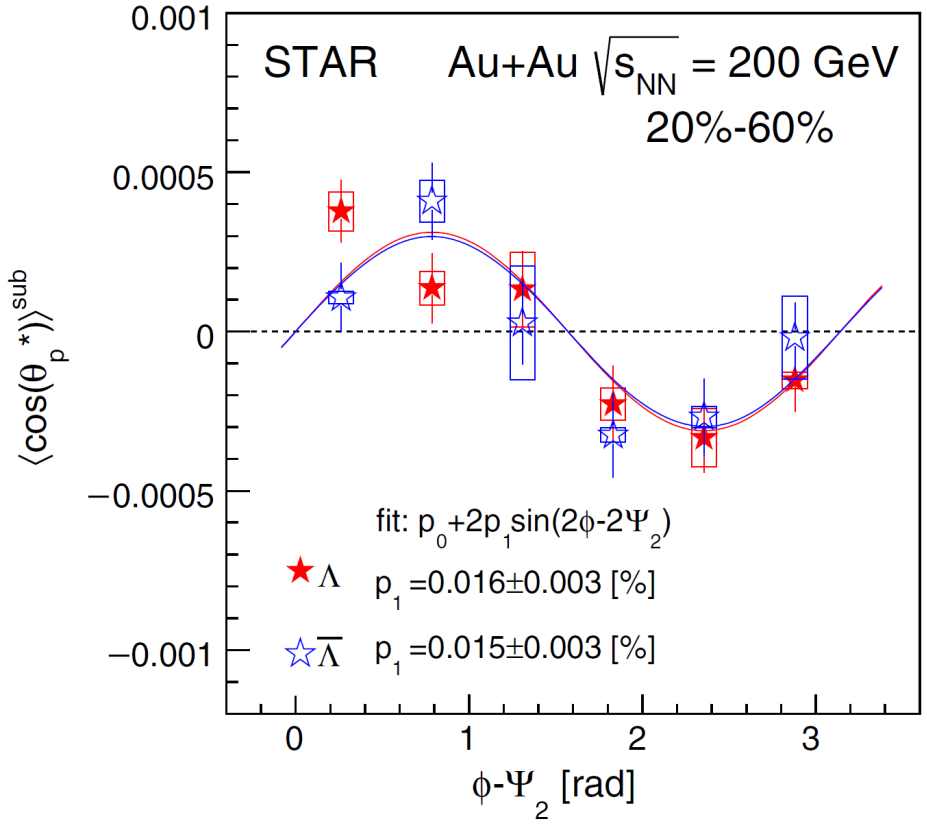
ψ_1: the first-order event plane angle

α_Λ: hyperon decay parameter

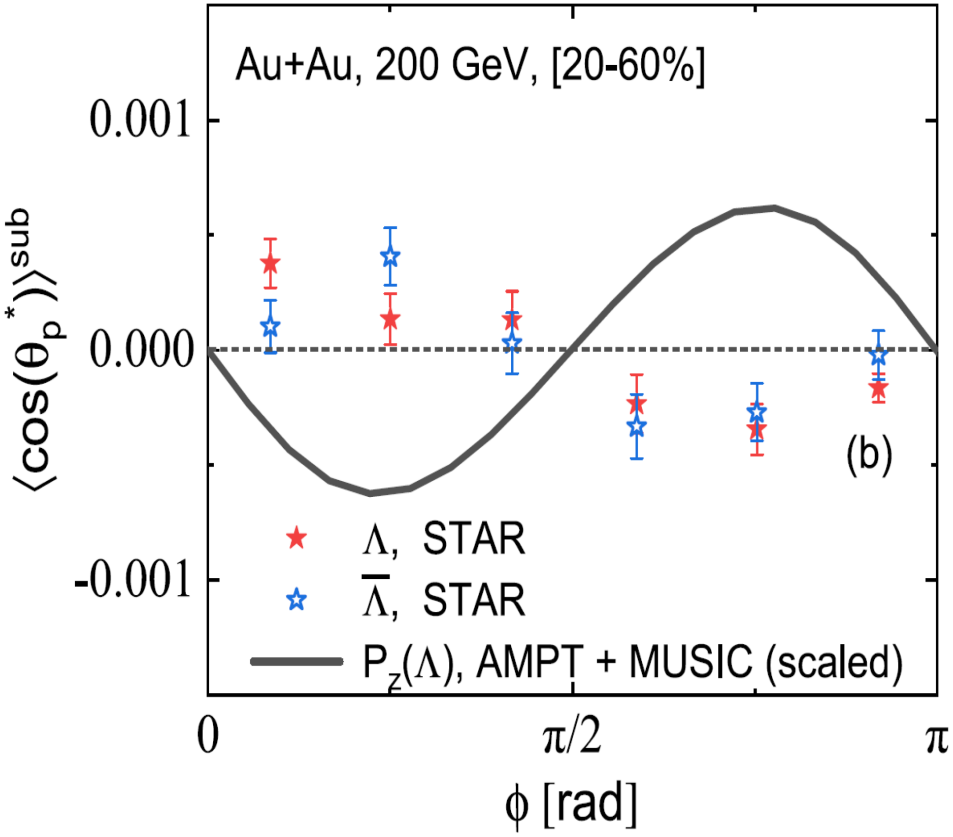
$R_{EP}^{(1)}$:the first-order event plane resolution

STAR, PRL 123,132301 (2019)

Local Spin Polarization



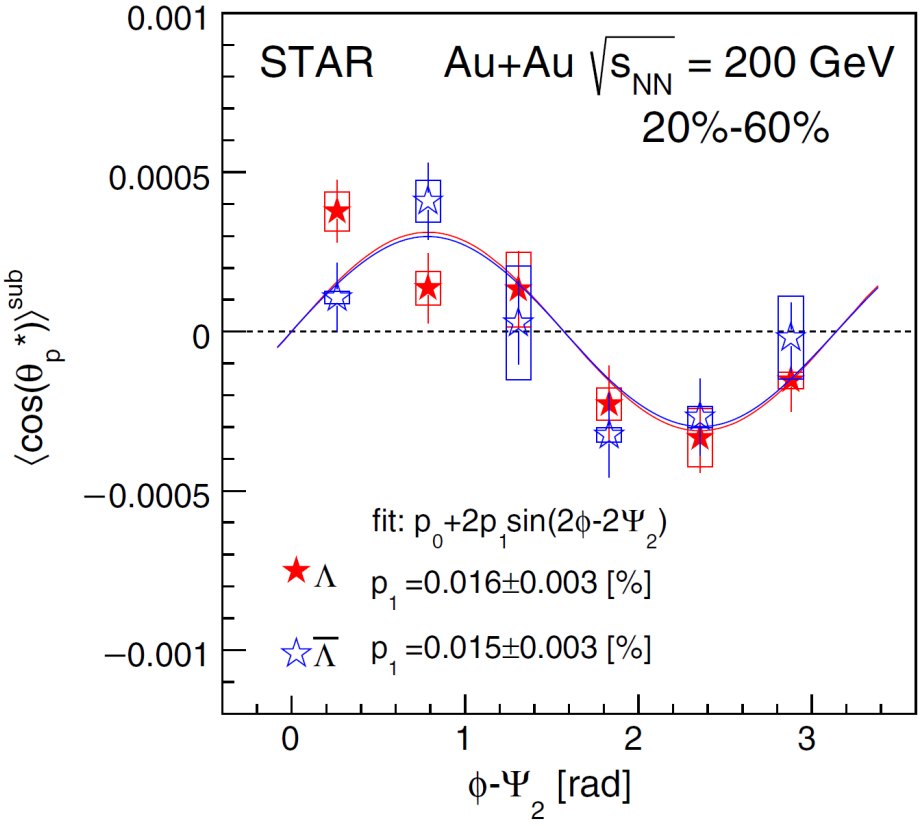
STAR, PRL 123,132301 (2019)



