

Systematics in the global polarization measurements of Λ hyperons with HADES at SIS18

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Abstract. The global polarization of Λ hyperons has been measured in Au+Au and Ag+Ag collisions at $\sqrt{s_{NN}} = 2.4$ and 2.55 GeV recorded with HADES. An increase of the polarization is observed following the trend measured by the STAR Collaboration. The high statistics Ag+Ag data allowed for differential measurements of the polarization. The study of acceptance effects is very important in the fixed target setup, as the phase-space coverage is not symmetric. These studies are reported together with the evaluation procedure of the systematic uncertainties.

Introduction. In non-central heavy-ion collisions, large orbital angular momenta are created [1] which might manifest itself in a global spin polarization of the produced particles [2, 3]. Such a global polarization can be accessed using weak decays of strange hyperons, where the spin direction is transferred to the momentum direction of the decay products. The most abundantly produced hyperons in heavy-ion collisions are Λ s. Measurements performed during the beam energy scan phase I by the STAR Collaboration show an increasing trend of the global polarization in Au+Au collisions down to $\sqrt{s_{NN}} = 7.7$ GeV [4]. Further measurements by the ALICE and STAR Collaboration confirm the decreasing trend towards higher collision energies [5, 6]. The HADES experiment at SIS-18 collected high statistics data samples for the reactions Au+Au at $\sqrt{s_{NN}} = 2.42$ and Ag+Ag at 2.55 GeV. A measurement of the global polarization of the Λ hyperons at these lower collision energies provides new insights into the evolution of the angular momentum and the collective behavior of the matter created. Theoretical predictions are not conclusive in this energy range [7–10].

Measurement technique. The measurement of the global polarization is performed using the decay channel $\Lambda \rightarrow p + \pi^-$ in which the proton is preferentially emitted in the spin direction of the Λ hyperon. Hence, the polarization P_Λ is connected to the momentum direction \vec{p}_p^* of the proton in the rest frame of the Λ by $P_\Lambda = (3/\alpha_\Lambda)\langle\vec{p}_p^*\rangle$ [11]. Here $\alpha_\Lambda = 0.732 \pm 0.014$ [12] is the decay parameter quantifying the emission probability of the proton along the spin direction of the Λ hyperon and $\langle.\rangle$ denotes the average over all Λ decays. The direction of the orbital angular momentum is perpendicular to the reaction plane, spanned by the impact parameter of the colliding nuclei and the beam direction. It can be defined by a single azimuthal angle Ψ_{RP} in the laboratory frame which is estimated from a Q-vector analysis using the spectator distributions [13, 14]. The result of this procedure is the so-called event plane angle Ψ_{EP} . This can be used to express the polarization in terms of azimuthal angles by integrating over the polar angle and assuming perfect detector acceptance [11]:

$$P_\Lambda = 8/(\pi\alpha_\Lambda) \times \langle \sin(\Psi_{EP} - \phi_p^*) \rangle / R_{EP}. \quad (1)$$

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Due to the finite resolution of the event plane reconstruction, the associated reduction of the measured correlation has to be taken into account by introducing the event plane resolution correction R_{EP} [14]. The event plane and its resolution are determined for the HADES detector [15] as described in [16]. The reconstruction of the Λ hyperons in HADES is done by identifying their decay topology in a multi-variate analysis. The polarization signal is extracted with the invariant mass method. More details can be found in [17].

Efficiency correction. The efficiency map for the reconstruction of Λ hyperons in HADES in transverse momentum and rapidity space is shown in the left panel of Fig. 1(bottom). As only relative changes are important for the averaged polarization observable, for application the efficiencies are rescaled to the weighted mean efficiency. The Λ hyperons reconstructed in the experimental data as displayed in the left panel of Fig. 1(top) are used as weights. To minimize effects related to the finite binning, a Savitzky-Golay filter is used in addition [18].

