PROCEEDINGS OF SCIENCE

Measurement of Λ^0-hyperon spin-spin correlations in p+p collisions at $\sqrt{s}$ = 200 GeV by the STAR experiment

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About 50 years ago, it was discovered that Λ^0 hyperons are produced polarized in collisions of unpolarized protons on beryllium. Despite enormous experimental and theoretical efforts, the origin of this polarization remains inconclusive to date. The Λ^0 polarization has also been observed in various collision systems, from e^++e^- to heavy-ion collisions. A recently proposed technique for the investigation of the Λ^0 hyperon polarization is a measurement of $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ spin-spin correlations. This technique is expected to help understand if the polarization is generated at early stages of the collisions, e.g. from initial state parton spin correlation, or if it is a final state effect originating from hadronization.

In these proceedings, we present a status of the first measurement utilizing this new experimental method in p+p collisions at $\sqrt{s}$ = 200 GeV by the STAR experiment. The Λ^0 and $\bar{\Lambda}^0$ candidates are reconstructed at mid-rapidity ($|y| < 1$) and in two transverse momentum (p_{T}) bins which allows us to extract the Λ^0-hyperon spin-spin correlations for various p_{T} combinations of hyperons in $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ pairs. This measurement will provide new insight into Λ^0 hyperon spin polarization in p+p collisions at RHIC energies.

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1. Introduction

The Λ^0 hyperons have an interesting property that they can be produced polarized in collisions of unpolarized particles. This phenomenon was first observed in Fermilab in collisions of 300 GeV proton beam with a Be target, where neither the beam or target was polarized. Since then, many more experimental measurements of the Λ polarization were performed and theoretical models attempted to explain the origin of the polarization were developed, but no definitive answer has been found yet.

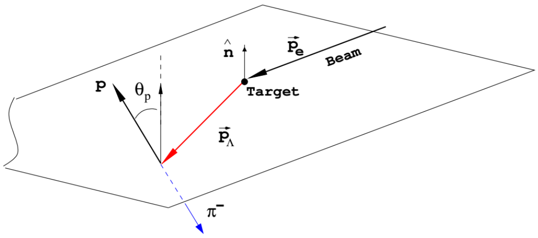

Figure 1: Cartoon illustrating definition of production plane used in single Λ^0 hyperon polarization analyses. Taken from Ref. [1].

In the standard experimental method, the Λ^0 hyperon polarization is measured with respect to the production plane. As shown in Fig. 1, the production plane is defined by the momentum of the beam (p_e) and the momentum of the Λ^0 hyperon (p_{Λ^0}). Only events where the Λ^0 ($\bar{\Lambda}^0$) hyperon decays via the hadronic decay channel $\Lambda^0 \rightarrow p\pi^-$ ($\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+$) are selected. The polarization is then quantified by measurement of the angle θ_p between the momentum of the decay proton boosted into the rest frame of the mother (p) and the normal vector to the production plane ($\hat{n}$). The polarization P_Λ can be then determined from the angular distribution of the decay protons given by:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^\star)} = 1 + \alpha P_\Lambda \cos(\theta_\mathrm{p}), \tag{1}$$

where α is the weak decay parameter of the Λ^0 hyperons: Λ^0: $\alpha_+ = 0.732 \pm 0.014$, $\bar{\Lambda}^0$: $\alpha_- = -0.758 \pm 0.012$ [2].

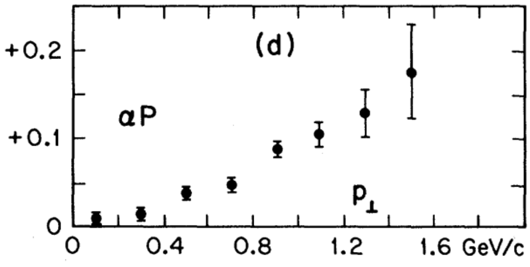

Figure 2: Single Λ^0 polarization as a function of p_T measured in p+Be collisions with 300 GeV proton beam on a Be target measured in Fermilab. Taken from Ref. [3].

An example of a measurement using this method is shown in Fig. 2, which shows the Λ^0 hyperon polarization as a function of Λ^0 hyperon transverse momentum (p_T) in p+Be collisions with 300 GeV proton beam on a Be target. As mentioned earlier, this is the first ever experimental observation of the Λ^0 hyperon polarization.

