

SPIN POLARIZATION MEASUREMENTS
IN RELATIVISTIC HEAVY-ION COLLISIONS* **

DEBOJIT SARKAR

Wayne State University, Detroit, USA
and

Niels Bohr Institute, University of Copenhagen, Denmark

*Received 6 September 2022, accepted 20 September 2022,
published online 14 December 2022*

The hot and dense matter formed in relativistic heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) and Large Hadron Collider (LHC) is termed quark–gluon plasma (QGP). The evolution of the medium is characterized by non-trivial velocity and vorticity fields, resulting in the polarization of the produced particles. The spin polarization, being sensitive to the hydrothermal (flow velocity and temperature) gradients, is unique compared to conventional observables that are sensitive to the hydrothermal fields only. Hence, the recent measurements of global and local hyperon spin polarization and vector meson spin alignment by the LHC and STAR collaborations provide a unique opportunity to probe the QGP substructure with finer details.

DOI:10.5506/APhysPolBSupp.16.1-A16

1. Introduction

The system created in relativistic heavy-ion collisions at RHIC and the LHC might retain a significant fraction of the initial orbital angular momentum of the colliding system through the initial shear in the longitudinal velocity profile of the participants [1]. This shear can generate vorticity perpendicular to the reaction plane defined by the impact parameter vector and the beam direction. Due to the spin–orbit coupling, the particles emerging from the system with non-zero spin get polarized along the vorticity of the system. This phenomenon is termed global polarization as all particles get polarized along one preferential direction defined by the orbital angular momentum of the colliding system [1–3]. The global polarization due to vorticity is expected to be the same for both particle and anti-particle in a

* Presented at the 29th International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

** D.S. is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, grant No. DE-FG02-92ER40713.

system with small or zero baryon chemical potential. However, the initial ultra-strong magnetic fields, aligned with the direction of the angular momentum, can polarize particles and anti-particles in an opposite direction due to the opposite sign of their magnetic moments. Therefore, the precise measurements of the particle and anti-particle polarization in heavy-ion collisions can provide valuable insights into the QGP properties.

2. Hyperon polarization and vector meson spin alignment measurements

The spin of a particle cannot be measured directly. The parity-violating weak decaying strange (Λ) and multi-strange (Ξ , Ω) hyperons are experimentally favorable as their spin direction can be reconstructed from the decay daughter angular distribution which is an odd function and depends on the direction of the angular momentum. The mother hyperon polarization is estimated from the daughter baryon angular distribution in the mother's rest frame [1], given by

$$4\pi \frac{dN}{d\Omega^*} = 1 + \alpha_H P_H \cdot \hat{\mathbf{p}}_B^* = 1 + \alpha_H P_H \cos \theta_B^*, \quad (1)$$

where P_H is the polarization vector, $\hat{\mathbf{p}}_B^*$ is the unit vector along the daughter momentum, and θ_B^* is the angle between the daughter momentum and the polarization vector. The asterisks denote that the quantities are in the rest frame of the parent. The hyperon decay parameter (α_H) [4] characterizes the anisotropy of the decay daughter angular distribution in the parent rest frame. The α_H values get updated in the Particle Data Group (PDG) from time to time [4–9].

In general, the polarization is estimated from the ensemble-averaged projection of the daughter baryon momentum direction along the vorticity source [1]. In heavy-ion collisions, the global polarization vector P_H along the initial angular momentum is given by [4]

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_{\text{SP}} - \phi_B^*) \rangle}{\text{Res}(\Psi_{\text{SP}})}, \quad (2)$$

where ϕ_B^* is the azimuthal angle of the daughter baryon in the parent hyperon rest frame and Ψ_{SP} the spectator plane angle. The Ψ_{SP} is estimated from the deflection direction of the spectator neutrons [4, 7], characterizing the orbital angular momentum direction of the colliding system. The $\text{Res}(\Psi_{\text{SP}})$ is the event plane resolution correction [10].

