PROCEEDINGS OF SCIENCE

The Ubiquitous Spin Correlation

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The longitudinal spin transfer, G_{1L}, describes the hadronization of polarized partons. It thus was usually measured in polarized reactions or high-energy collisions where weak interaction dominates. In a series of works, we propose the dihadron polarization correlation as a novel probe of this quantity. Such an observable does not require the fragmenting partons to be polarized and therefore can be measured in the currently available experimental facilities, such as e^+e^-, pp and ep colliders. We make quantitative predictions for these experiments. In light of the data already harvested, the experimental investigation of this observable provides more opportunity for the quantitative study of the longitudinal spin transfer. In particular, the measurements in unpolarized pp collisions can significantly constrain the fragmentation function of a circularly polarized gluon. This proceeding briefly summarizes the key concept.

QCD at the Extremes (QCDEX2025)
1–5 Sept 2025
Online

*Speaker

https://pos.sissa.it/

PoS(QCDEX2025)034

1. Introduction

Spin is always full of surprises. A successful theory must capture not only the dynamics in momentum space but also the intricate behavior in spin space. In the hadronization of high energy partons, the momentum space dynamics is characterized by the unpolarized fragmentation functions, which has been established fairly well through global analyses. In striking contrast, the polarized ones, describing how the spin polarization is transferred from partons to hadrons, remain less explored.

The reason is the following. Fragmentation functions are inherently non-perturbative objects, and first-principles calculations are not yet feasible. Their quantitative study therefore relies heavily on experimental input. However, producing polarized partons in experiments is highly challenging. Traditionally, one must either polarize the beams or work in kinematic regions where weak interactions dominate, so that the fragmenting quarks or gluons carry substantial polarization. Dedicated facilities capable of producing polarized partons were, and still are, exceedingly rare [1–3]. So far, the hadronization of polarized partons has only measured by the LEP experiment [4, 5], polarized semi-inclusive deep inelastic scattering (SIDIS) experiments [6, 7], neutrino SIDIS experiments [8], and RHIC experiment [9, 10]. This scarcity stands as the main bottleneck in advancing our understanding of spin-dependent fragmentation functions. Sizable uncertainties has been observed in the theoretical studies [11].

On the other hand, unpolarized hadron colliders have accumulated an abundance of high-quality experimental data. It would be extremely valuable if we could devise methods to extract spin effects directly utilizing these unpolarized facilities. A plausible approach has been emerged from a series of recent works [12–17]. It is built upon the fact that, even in unpolarized high-energy collisions, the final-state partons produced in the hard scattering still exhibit helicity correlations. These correlations provide a natural gateway to accessing spin-dependent fragmentation without the need for polarized beams. In this proceeding, we illustrate the underlying physical picture and summarize the key concepts behind this class of observables.

This proceeding is organized as follows. First, we discuss the spin correlations in electron-positron annihilations in Sec. II. Then, we apply this concept to the unpolarized proton-proton collisions. In the end, we give a summary in Sec. III.

2. Spin correlations in election-positron annihilations

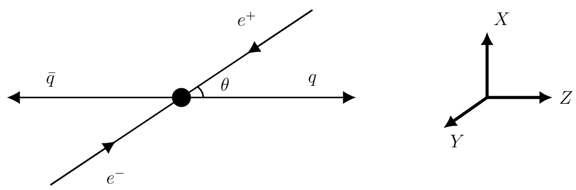

Figure 1: Reference frame for the $q\bar{q}$ production in e^+e^- annihilation.

At leading order, the quark and antiquark produced in electron–positron annihilation are almost back-to-back, where the relevant reference frame is illustrated in Fig. 1. In this setup, the quark momentum defines the positive Z-axis, while the incoming electron and positron lie in the XOZ-plane. The angle between the electron beam and the outgoing quark direction is denoted by θ. In spin space, the quark–antiquark pair can be viewed as a two-qubit system. The density matrix is then given by $\rho_{q\bar{q}} = \frac{1}{4}\left[\mathbb{I} + \sum_{ij} T_{ij}\sigma_i^q \otimes \sigma_j^{\bar{q}}\right]$, where T_{ij} encodes the spin correlation between quark and antiquark. In a general two-qubit system, the density matrix would also include terms describing the individual polarizations of each particle. In the case of electron–positron annihilation via electromagnetic interactions, however, parity is conserved, and neither the quark nor the antiquark acquires a net polarization. As a consequence, all single-spin terms vanish. Furthermore, the off-diagonal spin correlations disappear, leaving only the diagonal components given by

$$T_{ZZ} = 1, \qquad T_{XX} = \frac{\sin^2\theta}{1+\cos^2\theta}, \qquad T_{YY} = -\frac{\sin^2\theta}{1+\cos^2\theta}. \tag{1}$$

At $\theta = \pi/2$, the spin correlations along all three directions reach unity. In this special configuration, the final state quark-antiquark pair forms a Belle state with maximal entanglement. The maximal entanglement of dihadron pair production at the threshold region has also been investigated recently in Ref. [18]. The partonic spin correlations can be inherited by back-to-back dihadron through corresponding spin transfers. For example, the longitudinal spin correlation along the Z axis is transmitted through $G_{1L}^q G_{1L}^{\bar{q}}/D_1^q D_q^{\bar{q}}$. Likewise, the other two transverse spin correlations propagate into the hadronic final state via $H_{1T}^q H_{1T}^{\bar{q}}/D_1^q D_q^{\bar{q}}$.

