

Lambda polarization at Electron-ion collider in China

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Abstract

Lambda polarization can be measured through its self-analyzing weak decay, making it an ideal candidate for studying spin effects in high energy scatterings. In lepton-nucleon deeply inelastic scatterings (DIS), Lambda polarization measurements can probe the polarized parton distribution functions (PDFs) and the polarized fragmentation functions (FFs). One of the most promising facilities for high-energy nuclear physics research is the proposed Electron-ion collider in China (EicC). As a next-generation facility, EicC is set to propel our understandings of nuclear physics to new heights. In this article, we study the Lambda production in electron-proton collision at EicC energy, in particular Lambda's reconstruction based on the performance of the designed EicC detector. In addition, taking spontaneous transverse polarization as an example, we provide a theoretical prediction with statistical projection based on one month of EicC data taking, offering valuable insights into future research prospects.

Full Text

Preamble

Lambda polarization at the Electron-ion collider in China*

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In lepton-nucleon deeply inelastic scatterings (DIS), Lambda polarization measurements can probe the polarized parton distribution functions (PDFs) and the polarized fragmentation functions (FFs). One of the most promising facilities for high-energy nuclear physics research is the proposed Electron-ion collider in China (EicC). As a next-generation facility, EicC is set to propel our understanding of nuclear physics to new heights. In this article, we study Lambda production in electron-proton collisions at EicC energies, in particular Lambda reconstruction based on the performance of the designed EicC detector. In addition, taking spontaneous transverse polarization as an example, we provide a theoretical prediction with statistical projection based on one month of EicC data taking, offering valuable insights into future research prospects.

Keywords: Electron-ion collider in China; Lambda polarization; polarizing Fragmentation Functions; nucleon structure.

INTRODUCTION

Spin, as a fundamental property of particles, plays a crucial role in the advancement of modern physics. A growing number of experimental findings, such as the spontaneous transverse polarization of Λ and the proton spin crisis, have made it evident that there is much more to be understood about spin behaviors in high-energy reactions. The Lambda hyperon (Λ/Λ) emerges as an exceptionally powerful tool in spin physics, primarily due to its parity-violating weak decay, which results in a non-uniform angular distribution of its products with respect to Lambda's spin direction [?]. In high-energy reactions, Lambda can be abundantly produced and efficiently detected via the decay channel $\Lambda \rightarrow p\pi^-$ (branching ratio is 63.9%). In the Λ rest frame, the decay protons are preferentially emitted along the polarization direction of their parent Λ , with the following angular distribution: $dN/d\cos^* \propto \Lambda(1 + \alpha_\Lambda P_\Lambda \cos^*)$, where Λ is the detector acceptance, $\alpha_\Lambda = 0.732 \pm 0.014$ is the weak decay parameter [?], and * is the angle between the proton momentum direction and $\Lambda(\Lambda)$ polarization direction in the Λ rest frame.

The spontaneous transverse polarization of Λ was first observed in 1976 in unpolarized proton beam scattering on a Beryllium target [?], at a time when perturbative Quantum Chromodynamics (QCD) predicted only negligible polarization [?]. This puzzling result triggered a series of theoretical and phenomenological studies that extended far beyond Λ polarization itself. Experimentally, measurements of Λ polarization have since been extensively explored [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?] in various high-energy processes, encompassing electron-positron annihilation [?, ?, ?], lepton-nucleon deeply inelastic scattering (DIS) [?, ?, ?], hadron-hadron scattering [?, ?, ?], and heavy ion collisions [?, ?, ?, ?, ?], yielding invaluable insights into numerous aspects of physics. These measurements have served diverse purposes, including unraveling the physical origins of spontaneous polarization, understanding nucleon spin structure, comprehending spin effects in fragmentation processes, and exploring extreme conditions of high density and high temperature in heavy ion collisions.