The STAR Collaboration measured significant global polarization of Λ (P_Λ) and $\bar{\Lambda}$ ($P_{\bar{\Lambda}}$) hyperons in the collision energy range $\sqrt{s_{NN}} = 3\text{--}200$ GeV [4–6]. The polarization magnitude decreases monotonically with $\sqrt{s_{NN}}$ from

a few to a fraction of a percent, shown in Fig. 1 (left). The P_A and $P_{\bar{A}}$ are consistent with each other within experimental uncertainty. However, $P_{\bar{A}}$ is systematically higher than P_A , and the difference is more prominent at lower $\sqrt{s_{NN}}$. Initial magnetic field and higher baryon chemical potential at lower $\sqrt{s_{NN}}$ can contribute to this difference [1]. More precision measurements and data-model comparisons are required to understand the origin of this behavior. The $P_{A(\bar{A})}$ measured by the ALICE Collaboration for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [7] is consistent with zero within experimental uncertainties (Fig. 1) (left), following the decreasing trend of P_H with increasing $\sqrt{s_{NN}}$. However, hyperon global polarization and slope of the charged particle directed flow (v_1) at midrapidity, both related to the initial vorticity or tilt in the system, are found to be strongly correlated in the RHIC BES measurements [7]. The extrapolation of those measurements, combined with the experimentally observed three times smaller v_1 in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to the same in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [13], predict a small but finite P_H ($\approx 0.04\%$) at the LHC energies [7]. The Run 3 data at the LHC with higher statistics will provide a more precise estimate of global vorticity at the LHC energies.

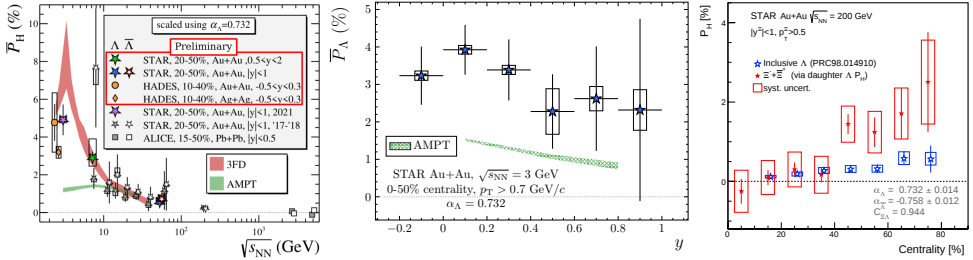


Fig. 1. Left: $\sqrt{s_{NN}}$ dependence of $P_{A(\bar{A})}$ and its comparison with the hydrodynamic (3FD) and transport (AMPT) model estimations [11]. Middle: Rapidity dependence of P_A in Au–Au collisions at $\sqrt{s_{NN}} = 3$ GeV with AMPT estimation [6]. Right: Centrality dependence of $P_{A,\Xi}$ in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [12].

Hydrodynamic (3FD) [14] and transport (AMPT) [15] calculations reasonably explain the $\sqrt{s_{NN}}$ dependence of P_H for $\sqrt{s_{NN}} \geq 7.7$ GeV as shown in Fig. 1 (left). These model calculations estimate the particle polarization from the thermal vorticity [2] at the freeze-out surface assuming local thermodynamic equilibrium of the spin degrees of freedom. It should be noted that the exact nature of the spin–orbit interaction and the spin relaxation times are not known. An extension of the Cooper–Frye formalism is used to calculate the polarization (particle property) from the thermal vorticity (fluid property) generated by hydrodynamic and transport models in all such calculations [1].

