

# $\phi$ Meson Spin Alignment and the Azimuthal Angle Dependence of $\Lambda$ ( $\bar{\Lambda}$ ) Polarization in Au+Au collisions at RHIC

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**Abstract.** Initial large global angular momentum in non-central relativistic heavy-ion collisions can produce strong vorticity, and through the spin-orbit coupling, causes the spin of particles to align with the system's global angular momentum. We present the azimuthal angle dependent (relative to the reaction plane) polarization for  $\Lambda$  and  $\bar{\Lambda}$  in mid-central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. We also present the  $\phi$  meson spin alignment parameter,  $\rho_{00}$  in Au+Au collisions at  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4$  and 200 GeV. The implications of the results are discussed.

## 1 Introduction

High-energy relativistic heavy-ion collisions at Relativistic Heavy Ion Collider (RHIC) produce a strongly interacting, hot and dense medium known as Quark Gluon Plasma (QGP) [1]. The initial orbital angular momentum, associated with the receding spectators, is large ( $\sim 1000\hbar$ ) in non-central collisions may be transferred to quarks through spin-orbit coupling [2–4], which is then transmitted to final-state hadrons and is detectable through the  $\Lambda$ ( $\bar{\Lambda}$ ) polarization and  $\phi$  meson spin alignment. Therefore, measurements of the polarization of the particles produced in heavy-ion collisions can provide new insights into the initial conditions and evolution of the QGP [5, 6].

The STAR experiment at RHIC has observed for the first time a significant alignment between the angular momentum of the medium produced in non-central collision and the spin of  $\Lambda$ ( $\bar{\Lambda}$ ) hyperons ( $J=1/2$ ), revealing that the matter produced in heavy-ion collisions is by far the most vortical system ever observed [7]. Such vorticity is expected to be maximal at the equator and due to the low viscosity of the system the vorticity may not be efficiently propagated to the poles. This can lead to a larger in-plane than out-of-plane polarization for hyperons. The study of the azimuthal angle dependence of hyperon polarization can help us in understanding transport properties of the system and shed light on dynamics in a highly vortical, low viscous environment.

The strong vorticity, when acting together with particle production mechanisms (e.g. coalescence and hadronization), may also influence the spin alignment of  $\phi$  mesons ( $J=1$ ). The magnitude and the transverse momentum ( $p_T$ ) dependence of the spin alignment are expected to be sensitive to different hadronization scenarios [4]. Thus the  $\phi$  meson spin alignment also probes the particle production mechanisms.

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## 2 Method

The global polarization of spin- $\frac{1}{2}$  hyperons can be determined from the angular distribution of hyperon decay products relative to the system orbital momentum  $\mathbf{L}$  [8]:

$$\frac{dN}{d \cos \theta^*} = \frac{1}{2}(1 + \alpha_H P_H \cos \theta^*) \quad (1)$$

where  $P_H$  is the hyperon global polarization,  $\alpha_H$  is the hyperon decay parameter ( $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642$ ), and  $\theta^*$  is the angle in the hyperon rest frame between the system orbital momentum  $\mathbf{L}$  and the three-momentum of the baryon daughter from the hyperon decay. Averaged over all phase space, we extract the average projection of the polarization on  $\mathbf{L}$ . It is shown that [9]:

$$\bar{P}_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\phi^* - \Psi_{EP}) \rangle}{R_{EP}} \quad (2)$$

where  $\Psi_{EP}$  is the angle of the first-order event plane that estimates the reaction plane angle  $\Psi_{RP}$ ,  $\phi^*$  azimuthal angle of the daughter proton (antiproton) in the  $\Lambda(\bar{\Lambda})$  frame,  $R_{EP} = \langle \cos(\Psi_{RP} - \Psi_{EP}) \rangle$  is the event plane resolution.

