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## Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

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The first evidence of spin alignment of vector mesons ( $K^{*0}$  and  $\phi$ ) in heavy-ion collisions at the Large Hadron Collider (LHC) is reported. The spin density matrix element  $\rho_{00}$  is measured at midrapidity ( $|y| < 0.5$ ) in Pb-Pb collisions at a center-of-mass energy ( $\sqrt{s_{NN}}$ ) of 2.76 TeV with the ALICE detector.  $\rho_{00}$  values are found to be less than 1/3 (1/3 implies no spin alignment) at low transverse momentum ( $p_T < 2$  GeV/c) for  $K^{*0}$  and  $\phi$  at a level of  $3\sigma$  and  $2\sigma$ , respectively. No significant spin alignment is observed for the  $K_S^0$  meson (spin = 0) in Pb-Pb collisions and for the vector mesons in  $pp$  collisions. The measured spin alignment is unexpectedly large but qualitatively consistent with the expectation from models which attribute it to a polarization of quarks in the presence of angular momentum in heavy-ion collisions and a subsequent hadronization by the process of recombination.

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Ultrarelativistic heavy-ion collisions create a system of deconfined quarks and gluons, called the quark-gluon plasma (QGP) [1–3] and provide the opportunity to study its properties. In collisions with nonzero impact parameter, a large angular momentum of  $O(10^7)\hbar$  [4] and magnetic field of  $O(10^{14})$  T [5] are also expected. While the magnetic field is short lived (a few fm/c), the angular momentum is conserved and could affect the system throughout its evolution. Experimental observables like correlations in azimuthal angle [6,7] could be used to study the influence of these initial conditions on the properties and the dynamical evolution of the QGP and its subsequent hadronization.

Spin-orbit interactions have wide observable consequences in several branches of physics [8–10]. In the presence of a large angular momentum, the spin-orbit coupling of quantum chromodynamics (QCD) could lead to a polarization of quarks followed by a net-polarization of vector mesons ( $K^{*0}$  and  $\phi$ ) [11–15] along the direction of the angular momentum.

The spin state of a vector meson is described by a  $3 \times 3$  Hermitian spin-density matrix [15]. Its trace is 1 and  $\rho_{11}$  and  $\rho_{-1-1}$  cannot be measured separately in two-body decays to pseudoscalar mesons. Consequently, there is only one independent diagonal element,  $\rho_{00}$ . The elements of the spin-density matrix can be studied by measuring the

angular distributions of the decay products of vector mesons with respect to a quantization axis. Here two different quantization axes are used: (i) a vector perpendicular to the production plane (PP) of the vector meson and (ii) the normal to the reaction plane (RP) of the system. The PP is defined by the flight direction of the vector meson and the beam direction.

The spin-density matrix element  $\rho_{00}$  is determined from the distribution of the angle  $\theta^*$  between the kaon decay daughter and the quantization axis in the decay rest frame [16,17],

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

$\rho_{00}$  is 1/3 in the absence of spin alignment and the angular distribution in Eq. (1) is uniform. The experimental signature of spin alignment is a nonuniform angular distribution ( $\rho_{00} \neq 1/3$ ).

The direction of the angular momentum in noncentral heavy-ion collisions is perpendicular to the reaction plane (subtended by the beam axis and impact parameter) [12]. The spin-orbit interaction is expected to lead to spin alignment with respect to the RP. The reaction plane orientation cannot be measured directly, but is estimated from the final state distributions of particles. This experimentally measured plane is called the event plane (EP) [18]. The deviation of the EP with respect to the RP is corrected using the EP resolution ( $R$ ) and observed  $\rho_{00}^{\text{obs}}$  [19],

$$\rho_{00} = \frac{1}{3} + \left( \rho_{00}^{\text{obs}} - \frac{1}{3} \right) \frac{4}{1 + 3R}. \quad (2)$$

