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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Abstract. We report the measurements of Λ hyperons' global and local spin polarization from second phase of the RHIC Beam Energy Scan (BES-II) in Au+Au collisions at $\sqrt{s_{NN}}$= 7.7 - 27 GeV. Global polarization measurements of $\bar{\Lambda}$ and Λ show no significant differences, offering insights into the late-stage evolution of the magnetic field. The new measurements of the local polarization of Λ perpendicular to the reaction plane ($P_{2,y}$) shows a monotonic increase with decreasing energy, while the component along the beam direction ($P_{2,z}$) for both Λ and $\bar{\Lambda}$ is small in magnitude with no strong energy dependence. The net local polarization observable, $P^{net}_{2,y} = \langle P_{2,y}(\Lambda) - P_{2,y}(\bar{\Lambda})\rangle$ and $P^{net}_{2,z} = \langle P_{2,z}(\Lambda) - P_{2,z}(\bar{\Lambda})\rangle$ designed to probe baryonic spin Hall effect, is consistent with zero with large uncertainty.

1 Introduction

Relativistic heavy-ion collisions provide an excellent opportunity to examine the property of the quark-gluon plasma (QGP) in the laboratory. In non-central heavy-ion collisions, the system carries large initial orbital angular momentum. Subsequently, the quarks and the final state hadrons with non-zero spin could be polarized along global angular momentum due to spin-orbit coupling [1, 2], which is known as global polarization. Due to parity violation in the decay of a Λ hyperon, the daughter proton tends to emit along the spin direction of its parent, making Λs excellent candidates for measuring polarization in heavy-ion collisions.

The global polarization is determined by $\left\langle P_y \right\rangle = \frac{8}{\pi\alpha_\Lambda}\frac{1}{R^{(1)}_{EP}}\left\langle \sin(\Psi_1 - \phi^*_p)\right\rangle$, where α_Λ is the decay parameter, Ψ_1 is the first-order of event plane angle and $R^{(1)}_{EP}$ its resolution, and ϕ^*_p is the azimuthal angle of baryon (proton) in Λ's rest frame. The STAR Collaboration carried out the polarization measurement of Λ hyperons in Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV, where the signal was consistent with zero within statistical uncertainties [3]. However, the data from first phase of the RHIC Beam Energy Scan (BES-I) provided the first evidence of non-zero global polarization for Λ hyperons [4, 5]. It supports the presence of vortices inside QGP and is considered as one of the important milestones in heavy-ion collisions. The BES-I results also show hints of a difference in global polarization between $\bar{\Lambda}$ and Λ which is expected from the effect of the late-stage magnetic field sustained by the QGP. Subsequently,

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global polarization has been measured by different collaborations in different systems from a few GeV to TeV.

The distribution of polarization as a function of azimuthal angle is referred to as local polarization. Local polarization can be measured with the polarization axis perpendicular to the reaction plane (along the out-of-plane, $P_{2,y}$) and along the reaction plane (along in-plane or beam-axis, $P_{2,z}$), and these components are defined as follows:

$$\left\langle P_{2,y} \right\rangle = \frac{8}{\pi\alpha_{\Lambda}} \frac{1}{R_{EP}^{(1)}} \left\langle \sin(\Psi_1 - \phi_p^*) \cos(2\phi_{\Lambda} - 2\Psi_2) \right\rangle, \tag{1}$$

$$\langle P_{2,z} \rangle = \frac{\left\langle \cos\theta_p^* \sin(2\phi_{\Lambda} - 2\Psi_2) \right\rangle}{\alpha_{\Lambda} \left\langle (\cos\theta_p^*)^2 \right\rangle}, \tag{2}$$

where ϕ_p^* presents the azimuthal angle of daughter baryon in the mother particle's rest frame, Ψ_2 is the second-order of event plane angle, ϕ_{Λ} is the azimuthal angle of Λ and $\langle(\cos\theta_p^*)^2\rangle$ is the azimuthal angle correction factor.