High-precision Lambda polarization measurements at proposed electron-ion colliders worldwide provide unique opportunities to study the spin-dependent fragmentation functions (FFs) and polarized parton distribution functions (PDFs) [?, ?, ?, ?, ?, ?, ?, ?]. The Electron-ion collider in China (EicC) is the proposed next-generation high-energy nuclear physics facility, which is based on the High Intensity Heavy-ion Accelerator Facility (HIAF) in Huizhou, China [?, ?]. It is conceptually designed to deliver high-luminosity electron-proton and electron-ion collisions, with electron, proton, and light ion beams highly polarized. With complementary kinematics coverage to other electron-ion collider proposals worldwide [?, ?, ?], the featured physics at EicC includes three-dimensional proton spin structure, nuclear partonic structure, exotic hadron states, etc. Lambda polarization measurement at EicC is expected to be sensitive not only to the spin-dependent parton distribution functions but also to the spin-dependent fragmentation functions. Potential measurements of Lambda transverse polarization and impact studies have been performed for the US-based EIC, which is designed to collide electron and proton/ion beams at significantly higher energies than EicC [?].

In this work, the Lambda production in electron-proton scattering under the EicC configuration is studied. Based on the current conceptual EicC detector design, especially the design of the tracking subsystem, the reconstruction performance for $\Lambda/\bar{\Lambda}$ is assessed. In Section II, we describe the simulation setup including the event generator in use, the detector configuration, and the corresponding fast simulation procedure. The performance of $\Lambda/\bar{\Lambda}$ reconstruction will be presented in Section III. In Section IV, taking spontaneous transverse polarization as an example, the potential statistical precision for polarization measurements will be given together with theoretical predictions. We provide a brief summary and outlook in Section V.

II. SIMULATION FRAMEWORK

To simulate Lambda production in electron-proton scattering, the event generator PYTHIAeRHIC [?], a modified version of PYTHIA6.4.28 [?], is used with Parton Distribution Functions (PDFs) input from LHAPDF [?]. The collision energy we choose is the baseline energy outlined in the EicC whitepaper [?]: 3.5 GeV electrons on 20 GeV protons. The leading-order diagram for Λ production in the DIS process is shown in Fig. 1 [Figure 1: see original paper]. The kinematics of the studied DIS events are constrained in the following ranges: Bjorken- x $10^{-3} < x_B < 1$, transferred 4-momentum squared $Q^2 > 1 \text{ GeV}^2$, and hadronic invariant mass squared $W^2 > 4 \text{ GeV}^2$. Ten million such DIS events are generated for the following studies.

At generator level, the average number of Λ produced per DIS event in the above kinematic ranges is about 0.1. In the laboratory frame, the momentum and polar angle distributions for Λ and the decay products are shown in Fig. 2 [Figure 2: see original paper]. Comparing distributions of daughter proton and pion with those of Λ , it can be found that the proton carries most of Λ '

s momentum while the pion only shares a small fraction. Λ is preferentially produced in the proton-going direction, with a large number produced at very forward angles. The same distributions in Fig. 2 for $\bar{\Lambda}$ are similar with slight differences that will be discussed later.

In this work, we are mostly interested in $\Lambda/\bar{\Lambda}$ from the struck quark fragmentation (current fragmentation region). Typically, Feynman- x is an effective variable to separate the current fragmentation region from the target fragmentation region. Feynman- x x_F is defined as $x_F = 2p_{\Lambda}(\Lambda)/W$, where $p_{\Lambda}(\Lambda)$ is the $\Lambda(\bar{\Lambda})$ longitudinal momentum in the hadronic center-of-mass frame, and W is the hadronic invariant mass. The criterion $x_F > 0$ is expected to suppress contributions from the target fragmentation region. The correlation between Feynman- x and $\Lambda/\bar{\Lambda}$ pseudorapidity are shown in the upper panels of Fig. 3 [Figure 3: see original paper]. Here, pseudorapidity is defined as $-\ln(\tan(\theta/2))$, where θ is the polar angle. Following the EicC convention, positive η is along the moving direction of the proton/ion beam. One can see that $\Lambda/\bar{\Lambda}$ with $x_F < 0$ are mostly produced in the very forward region, which will be discarded in the following simulation and analysis. Considering the limited coverage of the EicC central detector, $|\eta| < 3$ is applied for $\Lambda/\bar{\Lambda}$ and their daughter particles. Transverse momentum p_T versus η for Λ and $\bar{\Lambda}$, with $x_F > 0$ and $|\eta| < 3$, are shown in the lower panels of Fig. 3. By tracing back the full event records in PYTHIA, the origins of such $\Lambda/\bar{\Lambda}$ are shown in Fig. 4 [Figure 4: see original paper]. At EicC energy, about half of $\Lambda/\bar{\Lambda}$ are from decays of heavier hyperons. There are also significant contributions from beam remnants (di-quarks). In this study, we do not separate different sources for $\Lambda/\bar{\Lambda}$.

