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# Measurement of spin-orbital angular momentum interactions in relativistic heavy-ion collisions

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**Abstract**

The first measurement of spin alignment of vector mesons ($K^{*0}$ and $\phi$) in heavy-ion collisions at the Large Hadron Collider (LHC) is reported. The measurements are carried out as a function of transverse momentum ($p_{\rm T}$) and collision centrality with the ALICE detector using the particles produced at midrapidity ($|y| < 0.5$) in Pb–Pb collisions at a center-of-mass energy ($\sqrt{s_{\rm NN}}$) of 2.76 TeV. The second diagonal spin density matrix element ($\rho_{00}$) is measured from the angular distribution of the decay daughters of the vector meson in the decay rest frame, with respect to the normal of both the event plane and the production plane. The $\rho_{00}$ values are found to be less than 1/3 (= 1/3 implies no spin alignment) at low $p_{\rm T}$ ($< 2$ GeV/$c$) for both vector mesons. The observed deviations from 1/3 are maximal for mid-central collisions at a level of $3\sigma$ for $K^{*0}$ and $2\sigma$ for $\phi$ mesons. As control measurements, the analysis is also performed using the $K^0_S$ meson, which has zero spin, and for the vector mesons in pp collisions; in both cases no significant spin alignment is observed. The $\rho_{00}$ values at low $p_{\rm T}$ with respect to the production plane are closer to 1/3 than for the event plane; they are related to each other through correlations introduced by the elliptic flow in the system. The measured spin alignment is surprisingly large compared to the polarization measured for $\Lambda$ hyperons, but qualitatively consistent with the expectation from models which attribute the spin alignment to a polarization of quarks in the presence of large initial angular momentum in non-central heavy-ion collisions and a subsequent hadronization by the process of recombination.



*See Appendix A for the list of collaboration members

Ultra-relativistic heavy-ion collisions create a system of deconfined quarks and gluons, called the Quark–Gluon Plasma (QGP) and provide the opportunity to study its properties. In collisions with non-zero impact parameter, a large angular momentum and magnetic field are also expected. Theoretical calculations estimate a total angular momentum of $O(10^7)\ \hbar$ [1] and a magnetic field $O(10^{14})$ T [2]. While the magnetic field is expected to be short lived (a few fm/$c$), the angular momentum is conserved and could be felt throughout the evolution of the system formed in the collision. Experimental observables sensitive to these initial conditions [3, 4] could be used to study the influence of angular momentum and a magnetic field 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 [5–7]. The direction of the angular momentum in non-central heavy-ion collisions is perpendicular to the reaction plane (subtended by the beam axis and impact parameter) [8]. In the presence of such 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 $\phi$ ) [8–12] along the direction of the angular momentum.

The spin alignment of a vector meson is described by a 3 $\times$ 3 Hermitian spin-density matrix [12]. The trace of the spin-density matrix is 1 and diagonal elements $\rho_{11}$ and $\rho_{-1-1}$ cannot be measured separately. As a result, 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 the vector mesons with respect to a quantization axis. In the analysis presented 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 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 [13],

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

The complete expression is given in [14] and Eq. 1 is obtained by applying parity symmetry of QCD, the unit trace condition of the spin density matrix, and integrating over the azimuthal angle. The probability of finding a vector meson in spin state zero $\rho_{00}$ is 1/3 in the absence of spin alignment and the angular distribution in Eq. 1 is uniform. Deviations from $\rho_{00} = 1/3$ indicate that the vector meson has a preferred spin state, leading to a non-uniform angular distribution. This is the experimental signature of spin alignment.