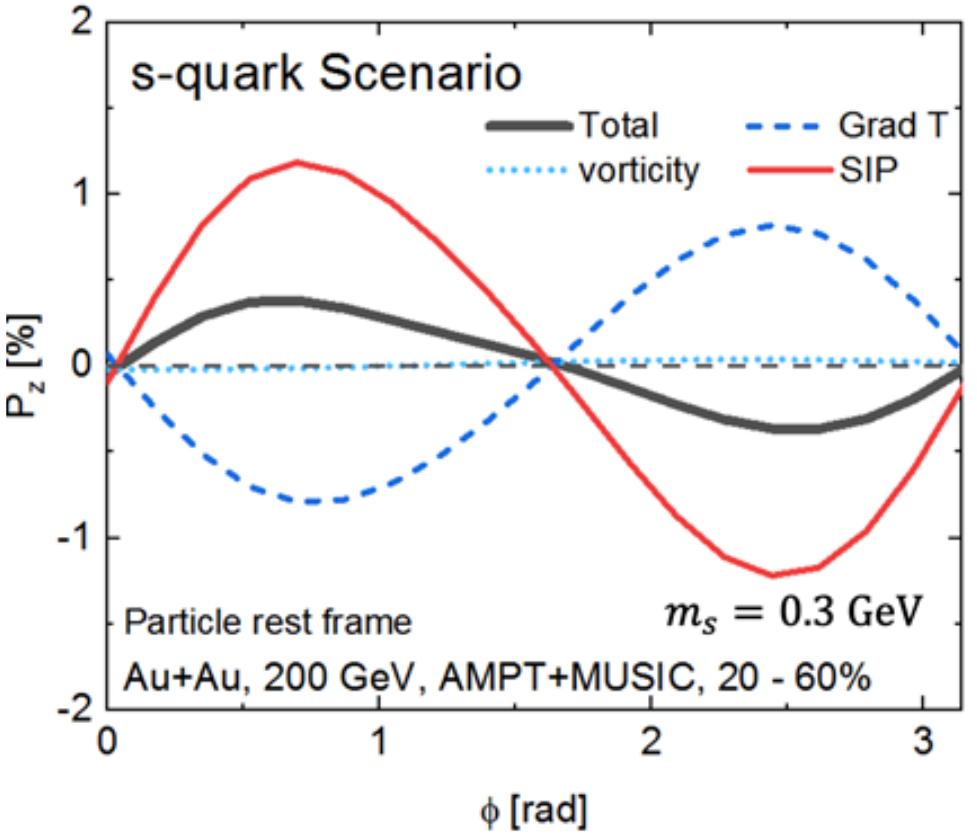
B Fu et al., PRC 103, 024903 (2021)

- **Observation of local P_z in Au+Au collisions at 200 GeV**
- **Many models fail to capture the trend with the proper sign**

Local Spin Polarization



STAR, PRL 123,132301 (2019)

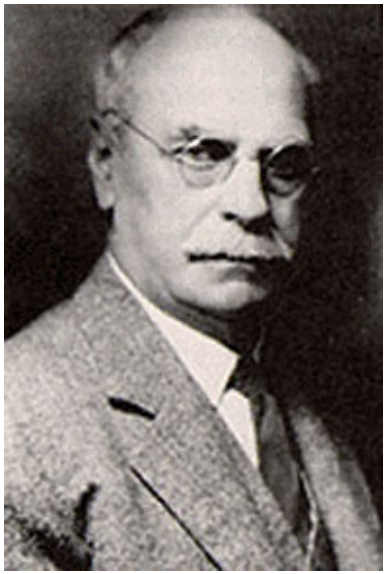


Total: Vorticity + Grad T + SIP

B. Fu, S. Liu et al. PRL 127, 142301 (2021)
F. Becattini et al. PRL 127, 272302 (2021)

- **New developments, Shear Induced Polarization (SIP) may capture the trend**
- **Local polarization to be measured in BES**

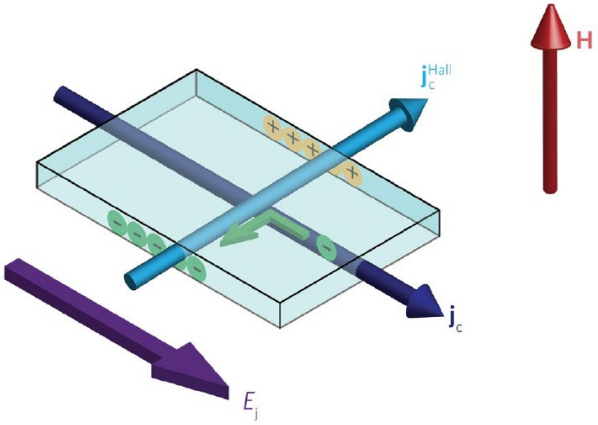
What is Spin Hall Effect ?



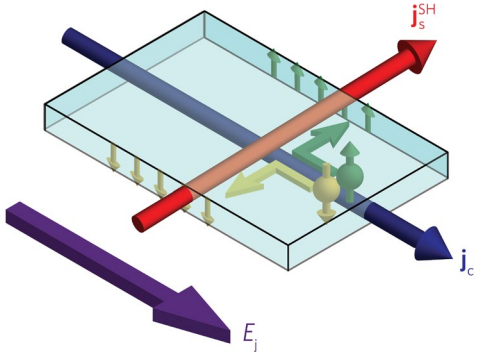
Edwin Herbert Hall (1855-1938)

Mikhail I. Dyakonov

Vladimir I. Perel



HE: charge imbalance (1879)



SHE: spin imbalance (2004)

S. Meyer et al., Nature Materials, 2017

Spin Hall Effect

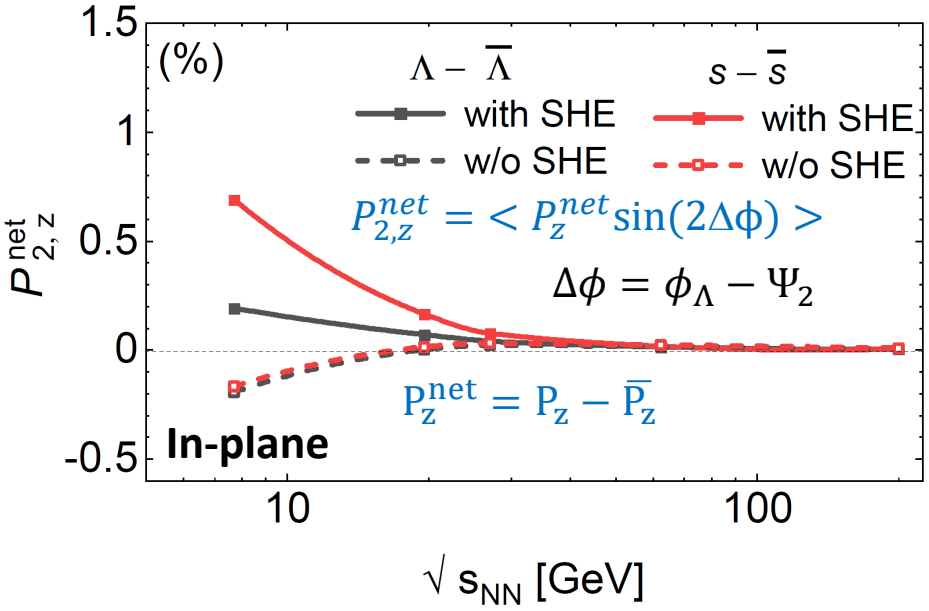
1971: predicted by Mikhail I. Dyakonov and Vladimir I. Perel

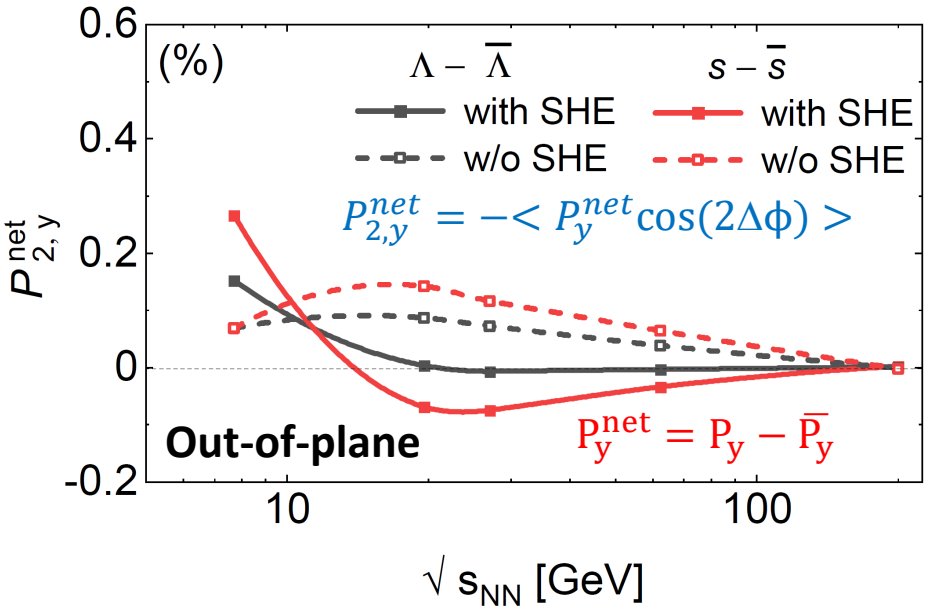
30 years later, it was observed in semiconductors (Y. K. Kato et al., Science 306,1910(2004))

