Spin-spin correlations in $\Lambda\bar{\Lambda}$ pair production at the SPD experiment at NICA

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Abstract

Recent measurements by the STAR collaboration have demonstrated that spin correlations of $\Lambda\bar{\Lambda}$ pairs provide sensitivity to the spin structure of $s\bar{s}$ pairs produced in hadronic collisions via different mechanisms, as well as to the transfer of spin information through the hadronization process. These results, together with recent CMS measurements at higher energies, open a new avenue for studying spin dynamics in the transition from partons to hadrons.

A feasibility study of spin-spin correlations in $\Lambda\bar{\Lambda}$ pairs at the SPD experiment at NICA is presented for pp and dd collisions at $\sqrt{s_{NN}} \leq 27$ GeV. The expected correlation $P_{\Lambda\bar{\Lambda}}$ is estimated within the SU(6) and Burkardt–Jaffe models for a spin-triplet $s\bar{s}$ pair. The kinematic properties of the process are analysed, and the suitability of the detector for such measurements is evaluated using a full simulation. The SPD experiment is shown to provide an opportunity to investigate the relative contributions of non-perturbative and perturbative $s\bar{s}$-production mechanisms and to explore the role of initial-state polarization in spin-dependent partonic dynamics.

1 Introduction

The study of spin-spin correlations is a powerful tool in modern physics, providing insight into the nature of interactions across a wide range of energy scales and offering a unique window into quantum phenomena such as entanglement and decoherence. From atomic physics to high-energy collisions, measurements of spin-dependent observables allow one to probe the underlying dynamics of a system, test fundamental symmetries, and explore quantum phenomena such as entanglement and decoherence. In high-energy physics, spin correlations between final-state particles reflect the spin structure of the underlying interactions and provide a sensitive probe of production and decay dynamics.

The study of spin-spin correlations at the quark level is one of the actively developing directions of quantum chromodynamics. In 2023, the ATLAS experiment at the LHC observed for the first time quantum entanglement in the spin correlations of top–antitop quark pairs [1]. Top–antitop pairs in proton–proton collisions are produced predominantly via gluon fusion ($gg \to t\bar{t}$). Near the production threshold, the spin density matrix of the $t\bar{t}$ system is dominated by a spin-singlet component, which corresponds to a maximally

entangled state. This was the first observation of quantum entanglement for a quark pair. These results have been confirmed and extended by measurements at CMS [2, 3].

The analysis of spin correlations at the level of secondary hadrons takes research to a new level. Thus, in the BESIII experiment, in the cascade decay $J/\psi \to \gamma\eta_c$, $\eta_c \to \Lambda\bar{\Lambda}$, a violation of Bell-like inequalities was observed for the first time in high-energy physics with a significance of more than 5σ [4]. This result provides a stringent test of local realism and constitutes evidence for quantum entanglement in the final-state hyperon pair.

The STAR experiment subsequently observed significant spin-spin correlations between Λ and $\bar{\Lambda}$ hyperons in proton–proton collisions, consistent with the interpretation that spin correlations of $s\bar{s}$ pairs produced from the QCD vacuum in a spin-triplet state can survive hadronization and be transferred to the final-state hyperons [5]. The correlation was found to be larger for smaller angular separations between the hyperons. Thus, measurements of spin correlations in hadronic final states provide a new way to investigate the interplay between quantum correlations and non-perturbative QCD dynamics during hadronization.

2 Spin correlations in strangeness production in hadronic collisions

In proton–proton collisions at the collision energy studied by STAR ($\sqrt{s} = 200$ GeV) and at lower energies, several mechanisms of $s\bar{s}$ pair production can be relevant. In the non-perturbative regime, $s\bar{s}$ pairs originating from the QCD vacuum (Fig. 1(a)) are expected to inherit the vacuum quantum numbers, $J^{PC} = 0^{++}$, which correspond to a $^3P_0$ state for a quark–antiquark pair. Another mechanism is gluon splitting in the parton shower, $g \to s\bar{s}$ (Fig. 1(b)), which can produce pairs with an opposite-sign spin correlation. Both mechanisms can produce $s\bar{s}$ pairs with small angular separation. In addition, hard processes such as gluon–gluon fusion, $gg \to s\bar{s}$, and quark–antiquark annihilation, $q\bar{q} \to s\bar{s}$ (Fig. 1(c) and (d), respectively), may contribute to the observed spin-spin correlations and can populate larger angular separations.