The large initial angular momentum in combination with the spin-orbit interaction is expected to lead to spin alignment with respect to the reaction plane (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 [15] (EP). To correct for the spread of the EP with respect to the RP, the observed $\rho_{00}^{obs}$ is corrected for the EP resolution ($R$) using [16],

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

There are specific qualitative predictions for the spin alignment effect [10]: (a) $\rho_{00} > 1/3$ if the hadronization of a polarized parton proceeds via a fragmentation and less than 1/3 for hadronization via recombination, (b) $\rho_{00}$ is expected to have a maximum deviation from 1/3 for mid-central heavy-ion collisions, where the angular momentum is also maximal, and a smaller deviation for both peripheral (large impact parameter) and central (small impact parameter) collisions, (c) the $\rho_{00}$ value is expected to have maximum deviation from 1/3 at low $p_{\mathrm{T}}$ and reach the value of 1/3 at high $p_{\mathrm{T}}$ in the recombination hadronization scenario, and (d) the effect is expected to be larger for $K^{*0}$ compared to $\phi$ due to their constituent quark composition. All of these features are probed for $K^{*0}$ and $\phi$ vector mesons in Pb–Pb collisions presented in this letter. In addition, to establish the results, 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 $K^0_S$ mesons, which have zero spin. As a further cross check, the measurements are carried out by randomizing the directions of the event (RndEP) and production planes (RndPP).

The analyses are carried out using 43 million minimum bias pp collisions at $\sqrt{s}$ = 13 TeV, taken in the year 2015 and 14 million minimum bias Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV, collected in the year 2010. The measurements for vector mesons are performed at midrapidity ($|y| < 0.5$) as a function of $p_{\rm T}$ and are reported for pp collisions as well as for different centrality classes in Pb–Pb collisions. The $K^0_S$ analysis is performed only for Pb–Pb collisions in the 20–40% centrality class. The details of the ALICE detector, trigger conditions, centrality selection, and second order event plane [17] estimation using the V0 detectors at forward rapidity, can be found in [18–20]. For the analysis, events are accepted with a primary vertex position within $\pm$ 10 cm of the detector center along the beam axis. The event selection in Pb–Pb collisions further requires 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 were classified by the collision centrality based on the amplitude measured in the V0 counters [20]. The $K^{*0}$ and $\phi$ vector mesons are reconstructed via their decays into charged K$\pi$ and KK pairs, respectively, while the $K^0_S$ is reconstructed via its decay into two pions. The Time Projection Chamber (TPC) [21] and Time-of-Flight (TOF) detector [22] 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 [23–25]. The background coming from combinatorial pairs and misidentified particles is removed by constructing the invariant mass distribution from the so-called mixed events for the $K^{*0}$ and $\phi$ [23, 24]. The combinatorial background for the $K^0_S$ candidates is significantly reduced by using topological criteria to select the distinctive V-shaped decay topology [25].

The invariant mass distributions are fitted with a Breit-Wigner (Voigtian: convolution of Breit-Wigner and Gaussian distributions) function for the $K^{*0}(\phi)$ signal and a 2$^{\rm nd}$ order polynomial that describes the residual background, in order to extract the yields [23, 24]. Extracted yields are then corrected for the reconstruction efficiency and acceptance in each $\cos\theta^*$ and $p_{\rm T}$ bin [23, 24]. The reconstruction efficiency is determined from Monte Carlo simulations of the ALICE detector response based on GEANT3 simulation [23, 24]. The signal extraction procedures for the vector mesons and $K^0_S$ are identical to those used in earlier publications reporting the $p_{\rm T}$ distribution of the mesons [23–25]. The mass peak positions and widths of the resonances across all the $\cos\theta^*$ bins for various $p_{\rm T}$ intervals in pp collisions and in different centrality classes of Pb–Pb collisions are consistent with those obtained from earlier analyses [23–25] and no significant dependence on $\cos\theta^*$ is seen. The resulting efficiency and acceptance corrected $dN/d\cos\theta^*$ distributions for selected $p_{\rm T}$ intervals in minimum bias pp collisions and in 10–50% central Pb–Pb collisions are shown in Fig. 1 along with those for $K^0_S$ in 20–40% central Pb–Pb collisions. These distributions are fitted with the functional form given in Eq. 1 to determine $\rho_{00}$ for each $p_{\rm T}$ bin in pp and Pb–Pb collisions. For the EP results, the values of resolution,$R$, used are 0.71, 0.53, 0.72, 0.66, and 0.40 for 10–50%, 0–10%, 10–30%, 30–50%, and 50–80%, respectively [17].