"Spin-orbit" interaction

$$\boldsymbol{P} \propto \pm \boldsymbol{p} \times \boldsymbol{E}$$

Baryonic Spin Hall Effect





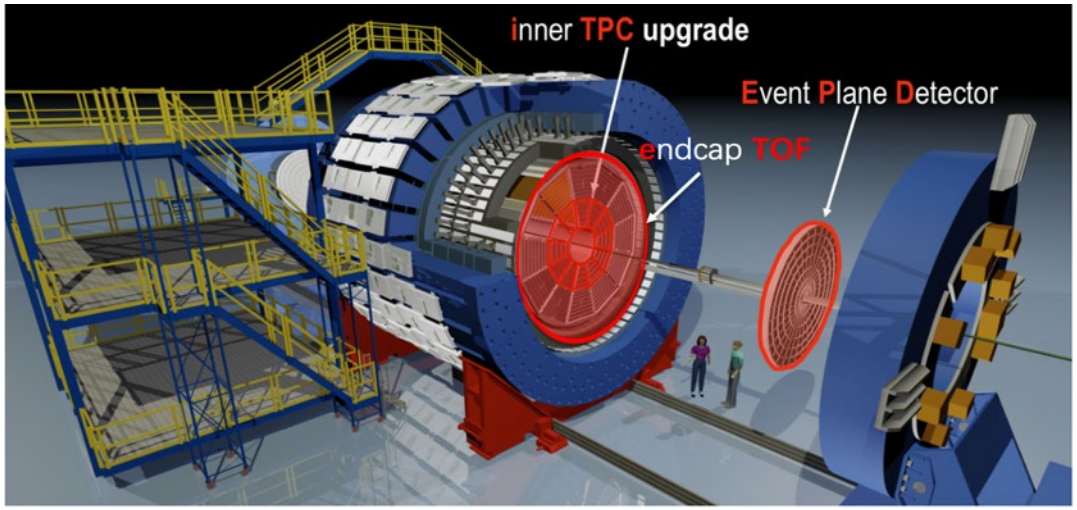
$$\boldsymbol{P \propto \pm p \times \nabla \mu_B}$$

- Sign of $P_{2,z}^{net}$ is opposite with and without SHE at BES energies

In heavy-ion collisions:
New proposal of probing spin Hall effect driven by baryon chemical potential gradient ($\nabla\mu_B$) via local Λ polarization

S. Y. F. Liu, Phys.Rev.D 104 , 054043 (2021)
B. Fu, S. Liu et al. PRL 127, 142301 (2021)
B. Fu et al., arXiv:2201.12970v1

The STAR Detector



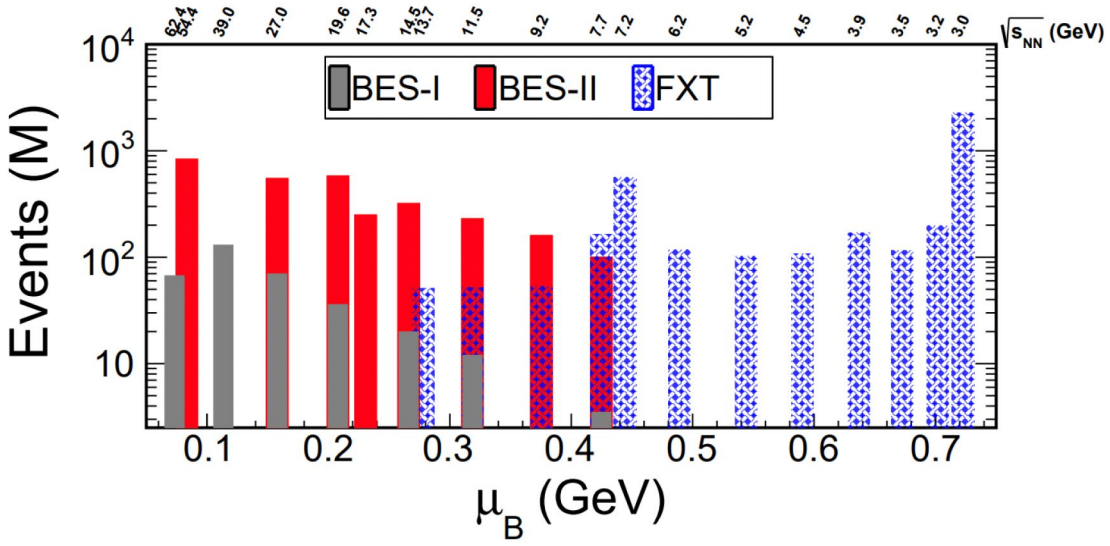
STAR Collaboration, Nature 548 (62) 2017

TPC: Time Projection Chamber (PID & Event plane reconstruction)

TOF: Time Of Flight →PID

EPD: Event Plane Detector (Event plane reconstruction), $|\eta| \in [2.1, 5.1]$

BES-I (2010-2017) and BES-II (2018-2021) statistics



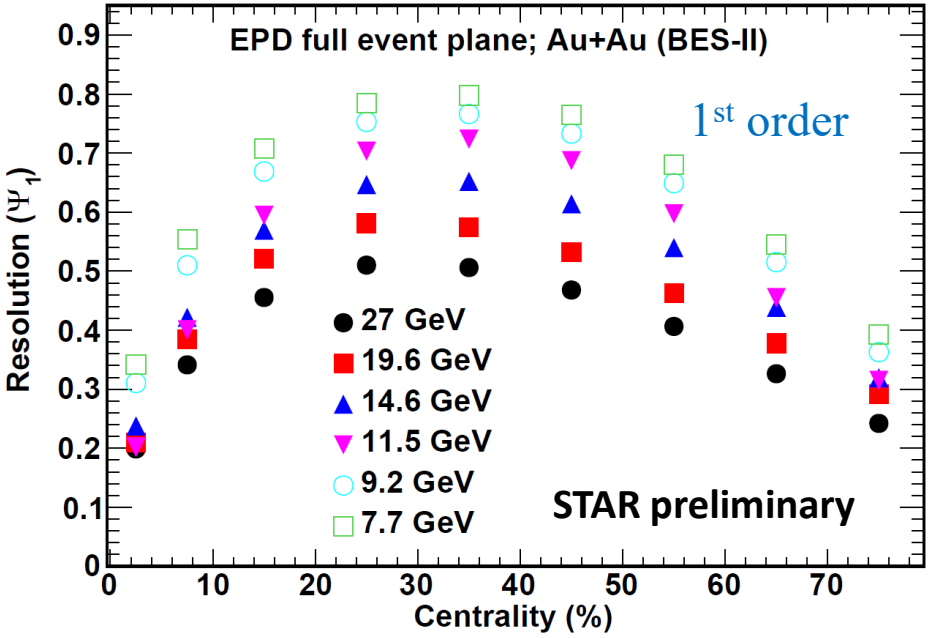
High statistics from BES-II

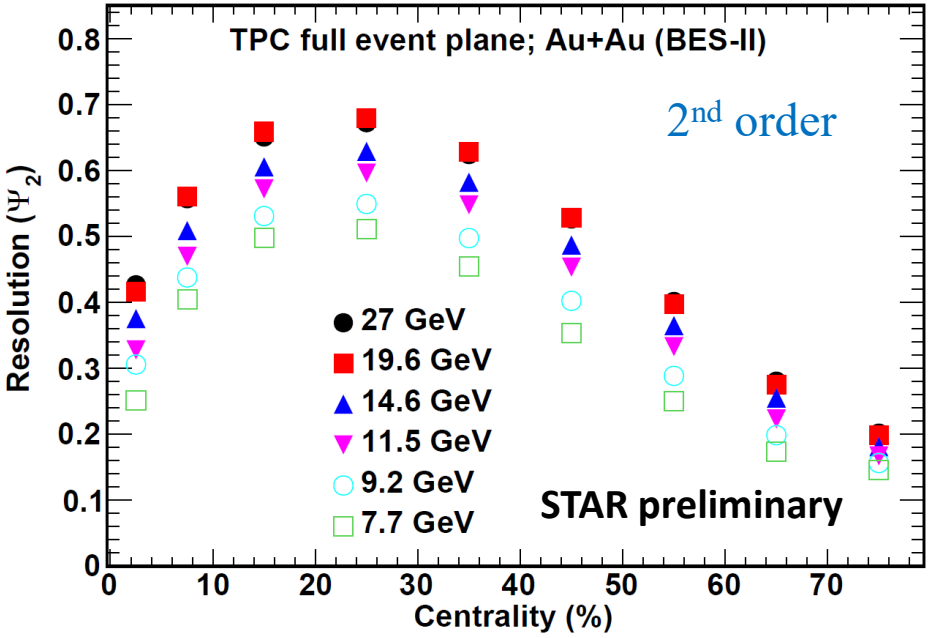
→ opportunity to measure polarization of Λ precisely

→ probe the polarization splitting between Λ and $\bar{\Lambda}$ with high precision