The possibility of using $\Lambda\bar{\Lambda}$ spin correlations to probe the mechanism of $s\bar{s}$ pair production at the quark level in hadronic collisions was investigated in Ref. [10]. In that

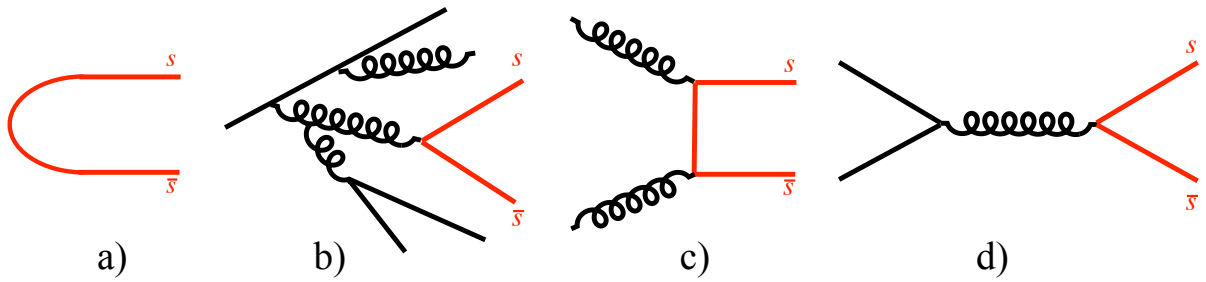

Figure 1: $s\bar{s}$-pair production mechanisms: materialisation of a triplet spin state from the QCD vacuum condensate (a); gluon splitting in the parton shower evolution (b); production in a hard interaction: gluon-gluon fusion (c) and quark-antiquark annihilation (d).

work, several perturbative production mechanisms were considered, including gluon splitting $g \to s\bar{s}$ and gluon–gluon fusion $gg \to s\bar{s}$. The resulting spin correlation depends on the spin state of the produced $s\bar{s}$ pair: a $^3S_1$ state gives a positive correlation, whereas a $^1S_0$ state gives a negative correlation. These different spin-correlation patterns provide a basis for studying the underlying mechanisms of $s\bar{s}$ pair production experimentally.

More recently, it was proposed in Ref. [11] that $\Lambda\bar{\Lambda}$ spin correlations can be used to probe quantum entanglement and to test Bell-type inequalities at high-energy colliders, establishing a direct connection between QCD dynamics and quantum information. The study also showed that the degree of quantum entanglement decreases with increasing hadron multiplicity, while the spin correlation itself can remain sizeable. Since the average hadron multiplicity generally increases with collision energy, the lower-energy regime accessible at NICA provides a complementary environment for studying quantum correlations with reduced multiplicity-induced dilution.

Measurement of spin-spin correlations of hyperon pairs in the final state allows one to probe both the production mechanism of $s\bar{s}$ pairs and their spin state, as well as the transfer of spin correlations from quarks to hyperons during hadronization. The $\Lambda\bar{\Lambda}$ pair is particularly suitable for such a probe because the Λ hyperon has a self-analyzing weak decay $\Lambda \to p\pi^-$ with a decay asymmetry parameter $\alpha_- \approx 0.75$ and a branching fraction of 63.9%. However, the situation is complicated by the fact that a significant fraction of strange quarks hadronize into strange hadrons heavier than the Λ, which subsequently decay into Λ hyperons (feed-down contribution). In the STAR kinematics, the fraction of $\Lambda\bar{\Lambda}$ pairs in which both hyperons are primary (i.e., produced directly in the fragmentation process rather than through decays of heavier strange hadrons) is only about 11%.

For reconstructed decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$, the (anti-)protons were boosted into the rest frames of their parent hyperons, and the angle $\theta^\star$ between the two boosted (anti-)protons was determined. The angular distribution was expected to be the following:

$$\frac{1}{N}\frac{dN}{d\cos\theta^\star} = \frac{1}{2}(1 + \alpha_-\alpha_+ P_{\Lambda\bar{\Lambda}}\cos\theta^\star). \tag{1}$$

Here $P_{\Lambda\bar{\Lambda}}$ is the spin correlation signal, α_- and α_+ are Λ and $\bar{\Lambda}$ decay parameters ($\alpha_- = 0.747 \pm 0.009$, α_+ = -0.757±0.004). For a spin-triplet $s\bar{s}$ state, the corresponding spin-spin correlation is $P_{\Lambda\bar{\Lambda}} = 1/3$, whereas a spin-singlet state gives $P_{\Lambda\bar{\Lambda}} = -1$ as the average of the product of the spin projections onto a quantization axis. Similar analysis was also performed for sets of $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs as well as $K^0_sK^0_s$ pairs to control systematic effects. This control sample is insensitive to spin correlations, as the K^0_s is a spin-0 meson, and serves to validate the background estimation procedure.