There are three main sources of systematic uncertainties in the measurements of the angular distribution of vector meson decays : (a) Meson yield extraction procedure: 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 varying the width of the resonance peak by leaving the corresponding parameter free in the fit, instead of keeping it fixed to the PDG value and the mass resolution obtained from simulations. These sources contribute to the uncertainties on the $\rho_{00}$ value at a level of 12(8)% at the lowest $p_{\rm T}$ and decrease with $p_{\rm T}$ to 4(3)% at the highest $p_{\rm T}$ studied for the $K^{*0}(\phi)$. (b) Track selection criteria: this contribution includes variations

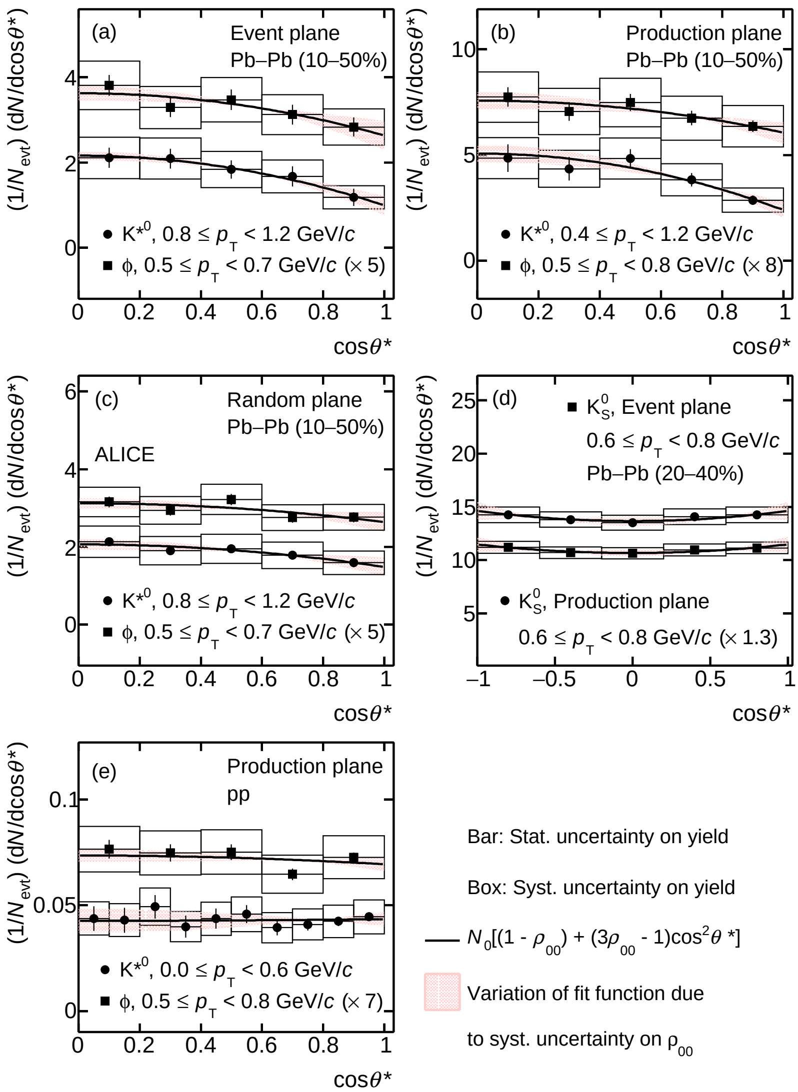


**Figure 1:** (Color online) Angular distribution of the decay daughter in the rest frame of the meson with respect to the quantization axis at $|y| < 0.5$ for pp collisions at $\sqrt{s}$ = 13 TeV and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. Panels (a) - (c) show results for $\mathrm{K}^{*0}$ and $\phi$ with respect to EP, PP, and random event plane. Panels (d) and (e) are the results for $\mathrm{K}^0_\mathrm{S}$ with respect to both the PP and EP and for vector mesons in pp collisions with respect to PP, respectively.