Results of Λ polarization

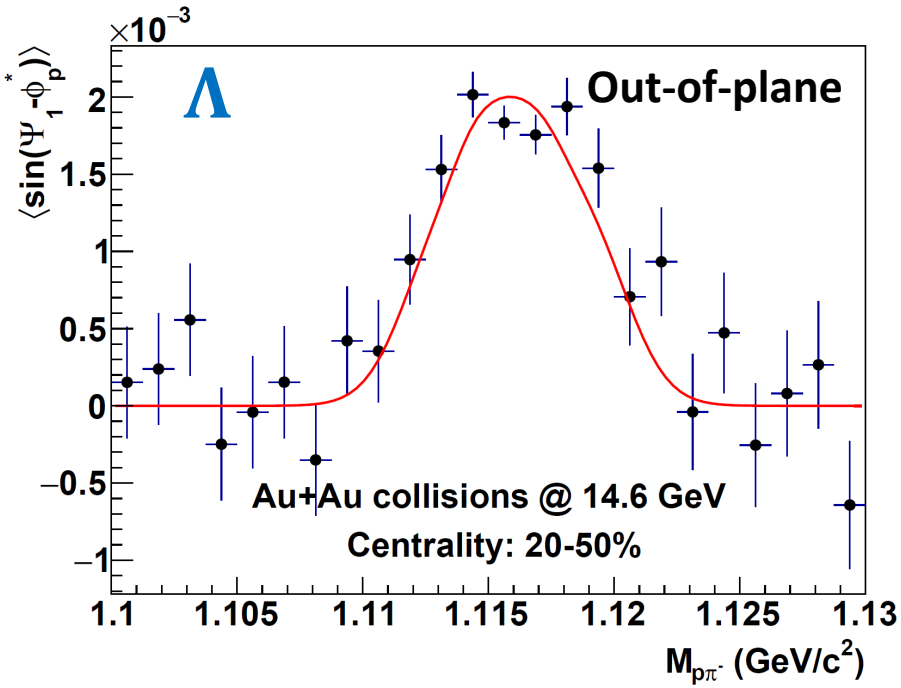
Event Plane Resolution

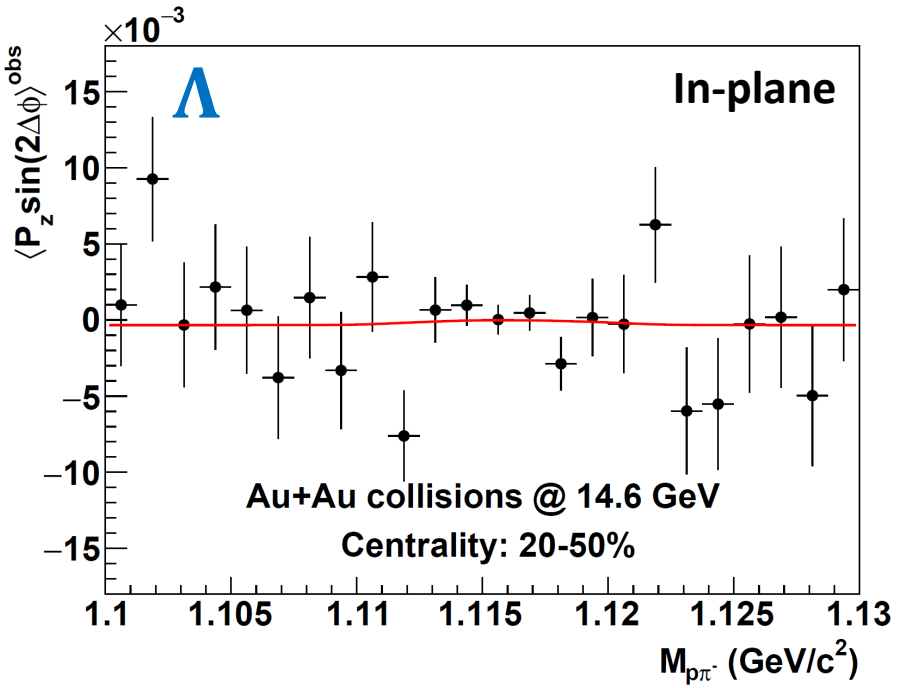




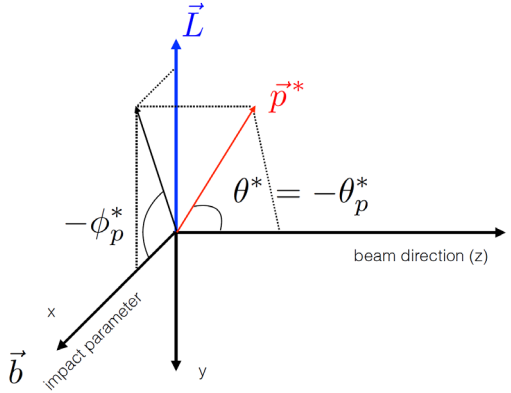
EPD (BES-II)
About a factor of 1.5 increase in event plane resolution compared to previously used BBC detector (BES-I)

Polarization Extraction





$$P_y = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$



$$\langle P_z sin(2(\phi_\Lambda - \psi_2)) \rangle^{obs}$$

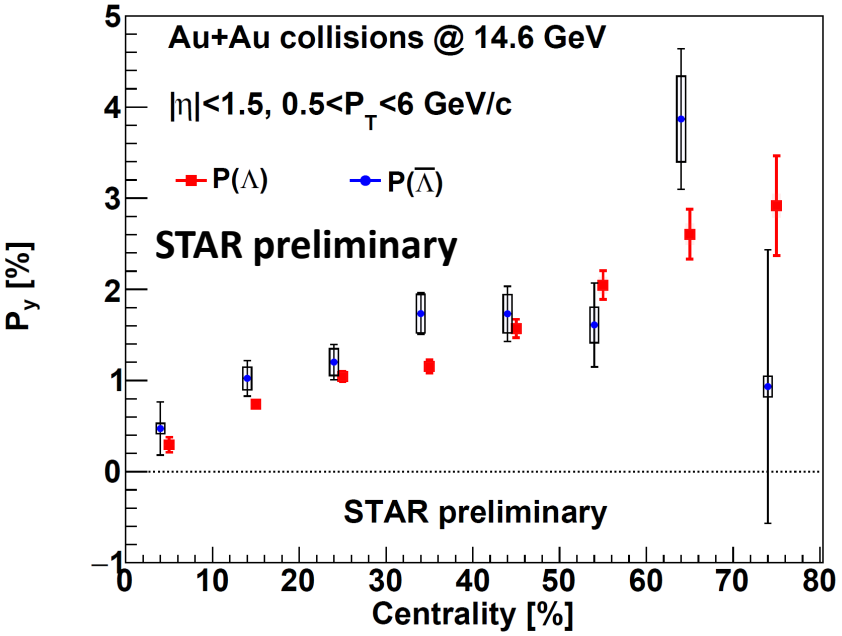
$$= \left(1 - f^{Bg}(M_{inv})\right) \langle P_z sin(2(\phi_\Lambda - \psi_2)) \rangle^{Sg}$$

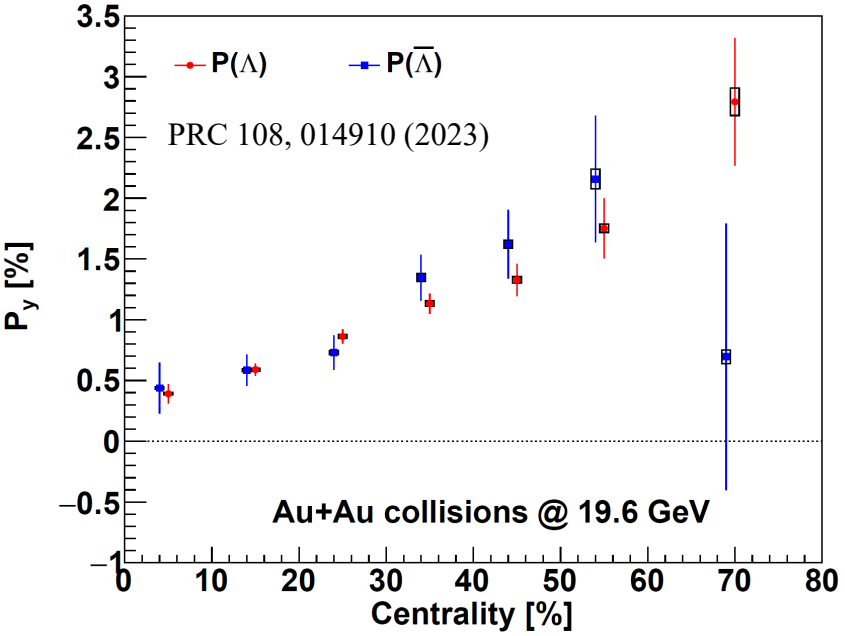
$$+ f^{Bg}(M_{inv}) \langle P_z sin(2(\phi_\Lambda - \psi_2)) \rangle^{Bg}$$