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There are specific qualitative predictions for the spin alignment effect [13]: (a)  $\rho_{00} > 1/3$  if the hadronization of a polarized parton proceeds via fragmentation and less than  $1/3$  for hadronization via recombination, (b)  $\rho_{00}$  is expected to have a smaller deviation from  $1/3$  for both central (impact parameter  $\lesssim 3$  fm) and peripheral (impact parameter  $\gtrsim 11$  fm) heavy-ion collisions, and a maximum deviation for mid-central collisions, where the angular momentum is also maximal, (c) the  $\rho_{00}$  value is expected to have maximum deviation from  $1/3$  at low  $p_T$  and reach the value of  $1/3$  at high  $p_T$  in the recombination scenario, and (d) the effect is expected to be larger for  $K^{*0}$  compared to  $\phi$  due to their constituent quark composition. The initial large magnetic field might also affect the  $\rho_{00}$  values [15]. This leads to  $\rho_{00} > 1/3$  for neutral and  $\rho_{00} < 1/3$  for charged vector mesons. Hence magnetic field and angular momentum could have opposite effects on electrically neutral  $K^{*0}$ ,  $\phi$ . All of these features are probed for  $K^{*0}$  and  $\phi$  mesons in Pb-Pb collisions presented in this Letter. As a cross check, a control measurement is carried out using  $pp$  collisions, which do not possess large initial angular momentum, and the same analysis is done in Pb-Pb collisions for  $K_S^0$  meson, which has zero spin. In addition, the measurements are carried out by randomizing the directions of the event (RNDEP) and production planes.

The analyses are carried out using 43 million minimum bias  $pp$  collisions at  $\sqrt{s} = 13$  TeV, taken in 2015 and 14 million minimum bias Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, collected in 2010. The minimum bias event selection in Pb-Pb collisions require at least one hit in any of V0A, V0C, and silicon pixel detectors while in  $pp$  collisions at least one hit in both V0A and V0C is required. The events are further required to have a primary vertex position within  $\pm 10$  cm of the detector center along the beam axis. The events were classified by collision centrality classes based on the amplitude measured in the V0 counters [20]. The measurements are performed at mid-rapidity ( $|y| < 0.5$ ) as a function of  $p_T$  and are reported for  $pp$  collisions as well as for different centrality classes in Pb-Pb collisions. The  $K_S^0$  analysis is performed only for Pb-Pb collisions in the 20–40% centrality class which corresponds to the top 20–40% of V0 amplitude distribution. The details of the ALICE detector, trigger conditions, centrality selection, and second order event plane estimation using the V0 detectors at forward rapidity, can be found in [20–23]. The  $K^{*0}$  and  $\phi$  candidates are reconstructed via their decays into charged  $K\pi$  and  $KK$  pairs, respectively, while the  $K_S^0$  is reconstructed via its decay into two charged pions. The time projection chamber (TPC) [24] and time-of-flight (TOF) detector [25] are used to identify the decay products of these mesons via specific ionization energy loss and time-of-flight measurements, respectively. The  $K^{*0}$  and  $\phi$  yields are determined via the invariant mass technique [26–28]. The background coming from combinatorial pairs and misidentified particles is

removed by constructing the invariant mass distribution from so-called mixed events for the  $K^{*0}$  and  $\phi$  [26,27]. The combinatorial background for the  $K_S^0$  candidates is significantly reduced by selecting the distinctive V-shaped decay topology [28].

The invariant mass distributions are fitted with a Breit-Wigner and Voigtian (convolution of Breit-Wigner and Gaussian distributions) function for the  $K^{*0}$  and  $\phi$  signals, respectively, along with a second-order polynomial that describes the residual background [26,27]. Extracted yields are then corrected for the reconstruction efficiency and acceptance in each  $\cos\theta^*$  and  $p_T$  bin [26,27]. The reconstruction efficiency is determined from Monte Carlo simulations of the ALICE detector response based on GEANT3 simulation [26,27]. The signal extraction procedures for the vector mesons and  $K_S^0$  are identical to those used in earlier publications reporting the  $p_T$  distribution of the mesons [26–28]. The mass peak positions and widths of the resonances across all the  $\cos\theta^*$  bins for various  $p_T$  intervals in  $pp$  collisions and in different centrality classes of Pb-Pb collisions are consistent with those obtained from earlier analyses [26–28] and no significant dependence on  $\cos\theta^*$  is seen. The resulting efficiency and acceptance corrected  $dN/d\cos\theta^*$  distributions for selected  $p_T$  intervals in minimum bias  $pp$  collisions and in 10–50% central Pb-Pb collisions are shown in Fig. 1. These distributions are fitted with the functional form given in Eq. (1) to determine  $\rho_{00}$  for each  $p_T$  bin in  $pp$  and Pb-Pb collisions. For the EP results, the resolution values  $R$  are 0.71, 0.53, 0.72, 0.66, and 0.40 for 10–50%, 0–10%, 10–30%,