Over the last 50 years, various experimental methods were developed in order to understand the Λ^0 hyperon polarization. In general, one common modification of the standard method described in the previous section is an alternative selection of the reference direction for the polarization measurement. An example of a few such measurements can be found in Ref. [4–6].

Overall, the main experimental observations in Λ^0 hyperon polarization measurements can be summarized in a few points. Firstly, the Λ^0 hyperon polarization depends mainly on $x_\mathrm{F} = p_\mathrm{z}/p_\mathrm{beam}$, where p_z is the component of the Λ^0 momentum along the beam axis and p_beam is the beam momentum. The polarization is larger for larger values of x_F [4]. The second important observation is that the polarization is observed also in e^++e^- collisions [5]. This indicates importance of final state effects on the polarization, as there are no hadrons in the initial state which could induce the polarization. Similar conclusion can be done from spin transfer measurement which attempts to evaluate if polarization of the beam has any influence on the polarization of the produced Λ^0 hyperons. Current results from the STAR experiment with polarized p+p collisions indicate that the Λ^0 hyperon polarization does not depend on the beam polarization [6].

2. Λ^0 hyperon spin-spin correlations

A new, alternative, method is the measurement of $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ pair spin-spin correlations. Compared to the standard method, this new method is similar, but the reference direction to measure the polarization of one Λ^0 ($\bar{\Lambda}^0$) is the polarization of the second Λ^0, or $\bar{\Lambda}^0$ hyperon in the same event, rather than the normal vector to the production plane. Both of the hyperons in the pair are required to decay via the $p\pi^-$ ($\bar{p}\pi^+$) decay channel. The momenta of the decay protons are subsequently boosted into the rest frame of their mother and the angle ($\theta^\star$) between the boosted momenta is measured.

The angular distribution of the proton pairs then follows:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^\star)} \propto 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^\star), \tag{2}$$

where α_1 and α_2 are the weak decay constants of the hyperons in the pair and $P_{\Lambda_1\Lambda_2}$ is the level of spin-spin correlation of the pair.

Most of the previous Λ^0 hyperon polarization measurements indicate the importance of the final state effects, such as fragmentation and hadronization. The main advantage of this new method is that it should be sensitive to initial state correlations between s (anti-)quark pairs produced in hard partonic scattering [7, 8].

3. Results

The dataset used in this analysis are p+p collisions at $\sqrt{s} = 200$ GeV collected by the STAR experiment in 2012. A total of 400M minimum bias events was accepted for the analysis. A pure samples of protons and pions were selected from those events using the Time Projection Chamber detector which are then paired to form unlike-sign (US) $p\pi$ pairs ($p\pi^-$ and $\bar{p}\pi^+$) and like-sign (LS) $p\pi$ pairs ($p\pi^+$ and $\bar{p}\pi^-$).

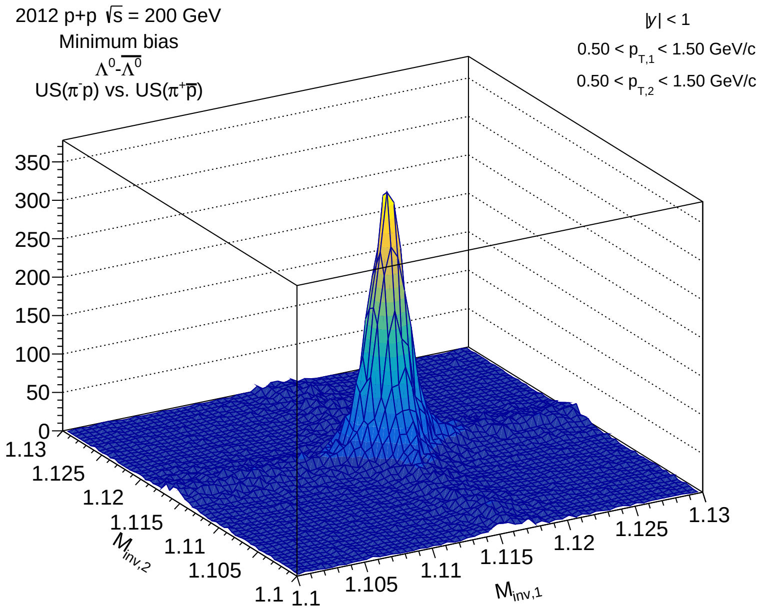

Figure 3: 2D invariant mass distribution for US-US $p\pi$ pairs for $\Lambda^0\bar{\Lambda}^0$ pair candidates. Both Λ^0 and $\bar{\Lambda}^0$ have $0.5 < p_\mathrm{T} < 1.5\,\mathrm{GeV}/c$.