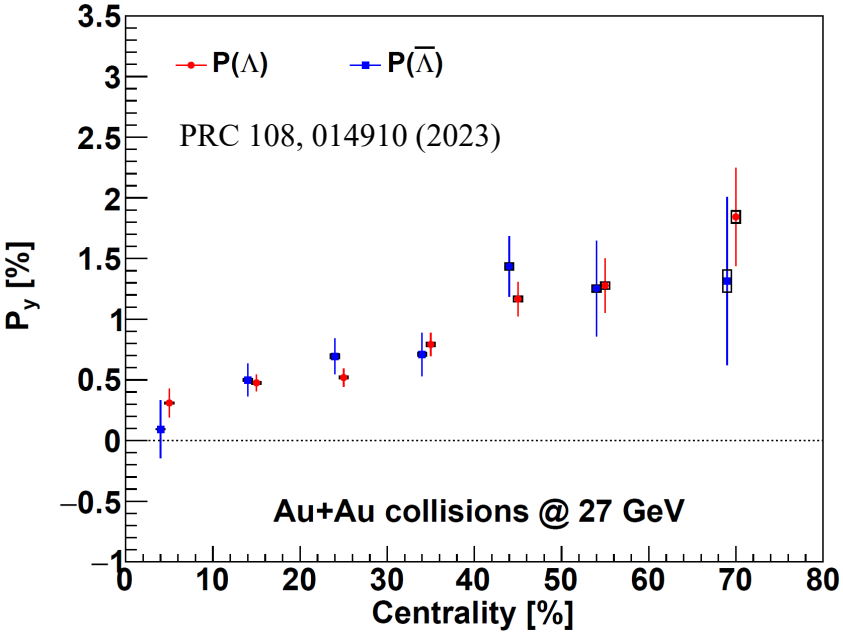
ϕ_p^*: azimuthal angle of the daughter (anti)proton in Λ's rest frame

$$\Delta\phi = \phi_\Lambda - \psi_2$$

Global Polarization P_y vs Centrality





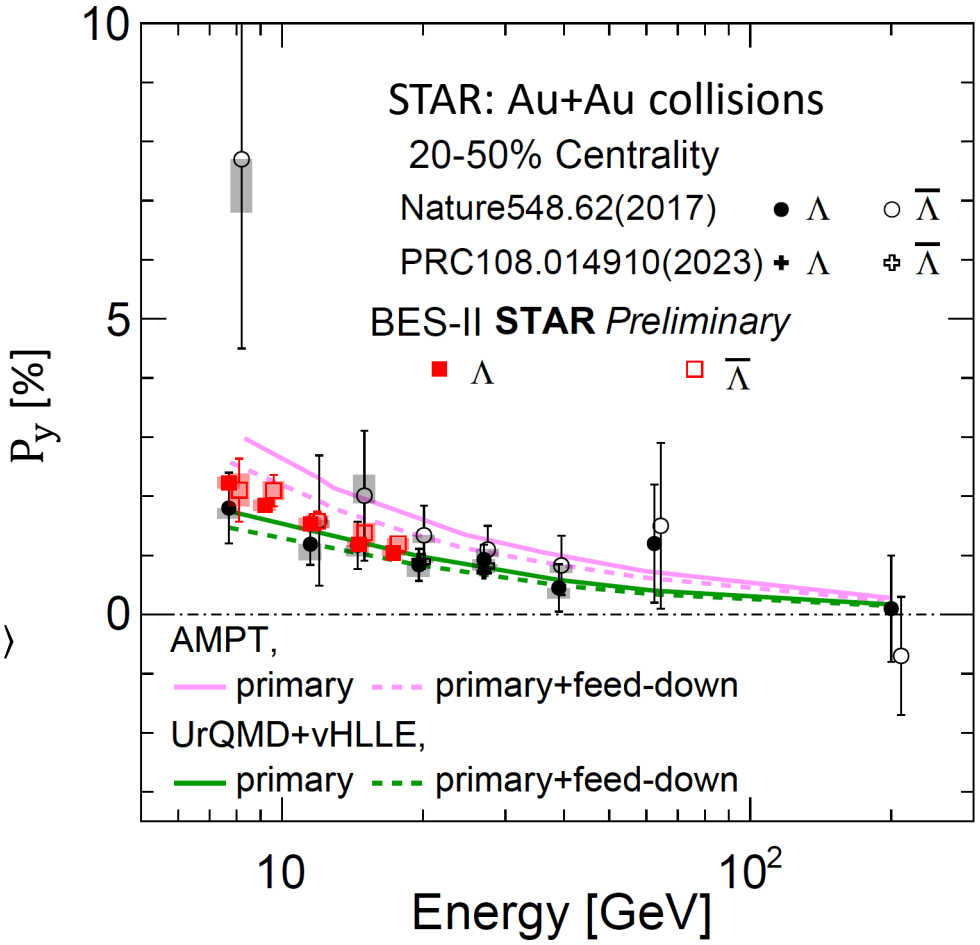


- **Clear centrality dependence of global polarization of Λ and $\bar{\Lambda}$ are observed**
- **Trend consistent with expectation from vorticity**

STAR, Phys. Rev. C 108, 014910 (2023)

Global Polarization P_y vs Energy

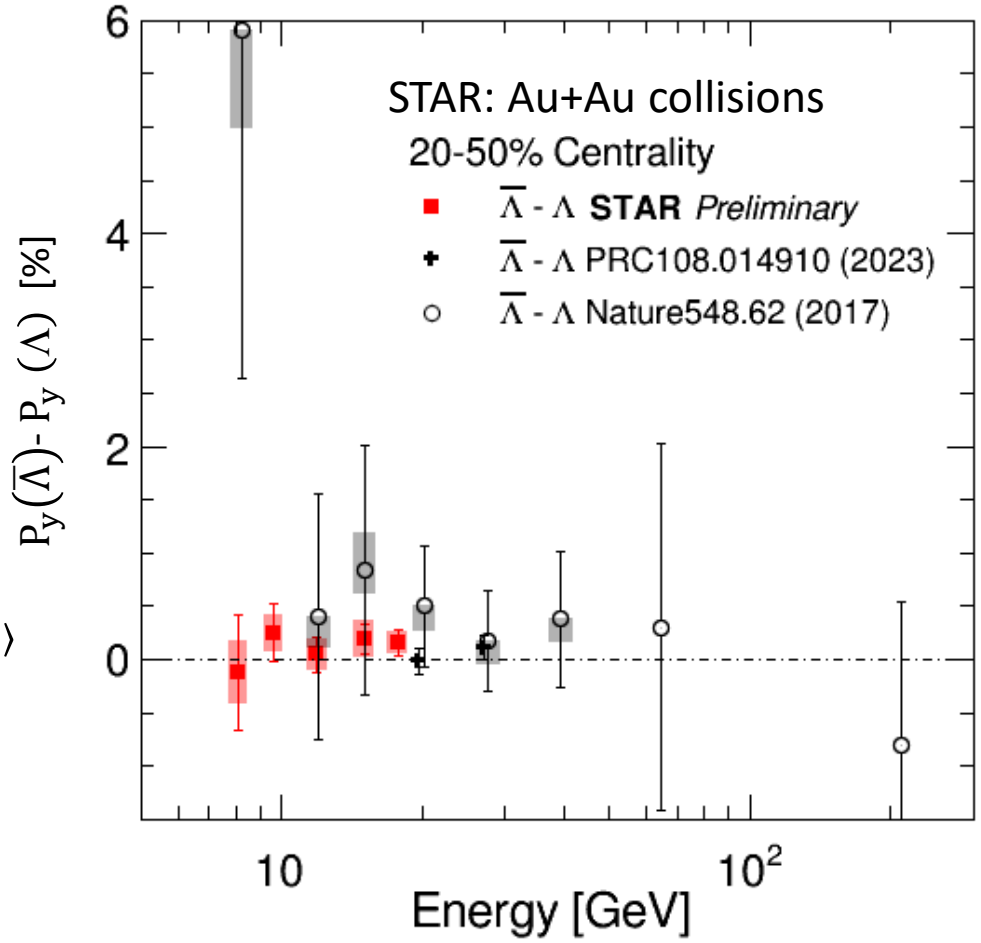
$$P_y = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$



- **Significant global polarization of Λ and $\bar{\Lambda}$ are observed**
- **Results from BES-II and BES-I are consistent within uncertainties (reduction of errors by about a factor of 5)**