The P_H is expected to vanish at $\sqrt{s_{NN}} = 2m_N$ due to the lack of system angular momentum [6, 16]. Therefore, a peak of P_H is expected in the range $2m_N \approx 1.9 < \sqrt{s_{NN}} < 7.7$ GeV [6]. The recent model calculations predict this maximum of P_H to be around $\sqrt{s_{NN}} \approx 3$ GeV [6, 16]. The STAR Collaboration measured the P_A at $\sqrt{s_{NN}} = 3$ GeV, the largest P_A ever measured in the experiment as shown in Fig. 1 (left) [6]. The P_A in Au+Au collisions at $\sqrt{s_{NN}} = 2.42$ GeV (HADES) is consistent with STAR $\sqrt{s_{NN}} = 3$ GeV result within measurement uncertainty, preventing a conclusion about the possible maximum of P_A at $\sqrt{s_{NN}} = 3$ GeV. The P_A in Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV (HADES) is lower than the same measured in Au+Au collisions at $\sqrt{s_{NN}} = 2.42$ GeV (HADES) and 3 GeV (STAR) due to the lower value of initial angular momentum in the Ag+Ag system (Fig. 1) (left). The 3FD hydro calculation [14] seems to work better at a lower $\sqrt{s_{NN}}$ range, whereas the AMPT [15] works well only for $\sqrt{s_{NN}} \geq 7.7$ GeV as seen in Fig. 1 (left). The observation of large P_H at $\sqrt{s_{NN}} \leq 7.7$ GeV indicates that the hadron gas may support enormous vorticity at low collision energies [6]. On the other hand, the decrease of P_H at mid-rapidity with the increase in $\sqrt{s_{NN}}$ can be attributed to the migration of vorticity toward forward rapidity (y) due to the longitudinal boost invariance at mid-rapidity at higher $\sqrt{s_{NN}}$ [17]. A forward detector upgrade at RHIC and the LHC is necessary to reconstruct hyperons and measure P_H at forward rapidities at higher $\sqrt{s_{NN}}$. In this context, the STAR FXT (Fixed Target) result at $\sqrt{s_{NN}} = 3$ GeV is unique as it covers the range of $-0.2 \leq y \leq y_{\text{beam}}$, reaching the upper limit of y_A at this collision energy [6]. As shown in Fig. 1 (middle), no rapidity dependence of P_H is observed at $\sqrt{s_{NN}} = 3$ GeV within the measurement uncertainty, and the AMPT cannot explain the data. Further precision measurements of P_H up to y_{beam} at higher $\sqrt{s_{NN}}$ are necessary to shed light on this topic as the medium properties at higher $\sqrt{s_{NN}}$ are quite different with the boost invariance at mid-rapidity being a better approximation.

The STAR Collaboration also measured the global polarization for multi-strange hyperons such as Ξ (spin 1/2) and Ω (spin 3/2) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [12]. This measurement provides insight into the global polarization picture based on thermal vorticity that warrants different particles to be polarized in the same direction with polarization magnitudes depending only on their spin [2]. The Ξ and Ω hyperons decay in two steps: $\Xi \rightarrow \Lambda + \pi^-$; $\Omega \rightarrow \Lambda + K$ with a subsequent decay of $\Lambda \rightarrow p + \pi^-$. Both steps in such a cascade decay are parity-violating and can be used for independent polarization measurement. However, the decay parameter $\alpha_\Omega (= 0.0157 \pm 0.0021)$ being very small, measuring Ω polarization directly from the daughter Λ angular distribution is practically impossible [12]. The Ξ and Ω polarization can be estimated from the daughter polarization (P_Λ , from $\Lambda \rightarrow p + \pi^-$ decay) using a polarization transfer factor ($C_{\Omega\Lambda}$, $C_{\Xi\Lambda}$),

assuming polarization transfer from the parent to the daughter [12]. Figure 1 (right) shows that for semi-central and peripheral collisions, $P_{\Xi} > P_{\Lambda}$, despite both being spin 1/2 particles. The measured P_{Ξ} and P_{Ω} for the collision centrality 20%–80% are found to be slightly larger than the P_{Λ} and in reasonable agreement with a multi-phase transport model (AMPT) [12]. These measurements indicate that a different spin (for Ω), as well as different freeze-out times or regions, may contribute to larger polarization for Ξ and Ω compared to that of Λ [18]. Further precision measurements for different species will be essential to understand the possible effects of particle mass, spin, and magnetic moments on particle polarization in the context of the fluid vorticity-based global polarization picture.