The signal region is determined from 2D invariant mass (M_inv) distributions of the $p\pi$ pairs. The distribution containing both signal and combinatorial background is formed by pairing an US $p\pi$ pair with a different US $p\pi$ pair from the same event and is denoted (US-US). An example of such 2D distribution for $\Lambda^0\bar{\Lambda}^0$ pair candidates is shown in Fig. 3. The large peak in the middle corresponds to true $\Lambda^0\bar{\Lambda}^0$ pairs, the combinatorial background is then visible as the two ridges and the continuum outside of the true $\Lambda^0\bar{\Lambda}^0$ pair peak.

The combinatorial background is estimated using an US $p\pi$ pair with a LS $p\pi$ pair from the same event which is further denoted (US-LS). This selection ensures that the background contains both components described above. The two ridges originate from true Λ^0 or $\bar{\Lambda}^0$ hyperons paired with combinatorial background $p\pi$ pair and the continuum which is a background $p\pi$ pair combined with another background $p\pi$ pair.

In the next step, the background (US-LS) is subtracted from the (US-US) distribution and the resulting distribution is fitted with a 2D Gaussian function. The signal region is then defined as $\mu_{1,2} \pm 3\sigma_{1,2}$, where $\mu_{1,2}$ are the two means of the 2D Gaussian and $\sigma_{1,2}$ are the two Gaussian widths. All of aforementioned parameters are taken from the fit.

The angle $\theta^\star$ is then calculated for the (US-US) and the background (US-LS) pairs which are within the signal M_inv window for all three possible charge combinations, corresponding to $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ pairs. The measured[1] $\mathrm{d}N/\mathrm{d}\cos(\theta^\star)$, as defined in Eq. (2), for the $\Lambda^0\bar{\Lambda}^0$ pairs is shown in Fig. 4. The (US-US) pairs are shown as red full circles and the combinatorial background (US-LS) pairs are shown as full blue squares.

These distributions have to be corrected for detector acceptance. This can be done using

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[1] Measured means before any detector and acceptance corrections.

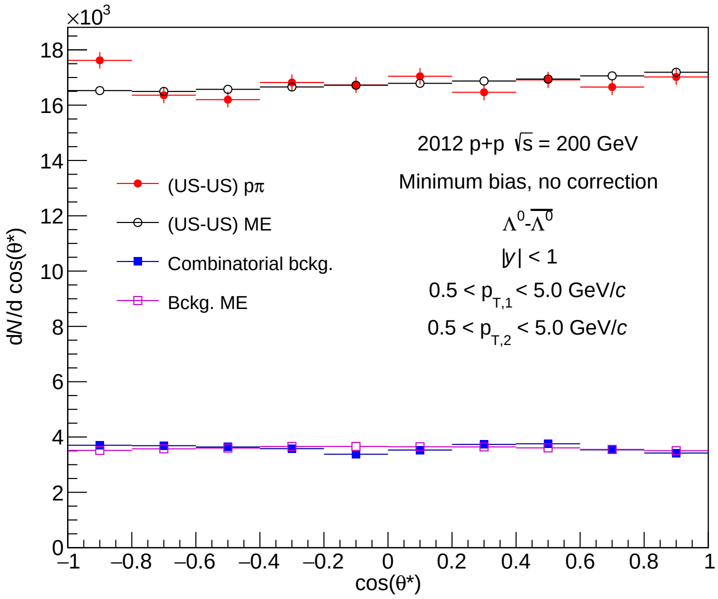

Figure 4: $\mathrm{d}N/\mathrm{d}\cos(\theta^\star)$ distributions for $\Lambda^0\bar{\Lambda}^0$ before acceptance correction and background subtraction. The red full circles are (US-US) $p\pi$ pairs, containing signal and background, the blue full squares are the combinatorial background. The open markers are the corresponding mixed event distributions.