The preliminary conceptual design of the EicC detector has been described in the white papers [?, ?]. From inner to outer, it consists of the vertex/tracking detector, the particle identification (PID) system, the calorimeter system, etc. For Λ measurement, the most relevant parts are the tracking and PID systems. The latest design of the EicC tracking detector is thoroughly described in Ref. [?]. The current design of the tracking system uses hybrid models. For mid-rapidity ($|\eta| < 1.1$), there are 5 layers of silicon and 4 layers of Micro-Pattern Gaseous Detectors (MPGD), radially ranging from 3.3 cm to 77.5 cm. For $|\eta| > 1.1$, the tracking system consists of silicon disks followed by large-area Micromegas in the forward (proton/nucleus-going) direction and all silicon disks in the backward (electron-going) direction. For the PID system, time-of-flight detectors and Cherenkov detectors will be used for particle identification at mid and forward rapidity, respectively.

For the tracking system, full GEANT4 simulation has been performed with the latest design, based on which the resolutions for primary vertex position, for distance from tracks to tracks and from tracks to points, and for track momentum, as well as the tracking detector efficiency as a function of track p_T and η are given in detail in Ref. [?] (Fig.4-9 therein). A fast simulation framework has also been developed to simulate the detector responses learned from the GEANT4-based simulation. In this work, we follow the same fast

simulation procedure described in Ref. [?]. The detailed GEANT4 simulation for the PID system is not available when this work is performed. To mimic particle identification imperfections, a simplified “PID smearing” is included in the detector effect fast simulation. In principle, the PID efficiency is correlated with the momentum of particles. However, we employ a toy model to study the PID effect with a typical PID efficiency of 95% as follows. Basically, the identified π , K, or p has a 95% probability to be correct, and a 2.5% probability to be one of the other two particles respectively, as described by the following matrix:

[PID efficiency matrix would be here]

Here 95% PID purity is specifically chosen, and a few other numbers are also checked for a complete study.

III. LAMBDA RECONSTRUCTION

Similar to the method used in other experiments with tracking detectors, $\Lambda/\bar{\Lambda}$ reconstruction in this study is based on the topological structure of the decay channel with a large branching ratio: $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. Taking Λ as an example, Fig. 5 [Figure 5: see original paper] schematizes the main topological features of its production and decay process in a tracking detector. The blue dot at the bottom-left represents the ep scattering vertex, named the “primary vertex.” $\Lambda/\bar{\Lambda}$ is emitted from the primary vertex, then moves along the magenta straight dash line and decays at the “V0 vertex.” The decay products $p\pi^-$ ($\bar{p}\pi^+$) travel along helical lines with opposite bending directions in the magnetic field.

Reconstruction of $\Lambda/\bar{\Lambda}$ starts with pairing proton and pion tracks with opposite charge. To select $\Lambda/\bar{\Lambda}$ candidates and suppress random backgrounds, the following selection variables are considered: (1) The distance of closest approach (DCA) of proton and pion tracks to the primary vertex. As indicated in Fig. 5, DCA_p and DCA _{π} from signals should be significantly higher than those from background, as the parent $\Lambda/\bar{\Lambda}$ flies a certain distance from the primary vertex before its decay. (2) The distance of closest approach (DCA) between paired proton tracks and pion tracks. For $\Lambda/\bar{\Lambda}$ signal, this variable should be consistent with zero within the track space resolution. The decay point (V0 vertex) is given by the middle point of these two tracks at the closest approach, as indicated by the brown triangle in Fig. 5. (3) The decay length of $\Lambda/\bar{\Lambda}$ candidates, which is the distance between the primary vertex and V0 vertex. The characteristic decay length of Λ hyperon $c\tau$ is 7.89 cm [?]. (4) The angle between $\Lambda/\bar{\Lambda}$ candidate momentum $\mathbf{p}$ and its trajectory $\mathbf{r}$ from the primary vertex. For $\Lambda/\bar{\Lambda}$ directly produced from the primary vertex, its momentum direction is supposed to be along its trajectory from the primary vertex. Correspondingly, $\cos(\mathbf{r} \cdot \mathbf{p})$ should be very close to 1.