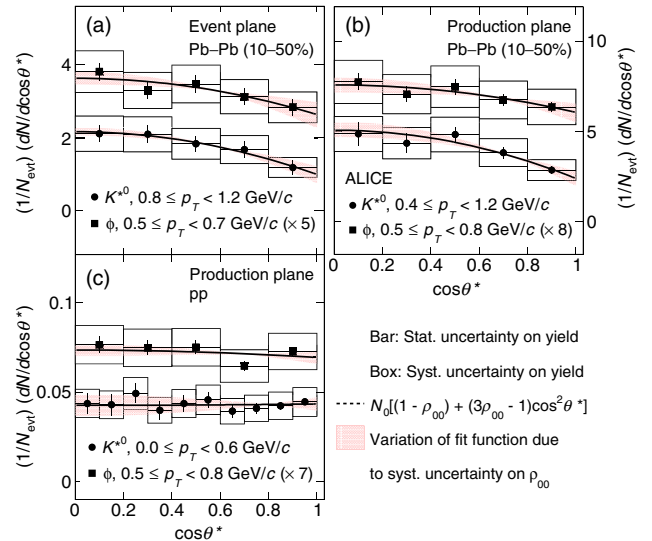


FIG. 1. Angular distribution of the decay daughter in the rest frame of the meson with respect to the quantization axis at  $|y| < 0.5$  for  $pp$  collisions at  $\sqrt{s} = 13$  TeV and Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. Panels (a) and (b) show results for  $K^{*0}$  and  $\phi$  with respect to EP and PP. Panel (c) is the results for vector mesons in  $pp$  collisions with respect to PP.

30–50%, and 50–80% collision centralities, respectively [29].

There are three main sources of systematic uncertainties in the measurements of the angular distribution of vector meson decays. (i) Meson yield extraction: this contribution is estimated by varying the fit ranges for the yield extraction, the normalization range for the signal + background and background invariant mass distributions, the procedure to integrate the signal function to get the yields, and by leaving the width of the resonance peak free or keeping it fixed to the PDG value as discussed in Refs. [26,27]. The uncertainties for  $\rho_{00}$  is at a level of 12(8)% at the lowest  $p_T$  and decrease with  $p_T$  to 4(3)% at the highest  $p_T$  studied for the  $K^{*0}(\phi)$ . (ii) Track selection: this contribution includes variations of the selection on the distance of closest approach to the collision vertex, the number of crossed pad rows in the TPC [24], the ratio of found clusters to the expected clusters, and the quality of the track fit. The systematic uncertainties for  $\rho_{00}$  are 14(6)% at the lowest  $p_T$  and about 11(5)% at the highest  $p_T$  for  $K^{*0}(\phi)$ . (iii) Particle identification: this is evaluated by varying the particle identification criteria related to the TPC and TOF detectors. The corresponding uncertainty is 5(3)% at the lowest  $p_T$  and about 4(4.5)% at the highest  $p_T$  studied for  $K^{*0}(\phi)$ . Systematic uncertainties due to different variations are considered as uncorrelated and the total systematic uncertainty on  $\rho_{00}$  is obtained by adding all the contributions in quadrature. Several consistency checks are carried out and details can be found in the Supplemental Material [17]. The final measurement is reported for the average yield of particles ( $K^{*0}$ ) and antiparticles ( $\bar{K}^{*0}$ ) as results for  $K^{*0}$  and  $\bar{K}^{*0}$  were consistent.