of the selection on the distance of closest approach to the collision vertex, the number of crossed pad rows in the TPC [21], the ratio of number of the found clusters to the number of expected clusters, and the quality of the track fit. The systematic uncertainties on the $\rho_{00}$ value due to variation on the track selection criteria are 14(6)% at the lowest $p_{\rm T}$ and about 11(5)% at the highest $p_{\rm T}$ for $K^{*0}(\phi)$. (c) Particle identification procedure: 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 $p_{\rm T}$ and about 4(4.5)% at the highest $p_{\rm T}$ studied for $K^{*0}(\phi)$. The total systematic uncertainty on $\rho_{00}$ is obtained by adding all the contributions in quadratures.

Several consistency checks are carried out. Specifically the yields of vector mesons are summed over $\cos\theta^*$ bins for each $p_{\rm T}$ interval to obtain the $p_{\rm T}$ distributions, which are found to be consistent within the statistical uncertainties with the published $p_{\rm T}$ distributions in Pb–Pb collisions [23, 24]. Similarly a closure test (comparison between generated and reconstructed angular distribution) is carried out for the Monte Carlo (MC) data which is used to obtain the reconstruction efficiencies for the mesons. Two different event generators are used to determine the reconstruction efficiency and the results are consistent. The effect of the shape of the $p_{\rm T}$ distributions in the MC simulations is studied in detail and the impact on the $\rho_{00}$ measurement is found to be small. The dependence of the reconstruction efficiency for a $\cos\theta^*$ range on the azimuthal angle of vector meson ($\phi_V$) relative to the event plane angle ($\Psi$) is also studied. The reconstruction efficiencies obtained in a $\cos\theta^*$ range by integrating over $\phi_V - \Psi$ are similar to the efficiency obtained by averaging over the $\phi_V - \Psi$ bins. Data samples with two different magnetic field polarities in the experiment are separately analyzed and the $\cos\theta^*$ distributions are found to be consistent. In addition, the analysis is performed separately for positive ($0 < y < 0.5$) and negative ($-0.5 < y < 0$) rapidity and also for $K^{*0}$ versus $\overline{K}^{*0}$; the different samples are also consistent. The final result is reported for average yield of particles ($K^{*0}$) and anti-particles ($\overline{K}^{*0}$), obtained from the combined mass distribution.

Figure 2 shows the measured $\rho_{00}$ as a function of $p_{\rm T}$ for $K^{*0}$ and $\phi$ mesons in pp collisions and Pb–Pb collisions, along with the measurements for $K^0_S$ in Pb–Pb collisions. In mid-central (10–50%) Pb–Pb collisions, $\rho_{00}$ is below 1/3 at the lowest measured $p_{\rm T}$ and increases to 1/3 within uncertainties for $p_{\rm T} > 2$ GeV/$c$. At low $p_{\rm T}$, 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 $p_{\rm T}$ and equal to 1/3 within uncertainties. For the spin zero hadron $K^0_S$, $\rho_{00}$ 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 $p_{\rm T}$ range, except for the smallest $p_{\rm T}$ bin, where $\rho_{00}$ less than 1/3 but still larger than for EP and PP measurements. The origin of this is discussed later in context of Fig. 4. 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 $p_{\rm T}$, which is a qualitatively consistent with the predictions [10].

Figure 3 shows $\rho_{00}$ for $K^{*0}$ and $\phi$ mesons as a function of average number of participating nucleons ($\langle N_{\rm part}\rangle$) [20] for Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. Large $\langle N_{\rm part}\rangle$ correspond to the central collisions, while peripheral events have low $\langle N_{\rm part}\rangle$. In the lowest $p_{\rm T}$ range, the $\rho_{00}$ values have maximum deviation from 1/3 for intermediate centrality and approach 1/3 for both central and peripheral collisions. This centrality dependence is qualitatively consistent with the dependence of initial angular momentum on impact parameter in heavy-ion collisions [1]. At higher $p_{\rm T}$, the $\rho_{00}$ measurements are consistent with 1/3 for all the collision centrality classes studied for both vector mesons. For the low-$p_{\rm T}$ measurements in mid-central Pb–Pb collisions, the maximum deviations of $\rho_{00}$ from 1/3 are 3.2 (2.6) $\sigma$ and 2.1 (1.9) $\sigma$ for $K^{*0}$ and $\phi$ mesons, respectively, for mid-central Pb–Pb collisions with respect to the PP (EP). The $\sigma$ are calculated by adding statistical and systematic uncertainties into quadrature.