The SU(6) quark model [6] and the Burkardt–Jaffe model [7] were used to describe the transfer of spin polarization from quarks to final-state Λ and $\bar{\Lambda}$ hyperons including their production through higher states. The maximum expected values of the spin-spin correlation $P_{\Lambda\bar{\Lambda}}$ were estimated to be 0.096 ± 0.004 and 0.015 ± 0.002 for the SU(6) and the Burkardt–Jaffe models, respectively.

The STAR experiment observed for the first time a significant spin-spin correlation between Λ and $\bar{\Lambda}$ hyperons: $P_{\Lambda\bar{\Lambda}} = 0.181 \pm 0.035_{\text{stat}} \pm 0.022_{\text{syst}}$. The observed correlation is consistent with the interpretation that $s\bar{s}$ pairs originating from the QCD vacuum form a quantum-entangled spin-triplet state and retain their spin correlation during hadronization, which is subsequently transferred to the final-state hyperons. A key observation is that the correlation is observed for hyperons emitted at small angular separations, $|\Delta y| < 0.5$ and $|\Delta\phi| < \pi/3$, and decreases with increasing angular separation. This result

provides a new experimental tool to probe non-perturbative QCD, enabling the study of confinement dynamics and the role of spin degrees of freedom in the transition from quarks to hadrons.

Recently, the CMS collaboration at the LHC has significantly extended these studies by reporting the first measurement of spin-spin correlations of hyperon pairs in pp collisions at $\sqrt{s} = 13$ TeV and in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [8]. In contrast to the positive correlation observed by STAR for $\Lambda\bar{\Lambda}$ pairs at $\sqrt{s} = 200$ GeV, CMS found negative values for $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs at small angular separations, of about -0.1, while no significant signal was observed for $\Lambda\bar{\Lambda}$ pairs.

An attempt to explain the observed dependence of the spin correlation on the angular separation $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$ was made in Ref. [9] within the framework of open quantum systems. In this phenomenological approach, the $s\bar{s}$ pair is treated as an open quantum system interacting with the surrounding hadronic environment during hadronization. The loss of spin information is described by a depolarizing channel with a separation-dependent decoherence rate, leading to an exponential suppression of $P_{\Lambda\bar{\Lambda}}$ with increasing ΔR. The model provides a reasonable description of both the STAR and CMS data. Within this framework, the observed decrease of the spin correlation with ΔR is interpreted as a manifestation of quantum decoherence during the transition from quarks to hadrons.

These results suggest that the mechanisms governing hyperon production and spin transfer may depend on the collision energy and collision system, making the intermediate-energy range accessible at NICA particularly relevant for further studies.

3 Physics prospects for spin-spin correlations in $\Lambda\bar{\Lambda}$ pairs production at SPD

The Spin Physics Detector (SPD) project at the NICA collider plans to study the spin structure of nucleons and spin-dependent effects in collisions of polarized protons and deuterons at energies up to 27 GeV [12, 13]. Already in the first phase of the experiment, the SPD tracking system will be available, consisting of the main tracker based on straw tubes and the central tracker based on Micromegas detectors, placed in the magnetic field of a superconducting solenoid with a field of 1 T [14]. Such a configuration of the experimental setup will make it possible to study spin-spin correlations in hyperon production from the beginning of the experiment. In its complete configuration, the detector will feature improved tracking performance and enhanced capabilities for secondary particle identification.

The study of $\Lambda\bar{\Lambda}$ spin correlations at SPD can address several complementary questions. First, the lower collision energies and, consequently, lower event multiplicities accessible at NICA provide a complementary environment for searching for quantum entanglement in the $\Lambda\bar{\Lambda}$ system and for studying its relation to the spin density matrix. Second, measurements of the spin correlation as a function of the angular separation ΔR at energies below those explored by STAR and CMS will provide a new test of the mechanisms responsible for spin decoherence during hadronization. The dependence on event multiplicity can further help to disentangle decoherence effects associated with the hadronic environment. Third, the energy, kinematic, and beam-polarization dependences of the correlations can provide sensitivity to different mechanisms of $s\bar{s}$ production, including non-perturbative production, gluon splitting, and hard scattering. Finally, measurements

with different Λ parentage and spin-dependent observables can provide information on the transfer of the s-quark polarization to the final-state hyperons.