Radial distance asymmetry (RDA) correction. A strong dependence of the extracted polarization signal has been observed on the proton radial distance R_p . The R_p is a signed value, calculated as the minimum distance of the proton track to a straight line parallel to the beam axis through the event vertex of the collision. The sign is determined by the cross product between the minimum distance vector and the track direction. The same dependence could be reproduced using Monte-Carlo simulations with polarized Λ hyperons and a multi-differential flow pattern. However, the signal distribution as a function of R_p is not symmetric around zero in the experiment in contrast to the simulations. A data driven approach has been developed to correct for this asymmetry. Therefore, the distribution is divided into a finite amount of bins which are weighted in order to restore the symmetry of the distribution. The application of the same weights to the polarization observable results in a slight increase of the extracted signal value by $\sim 8\%$ consistently for both, Au+Au and Ag+Ag. Variations of the correction procedure, in an extreme scenario by flattening the distribution of R_p , give consistent results within statistical uncertainties.

Acceptance effects. The phase-space coverage in fixed target experiments is usually not symmetric as displayed in the left panel of Fig. 1. To study the acceptance effects in more detail, Monte-Carlo simulations with polarized Λ hyperons are used. The flow pattern for the directed and elliptic flow has been implemented in addition according to the experimentally measured values. Different input values have been tested for the Λ polarization. For the different samples the input value could be reconstructed within statistical uncertainties as summarized in the right panel of Fig. 1. A non-zero background polarization is extracted which qualitatively matches the observations in the experimental data. It could be traced back to a mis-matching of π^- from polarized Λ hyperons with primary protons. However, the effect on the polarization extraction is negligible.

Systematic uncertainties. The systematic uncertainties are evaluated by varying single parameters in the analysis and comparing the extracted polarization signals. In order to remove statistical fluctuations the Barlow criterion [19] is used for the difference between the measured result $P_M \pm \sigma_M$ and the result from the varied set $P_V \pm \sigma_V$:

$$B_{\text{crit}} = |P_M - P_V| / \sqrt{|\sigma_M^2 - \sigma_V^2|}. \quad (2)$$

If $B_{\text{crit}} > 1$ a variation is treated as significant beyond statistical fluctuations and added in quadrature to the overall systematic uncertainty. Otherwise it is neglected. For the particle selection, the decay topology parameters and MVA response have been varied such that the amount of reconstructed Λ hyperons differs by $\pm 15\%$. In general, the variations are around 2% , except for the distance of the proton track to the primary vertex where it is found to be 7.5% . Concerning the invariant mass method, the difference between determining the signal

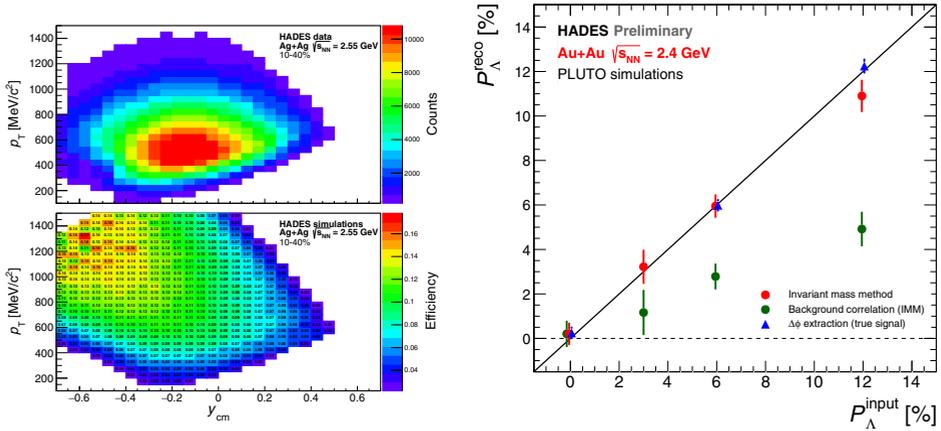


Figure 1. Left panel: Phase-space distribution (top) of the reconstructed Λ hyperons and the corresponding reconstruction efficiency (bottom) in Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV. Right panel: Extraction of the Λ polarization from Monte-Carlo simulations as a function of the input polarization using two different methods (blue and red points). The background "polarization" extracted from the invariant mass method is depicted by the green points.