The vector mesons (e.g. K^{*0} , ϕ) decay through the parity-conserving strong decay process. In strong decay, the angular distribution of the decay daughters is an even function and depends only on the strength and not on the direction of the system angular momentum [19, 20]. Hence, the angular distribution of the decay daughters with respect to a quantization axis (along the system angular momentum, normal to the event plane) in the vector meson’s rest frame provides an estimation of the spin alignment [19]

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

where ρ_{00} is the only independent diagonal element of 3×3 Hermitian spin density matrix with a unit trace and is used to quantify the vector meson spin alignment [19]. ρ_{00} corresponds to the probability of finding a vector meson in spin state 0 out of 3 possible spin states of -1 , 0 and 1 (ρ_{11} , ρ_{00} , and ρ_{-1-1}). In absence of spin alignment, $\rho_{00} = 1/3$. Any deviation of ρ_{00} from $1/3$ is considered an experimental signature of the vector meson spin alignment [20].

The ALICE and STAR collaborations recently measured the ρ_{00} for K^{*0} and ϕ in Pb–Pb and Au–Au collisions [20, 21]. Figure 2 (left) shows that the $\rho_{00} < 1/3$ for K^{*0} and ϕ at low p_T (< 2 GeV) in semi-central Pb–Pb collisions, whereas the high- p_T measurements are consistent with $\rho_{00} = 1/3$ [19]. The deviation of ρ_{00} from $1/3$ is the highest in semi-central collisions whereas consistent with $1/3$ in most central and peripheral collisions, following the impact parameter dependence of the global angular momentum [20, 21]. The ρ_{00} for K^{*0} follows the similar pattern in Au–Au collisions at RHIC [21]. These results are consistent with the quark recombination model that attributes the low- p_T vector meson spin alignment to the quark polarization through spin–orbit coupling and hadronization via recombination of polarized quarks [19, 22]. The ρ_{00} is consistent with $1/3$ for K_S^0 (spin 0) in semi-central Pb–Pb (Fig. 2 (middle and right)) and Au–Au collisions, and also for vector mesons in pp collisions where the initial angular momentum is not expected [20, 21].

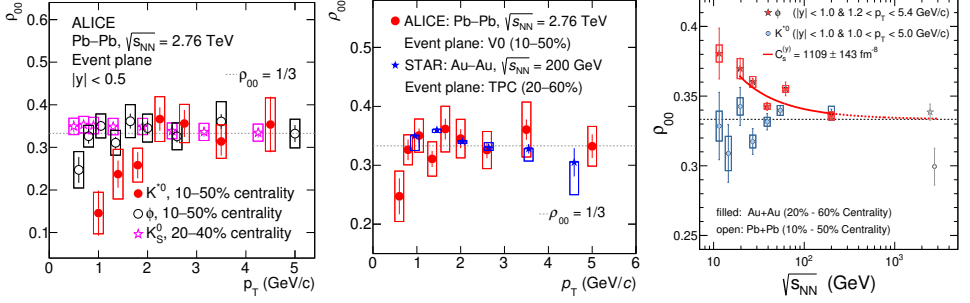


Fig. 2. Left: p_T dependence of ρ_{00} for K^{*0} and ϕ vector mesons and its comparison with K_S^0 (spin 0) in semi-central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [19]. Middle: p_T dependence of ρ_{00} for ϕ in semi-central Pb–Pb (ALICE) and Au–Au collisions (STAR) [19]. Right: $\sqrt{s_{NN}}$ dependence of ρ_{00} for K^{*0} and ϕ vector mesons and its comparison with the theoretical calculation based on ϕ -meson field [21].

Interestingly, $\rho_{00} > 1/3$ for ϕ at intermediate p_T in Au–Au collisions at RHIC [21] as shown in Fig. 2. This is inconsistent with the $\rho_{00}(\phi) < 1/3$ at the LHC and quark recombination model estimations [19]. Recent theory calculation indicates that the coherence ϕ meson field can generate $\rho_{00} > 1/3$ for ϕ meson at RHIC [23]. Overall, the finite ρ_{00} values indicating vector meson spin alignment at RHIC and the LHC are surprisingly large in the context of Λ polarization. In a thermal and non-relativistic approach, the hyperon polarization and vector meson spin alignment are associated with the thermal vorticity (ω/T) in the following way: $P_A \simeq \frac{1}{4} \frac{\omega}{T}$ and $\rho_{00} \simeq \frac{1}{3} \left(1 - \frac{(\omega/T)^2}{3} \right)$ [19]. At the LHC, $P_A \approx 0$ (Fig. 1 (left)) implies $\rho_{00} \approx 1/3$. However, the ρ_{00} values (Fig. 2) are surprisingly large, and local polarization of quarks and anti-quarks may contribute to such a large vector meson spin alignment [19]. More theoretical input is needed for a better understanding of the vector meson spin alignment results at relativistic heavy-ion collisions.