The relation between the $\rho_{00}$ values with respect to different quantization axes can be expressed using Eq. 2 and calculating the corresponding factor $R$. This gives $\rho_{00}(\text{RndEP}) - \frac{1}{3} = (\rho_{00}(\text{EP}) - \frac{1}{3}) \times \frac{1}{4}$

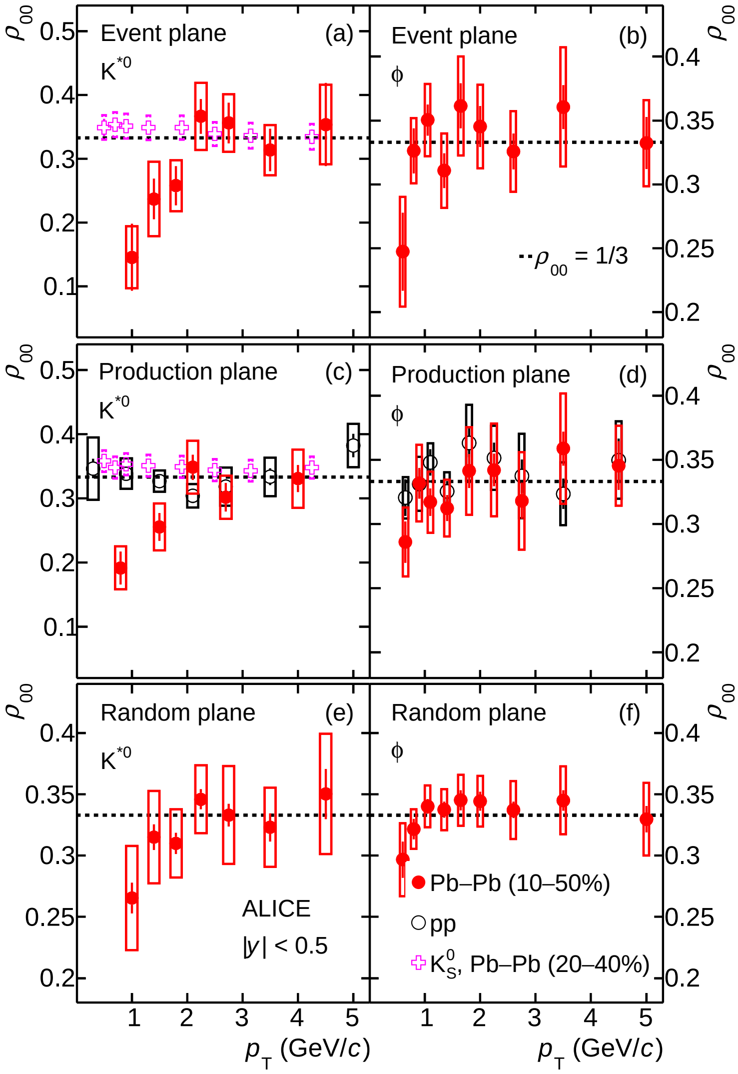


**Figure 2:** (Color online) Transverse momentum dependence of $\rho_{00}$ corresponding to $K^{*0}$, $\phi$ , and $K^0_S$ mesons at $|y| < 0.5$ in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and minimum bias pp collisions at $\sqrt{s}$ = 13 TeV. Results are shown for spin alignment with respect to 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.

