Spin correlations in e^+e^- and relativistic heavy-ion collisions

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Abstract. Motivated by recent STAR's measurements on the global spin alignment of vector mesons which suggest quark-antiquark spin correlation, we carry out a systematic study on the spin correlations in high energy e^+e^- and heavy-ion collisions in a unified framework, on which we give a brief overview.

1. *Introduction and summary*. The global hyperon polarization was first observed by the STAR Collaboration at the Relativistic Heavy Ion Collider (RHIC) [1] and later in a series of subsequent experiments. This confirms the theoretical predictions made two decades ago [2, 3] and open a new field in heavy-ion collisions. Following some early studies [4–6], there are many later developments in phenomenologies and theories [7–11], see, e.g. Refs. [12–16] for recent reviews.

Recently, the STAR Collaboration published their measurements on vector mesons' global spin alignment [17] and brought the field of spin physics in heavy-ion collisions to a new frontier. The STAR results suggest that there is strong spin correlation between the quark and anti-quark that combine into the vector meson [18–20], for recent reviews, see, e.g. Refs. [21, 22]. The experimental observation and corresponding theoretical studies provide an opportunity to study the spin correlations at the quark level in high energy heavy-ion collisions for the first time.

The quark-antiquark spin correlations not only lead to the vector meson's spin alignment but also influence spin correlations between the hyperon and antihyperon. The former corresponds to a short distance correlation (within the vector meson), whereas the latter corresponds to a long distance correlation (between two different hadrons).

In contrast to a many-body environment in heavy-ion collisions, the exclusive production of hyperon-antihyperon in electron-positron annihilation provides a clean probe to the mechanism of spin correlations. The insights and tools developed in electron-positron annihilation can be applied to heavy-ion collisions. We give a brief overview on our recent works on spin correlations in collisions of electron-positron and heavy ions in a unified framework.

2. *Spin correlations of hyperon-antihyperon in e^+e^- annihilation*. The weak decay of a spin-1/2 hyperon to a baryon and a meson can be regarded as a generalized measurement acting on the parent's spin state [23]. The measurement outcome is the momentum direction of the daughter baryon, whose angular distribution serves as the probability rule associated with the measurement. The decay acts as a quantum channel that transforms the parent spin density matrix into the daughter's ensemble-averaged spin state. This creates a bridge between particle physics observables to quantum-information quantities.

When a hyperon-antihyperon pair is produced, the two spins form an effective two-qubit state described by the hyperon's and antihyperon's polarization vectors and a 3×3 spin correlation matrix [23]. The joint decay into a baryon and an antibaryon is then described by parallel generalized measurements acting on both qubits. The resulting joint angular distribution of the daughters contains all information needed to reconstruct the two-qubit density matrix of the parent pair. With the spin density matrix of the hyperon-antihyperon pair, one can evaluate standard indicators of quantum correlations, such as the Bell-type inequality and quantum entanglement.

A quantum entangled two-qubit state may violate the Bell-type inequality that any local realistic theory must satisfy, while the entanglement denotes the failure of a bipartite quantum state to be described as a statistical mixture of product states.

To test the Bell-type inequality in the two-qubit state of hyperon-antihyperon, one can convert it into a standard X-state form by a local unitary transformation. For an X-state, the relevant quantity can be expressed entirely in terms of the two largest eigenvalues of the squared correlation matrix. When that function exceeds a fixed bound, the state is nonlocal in the Bell sense. The result depends on three variables: a decay parameter linked to the ratio of form factors, the relative phase between the form factors, and the scattering angle of the hyperon in the center-of-mass frame [24].

The analysis shows that the Bell-type inequality is violated only within a central band around $\pi/2$ of the scattering angle in $e^+e^- \to J/\psi \to Y\bar{Y}$ with $Y = \Lambda, \Sigma^+, \Xi^-, \Xi^0$. Near the beam direction, the Bell-type inequality is satisfied even though the entanglement may persist. The maximum violations of the Bell-type inequality (which must be larger than 2) are 2.214, 2.243, 2.318, 2.249 for $\Lambda\bar{\Lambda}$, $\Sigma^+\bar{\Sigma}^+$, $\Xi^-\bar{\Xi}^-$ and $\Xi^0\bar{\Xi}^0$ respectively [24].