In addition to the global vorticity due to orbital angular momentum, anisotropic expansion of the medium generates non-trivial vorticity fields along different directions [8]. For example, in non-central nucleus–nucleus collisions, the strong elliptic flow generates a non-zero vorticity component along the beam axis (z). The vorticity direction and the resulting hyperon polarization exhibit a quadrupole structure in the transverse plane, hence termed local polarization [8]. The Λ ($\bar{\Lambda}$) polarization due to elliptic flow-induced vorticity is measured relative to the second harmonic symmetry plane Ψ_2 , and is evaluated as [8, 9]

$$P_{z, s2} = \frac{\langle P_z \sin(2\varphi - 2\Psi_2) \rangle}{\text{Res}(\Psi_2)}, \quad P_z = \frac{\langle \cos \theta_p^* \rangle}{\alpha_H \langle (\cos \theta_p^*)^2 \rangle}, \quad (4)$$

where θ_p^* is the polar angle of the daughter momentum direction in the hyperon rest frame. φ is the hyperon azimuthal angle, Ψ_2 is the reconstructed second harmonic event plane angle, and $\text{Res}(\Psi_2)$ is the event plane resolution correction [10]. The factor $\langle (\cos \theta_p^*)^2 \rangle$ corrects for finite acceptance along the longitudinal direction. The sign of $P_{z,s2}$ determines the phase of the P_z modulation relative to the second harmonic symmetry plane.

The centrality and p_T dependences of $P_{z,s2}$ measured by the ALICE Collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [8] and its comparison with the STAR measurement for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [9] are shown in Fig. 3 (left and middle). The STAR results are rescaled with a factor of 0.856 to take into account the different α_H values used in these measurements [8]. The $P_{z,s2}$ for Λ and $\bar{\Lambda}$ are consistent with each other as expected from the elliptic flow-induced vorticity and combined to calculate the final result. The $P_{z,s2}$ measured at both $\sqrt{s_{NN}}$ has a similar magnitude and phase dependence, and it does not exhibit a significant dependence on rapidity [8]. Figure 3 also shows the comparison between the ALICE results and the $P_{z,s2}$ values estimated from the fluid shear and thermal vorticity in a 3+1 D hydrodynamical model (MUSIC) with AMPT initial conditions [8, 24]. The model generates positive $P_{z,s2}$ and qualitatively explains the data assuming constituent strange quark mass as the spin carrier mass. However, the model generates negative $P_{z,s2}$ in case the hyperon mass is used as the spin carrier mass in the calculation. It is important to note that the thermal vorticity-based hydro and transport calculations explain the $\sqrt{s_{NN}}$ dependence of global polarization (P_H) reasonably well as shown in Fig. 1 (left), however, fail to explain the azimuthal angle dependence P_H [24, 25]. The introduction of shear-induced polarization along with additional assumptions on the hadronization temperature or mass of the spin carrier reproduce the experimentally observed positive $P_{z,s2}$, and the phase of P_H at RHIC and the LHC energies [24, 25].

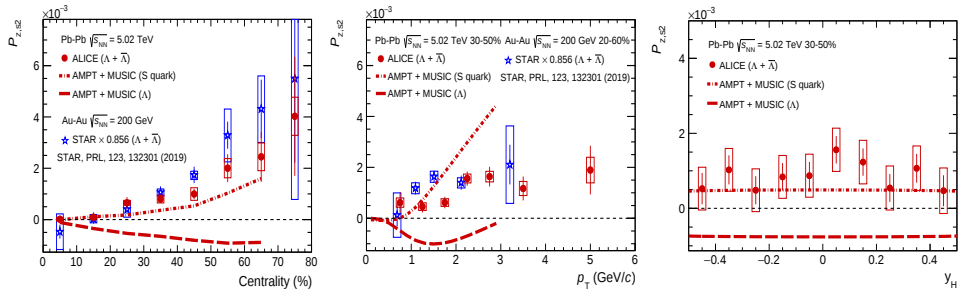


Fig. 3. (Color online) Left: Centrality dependence of $P_{z,s2}$ and middle: p_T dependences of $P_{z,s2}$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: Rapidity dependence of $P_{z,s2}$. The AMPT+MUSIC estimations for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in all three plots [8].