Figure 2 shows the measured  $\rho_{00}$  as a function of  $p_T$  for  $K^{*0}$  and  $\phi$  mesons in  $pp$  collisions and Pb-Pb collisions, along with the measurements for  $K_S^0$  in Pb-Pb collisions. In mid-central (10–50%) Pb-Pb collisions,  $\rho_{00}$  is below 1/3 at the lowest measured  $p_T$  and increases to 1/3 within uncertainties for  $p_T > 2$  GeV/c. At low  $p_T$ , the central value of  $\rho_{00}$  is smaller for  $K^{*0}$  than for  $\phi$ , although the results are compatible within uncertainties. In  $pp$  collisions,  $\rho_{00}$  is independent of  $p_T$  and equal to 1/3 within uncertainties. For the spin zero hadron  $K_S^0$ ,  $\rho_{00}$  is consistent with 1/3 within uncertainties in Pb-Pb collisions. The results with random event plane directions are also compatible with no spin alignment for the studied  $p_T$  range, except for the smallest  $p_T$  bin, where  $\rho_{00}$  less than 1/3 but still larger than for EP and PP measurements. The results for the random production plane (the momentum vector direction of each vector meson is randomized) are similar to RNDEP measurements. These results indicate that a spin alignment is present at lower  $p_T$ , which is a qualitatively consistent with predictions [13].

Figure 3 shows  $\rho_{00}$  for  $K^{*0}$  and  $\phi$  mesons as a function of average number of participating nucleons ( $\langle N_{\text{part}} \rangle$ ) [20,22] for Pb-Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV. Large  $\langle N_{\text{part}} \rangle$

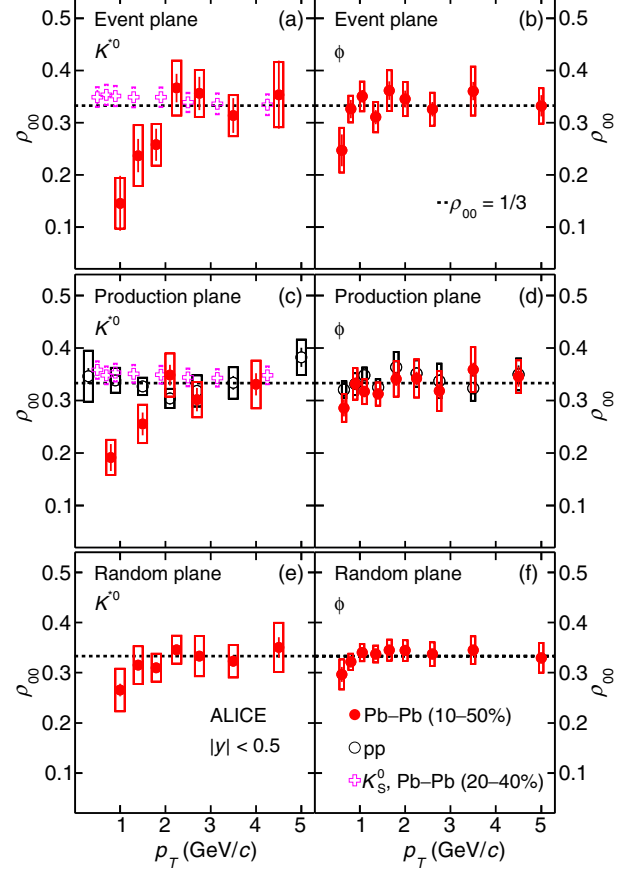


FIG. 2. Transverse momentum dependence of  $\rho_{00}$  for  $K^{*0}$ ,  $\phi$ , and  $K_S^0$  mesons at  $|y| < 0.5$  in Pb-Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV and minimum bias  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Results are shown for spin alignment with respect to the event plane [panels (a),(b)], production plane [(c),(d)], and random event plane [(e),(f)] for  $K^{*0}$  (left column) and  $\phi$  (right column). The statistical and systematic uncertainties are shown as bars and boxes, respectively.