To quantitatively determine the selection criteria, the distributions of proton-pion pairs from a pure $\Lambda/\bar{\Lambda}$ sample are compared with proton-pion pairs from backgrounds, and the comparisons are shown in Fig. 6 [Figure 6: see original

paper]. Based on these comparisons, a set of selection criteria are optimized to balance the background fraction and the $\Lambda/\bar{\Lambda}$ reconstruction efficiency, in order to keep as many signals as possible while maintaining the background fraction at a relatively low level. The numerical cut conditions are listed in Table 1.

By implementing the aforementioned selection criteria, we successfully obtained a clean sample of $\Lambda/\bar{\Lambda}$ candidates. The invariant mass spectrum of $\Lambda/\bar{\Lambda}$ candidates with kinematic cuts of $x_F > 0$, $|\eta| < 3$, and $z_\Lambda > 0.1$ (fractional momentum of $\Lambda/\bar{\Lambda}$ is defined as $z_\Lambda = P \cdot p_\Lambda / P \cdot q$) is shown in Fig. 7 [Figure 7: see original paper]. Here the histograms are scaled to an integrated luminosity of 5 fb^{-1} , which corresponds to about one month of EicC data taking. With all selection criteria applied, more Λ than $\bar{\Lambda}$ are reconstructed due to baryon number enhancement. There is a clean Gaussian signal peak with very limited background. The residual background mainly comes from random combinations of oppositely charged particles and particle mis-identification. The invariant mass distribution of this background is expected to be linear. Using a typical side-band method, the residual background fraction is estimated to be about 2.6% for Λ and 3.0% for $\bar{\Lambda}$. The signal mass window is set to be within 3σ width of the Gaussian fit, which is (1.106, 1.124) GeV/c^2 . As for the side bands, they are limited to regions far from the mass window to avoid fluctuations from signals, but not far enough to escape the signal peak. The left side band is (1.083, 1.093) GeV/c^2 and the right side band is (1.137, 1.147) GeV/c^2 . The background under the signal peak is estimated as the sum of the two side-bands normalized to the signal window. As mentioned in Section II, the sensitivity of $\Lambda/\bar{\Lambda}$ reconstruction to the PID performance is assessed by varying the PID “purity” number. For 100% PID purity, the residual background fraction is 1.7%, while for a 90% case, the residual background fraction increases to 3.4%, which is still under good control.

Figure 8 [Figure 8: see original paper] shows the Λ and $\bar{\Lambda}$ reconstruction efficiency versus transverse momentum. The reconstruction efficiency involves several effects including topological cuts, detector acceptance, and track efficiency which depends on track p_T , track η , etc. For $\Lambda/\bar{\Lambda}$ with large decay length, the number of tracking detector layers the daughter tracks pass through decreases, and so does the tracking efficiency. The efficiency at very low p_T is limited by the detector acceptance due to the magnetic field. Due to low transverse momenta in the forward region (large $|\eta|$), the efficiency decreases significantly. As already shown in Fig. 3, more Λ than $\bar{\Lambda}$ are produced at large pseudorapidity where the reconstruction efficiency is low, which leads to significantly higher efficiency for Λ compared to $\bar{\Lambda}$ at $p_T > 0.5 \text{ GeV}/c$. When p_T is larger than 2 GeV/c , the efficiency for $\bar{\Lambda}$ reconstruction increases and gets closer to Λ since $\bar{\Lambda}$ at mid-rapidity start to dominate its production.

IV. SPONTANEOUS TRANSVERSE POLARIZATION

In this section, we take $\Lambda/\bar{\Lambda}$ spontaneous transverse polarization as an example to explore the physics potential of EicC. The theoretical calculation and

statistical projection based on our simulation results are described below.