mixed-event (ME) (US-US) and (US-LS) $p\pi$ pairs, where each of the $p\pi$ pairs come from a different event. The correction itself is done by dividing the same event $\mathrm{d}N/\mathrm{d}\cos(\theta^\star)$ distribution by the corresponding ME distribution normalized to unity. The ME distributions, scaled so that they match the same event distributions, are shown in Fig. 4 as open markers. Both the same event and the ME background (US-LS) distribution do not have any strong $\cos(\theta^\star)$ dependence, or acceptance effect. In case of the (US-US) distribution, on the other hand, the ME has clear dependence on $\cos(\theta^\star)$ indicating importance of the acceptance effect correction.

After the ME correction and the combinatorial background subtraction, the $\mathrm{d}N/\mathrm{d}\cos(\theta^\star)$, is fitted with Eq. (2) and the spin-spin correlation $P_{\Lambda_1\Lambda_2}$ is then extracted. An example of the ME corrected and background subtracted distribution for $\Lambda^0\bar{\Lambda}^0$ pairs is shown in Fig. 5.

The same procedure as was shown in the examples for $\Lambda^0\bar{\Lambda}^0$ pairs was performed also for $\Lambda^0\Lambda^0$ and $\bar{\Lambda}^0\bar{\Lambda}^0$ pairs. The extracted spin-spin correlations for all three hyperon pairs are shown in Fig. 6. The solid error-bar is the statistical uncertainty and the shaded box is the systematic uncertainty. The two main contributions to the systematic uncertainty are from the uncertainty of the weak decay constant α_+ and α_-, and from the mixed-event acceptance correction method.

All three values are consistent with zero with the current statistical and systematic precision which suggests no spin-spin correlation of $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ hyperon pairs in p+p collisions at $\sqrt{s}$ = 200 GeV. Due to the large uncertainties, it is not possible to completely rule out the presence of the spin-spin correlations in p+p collisions at RHIC, but the result gives first experimental limit on the correlations.

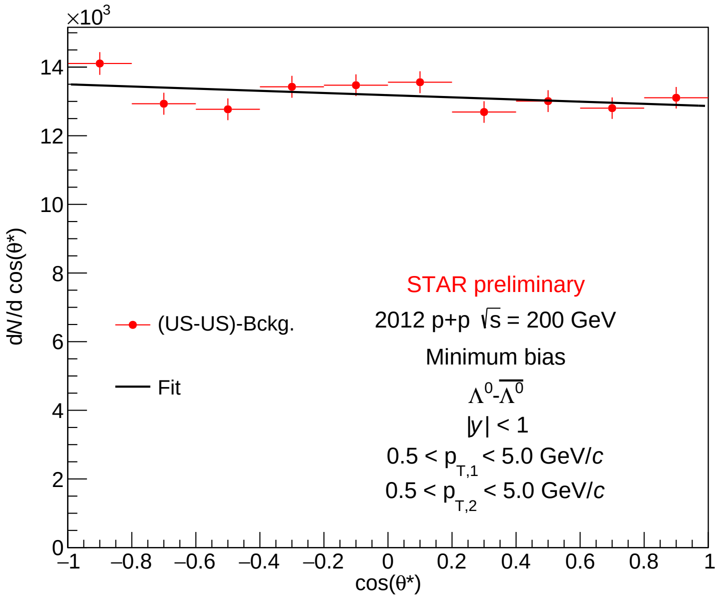

Figure 5: $\mathrm{d}N/\mathrm{d}\cos(\theta^\star)$ distributions for $\Lambda^0\bar{\Lambda}^0$ after acceptance correction and background subtraction. The fit is used to extract the $\Lambda^0\bar{\Lambda}^0$ pair spin-spin correlation $P_{\Lambda_1\Lambda_2}$ according to Eq. (2).