3. Conclusions

In short, a detailed theoretical understanding of the quark spin polarization in the QGP, spin transfer at the hadronization, and the effect of hadronic scattering on the spin polarization are required for a better understanding of the experimental results. The ongoing and future precise measurements of spin polarization and spin alignment in different collision systems and energies would provide further insights into the dynamics of vorticity and particle polarization in heavy-ion collisions.

REFERENCES

- [1] F. Becattini, M.A. Lisa, *Annu. Rev. Nucl. Part. Sci.* **70**, 395 (2020).
- [2] F. Becattini *et al.*, *Phys. Rev. C* **95**, 054902 (2017).
- [3] S.A. Voloshin, [arXiv:nucl-th/0410089](https://arxiv.org/abs/nucl-th/0410089).
- [4] STAR Collaboration (L. Adamczyk *et al.*), *Nature* **548**, 62 (2017).
- [5] STAR Collaboration (J. Adam *et al.*), *Phys. Rev. C* **98**, 014910 (2018).
- [6] STAR Collaboration (M. Abdallah *et al.*), *Phys. Rev. C* **104**, L061901 (2021).
- [7] ALICE Collaboration (S. Acharya *et al.*), *Phys. Rev. C* **105**, 029902 (2022).
- [8] ALICE Collaboration (S. Acharya *et al.*), *Phys. Rev. Lett.* **128**, 172005 (2022).
- [9] STAR Collaboration (J. Adam *et al.*), *Phys. Rev. Lett.* **123**, 132301 (2019).
- [10] A.M. Poskanzer, S.A. Voloshin, *Phys. Rev. C* **58**, 1671 (1998).
- [11] Figure made by J.R. Adams, presented at the Quark Matter 2022 Conference, Kraków, Poland, 4–10 April, 2022, <https://indico.cern.ch/event/895086/contributions/4724885/>
- [12] STAR Collaboration (J. Adam *et al.*), *Phys. Rev. Lett.* **126**, 162301 (2021).
- [13] ALICE Collaboration (B. Abelev *et al.*), *Phys. Rev. Lett.* **111**, 232302 (2013).
- [14] Y.B. Ivanov, *Phys. Rev. C* **103**, L031903 (2021).
- [15] Y. Guo *et al.*, *Phys. Rev. C* **104**, 041902 (2021).
- [16] X.-G. Deng *et al.*, *Phys. Rev. C* **101**, 064908 (2020).
- [17] Yu.B. Ivanov *et al.*, *Phys. Rev. C* **100**, 014908 (2019).
- [18] O. Vitiuk *et al.*, *Phys. Lett. B* **803**, 135298 (2020).
- [19] B. Mohanty *et al.*, *Mod. Phys. Lett. A* **36**, 2130026 (2021).
- [20] ALICE Collaboration (S. Acharya *et al.*), *Phys. Rev. Lett.* **125**, 012301 (2020).
- [21] STAR Collaboration (M. Abdallah *et al.*), [arXiv:2204.02302](https://arxiv.org/abs/2204.02302) [hep-ph].
- [22] Z.-T. Liang *et al.*, *Phys. Rev. Lett.* **94**, 102301 (2005).
- [23] X.-L. Sheng, L. Oliva, Q. Wang, *Phys. Rev. D* **101**, 096005 (2020).
- [24] B. Fu *et al.*, *Phys. Rev. Lett.* **127**, 142301 (2021).
- [25] F. Becattini *et al.*, *Phys. Rev. Lett.* **127**, 272302 (2021).