The possibility of using beam polarization is particularly important for the latter two questions. In collisions of longitudinally polarized protons or deuterons, the spin-spin correlations of $\Lambda\bar{\Lambda}$ pairs may acquire a dependence on the beam spin configuration. Different mechanisms of $s\bar{s}$-pair production can respond differently to the polarization of the initial partons. The production of $s\bar{s}$ pairs through a non-perturbative mechanism associated with the QCD vacuum is not expected to have a direct dependence on the beam polarization, whereas spin-dependent hard processes and the spin-dependent partonic structure of the initial state can introduce such a dependence. Spin-dependent effects in the parton shower may further modify the observed correlations. Thus, measurements with longitudinally polarized beams at SPD provide an opportunity not only to study hyperon spin-spin correlations, but also to investigate the role of initial-state polarization and spin-dependent partonic dynamics in their production. In transversely polarized collisions, spin-dependent hard processes and parton-shower dynamics can give rise to azimuthal modulations of the measured $\Lambda\bar{\Lambda}$ spin correlations.

4 Expectations and detector performance

The maximum expected $\Lambda\bar{\Lambda}$ spin-spin correlation for a spin-triplet $s\bar{s}$ pair, based on the SU(6) quark model and the Burkardt–Jaffe model, is calculated according to

$$P_{\Lambda\bar{\Lambda}} = \frac{1}{3}\sum_{i,j} R_{ij}\, P^i_{\Lambda} P^j_{\bar{\Lambda}}, \tag{2}$$

where R_{ij} is the fraction of $\Lambda\bar{\Lambda}$ pairs in which the Λ and $\bar{\Lambda}$ belong to production categories i and j, respectively, as estimated using the PYTHIA 8.312 event generator [15] (see Fig. 2(a)). The quantities P^i_{Λ} ($P^j_{\bar{\Lambda}}$) denote the contribution of the s ($\bar{s}$)-quark spin to the spin of a Λ ($\bar{\Lambda}$) hyperon produced either directly or through the decay of a heavier state (see Table 1).

Figure 2(b) shows the maximum correlation $P_{\Lambda\bar{\Lambda}}$ as a function of proton-proton collision energy $\sqrt{s}$, calculated within the SU(6) and Burkardt-Jaffe (BJ) models. The solid curves represent the total correlation including all pairs. The increase in the correlation at lower collision energies is driven by the rapid decrease of the feed-down contribution. The dashed curves correspond to the scenario where pairs in which at least one hyperon does not point to the primary vertex (i.e., is identified as originating from feed-down from Ξ hyperons) are excluded. As one can see, the Ξ feed-down contribution significantly modifies the prediction of the BJ model due to the negative sign of the corresponding spin-transfer coefficient $P_{\Lambda(\bar{\Lambda})}$, while its effect on the SU(6) model prediction is negligible. Assuming that nuclear effects are negligible, a similar spin-transfer pattern is expected for dd collisions as a consequence of isospin symmetry.

To assess the applicability of the PYTHIA description of strangeness production over the energy range under study, the calculated Ξ^-/Λ and Σ^0/Λ yield ratios were compared with experimental measurements obtained at $\sqrt{s} = 17.3$ and 7.3 GeV, respectively. The results of the comparison are presented in Fig. 3(a). Taking into account the experimental uncertainties, satisfactory agreement between the calculations and the experimental data is observed.

Figure 3(b) shows the angular separation ΔR of the $\Lambda\bar{\Lambda}$ pairs, while Fig. 4 presents the distributions of the pairs in transverse momentum p_T and rapidity y for $\sqrt{s} = 27$ GeV. The

Table 1: Contribution of the s-quark spin to the spin of a Λ hyperon produced either directly or through the feed-down mechanism calculated within the SU(6) and Burkardt–Jaffe models [16]

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Λ's parent	$c\tau$, cm	Main decay channel, %	$P_{\Lambda(\bar{\Lambda})}$, SU(6) model	$P_{\Lambda(\bar{\Lambda})}$, Burkardt–Jaffe model
s-quark	-	-	1	0.63
Σ^0	2.2×10^{-9}	$\Lambda\gamma$, 100	1/9	0.15
Ξ^0	8.7	$\Lambda\pi^0$, 99.5	0.6	-0.37
Ξ^-	4.9	$\Lambda\pi^-$, 99.9	0.6	-0.37
$\Sigma^*(1385)$	7×10^{-13}	$\Lambda\pi$, 87	5/9	-