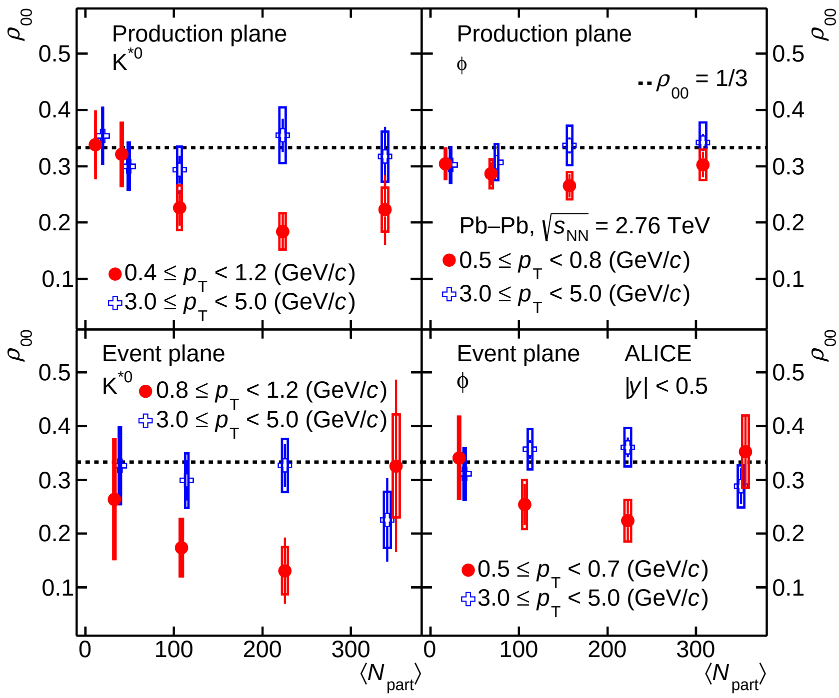


**Figure 3:** (Color online) Measurements of $\rho_{00}$ as a function of $\langle N_{\text{part}}\rangle$ for $K^{*0}$ and $\phi$ mesons at ranges of low and high $p_T$ in Pb–Pb collisions. The statistical and systematic uncertainties are shown as bars and boxes, respectively. Few data points are shifted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

($R$ = 0 for random plane) and $\rho_{00}(\text{PP}) - \frac{1}{3} = (\rho_{00}(\text{EP}) - \frac{1}{3}) \times \frac{1+3v_2}{4}$ ($R = \frac{1}{2\pi}\int_{-\pi}^{\pi} cos(2\psi_{\text{EP}})[1 + 2v_2 cos(2\psi_{\text{EP}})]d\psi_{\text{EP}}$, where $\psi_{\text{EP}}$ is the event plane angle and $v_2$ is the azimuthal anisotropy). This is further confirmed (see Fig. 4) using a toy model simulation with PYTHIA 8.2 event generator by incorporating $v_2$ and spin alignment through appropriate rotation of $K^{*0}$ and its decay products momentum [26, 27].

Spin alignment measurements have been performed in various collision systems in the past. Several measurements in $e^+e^-$ [28–30], hadron–proton [31] and nucleon–nucleus collisions [32] were carried out to understand the role of spin in the dynamics of particle production. These measurements in small collision systems with respect to the production plane have $\rho_{00} > 1/3$ and off-diagonal elements close to zero. For pp collisions at $\sqrt{s}$ = 13 TeV the $\rho_{00} \sim 1/3$ for the $p_T$ range studied (see Fig.3). Initial measurements at RHIC[1] with a relatively small sample of Au–Au collisions at $\sqrt{s_{\text{NN}}}$ = 200 GeV did not find significant spin alignment for the vector mesons [33]. Significant polarization of $\Lambda$ baryons (spin = 1/2) was reported at low RHIC energies. The polarization is found to decrease with increasing $\sqrt{s_{\text{NN}}}$ [34]. At the LHC energies, the global polarization for $\Lambda$ baryons was measured to less than 0.15% [35] and compatible with zero within uncertainties. Measurements of particles with spin-1/2 are performed with respect to the 1st order event plane in order to know the orientation of the angular momentum vector. However, the effect of "spin up" and "spin down" is the same for particles with spin-1, hence the second order event plane suffices. In the recombination model, $\rho_{00}$ is expected to depend on the square of the quark polarization whereas the $\Lambda$ polarization depends linearly on it, therefore using quark polarization information from $\Lambda$ measurements will yield a $\rho_{00} \sim 1/3$ at LHC energies. The large effect observed for the central value of $\rho_{00}$ for mid-central Pb–Pb collisions at low $p_T$ is therefore puzzling. However, the magnitude of the spin alignment also depends on the details of the transfer of the quark

[1]STAR experiment results have a different event plane resolution correction.