The entanglement of $Y\bar{Y}$ is evaluated using the concurrence, a standard two-qubit entanglement monotone. The concurrence is found to be nonzero for the entire range of scattering angles except along the beam direction of e^+ or e^-, implying that the pairs are generically entangled. The scattering angle at which the entanglement is maximal does not always coincide with $\pi/2$. For $\Xi^-\bar{\Xi}^-$ and $\Xi^0\bar{\Xi}^0$, the peaks occur at angles displaced from $\pi/2$, reflecting the interplay between polarization and correlation components caused by the structure of a specific hyperon species and the production mechanism [24].

The violation of the Bell-type inequality and entanglement are connected but not equivalent. Every state that violates the Bell-type inequality is entangled, but the reverse is not guaranteed [24]. A hierarchy exists: while the concurrence indicates widespread entanglement across most scattering angles, the violation of the Bell-type inequality appears only within a restricted angular window. Another noteworthy feature emerges when the relative phase between the electric and magnetic form factors of the hyperon vanishes. In this limit a simple identity holds between the Bell variable and the entanglement measure for all scattering angles. This is the case for elementary particles: their electric and magnetic form factors are the same. It turns out to be a criterion for the compositeness of the particle in the pair production process whether the identity holds between the Bell variable and the entanglement measure [24].

3. *Spin correlations in heavy-ion collisions.* In order to describe the spin states of hadrons and hadron-hadron's spin correlations in heavy-ion collisions, we start from the spin density matrices for multi-quark systems [25]: $q_1\bar{q}_2$, $q_1q_2q_3$, $q_1q_2\bar{q}_3\bar{q}_4$, $q_1q_2q_3\bar{q}_4\bar{q}_5\bar{q}_6$, etc.. These spin density matrices incorporate spin correlations of multi-quark: two-quark correlation, three-quark correlation, etc.. The spin density matrices for hadrons can be obtained from those of two-quark (meson) and three-quark (baryon) through the transition matrices which map the quark state to hadron state [25]. The transition matrices play the role of the quantum measurement [23].

Different kinds to spin correlations in multi-quark systems are introduced [25]. The genuine correlations originate from the dynamics of productions and interactions. The induced correlations arise when one averages over other degrees of freedom such as coordinate or momentum variables. These can be nonzero even if the underlying state has no genuine multi-body spin correlation. In taking average over coordinate or momentum variables, one distinguishes the local and long range correlations depending on whether they are short or long ranged in phase space.

Starting from the spin density matrices of multi-quark systems, we can calculate those of vector mesons, hyperons and hyperon-antihyperon systems [25]. For vector mesons, the average of the spin density matrix elements involves the local spin correlation between the forming quark and antiquark within a compact region of phase space where they combine in the vector meson. For hyperons such as Λ, its spin polarization comes not only from that of the s quark but also from the correlations between the s quark and the light quarks (u and d). Consequently, the Λ polarization is equal to the polarization of the s quark only in the limit of negligible quark-quark correlations. The formalism can also be applied to hyperon-antihyperon spin correlations from the spin density matrix of three quarks and three antiquarks. Cross-terms involving correlations between an s quark in one hyperon and light quarks in the other also appear. Importantly, while vector-meson observables involve local correlations, hyperon-antihyperon spin correlations involve long-range correlations across the pair. This complementarity allows experiments to separate local and long-range components by comparing the vector meson's spin alignment to the spin correlation of hyperon-antihyperon in similar kinematic regimes.

With these relationships, we perform exploratory fits using available data for Λ's global polarization and vector-meson's spin alignment [25]. We can extract, in a model-guided way, the s quark polarization and the spin correlation of $s\bar{s}$ as functions of collision energy. Two scenarios are then considered for the $s\bar{s}$ correlation underlying hyperon-antihyperon pairs: one in which it is equal to the local correlation relevant for vector mesons, and another in which it vanishes. The resulting predictions for the spin correlation of hyperon-antihyperon diverge between these scenarios, which can be tested in future experiments.

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