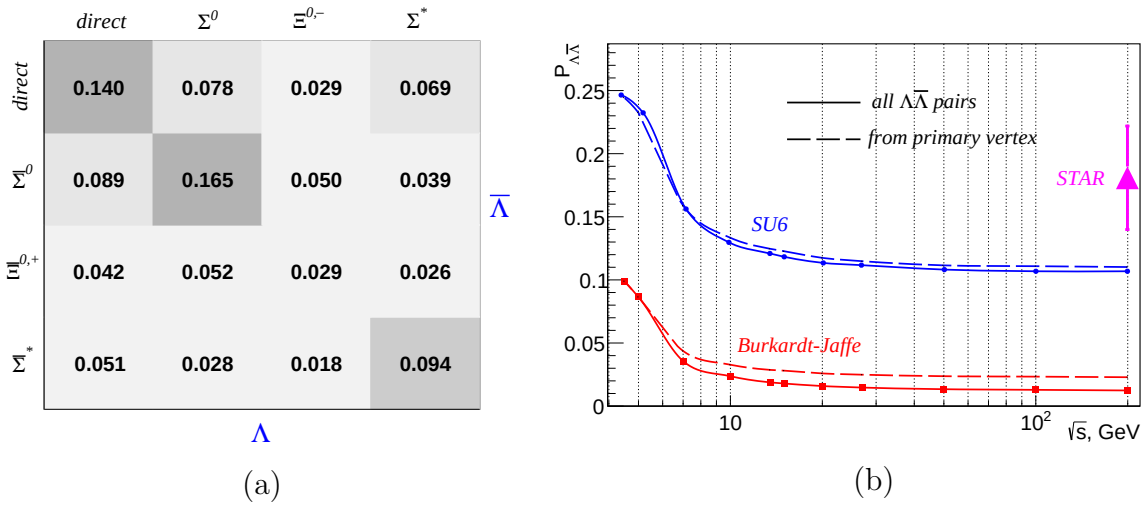


Figure 2: Relative contributions R_{ij} of different sources of $\Lambda\bar{\Lambda}$ pairs in pp collisuins at $\sqrt{s}$ =27 GeV (a). Maximum correlation $P_{\Lambda\bar{\Lambda}}$ as a function of collision energy $\sqrt{s}$ estimated within the SU(6) and BJ models for all pairs (solid) and for the case when at least one hyperon does not point to the primary vertex (dashed) (b).

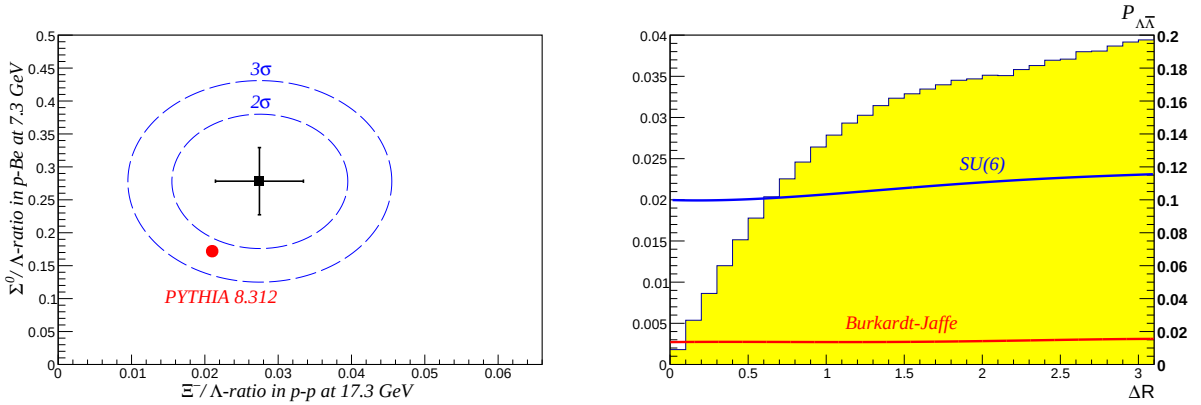
right-side axes of these figures also show the corresponding maximum spin correlation $P_{\Lambda\bar{\Lambda}}$ as a function of these variables, evaluated within the SU(6) and BJ models. The notable dependence of $P_{\Lambda\bar{\Lambda}}$ on rapidity can be attributed to the fact that pairs with a feed-down contribution tend to be emitted, on average, at larger angles relative to the beam axis.

The expected inclusive cross section for $\Lambda\bar{\Lambda}$ pair production as a function of collision energy for pp and dd collisions, according to PYTHIA, is shown in Fig. 5(b). For the estimation of the cross section for dd collisions, the Angantyr framework within PYTHIA was employed. This framework uses a Glauber-based initial-state description to determine the number and geometry of nucleon–nucleon subcollisions and does not take into account collective behaviour of nucleons that may lead to a slight underestimation of the cross section near the threshold.