The recently predicted baryonic spin Hall effect (SHE) [7–9] in heavy-ion collisions describes the splitting of particles with spin up and spin down, driven by the gradient of the baryon chemical potential, similar to how an electric field induces the traditional spin Hall effect in condensed matter physics. The net local polarization, defined as the polarization difference between Λ and $\bar{\Lambda}$, denoted by $P_{2,y,z}^{net} = \langle P_{2,y,z}(\Lambda)\rangle - \langle P_{2,y,z}(\bar{\Lambda})\rangle$, is predicted to be a sensitive probe for SHE.

2 Analysis

In these proceedings, we analyzed the global and local polarization of Λ and $\bar{\Lambda}$ in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 9.2, 11.5, 14.6, 19.6 and 27 GeV, based on datasets from the second phase of the RHIC Beam Energy Scan (BES-II). The first-order event plane, Ψ_1 is reconstructed with the upgraded Event Plane Detector (EPD). The second-order event plane, Ψ_2, is determined by the Time of Projection Chamber (TPC) detector. The particle identification is done with the TPC and Time-of-Flight (ToF) detector. The invariant mass spectra of Λ and $\bar{\Lambda}$ are reconstructed with the decay channels of $\Lambda \longrightarrow p + \pi^-$ and $\bar{\Lambda} \longrightarrow \bar{p} + \pi^+$. The background is evaluated by fitting the side band with the second order polynomial function. Then the ratio of signal to background (f^{sig}) could be obtained. The distribution of $\langle \sin(\Psi_1 - \phi_p^*)\rangle$ and $\langle P_z \sin(2\Delta\phi)\rangle$ (where $\Delta\phi = \phi_{\Lambda} - \Psi_2$) as functions of Λ invariant mass as shown in Fig. 1, are fitted with the expression $\langle P_H\rangle^{obs} = f^{Sig}(M_{inv})\langle P_H\rangle^{Sig} + (1 - f^{Sig}(M_{inv}))\langle P_H\rangle^{Bg}$ to extract the signal of polarization after event plane resolution correction.

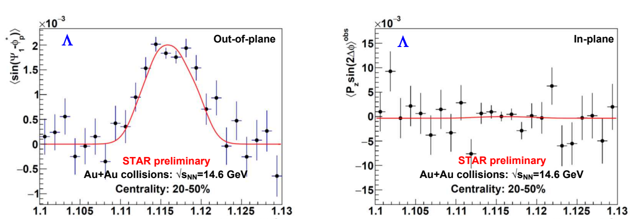

Figure 1. $\langle \sin(\Psi_1 - \phi_p^*)\rangle$ and $\langle P_z \sin(2\Delta\phi)\rangle^{obs}$ as functions of invariant mass of Λ in Au+Au collisions at $\sqrt{s_{NN}} = 14.6$ GeV. Only statistical uncertainties are shown in the plots.

3 Results and discussion

The left and right panels of Fig. 2 present the comparison of Λ and $\bar{\Lambda}$ global polarization and their difference, respectively. The global polarization increases as the energy decreases, and the results from BES-I and BES-II are consistent within uncertainties. The high-precision BES-II results show no significant splitting between Λ and $\bar{\Lambda}$. Upper limit on the late-stage magnetic field at $\sqrt{s_{NN}}$ = 19.6 and 27 GeV, are estimated to be $B < 9.2 \times 10^{12}$ T and $B < 1.4 \times 10^{13}$ T, respectively [6]. The left and right panels of Fig. 3 present the local polarization $P_{2,y}$ and $P_{2,z}$ for Λ and $\bar{\Lambda}$ as a function of energy. For $P_{2,y}$, the polarization of Λ hyperons shows a clear increase with decreasing energy, while no distinct trend is observed for $\bar{\Lambda}$ within the current uncertainties. For $P_{2,z}$, both Λ and $\bar{\Lambda}$ exhibit small magnitudes and no energy dependence. The left and right panels of Fig. 4 present the net Λ polarization, $-P^{net}_{2,y}$ and $P^{net}_{2,z}$, as a function of collision energy, an observable proposed to probe the SHE. [1] No significant energy dependence has been observed for either $-P^{net}_{2,y}$ or $P^{net}_{2,z}$. However, $P^{net}_{2,z}$ shows non-trivial trends with hints of a sign change, albeit with large uncertainties. In previous studies, global polarization could be explained by thermal vorticity, and the sign of local polarization along the beam direction could be captured by incorporating shear-induced polarization into the models [8, 10]. However, the new results for Λ hyperons could not be described by current models. More studies are needed to further understand Λ polarization, especially at BES energies.