and background fractions using either a direct fit to the same-event data or the mixed-event technique are found to be negligible. The same applies to variations of the invariant mass range used to fix the background shape. Different assumptions have been tested, i.e. a linear and constant background shape as a function of the invariant mass, however, the magnitude of the variation is small $\sim 1\%$. As a second method the $\Delta\phi$ extraction method [20] has been used, but no significant difference to the default result has been observed. The same observation has been made for the systematic variations related to the efficiency and RDA corrections. Finally, two scaling uncertainties are included in the systematic uncertainties: 2% due to the measurement uncertainty of the decay parameter α_Λ [12] and 5% related to the uncertainty in the determination of the event plane resolution correction R_{EP} . A summary of this evaluation procedure is shown in the left panel of Fig. 2 for both data sets. Most of these systematic uncertainties also apply to the differential study of the global polarization. However, sources that might be different for different regions of phase-space are re-evaluated for each bin separately and the overall uncertainties are plotted in the right panel of Fig. 2 for the rapidity dependence of the global Λ polarization. These are: the efficiency and RDA corrections, the $\Delta\phi$ extraction method and the constant background assumption.

In summary, the global polarization of Λ hyperons has been measured in Au+Au and Ag+Ag collisions at $\sqrt{s_{NN}} = 2.4$ and 2.55 GeV with the fixed-target experiment HADES. Acceptance effects have been studied using experimental data but also Monte-Carlo simulations. An effect related to the direction of the proton tracks has been studied and an experimental approach has been developed to correct for it. The appearance of a background correlation in the experimental data could be qualitatively reproduced in the simulations and is found to be insignificant for the signal extraction.

A detailed study of the systematic uncertainties has been performed using the Barlow criterion to identify relevant contributions beyond statistical fluctuations. For the Ag+Ag data, the global polarization has been extracted differentially as a function of centrality, rapidity and transverse momentum. Overall, the increasing trend towards lower collision energies observed by STAR is found to continue down to $\sqrt{s_{NN}} = 2.4$ GeV. HADES measured

Systematic on P_Λ [%]	Au+Au@1.23, 4GeV			Ag+Ag@1.58, 4GeV		
	Absolute	Relative	B_{crit}	Absolute	Relative	B_{crit}
$D_{min}(MVA)$	± 0.553	$\pm 11.9\%$	✓	± 0.042	$\pm 1.3\%$	×
d_e	± 0.301	$\pm 6.5\%$	✓	± 0.084	$\pm 2.6\%$	✓
d_1	± 0.263	$\pm 5.7\%$	✓	± 0.051	$\pm 1.6\%$	✓
d_2	± 0.672	$\pm 14.6\%$	✓	± 0.237	$\pm 7.5\%$	✓
d_3	± 0.233	$\pm 5.0\%$	✓	± 0.019	$\pm 0.6\%$	×
d_4	± 0.341	$\pm 7.4\%$	✓	± 0.074	$\pm 2.3\%$	✓
Best $D_{min}(MVA)$	± 0.005	$\pm 0.1\%$	×	± 0.013	$\pm 0.4\%$	×
Same-event mass fit	± 0.000	$\pm 0.0\%$	×	± 0.023	$\pm 0.7\%$	×
Fit range	± 0.102	$\pm 2.2\%$	×	± 0.032	$\pm 1.0\%$	×
Pol0 BG fit	± 0.088	$\pm 1.9\%$	×	± 0.035	$\pm 1.1\%$	✓
Efficiency	± 0.611	$\pm 13.3\%$	✓	± 0.053	$\pm 1.7\%$	×
Δo method	± 0.253	$\pm 5.5\%$	×	± 0.053	$\pm 1.7\%$	×
R_{EP}	± 0.138	$\pm 3.0\%$	✓	± 0.159	$\pm 5.0\%$	✓
α_Λ	± 0.094	$\pm 2.0\%$	✓	± 0.063	$\pm 2.0\%$	✓
RDA	± 0.686	$\pm 14.9\%$	×	± 0.121	$\pm 3.8\%$	×
Δ_{obs}^{total}	± 1.220	$\pm 26.5\%$	-	± 0.319	$\pm 10.1\%$	-