The efficiency for the simultaneous reconstruction of the decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ was estimated using a full simulation of the SPD detector in its complete configuration at a collision energy of 27 GeV and in the initial configuration at 10 GeV, performed with the SPDROOT software package. The main event selection criteria were the poor

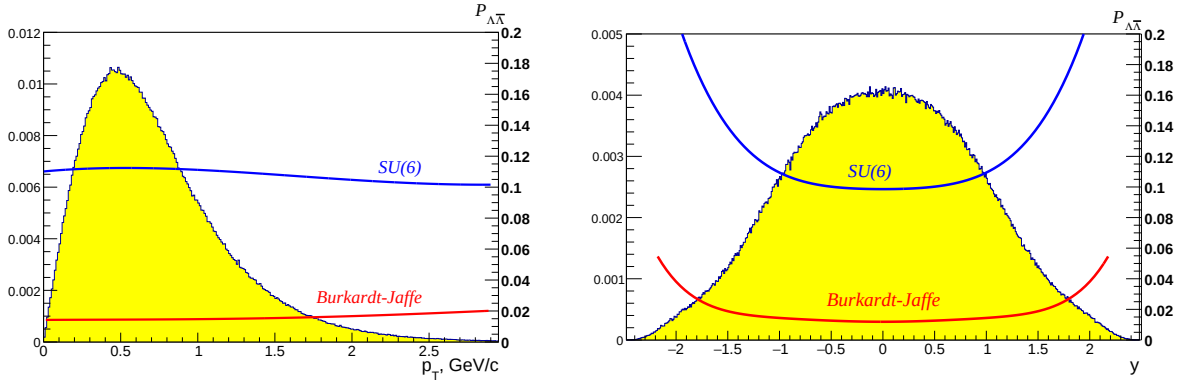
Table 2: Ratios of hyperon yields measured in the experiment as compared with those obtained from PYTHIA.

Ratio	$\sqrt{s}$, GeV	Measurement	PYTHIA 8.312
Ξ^-/Λ	17.3 (p-p)	0.028±0.0060 [17, 18]	0.021
Σ^0/Λ	7.3 (p-Be)	0.278±0.051 [19]	0.171



(a) (b)

Figure 3: Ratios of hyperon yields measured in the experiment as compared with those obtained from PYTHIA (a). Angular separation ΔR of Λ and $\bar{\Lambda}$ distribution for $\sqrt{s} = 27$ GeV (b).

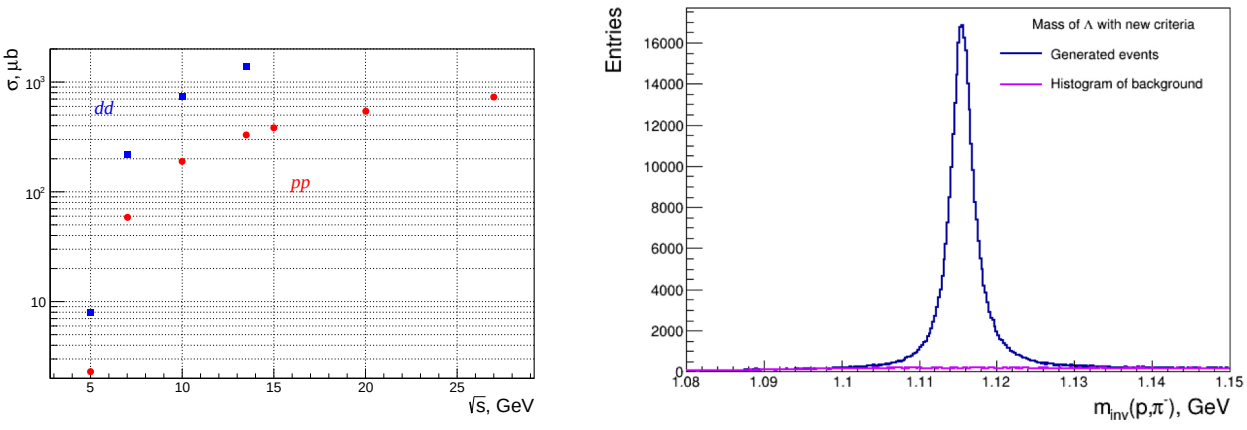


(a) (b)

Figure 4: Distributions for transverse momentum p_T (a) and rapidity y (b) of $\Lambda\bar{\Lambda}$ pairs for $\sqrt{s} = 27$ GeV.