However, QCD evolution affects these correlations: collinear splittings tend to reduce transverse spin polarization, leading to a decoherence effect [17]. As a result, the entanglement observed at the hadron level becomes significantly diluted compared to the maximal partonic entanglement at the hard-scattering scale.

3. Spin correlations in deep-inelastic scatterings

In electron–proton deep-inelastic scattering, back-to-back jets can also be produced in the final state. The process factorizes naturally into three stages. (1) The incoming electron emits a deeply virtual photon with $Q^2 = -q^2 \gg \Lambda_{\rm QCD}^2$. (2) The virtual photon interacts with a parton inside the proton and produces two nearly back-to-back jets. At leading order, two partonic channels contribute: $\gamma^* g \to q\bar{q}$ and $\gamma^* q \to qg$. (3) Each jet subsequently fragments into hadrons, and in particular may produce a Λ or $\bar{\Lambda}$ hyperon.

Since the exchanged photon is deeply virtual, both the physical transverse polarization components and the longitudinal polarization of the photon contribute to the hard-scattering process. The above factorization is an over-simplification. It only works when the azimuthal angle φ between the lepton plane and the hadronic plane has been integrated over. If we want to investigate the differential cross section as a function of φ, the interference between L/T and T/T photons leads to $\cos\varphi$ and $\cos 2\phi$ harmonics.

After averaging over the azimuthal angle, these L/T and T/T interference terms vanish and we arrive at the factorized framework mentioned above. The spin correlation in the $\gamma_L^* g$ process with a longitudinally polarized photon is rather interesting. The final state $q\bar{q}$ pair forms a Belle state regardless of the collision kinematics. Following a similar way in defining the reference frame. We define the final-state quark going direction as the Z axis. The Y axis is defined as the normal direction of the event plane, so that the incoming beams lie in the XOZ plane. The spin correlation matrix thus reads

$$T_{XX} = -1, \qquad T_{YY} = +1, \qquad T_{ZZ} = +1. \tag{2}$$

Notice that there is no θ-dependence in the above expression.

4. Spin correlations in hadronic collisions

In hadronic collisions, the structure of spin correlations becomes significantly more involved. Even at the leading order, eight partonic scattering channels contribute, and each channel exhibits its own characteristic pattern of spin correlations. These differences arise from the distinct helicity structures of the underlying QCD amplitudes.

Nonetheless, a perturbative calculation [19] shows that the *connected channels*, where the final state quark and antiquark are connected by the same Fermion line, contributes to the negative helicity correlation. The other channels contribute to the positive one. The partial cancellation significantly reduces the helicity correlation that can be observed in hadronic collisions. Nonetheless, future measurements of this observable can still shed new light on the quantitative study of the polarized fragmentation functions.

Concerning the transverse spin correlation, it is even more interesting. Since we are talking about spin-$1/2$ hyperon production in the collinear factorization, linearly polarized gluons cannot generate transversely polarized hyperons. Furthermore, these unconnected channels do not exhibit transverse spin correlation. Only the connected channels contribute. To be more explicit, we have contributions from the following channels: $q_i\bar{q}_i \to q_i\bar{q}_i$, $q_j\bar{q}_j \to q_i\bar{q}_i$, $gg \to q_i\bar{q}_i$ and $q_iq_i \to q_iq_i$. Notice that the last channel is the scattering of identical quarks where the transverse spin correlation arises from the interference between t-channel and u-channel diagrams. However, it would also be interesting to investigate the spin correlation between linearly polarized gluons in the future. This correlation can usually be expressed through two dihadron fragmentation functions, which describe the dihadron production inside of the single jet.

Investing the spin correlation per se in a variety of high energy collisions is already very interesting. On top of that, it also serves as a powerful tool to probe the spin aspect of jet quenching in relativistic heavy-ion collisions. A toy model calculation, implementing the energy loss effect, shows that the spin correlation observable is rather sensitive to the jet quenching effect. It is thus indeed plausible to investigate jet quenching from the spin degree-of-freedom.

5. Summary

In this proceeding, we demonstrated how spin correlations naturally arise in a variety of high-energy processes, even when the initial beams are unpolarized, and how these correlations provide new access to polarized fragmentation functions. In electron–positron annihilations, the quark–antiquark pair produced at leading order exhibits clean and highly structured spin correlations, reaching maximal entanglement at certain kinematics. These partonic correlations can be transmitted to back-to-back hadron pairs through the corresponding spin-transfer fragmentation functions, although QCD evolution inevitably introduces decoherence that reduces the observed hadron-level effects.

We extended this picture to deep-inelastic scattering and hadronic collisions, where additional partonic channels and helicity structures lead to more intricate correlation patterns. While cancellations across channels reduce the net observable correlation in proton–proton collisions, the surviving signals remain sensitive probes of polarized fragmentation. Moreover, spin-correlation observables offer a novel handle on the spin aspects of jet quenching in heavy-ion collisions. Together, these results highlight the potential of unpolarized facilities to significantly advance our understanding of spin-dependent hadronization dynamics.

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