The spin alignment for a spin-1 vector meson is described by a spin-density matrix  $\rho$ ,  $3 \times 3$  Hermitian matrix with a unit trace. A deviation of the diagonal elements  $\rho_{mm}$  ( $m = -1, 0, 1$ ) from  $1/3$  signals a net spin alignment. Because vector mesons decay strongly, the diagonal elements  $\rho_{-1-1}$  and  $\rho_{11}$  are degenerate and  $\rho_{00}$  is the only independent observable. It can be determined from the angular distribution of the decay products that [10]:

$$\frac{dN}{d \cos \theta^*} = N_0 \times [(1 - \rho_{00}) + (3\rho_{00} - 1) \cos^2 \theta^*] \quad (3)$$

where  $N_0$  is the normalization and  $\theta^*$  is the angle between the system orbital momentum  $\mathbf{L}$  and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

This analysis use charged particles reconstructed by the Time Projection Chamber (TPC) and matched to the Time Of Flight (TOF) detector near mid-rapidity ( $|\eta| < 1.0$ ). We reconstruct  $\Lambda(\bar{\Lambda})$  and  $\phi$  meson's invariant masses through their decay channels:  $\Lambda(\bar{\Lambda}) \rightarrow p + \bar{\pi}(\bar{p} + \pi)$  and  $\phi \rightarrow K^+ + K^-$ , respectively. Topological and kinematic cuts are applied to reduce the combinatorial background. In the study of  $\Lambda(\bar{\Lambda})$  polarization, the direction of  $\mathbf{L}$  is determined by the first-order event plane reconstructed with information from the Shower Maximum Detectors at Zero Degree Calorimeter. In the study of  $\phi$  spin alignment, the direction of  $\mathbf{L}$  is determined by the second-order event plane reconstructed with TPC tracks. For  $\Lambda(\bar{\Lambda})$  analysis, the results are based on 440 M and 1000 M minimum bias events taken in years 2011 and 2014. For  $\phi$  spin alignment analysis, the results are based on 118 M(39 GeV), 55 M(62.4 GeV) minimum bias events taken in 2010 and 29 M(19.6 GeV), 58 M(27 GeV), 375 M(200 GeV) minimum bias events taken in 2011.

## 3 Results

### 3.1 Azimuthal angle dependence of $\Lambda(\bar{\Lambda})$ polarization

The left panel of Figure 1 shows the  $\Lambda$  and  $\bar{\Lambda}$  polarization( $P_H$ ) as a function of  $\phi - \Psi_{obs}$  at midrapidity in 20-50% central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The  $\phi$  here is the azimuthal angle of  $\Lambda(\bar{\Lambda})$ . The  $P_H$  from the off-peak for  $\Lambda$  and  $\bar{\Lambda}$  are consistent with zero, which is as expected and could be served as a consistency check. The  $P_H$  from the mass peak for  $\Lambda$  and  $\bar{\Lambda}$  decreases with increasing  $\phi - \Psi_{obs}$ . This feature is the same for both  $\Lambda$  and  $\bar{\Lambda}$ , and there is no significant difference in values

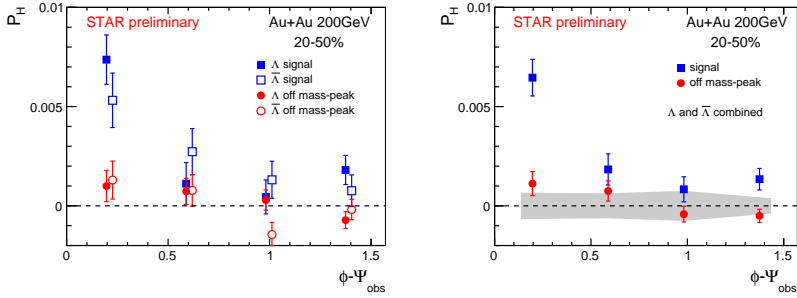


Figure 1: (Color online) Left panel:  $P_H$  for  $\Lambda$  and  $\bar{\Lambda}$  are plotted as a function of  $\phi - \Psi_{obs}$  in 20-50% central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. Only the statistical errors are plotted. Right panel: Combined  $P_H$  between  $\Lambda$  and  $\bar{\Lambda}$ , are plotted as a function of  $\phi - \Psi_{obs}$  in 20-50% central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The systematic uncertainties are shown with shadowed band.

between  $\Lambda$  and  $\bar{\Lambda}$ . Because  $\Lambda$  and  $\bar{\Lambda}$  have opposite signs in intrinsic magnetic moments, it is expected that a magnetic field will enhance (reduce) the polarization for  $\bar{\Lambda}$  ( $\Lambda$ ). Within statistics our data shows that such effect is not visible for Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. This may be due to the short lifetime of magnetic field which gives little time for particles to align their spin, and/or the late hyperon production time at which moment the magnetic field diminished. The finite averaged  $P_H$  over four bins is  $\sim 0.2\%$  which is consistent with STAR's previous published result [7].