correspond to central collisions and small  $\langle N_{\text{part}} \rangle$  correspond to peripheral collisions (see Table I of the Supplemental Material [17]). In the lowest  $p_T$  range,  $\rho_{00}$  shows maximum deviation from 1/3 for intermediate centrality and approaches 1/3 for both central and peripheral collisions. This centrality dependence is qualitatively consistent with the dependence of the initial angular momentum on impact parameter in heavy-ion collisions [4]. At higher  $p_T$ ,  $\rho_{00}$  is consistent with 1/3 for all centrality classes. For the low- $p_T$  measurements in 10–30% (20–40% for  $\phi$  meson with respect to PP) mid-central Pb-Pb collisions, the maximum deviations of  $\rho_{00}$  from 1/3 with respect to the PP (EP) are 3.2 (2.6)  $\sigma$  and 2.1 (1.9)  $\sigma$  for  $K^{*0}$  and  $\phi$  mesons, respectively. The errors ( $\sigma$ ) are calculated by adding statistical and systematic uncertainties in quadrature.

The relation between the  $\rho_{00}$  values with respect to different quantization axes can be expressed using Eq. (2)

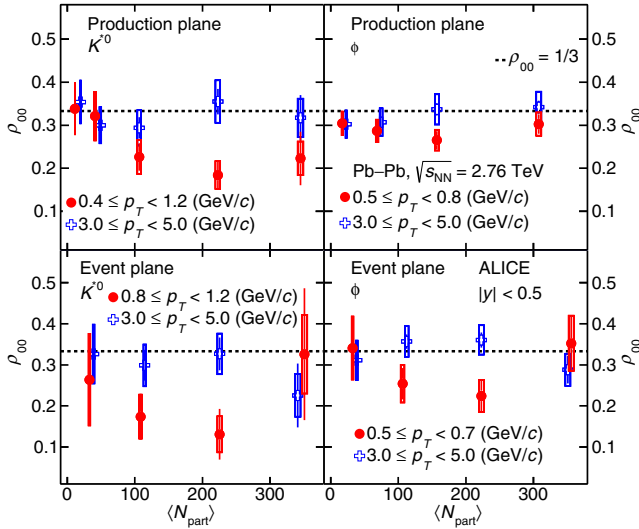


FIG. 3. Measurements of  $\rho_{00}$  as a function of  $\langle N_{\text{part}} \rangle$  for  $K^{*0}$  and  $\phi$  mesons at low and high  $p_T$  in Pb-Pb collisions. The statistical and systematic uncertainties are shown as bars and boxes, respectively. Some data points are shifted horizontally for better visibility.

and calculating the corresponding factor  $R$ . This gives  $\Delta\rho_{00}(RNDEP) = \Delta\rho_{00}(EP) \times \frac{1}{4}$  ( $R = 0$  for random plane) and  $\Delta\rho_{00}(PP) = \Delta\rho_{00}(EP) \times (1 + 3v_2)/4$  ( $R = v_2$  for production plane, where  $v_2$  is the second Fourier coefficient of the azimuthal distribution of produced particles relative to the event plane angle). Here  $\Delta\rho_{00} = \rho_{00} - 1/3$ . This is further confirmed using a toy model simulation with the PYTHIA 8.2 event generator [30] by incorporating  $v_2$  and spin alignment (see the Supplemental Material [17] for further details).

In the past, spin alignment measurements in  $e^+e^-$  [31–33], hadron-proton [34] and nucleon-nucleus collisions [35] were carried out to understand the role of spin in the dynamics of particle production, finding  $\rho_{00} > 1/3$  and off-diagonal elements close to zero with respect to the PP. For  $pp$  collisions at  $\sqrt{s} = 13$  TeV, we find  $\rho_{00} \sim 1/3$  within the studied  $p_T$  range (see Fig. 2). New preliminary results from RHIC have found deviations of  $\rho_{00}$  from  $1/3$  indicating spin alignment for vector mesons at lower  $\sqrt{s_{NN}}$  [36,37]. The  $\rho_{00}$  for  $\phi$  mesons in mid-central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV is less than  $1/3$  while the preliminary finding for mid-central Au-Au collisions at  $\sqrt{s_{NN}} = 200$  GeV is  $\rho_{00}$  greater than  $1/3$ . The  $\rho_{00} > 1/3$  for  $\phi$  mesons has been interpreted as evidence for a coherent  $\phi$  meson field [38]. Similar conclusions cannot be easily applied to  $K^{*0}$  as it consists of valence quarks of unequal mass ( $s$  and  $\bar{d}$ ), which makes it impossible to separate the effects of vorticity and due to electromagnetic and mesonic fields. Significant polarization of  $\Lambda$  baryons (spin =  $1/2$ ) was reported at low RHIC energies. The polarization is found to decrease with increasing  $\sqrt{s_{NN}}$