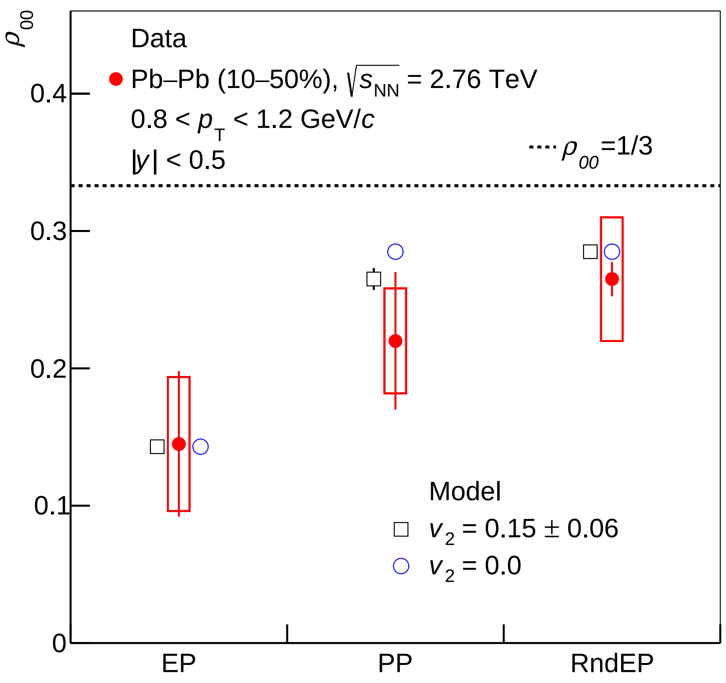


**Figure 4:** (Color online) $\rho_{00}$ values from data in 10–50% Pb–Pb collisions at $0.8 < p_T < 1.2$ GeV/$c$ with respect to various planes compared with expectations from model simulations with and without added elliptic flow ($v_2$). The statistical and systematic uncertainties are shown as bars and boxes, respectively.

polarization to the hadrons (baryon vs. meson), details of the hadronization mechanism (recombination vs. fragmentation), re-scattering, regeneration, and possibly the lifetime and mass of the hadrons in the system. Moreover, the vector mesons are predominantly primordially produced whereas the hyperons are expected to have large contributions from resonance decays. To date, no quantitative theory expectation for $\rho_{00}$ at LHC energies exists. We expect that these measurements will encourage further theoretical work on this topic.

In conclusion, for the first time we obtain evidence of a significant spin alignment effect for vector mesons in heavy-ion collisions. The effect is strongest when the alignment is measured 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 non-central heavy-ion collisions, which leads to quark polarization via spin-orbit coupling and is 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.

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[14] $\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*\mathrm{d}\varphi^*} \propto [\cos^2\theta^*\rho_{00} + \sin^2\theta(\rho_{11}+\rho_{-1-1})/2 \ - \ \sin 2\theta(\cos\varphi^*\mathrm{Re}\rho_{10} - \sin\varphi^*\mathrm{Im}\rho_{10})/\sqrt{2} \ + \ \sin 2\theta(\cos\varphi^*\mathrm{Re}\rho_{-10} + \sin\varphi^*\mathrm{Im}\rho_{-10})/\sqrt{2} \ - \ \sin^2\theta(\cos 2\varphi^*\mathrm{Re}\rho_{1-1} - \sin 2\varphi^*\mathrm{Im}\rho_{1-1})]$, The angle denoted here as $\theta^*$ is that made by one of the decay daughters in the rest frame of the vector meson with respect to the quantization axis and $\varphi^*$ is the corresponding azimuthal angle.

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## A The ALICE Collaboration

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