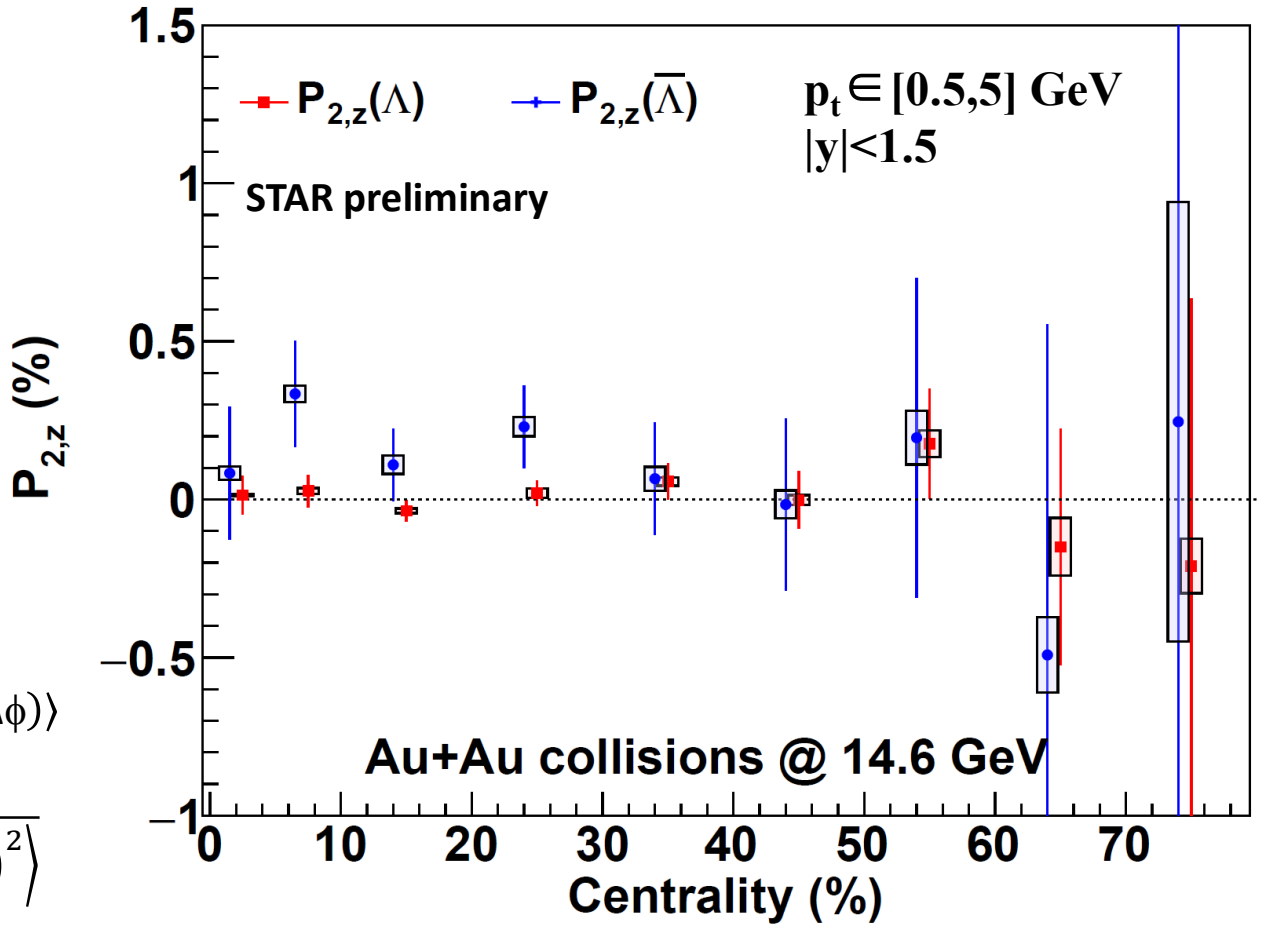
Global Polarization Splitting vs Energy

$$P_y = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$



- **No splitting between Λ and $\overline{\Lambda}$ global polarization within uncertainties**
- **Upper limit on the late-stage magnetic field: $B<9.4\times10^{12}$ T and $B<1.4\times10^{13}$ T at $\sqrt{s_{NN}} = 19.6$ and 27 GeV, respectively.** (PRC 108, 014910 (2023))

Λ's Local Polarization $P_{2,z}$ vs Centrality



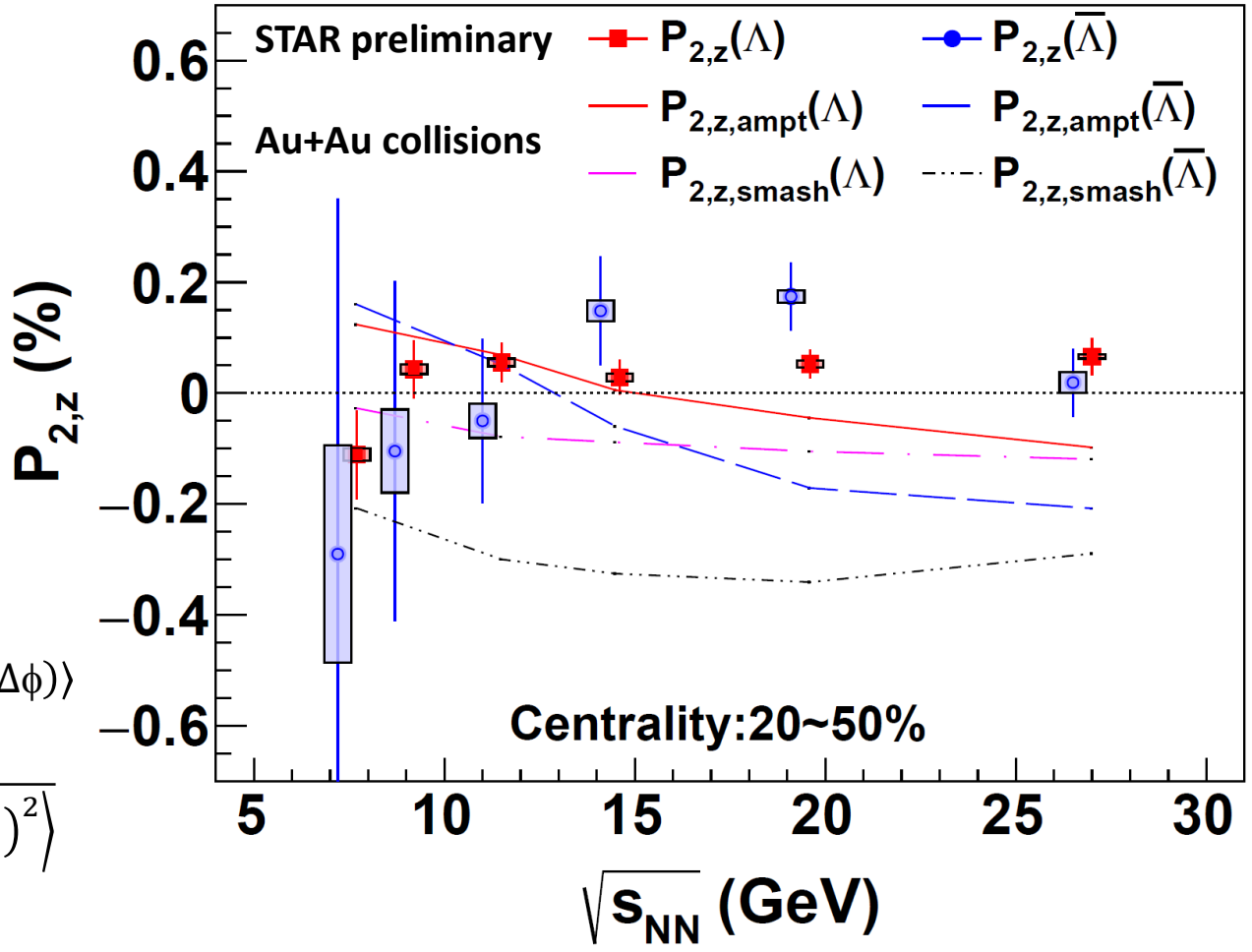
$$P_{2,z} = \langle P_z sin(2\Delta\phi) \rangle$$

$$P_z = \frac{\langle \cos\theta_p^\star \rangle}{\alpha_\Lambda \left\langle (\cos\theta_p^\star)^2 \right\rangle}$$