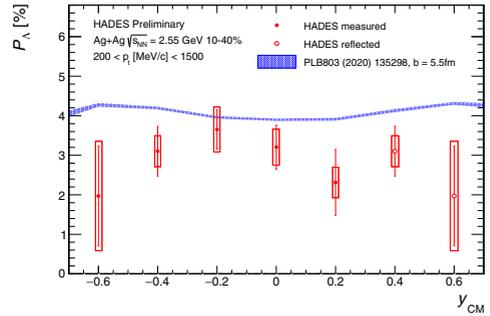


Figure 2. Left panel: Summary table of the systematic uncertainty evaluation for the integrated results in Au+Au and Ag+Ag collisions at $\sqrt{s_{NN}} = 2.4$ and 2.55 GeV. Right panel: Global polarization measurement of Λ hyperons as a function of rapidity in the center-of-mass frame. The two data points at most negative rapidity have been reflected (open symbols) as the polarization is expected to be symmetric around midrapidity ($y_{CM} = 0$). The experimental data is compared to model calculations based on UrQMD [9] depicted by the blue area.

the polarization to reach a value of $P_\Lambda[\%] = 4.6 \pm 1.0$ (stat.) ± 1.2 (syst.) in Au+Au and $P_\Lambda[\%] = 3.2 \pm 0.3$ (stat.) ± 0.3 (syst.) in Ag+Ag collisions.

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References

- [1] F. Becattini et al., Phys. Rev. C **77**, 024906 (2008).
- [2] Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. **94**, 102301 (2005).
- [3] S. A. Voloshin, arXiv:nucl-th/0410089 (2005).
- [4] L. Adamczyk et al. (STAR), Nature **548**, 62-65 (2017).
- [5] J. Adam et al. (STAR), Phys. Rev. C **98**, 014910 (2018).
- [6] S. Acharya et al. (ALICE), Phys. Rev. C **101**, 044611 (2020).
- [7] Y. B. Ivanov, Phys. Rev. C **102**, 044904 (2020).
- [8] X.-G. Deng et al., Phys. Rev. C **101**, 064908 (2020).
- [9] O. Vitiuk et al., Phys. Lett. B **803**, 135298 (2020).
- [10] A. Ayala et al., arXiv:2106.14379 [hep-ph] (2021).
- [11] B. I. Abelev et al. (STAR), Phys. Rev. C **76**, 024915 (2007).
- [12] P. A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).
- [13] J.-Y. Ollitrault, Nucl. Phys. A **638**, 195-206 (1998).
- [14] A. M. Poskanzer et al., Phys. Rev. C **58**, 1671-1678 (1998).
- [15] G. Agakishiev et al., EPJA **41**, 243 (2017).
- [16] J. Adamczewski-Musch et al. (HADES), Phys. Rev. Lett. **125**, 262301 (2020).
- [17] F. J. Kornas, Springer Proc. Phys. **250**, 435-439 (2020).
- [18] A. Savitzky and M.J.E. Golay, Analytical Chemistry **36**, 1627-1639 (1964).
- [19] R. Barlow, Conf. on Adv. Stat. Techniques in Particle Physics (2002) 134-144.
- [20] S. A. Voloshin et al., Landolt-Bornstein **23**, 293 (2010).