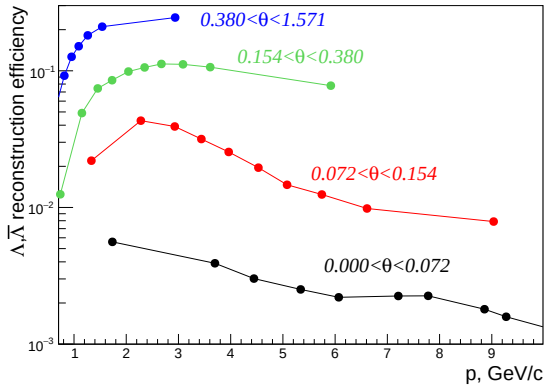
association of charged daughter tracks with the primary vertex, the distance from the candidate $\Lambda(\bar{\Lambda})$ decay vertex to the primary vertex, and the angle between the hyperon momentum direction and the vector connecting the primary and secondary vertices. Over the full kinematic range, the reconstruction efficiency is found to be 1.5% and 0.4% for 27 GeV and 10 GeV, respectively. These values do not include the potential inefficiency associated with the software trigger (online filter). The corresponding suppression may reach tens of percent at low energy and up to a factor of several at high energy.

The main sources of systematic uncertainties in the measurement of spin-spin correlations at the SPD experiment are expected to be the residual background contributions



(a) (b)

Figure 5: Inclusive cross section for $\Lambda\bar{\Lambda}$ pair production as a function of collision energy $\sqrt{s_{NN}}$ for pp and dd collisions (a).



(a)

under the signal peak, despite the sideband subtraction, as well as the systematics related to the normalisation of the angular distributions. Following the approach adopted by STAR, the systematic effects can be estimated by analysing the control sample of $K^0_s K^0_s$ pairs, where, due to the scalar nature of these mesons, no spin correlations are expected to be observed.

5 Conclusion

In this work, we have studied the feasibility of measuring spin-spin correlations in $\Lambda\bar{\Lambda}$ pairs at the SPD experiment, focusing on the intermediate-energy regime accessible at the NICA collider. The expected production rates, the relative contributions of different sources of $\Lambda\bar{\Lambda}$ pairs, and the reconstruction efficiency were evaluated using the Pythia 8 event generator and a full simulation of the SPD detector.

The maximum expected spin-spin correlation $P_{\Lambda\bar{\Lambda}}$ was estimated within the SU(6) and Burkardt–Jaffe models for a spin-triplet $s\bar{s}$ state, taking into account both direct production and feed-down contributions. The results show that the predicted correlation increases towards lower collision energies, driven by the rapid decrease of the feed-down contribution. The Ξ feed-down contribution significantly modifies the prediction of the

Burkardt–Jaffe model because of the opposite sign of the corresponding spin-transfer coefficient, whereas its effect on the SU(6) prediction is small. The comparison of the Ξ^-/Λ and Σ^0/Λ yield ratios with available experimental measurements provides a validation of the PYTHIA-based description of strange-hadron production in the energy range relevant for the study.

The SPD energy range also provides several complementary opportunities for studying the physics of spin correlations in hyperon production. Measurements of $P_{\Lambda\bar{\Lambda}}$ as a function of the angular separation ΔR at collision energies below those explored by STAR and CMS can provide a new test of the mechanisms responsible for the loss of spin correlations during hadronization. In combination with measurements as a function of event multiplicity, such studies can help clarify the interplay between the angular separation of the hyperons and the surrounding hadronic environment in the decoherence of spin correlations.

The relatively low multiplicities expected at NICA also provide a complementary regime for searching for quantum entanglement in the $\Lambda\bar{\Lambda}$ system. A measurement of the full spin density matrix, rather than only the spin-spin correlation coefficient, would allow entanglement-sensitive observables and Bell-type inequalities to be investigated. Such a measurement would provide a substantially stronger test of the quantum nature of the correlations than the measurement of $P_{\Lambda\bar{\Lambda}}$ alone.

Furthermore, the dependence of the correlations on collision energy, kinematics, and beam polarization can provide sensitivity to different $s\bar{s}$ production mechanisms, including non-perturbative production, gluon splitting, and hard scattering. In particular, measurements with longitudinally and transversely polarized beams can probe the role of initial-state polarization and spin-dependent partonic dynamics. Measurements with different Λ parentage can additionally constrain the transfer of spin information from the s quark to the final-state hyperon and help distinguish direct production from feed-down contributions.

These results demonstrate that the SPD experiment can extend the study of hyperon spin correlations to a previously unexplored energy domain. The combination of collision-energy, angular-separation, multiplicity, kinematic, and beam-polarization dependences makes SPD a promising facility for studying the evolution of spin correlations from $s\bar{s}$ production to the final-state $\Lambda\bar{\Lambda}$ system, including their possible quantum origin, decoherence during hadronization, production mechanisms, and spin transfer.