[39,40]. At the LHC, the global polarization for  $\Lambda$  baryon is compatible with zero within uncertainties [ $P_\Lambda(\%) = 0.01 \pm 0.06 \pm 0.03$ ] [41]. The spin alignment for vector mesons in heavy ion collisions could have contributions from angular momentum [12,13], electromagnetic fields [15] and mesonic fields [38]. While no quantitative theoretical calculation for vector meson polarization at LHC energies exists, the expected order of magnitude can be estimated and the measurements for vector mesons and hyperons can be related in a model dependent way. Considering only the angular momentum contribution and recombination as the process of hadronization [13], the  $\rho_{00}$  of vector mesons are related to quark polarization as  $\rho_{00} = (1 - P_q P_{\bar{q}})/(3 + P_q P_{\bar{q}})$  where  $P_q$  and  $P_{\bar{q}}$  are quark and antiquark polarization, respectively. Assuming  $P_u = P_{\bar{u}} = P_d = P_{\bar{d}}$  and  $P_s = P_{\bar{s}}$ , the measured  $p_T$  integrated  $\rho_{00}$  values for  $K^{*0}$  and  $\phi$  mesons in 10–50% Pb-Pb collisions could translate to light quark polarization of  $\sim 0.8$  and strange quark polarization of  $\sim 0.2$ . Using a thermal and nonrelativistic approach as discussed in [42], vorticity ( $\omega$ ) and temperature ( $T$ ) are related to  $\rho_{00}$  and vector meson polarization ( $P_V$ ) as  $\rho_{00} \simeq \frac{1}{3} \{1 - [(\omega/T)^2/3]\}$  and  $P_V \simeq (2\omega/3T)$ , respectively. Also in this approach, the measured  $\rho_{00}$  for  $K^{*0}$  would correspond to  $K^{*0}$  polarization of  $\sim 0.6$  and the  $\rho_{00}$  for  $\phi$  mesons would give  $\phi$  meson polarization of  $\sim 0.3$ .

In the recombination model,  $\Lambda$  polarization depends linearly on quark polarization whereas vector meson polarization depends quadratically on it. One would therefore expect the polarization for  $K^{*0}$  to be of the same order or smaller than the one measured for the  $\Lambda$  at LHC [41], i.e., vanishing small [ $O(0.01\%)$ ] rather than order 1. The large effect observed for the  $\rho_{00}$  in mid-central Pb-Pb collisions at low  $p_T$  is therefore puzzling. This result should stimulate further theoretical work in order to study which effects could make such a huge difference between  $\Lambda$  and  $K^{*0}$  polarization. Possible reasons may include the transfer of the quark polarization to the hadrons (baryon vs meson), details of the hadronization mechanism (recombination vs fragmentation), rescattering, regeneration, and possibly the lifetime and mass of the relevant hadron. Moreover, the vector mesons are predominantly directly produced whereas the hyperons have large contributions from resonance decays.

In conclusion, for the first time, evidence has been found for a significant spin alignment of vector mesons in heavy-ion collisions. The effect is strongest at low  $p_T$  with respect to a vector perpendicular to the reaction plane and for mid-central (10–50%) collisions. These observations are qualitatively consistent with expectations from the effect of large initial angular momentum in noncentral heavy-ion collisions, which leads to quark polarization via spin-orbit coupling, subsequently transferred to hadronic degrees of freedom by hadronization via recombination. However, the measured spin alignment is surprisingly large compared to

the polarization measured for  $\Lambda$  hyperons where, in addition, a strong decrease in polarization with  $\sqrt{s_{NN}}$  is observed. In future measurements, the difference in the polarization of  $K^{*\pm}$  and  $K^{*0}$ , due to their difference in magnetic moment, would be directly sensitive to the effect of the large initial magnetic field produced in heavy-ion collisions.

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