$$\Delta\phi = \phi_\Lambda - \psi_2$$

- **No significant centrality dependence of $P_{2,z}$ within uncertainties**

Λ's Local Polarization $P_{2,z}$ vs Energy



$p_t \in [0.5,5]$ GeV/c

27 GeV: $|\eta|<1.0$

Other energies: $|\eta|<1.5$

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

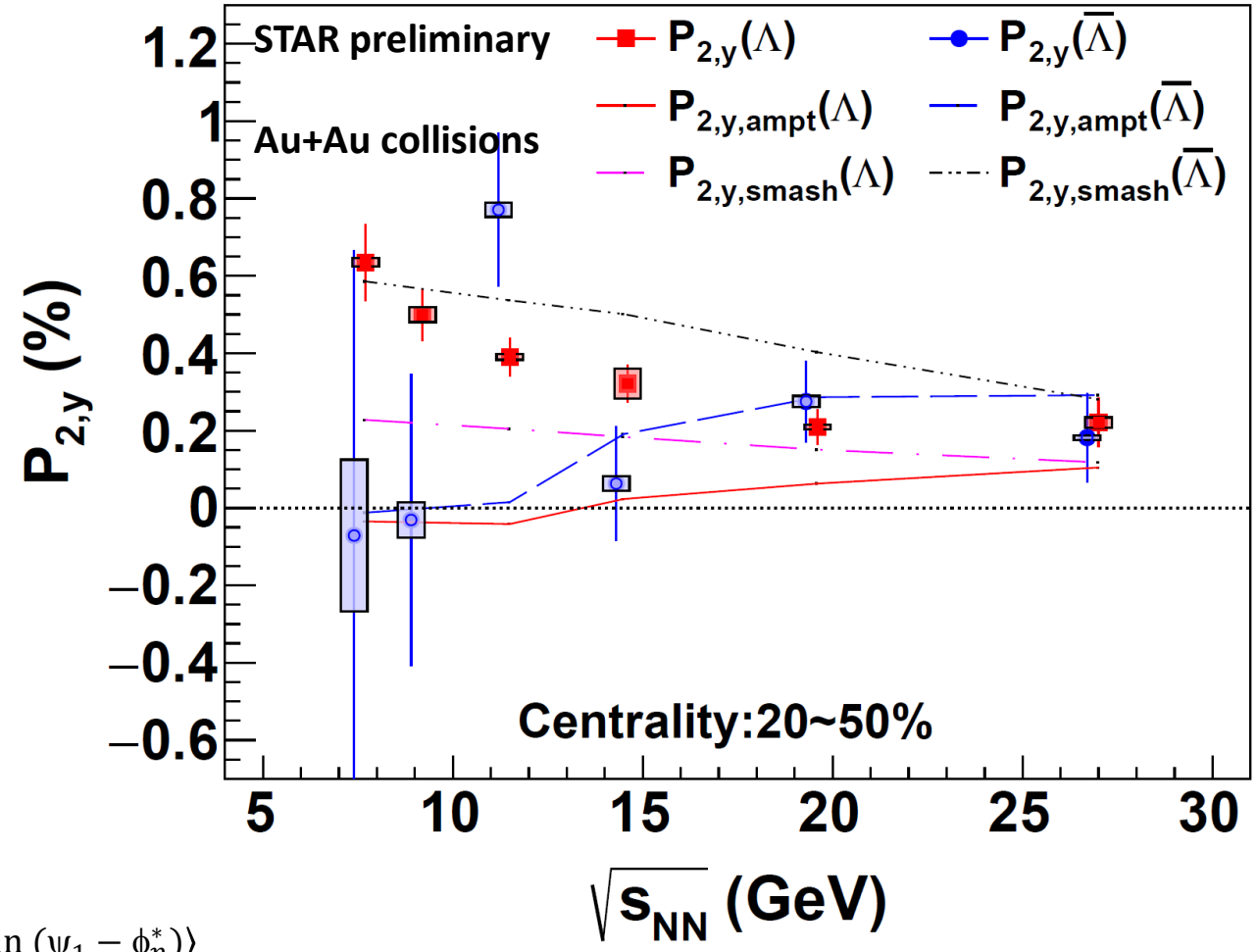
$$P_z = \frac{\langle \cos\theta_p^\star \rangle}{\alpha_\Lambda \left\langle (\cos\theta_p^\star)^2 \right\rangle}$$

$$\Delta\phi = \phi_\Lambda - \psi_2$$

- **Hints of sign change of $P_{2,z}$ at 7.7 GeV, baryon diffusion with Λ–scenario predicts sign change opposite to data**
- **Measurements at lower energies underway**

Model: X. Wu et al., PRC 105 (2022) 064909

Λ's Local Polarization $P_{2,y}$ vs Energy



$p_t \in [0.5,5]$ GeV/c

27 GeV: $|\eta| < 1.0$

Other energies: $|\eta| < 1.5$

$$P_y = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$

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

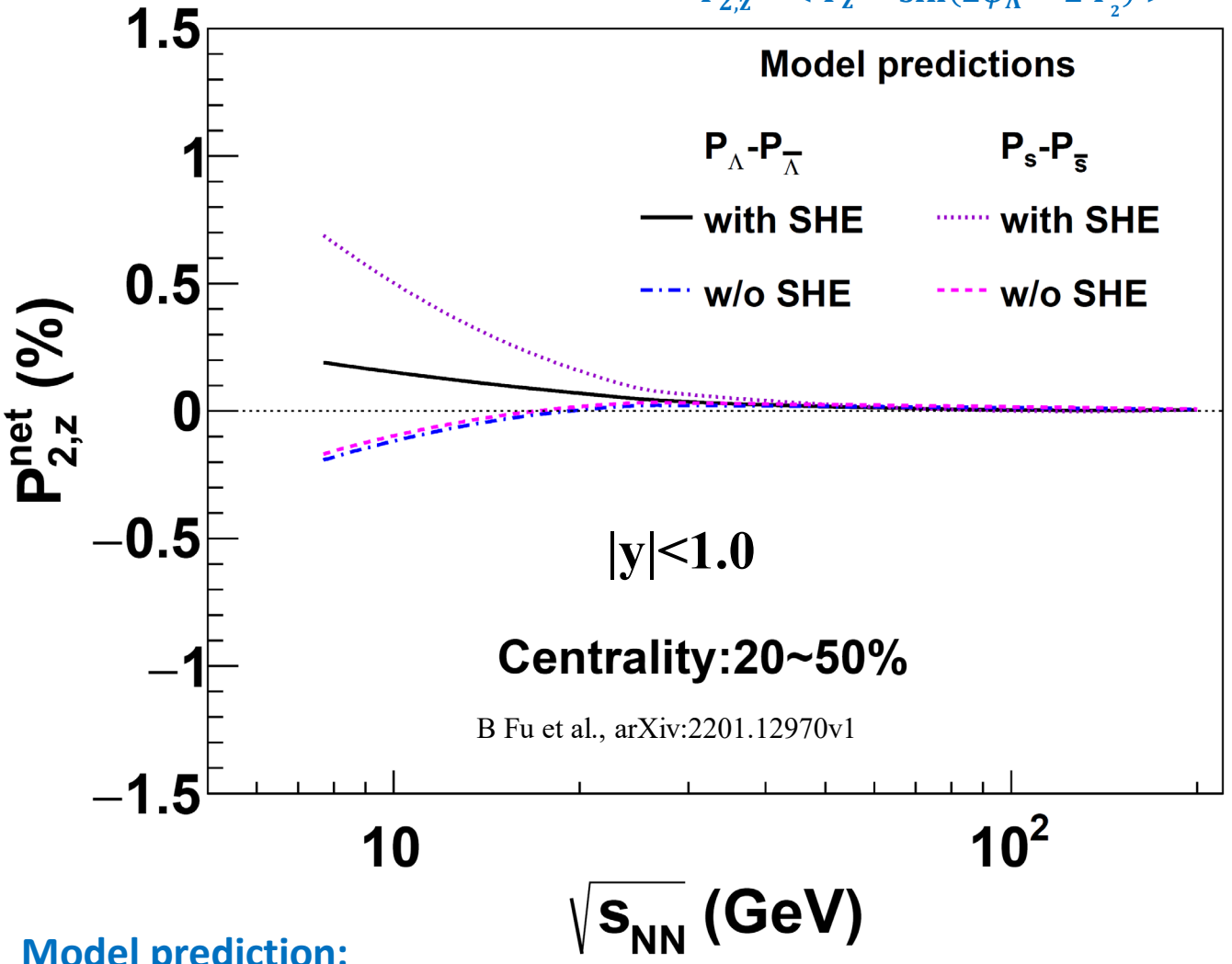
$$\Delta\phi = \phi_\Lambda - \psi_2$$

- **Λ shows monotonic increase with decrease in energy**
- **Current models can not depict the results properly**