The QCD formalism is used to describe Λ spontaneous transverse polarization P_Λ in the semi-inclusive DIS process, $e^-(l) + p(P) \rightarrow e^-(l') + \Lambda(p_\Lambda, S_\Lambda) + X$. The Trento convention [?] is followed in the calculation, where the virtual photon moves in the positive z direction and the proton moves in the negative z direction, and the differential cross section can be written as [?, ?]:

$$d\sigma(S_\Lambda) / (dx_B dy dz_\Lambda d^2p_\Lambda) = (2\pi\alpha^2 / Q^4) (1 + (1-y)^2) [F_{\{UU\}} + \dots + |S_\Lambda| \sin(\phi_{SA} - \phi_A) F_{\{UT\}}^{\sin}(\phi_{SA} - \phi_\Lambda)]$$

where $\gamma = 2x_B M/Q$ and $Q^2 = -q^2$, $x_B = Q^2/(2P \cdot q)$, $y = (P \cdot q)/(P \cdot l)$, $z_\Lambda = (P \cdot p_\Lambda)/(P \cdot q)$ are Lorentz invariant variables, and S_Λ , p_Λ are the transverse spin vector and transverse momentum of the Λ hyperon, respectively. $F_{\{AB\}} = F_{\{AB\}}(x_B, z_\Lambda, p_\Lambda, Q)$, where the subscripts indicate the polarization of proton and Λ , respectively. $F_{\{UU\}}$ is the spin-averaged structure function, and $F_{\{UT\}}^{\sin}(\phi_{SA} - \phi_\Lambda)$ is the spin-dependent term that contributes to $\sin(\phi_{SA} - \phi_\Lambda)$ modulation for spontaneous transverse polarization. The experimentally measured polarization P_Λ is related to the structure functions as follows:

$$P_\Lambda = F_{\{UT\}}^{\sin}(\phi_{SA} - \phi_A) / F_{\{UU\}}$$

Within the usual transverse momentum distribution (TMD) factorization, at leading twist the structure functions can be written as:

$$F_{\{UU\}} = \sum_q d^2p_\perp d^2k_\perp \delta^2(z_\Lambda p_\perp + k_\perp - p_\Lambda) f_1^q(x_B, p_\perp^2, Q) D_{1\{q\}}^{\Lambda}(z_\Lambda, k_\perp^2, Q)$$

$$F_{\{UT\}}^{\sin}(\phi_{SA} - \phi_\Lambda) = \sum_q d^2p_\perp d^2k_\perp \delta^2(z_\Lambda p_\perp + k_\perp - p_\Lambda) (\hat{p}_A \cdot k / M_\Lambda) f_1^q(x_B, p_\perp^2, Q) D_{\{1T\}}^{\Lambda q}(z_\Lambda, k_\perp^2, Q)$$

where $p_\perp$ and $k_\perp$ denote the transverse momentum of the quark relative to the initial proton and the transverse momentum of Λ relative to its parent quark, respectively.

We parameterize the TMDs using the usual Gaussian form, as the product of collinear functions and Gaussian widths:

$$f_1^q(x_B, p_\perp^2; Q) = f_1^q(x_B, Q) (1/\pi p_\perp^2) \exp(-p_\perp^2 / p_\perp^2)$$

$$D_{1\{q\}}^{\Lambda}(z_\Lambda, k_\perp^2; Q) = D_{1\{q\}}^{\Lambda}(z_\Lambda, Q) (1/\pi k_\perp^2) \exp(-k_\perp^2 / k_\perp^2)$$

$$D_{\{1T\}}^{\Lambda q}(z_\Lambda, k_\perp^2; Q) = D_{\{1T\}}^{\Lambda q}(z_\Lambda, Q) (1/\pi M_\Lambda^2) \exp(-k_\perp^2 / M_\Lambda^2)$$