References

[1] G. Aad *et al.* [ATLAS], "Observation of quantum entanglement with top quarks at the ATLAS detector," Nature **633** (2024) no.8030, 542-547

[2] A. Hayrapetyan *et al.* [CMS], "Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV," Rept. Prog. Phys. **87** (2024) no.11, 117801

[3] E. Yazgan, "Measurements of top quark properties in CMS: $\mathrm{tt}^{-}\mathrm{tt}^{-}$ spin density matrix, quantum entanglement and quantum magic," PoS **EPS-HEP2025** (2026), 273

[4] M. Ablikim *et al.* [BESIII], "Test of local realism via entangled $\Lambda\bar{\Lambda}$ system," Nature Commun. **16** (2025), 4948

[5] B. E. Aboona *et al.* [STAR], "Measuring spin correlation between quarks during QCD confinement," Nature **650** (2026) no.8100, 65-71

[6] F. A. Riazuddin "Modern Introduction to Particle Physics," Physics **159** (2011) 180

[7] M. Burkardt and R. L. Jaffe, "Polarized $q \to \Lambda$ fragmentation functions from $e^+e^- \to \Lambda + X$," Phys. Rev. Lett. **70** (1993), 2537-2540

[8] [CMS], "Measurements of Lambda hyperon spin correlations in proton-proton and proton-lead collisions," CMS-PAS-HIN-26-002 (2026).

[9] J. Barata, I. Cuntín, E. Rico and B. Wu, "$\Lambda\bar{\Lambda}$ spin correlations in high-energy collisions from quantum channels: an open quantum system view of hadronization," arXiv:2606.30737 [hep-ph].

[10] J. Ellis and D. S. Hwang, "Spin Correlations of Lambda anti-Lambda Pairs as a Probe of Quark-Antiquark Pair Production," Eur. Phys. J. C **72** (2012), 1877

[11] W. Gong, G. Parida, Z. Tu and R. Venugopalan, "Measurement of Bell-type inequalities and quantum entanglement from Λ-hyperon spin correlations at high energy colliders," Phys. Rev. D **106** (2022) no.3, L031501

[12] A. Arbuzov, A. Bacchetta, M. Butenschoen, F. G. Celiberto, U. D'Alesio, M. Deka, I. Denisenko, M. G. Echevarria, A. Efremov and N. Y. Ivanov, *et al.* "On the physics potential to study the gluon content of proton and deuteron at NICA SPD," Prog. Part. Nucl. Phys. **119** (2021), 103858

[13] V. V. Abramov, A. Aleshko, V. A. Baskov, E. Boos, V. Bunichev, O. D. Dalkarov, R. El-Kholy, A. Galoyan, A. V. Guskov and V. T. Kim, *et al.* "Possible Studies at the First Stage of the NICA Collider Operation with Polarized and Unpolarized Proton and Deuteron Beams," Phys. Part. Nucl. **52** (2021) no.6, 1044-1119

[14] V. Abazov *et al.* [SPD], "Technical Design Report of the Spin Physics Detector at NICA," Natural Sci. Rev. **1** (2024), 1

[15] C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, P. Ilten, L. Lönnblad, S. Mrenna, S. Prestel and C. T. Preuss, *et al.* "A comprehensive guide to the physics and usage of PYTHIA 8.3," SciPost Phys. Codeb. **2022** (2022), 8

[16] J. R. Ellis, A. Kotzinian, D. Naumov and M. Sapozhnikov, "Longitudinal Polarization of Lambda and anti-Lambda Hyperons in Lepton-Nucleon Deep-Inelastic Scattering," Eur. Phys. J. C **52** (2007), 283-294

[17] A. Aduszkiewicz *et al.* [NA61/SHINE], "Production of Λ -hyperons in inelastic p+p interactions at 158 GeV/c," Eur. Phys. J. C **76** (2016) no.4, 198

[18] A. Aduszkiewicz *et al.* [NA61/SHINE], "Measurements of Ξ^- and $\overline{\Xi}^+$ production in proton-proton interactions at $\sqrt{s_{NN}} = 17.3$ GeV in the NA61/SHINE experiment," Eur. Phys. J. C **80** (2020) no.9, 833 [erratum: Eur. Phys. J. C **82** (2022) no.2, 174]

[19] E. C. Dukes, "Measurement of the ratio of Σ^0/Λ inclusive production and the Σ^0 and Λ polarizations by 28.5 GeV/C protons on beryllium," AIP Conf. Proc. **187** (2008), 58-65