Model: X. Wu et al., PRC 105 (2022) 064909

Baryonic SHE

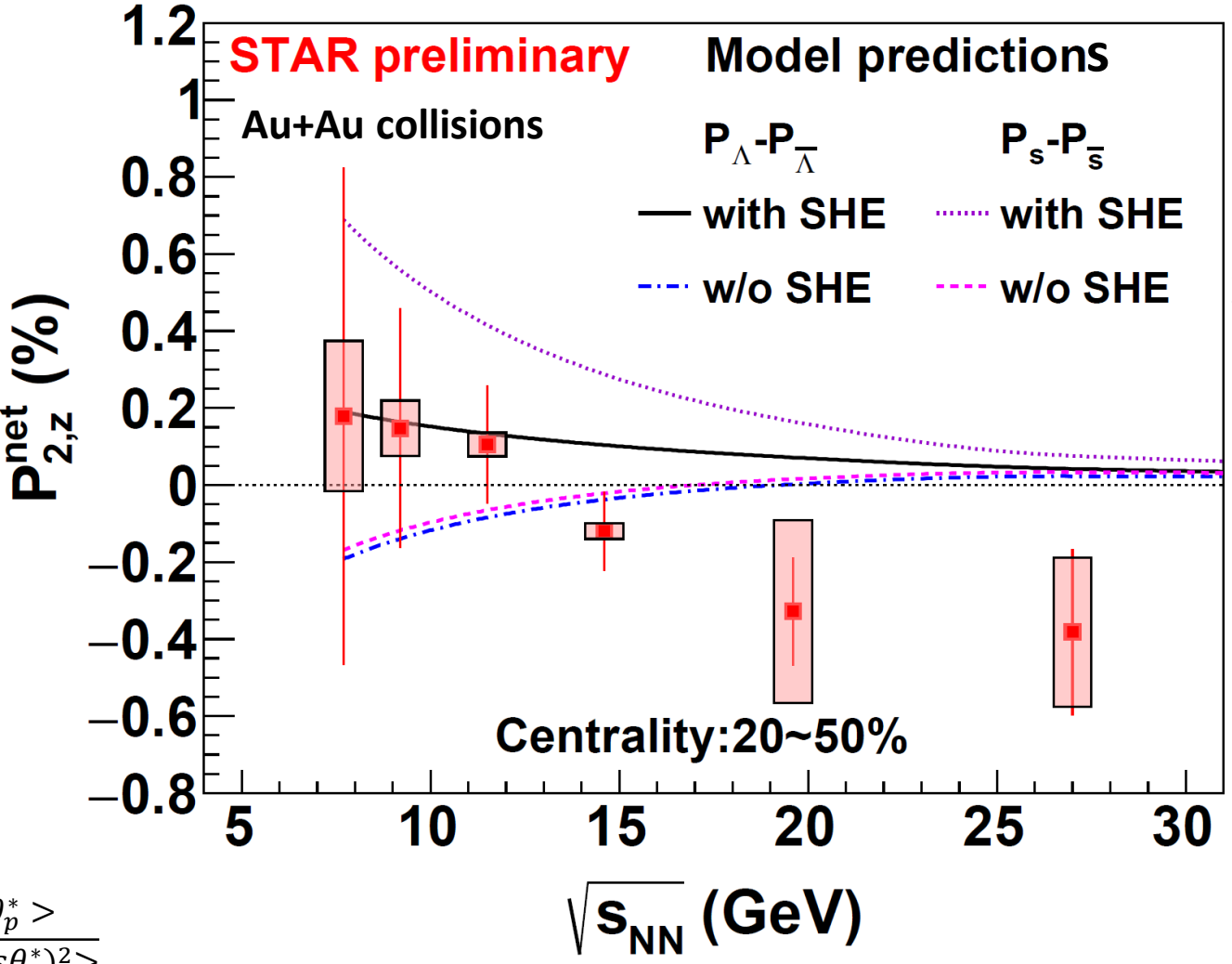
$P_{2,z}^{net} = < P_z^{\Lambda-\bar{\Lambda}} \sin(2\phi_\Lambda - 2\Psi_2) >$



Model prediction:

- Monotonic energy dependence of net local polarization of $P_{2,z}^{net}$
- SHE may change the sign of $P_{2,z}^{net}$ at high baryon density region

Baryonic SHE



$p_t \in [0.5,5]$ GeV/c

27 GeV: |y|<1.0

Other energies: |y|<1.5

$$P_z = \frac{< cos\theta_p^* >}{\alpha_H < (cos\theta_p^*)^2 >}$$

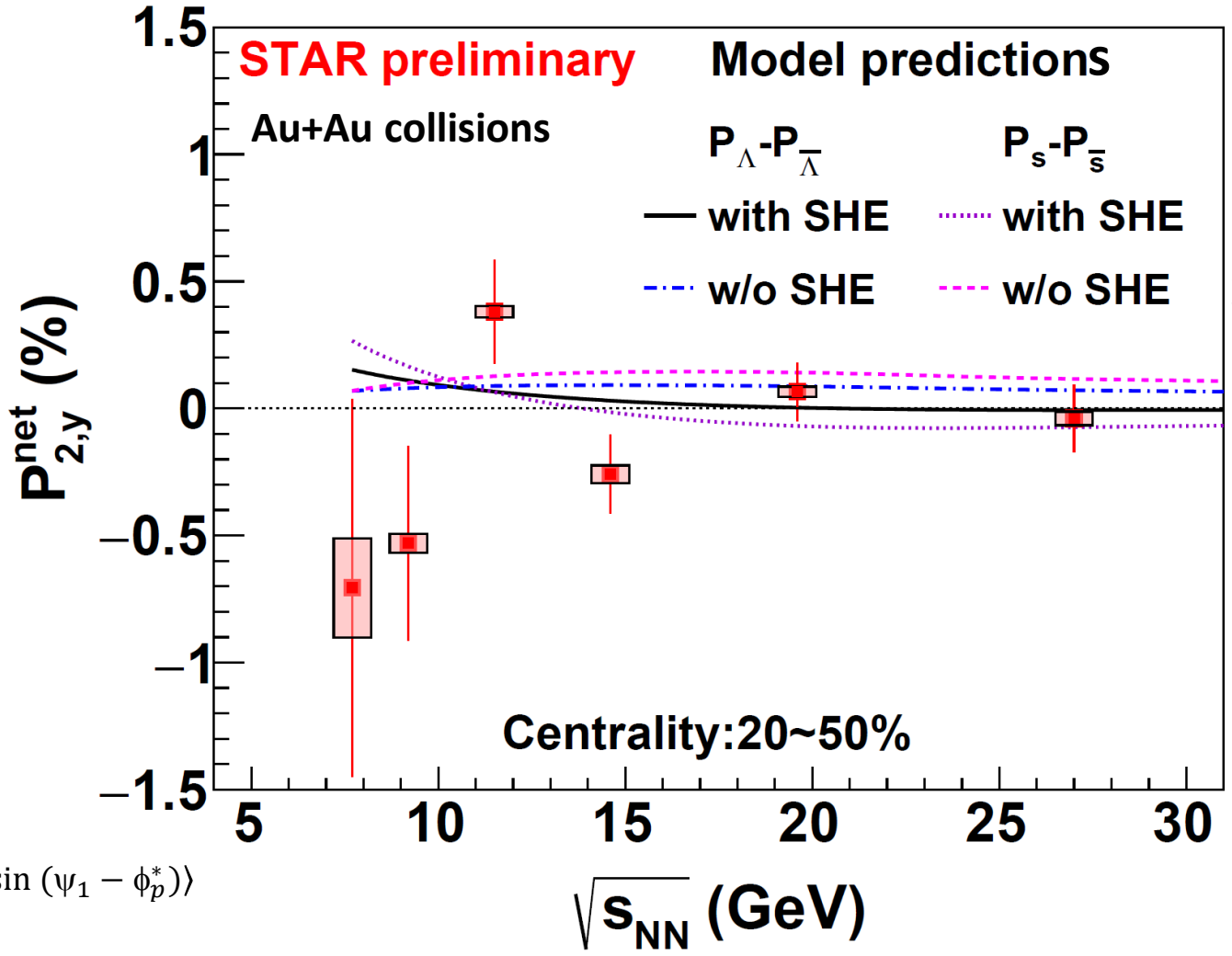
$$P_z^{net} = P_z(\Lambda) - P_z(\bar{\Lambda})$$

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

- **Hints of sign change with decreasing energy**

Model: B Fu et al., arXiv:2201.12970v1

Baryonic SHE



$p_t \in [0.5,5]$ GeV/c

27 GeV: |y|<1.0

Other energies: |y|<1.5

$$P_y = \frac{8}{\pi\alpha_\Lambda}\frac{1}{R^{(1)}_{EP}}\langle \sin(\psi_1 - \phi^*_p)\rangle$$

$$P_y^{net} = P_y(\Lambda) - P_y(\bar\Lambda)$$

$$P^{net}_{2,y} = -\langle P_y^{net}\cos(2\Delta\phi)\rangle$$

- **Hints of sign change with decreasing energy**

Model: B Fu et al., arXiv:2201.12970v1

Summary

- ✓ **Global polarization of Λ and $\bar{\Lambda}$ in Au+Au collisions at 7.7, 9.2, 11.5, 14.6 GeV (BES-II)**
  - **Global polarization of Λ and $\bar{\Lambda}$ may be unaffected by the magnetic field**
- ✓ **Local polarization of Λ and $\bar{\Lambda}$ in Au+Au collisions at 7.7, 9.2, 11.5, 14.6, 19.6, 27 GeV (BES-II)**
  - **Hints of sign change of $P_{2,z}$ at 7.7 GeV is observed**
  - **Monotonic energy dependence in $P_{2,y}$ of Λ with the decreasing energy**
- ✓ **Baryonic SHE**
  - **First study of baryonic spin Hall effect by measuring net local polarization $P^{net}_{2,z(y)}$ in Au+Au from 7.7 to 27 GeV**
  - **Hints of sign change of $P^{net}_{2,z(y)}$**
  - ➢ **Analysis of Au+Au collisions at lower energies underway**

Thank you for your attention !