With this expression, we can estimate the magnitude of P_Λ in SIDIS. Taking $Q^2 = 5 \text{ GeV}^2$, we plot P_Λ as a function of p_Λ in Fig. 9 [Figure 9: see original paper]. The results are obtained for different values covered by the kinematic range of the future EicC. To get P_Λ dependence on the Feynman variable x_F , we parameterize x_F as a function of Lorentz invariant variables (x_B, z_Λ, Q) through a kinematic transformation:

$$x_F = (2M_\Lambda / W) [x_B M_\Lambda + (1 - x_B) Q^2 / (2M)] [\sqrt{(1 + (M_\Lambda^2 + p_\Lambda^2) / (z_\Lambda^2 Q^2))} + \sqrt{(M_\Lambda^2 + p_\Lambda^2) / (z_\Lambda^2 Q^2)}]$$

where $p_\perp^2 = 0.61$, $k_\perp^2 = 0.19$ and $M_D^2 = 0.118$ are the corresponding Gaussian widths from Ref. [?, ?].

In this analysis, we use the CT18NLO [?] parametrization for the collinear PDF while using the DSV [?] and AKK08 [?] parametrizations for the collinear unpolarized FF. Both parametrizations describe experimental data but differ significantly, with AKK08 including substantial isospin symmetry violations and DSV parametrization conserving it. Additionally, the universality of the polarizing FF $D_{1T}^{\Lambda q}$ has been proven [?, ?, ?]. Similarly, $D_{1T}^{\Lambda q}$, as a modulation of $D_{1T}^{\Lambda q}$ by an additional collinear function, is also described by two different parametrizations: CLPSW [?] considering isospin symmetry and CKT allowing isospin symmetry violations [?]. The future EicC experiment provides an ideal place to test the Λ isospin symmetry of FFs. In our study, we employ these different parametrizations to calculate the polarization observables and perform comparisons.

Using these parametrizations for the TMDs, the spontaneous transverse polarization of Λ has the analytic form:

$$P_\Lambda(x_B, z_\Lambda, p_\Lambda, Q) = [\Sigma_q f_{1T}^q(x_B, Q) D_{1T}^{\Lambda q}(z_\Lambda, Q)] / [\Sigma_q f_{1T}^q(x_B, Q) D_{1T}^{\Lambda q}(z_\Lambda, Q)] \times [p_\Lambda / (M_\Lambda (M_D^2 + z_\Lambda^2 p_\perp^2))] \times [M_D^2 (k_\perp^2 + z_\Lambda^2 p_\perp^2) / (k_\perp^2 + z_\Lambda^2 p_\perp^2 + p_\Lambda^2)]$$

Using Eq.(7,8) and integrating over p_Λ , we plot the result of the x_F and z_Λ dependent P_Λ in Fig. 9 [Figure 9: see original paper].

The statistical projection of Λ/Λ polarization is based on an integrated luminosity of 5 fb^{-1} , which is the same size of data sample as shown in Fig. 7. The statistical uncertainties follow the equation format as $\delta P = 1/\sqrt{N}$ based on the polarization extraction procedure. The Λ and Λ projected precision versus p_Λ , x_F , and z_Λ are also shown in Fig. 9 together with theoretical predictions. The size of the error bars are smaller than the marker sizes, thus invisible. Depending on the statistics in different bins, the range of the errors is from 0.002 to 0.007.

V. SUMMARY AND OUTLOOK

EicC is the proposed next-generation nuclear physics facility which is expected to provide unique opportunities for precisely studying the three-dimensional nucleon structure, nuclear partonic structure, exotic hadron states, etc. The Lambda hyperon, serving as a natural final-state polarimetry, is a powerful tool for studying nucleon spin structure and spin effects in the fragmentation process. Lambda measurements at EicC are of special importance and interest.

Based on a conceptual design of the EicC tracking system and GEANT4 simulation, we performed a detailed study of Lambda production and reconstruction.

Also, taking spontaneous transverse polarization as an example, theoretical predictions are given as functions of different kinematic variables, together with statistical projections with one month's data taking at EicC. We find that measurements with EicC data taken in only one month's running based on the current accelerator design could provide distinguishable constraints for different parameterizations of the fragmentation functions.

EicC is designed to have both beams polarized, and the Lambda polarization transferred either from the lepton or the proton beam could provide important constraints on the spin-dependent PDFs and FFs, in both collinear and transverse momentum dependent frameworks. In future work, more observables will be studied. What could be improved in the future also includes decay contributions from heavier particles, more realistic PID, etc.

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