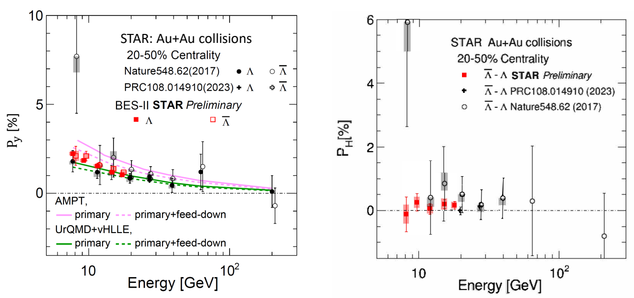

Figure 2. (Colour online) The Λ and $\bar{\Lambda}$ global polarization P_y (left panel) and their difference $P_H = P_y(\bar{\Lambda}) - P_y(\Lambda)$ (right panel) as a function of energy in Au+Au collisions. The points are data. Vertical line and shaded boxes are statistical and systematic uncertainties.

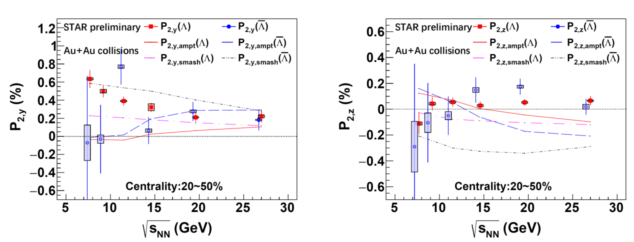

Figure 3. (Colour online) The Λ and $\bar{\Lambda}$ local polarization $P_{2,y}$ (left pannel) and $P_{2,z}$ (right panel) as a function of energy in Au+Au collisions. The red and blue points are data of Λ and $\bar{\Lambda}$, respectively. Vertical line and shaded boxes are statistical and systematic uncertainties.

4 Summary

In a summary, we report the collision energy dependence of global and local spin polarization of Λ and $\bar{\Lambda}$ hyperons, as well as their difference in Au+Au collisions at 7.7, 9.2, 11.5, 14.6, 19.6 and 27 GeV from the second phase of RHIC beam energy scan. With the high precision

[1] In the presentation at SQM2024, the results for $P^{net}_{2,y} = P^{\Lambda}_{2,y} - P^{\bar{\Lambda}}_{2,y}$ were incorrectly plotted with a factor of -1 multiplied to the data. It is corrected in these proceedings.

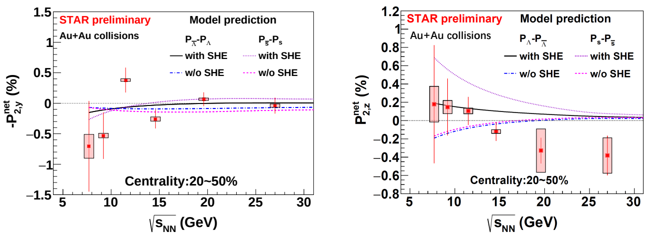

Figure 4. (Colour online) The net local polarization $-P_{2,y}^{net}$ (left panel) and $P_{2,z}^{net}$ (right panel) as a function of energy in Au+Au collisions. The red solid squares are data. Vertical line and shaded boxes are statistical and systematic uncertainties.

measurements, no splitting of global polarization between Λ and $\bar{\Lambda}$ has been observed. The upper limit of late stage magnetic field at 19.6 and 27 GeV have been estimated. The local polarization of Λ and $\bar{\Lambda}$ ($P_{2,y,z}$) are measured for the first time at RHIC BES energies. A monotonic energy dependence of Λ local polarization along out-of-plane direction has been observed. The net local polarization perpendicular to the reaction plane and along the beam directions have been measured. The newly proposed mechanism of the baryonic spin Hall effect has been probed using the local polarization difference between Λ and $\bar{\Lambda}$, and no indication of SHE is observed within the current precision. However, it brings challenges to the hydrodynamic models to describe $P_{2,y}$ and $P_{2,z}$ simultaneously with or without SHE. More theoretical input is needed to understand Λ polarization at high baryon densities.

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