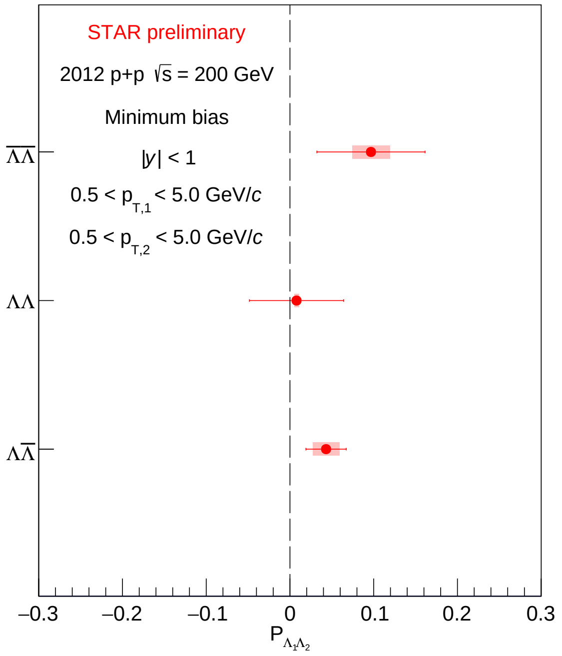

Figure 6: $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ hyperon pair spin-spin correlation $P_{\Lambda_1\Lambda_2}$ measured in p+p collisions at $\sqrt{s}$ = 200 GeV.

4. Summary and conclusions

The Λ^0 polarization puzzle has been experimentally and theoretically explored since its discovery in 1976 in Fermilab. Majority of the current results indicate the importance of final state effects, such as fragmentation and hadronization, on the polarization. Despite this extensive efforts, there is no conclusive explanation of the origin of the polarization. It is therefore important to develop alternative experimental and theoretical techniques in order to resolve the polarization puzzle. One possible way is to investigate if initial stage effects play any role in the Λ^0 hyperon polarization. This can be done by measurement of $\Lambda^0\bar{\Lambda}^0$, $\Lambda^0\Lambda^0$, and $\bar{\Lambda}^0\bar{\Lambda}^0$ hyperon pair spin-spin correlations. We conducted the first ever experimental measurement of such spin-spin correlations using *p*+*p* collisions at $\sqrt{s} = 200\,\text{GeV}$ measured by the STAR experiment in 2012. The spin-spin correlations for all three pair combinations are consistent with zero with the current statistical and systematic precision, which indicates no significant spin-spin correlations of the initial stage *s* (anti-)quark pairs produced in *p*+*p* collisions at $\sqrt{s} = 200\,\text{GeV}$ at RHIC.

References

[1] Airapetian A., *et al.* [HERMES Collaboration], Transverse Polarization of Λ^0 and $\bar{\Lambda}^0$ Hyperons in Quasireal Photoproduction, Phys.Rev.D 76, 092008 (2007)

[2] Zyla, P.A., *et al.* [Particle Data Group], The Review of Particle Physics, Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

[3] Bunce G., *et al.*, Λ^0 Hyperon Polarization in Inclusive Production by 300-GeV Protons on Beryllium, Phys. Rev. Lett. 36, 1113 (1976)

[4] Aad G., *et al.* [ATLAS Collaboration], Measurement of the transverse polarization of Λ^0 and $\bar{\Lambda}^0$ hyperons produced in proton-proton collisions at $\sqrt{s}$ = 7 TeV using the ATLAS detector, Phys. Rev. D 91, 032004 (2015)

[5] Guan Y., *et al.* [BELLE Collaboration], Observation of Transverse $\Lambda^0/\bar{\Lambda}^0$ Hyperon Polarization in e^++e^- Annihilation at Belle, Phys. Rev. Lett. 122, 042001 (2019)

[6] Adam J., *et al.* [STAR Collaboration], Improved measurement of the longitudinal spin transfer to Λ^0 and $\bar{\Lambda}^0$ hyperons in polarized proton-proton collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, Phys. Rev. D 98, 112009 (2018)

[7] Gong, W., *et al.*, Measurement of Bell-type inequalities and quantum entanglement from Λ^0-hyperon spin correlations at high energy colliders, Phys. Rev. D 106, L031501 (2022)

[8] Törnqvist, N.A. Suggestion for Einstein-Podolsky-Rosen experiments using reactions like $e^+e^- \to \Lambda^0\bar{\Lambda}^0 \to \pi^- p \pi^+ \bar{p}$., Found Phys 11, 171–177 (1981)