The right panel shows the combined  $P_H$  between  $\Lambda$  and  $\bar{\Lambda}$  as a function of  $\phi - \Psi_{obs}$  at mid-rapidity in 20-50% central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The significance of  $\Delta P_H$ , for  $\Lambda$  and  $\bar{\Lambda}$  combined, between  $\phi - \Psi_{obs}$  bin of  $[0, \pi/8]$  and  $[3\pi/8, \pi/2]$  is  $4.7\sigma$ . The larger in-plane than out-of-plane polarization is consistent with the picture of maximum vorticity in the equator and low viscosity of the system. Please note that although  $P_H$  has been corrected for the event plane resolution, when presented as a function of  $\phi - \Psi_{obs}$ . The smearing correction of  $\phi - \Psi_{obs}$  bins is not applied yet.

### 3.2 $\phi$ meson spin alignment

The left panel of Figure 2 shows  $\rho_{00}$  as a function of  $p_T$  in 20-60% central Au+Au collisions at  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4$  and 200 GeV. No clear  $p_T$  dependence has been found within currently large systematic uncertainties. The systematic uncertainties are dominated by the residual background estimation and  $\rho_{00}$  extraction procedure, and are under further investigation.

The right panel shows  $\rho_{00}$  for  $\phi$  meson within  $0.4 < p_T < 3.0$  GeV as a function of beam energy for 20-60% central Au+Au collisions [11]. The central values of  $\rho_{00}$  are slightly larger than  $1/3$  while the large systematic uncertainties prevents us from making definite conclusions. Note that the efficiency corrections due to kinematic cuts have not been applied to the data.

## 4 Summary

The measurement of the  $\Lambda$  and  $\bar{\Lambda}$  polarization as a function of azimuthal angle relative to the reaction plane is presented. The difference of  $P_H$ , for  $\Lambda$  and  $\bar{\Lambda}$  combined, between the most in-plane bin  $[0, \pi/8]$  and the most out-of-plane bin  $[3\pi/8, \pi/2]$  is  $4.7\sigma$ . The data are consistent with the picture of a low

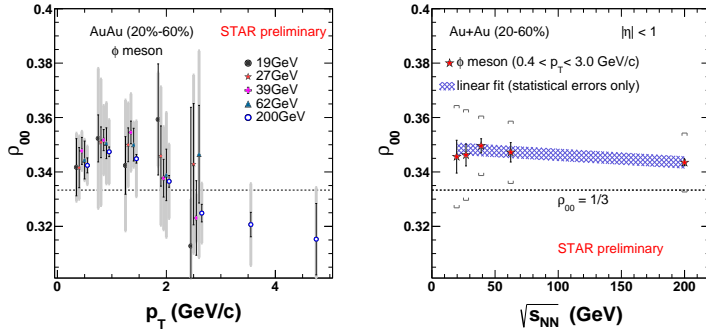


Figure 2: (Color online) Left panel: The  $\rho_{00}$  for  $\phi$  meson are plotted as a function of  $p_T$  in 20-60% central Au+Au collisions at  $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4$  and 200 GeV. The gray shadow indicate the systematic uncertainties. Right panel: The  $\rho_{00}$  for  $\phi$  meson within  $0.4 < p_T < 3.0$  GeV are plotted as a function of beam energy for 20-60% central Au+Au collisions. The square brackets indicate the systematic uncertainties. The shadow band is a linear fit for these points. The acceptance and efficiency corrections have not been applied.

viscosity system with maximum vorticity at the equator. The measurement of  $\phi$  meson spin alignment at  $\sqrt{s_{NN}} = 19.6-200$  GeV is shown. Within current large systematics errors,  $\phi$  spin alignment signal  $\rho_{00}$  shows little beam energy dependence and non-significant  $p_T$  dependence.

## 5 Acknowledgments

We thanks the RHIC Operations Group and RCF at BNL, and the NERSC Center at LBNL. B. Tu is supported by the China Scholarship Council (CSC). This work was supported in part by the MoST of China 973-Project No. 2015CB856901, NSFC under Grants No. 11521064.

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