Deep exclusive meson production as a probe to the puzzle of Λ hyperon polarization

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In the 1970s, an unexpected transverse Λ polarization in unpolarized proton-beryllium collisions was discovered, which initiated extensive studies on spin phenomena in high-energy physics. Over the past five decades, similar transverse Λ polarization has been observed across various collision systems, including lepton-hadron deep-inelastic scattering, hadron-hadron collisions, and electron-positron collisions. Despite numerous promising theoretical models, the fundamental mechanism underlying this polarization phenomenon remains inconclusive to this day. However, in both longitudinally and transversely polarized lepton-hadron and hadron-hadron collisions, it is found that the Λ hyperon is *not* polarized with respect to the initial parton spin direction. How the Λ hyperon acquires its spin has become one of the most crucial questions to address in order to resolve this puzzle. In this paper, I propose to use an exclusive process that can be measured at the Electron-Ion Collider, the deep exclusive meson production, to explicitly test the mechanism of Λ polarization. The outcomes of this experimental measurement are anticipated to unveil the dominant mechanism by which Λ obtains its spin, eliminating many of the ambiguities that have been encountered in previous studies. Finally, experimental challenges and requirements are discussed.

I. INTRODUCTION

Almost 50 years ago, a Fermilab experiment discovered a large transverse polarization of Λ hyperons in inclusive unpolarized proton-beryllium collisions [1]. This was highly unexpected, because perturbative quantum chromodynamics (QCD) forbids a large polarization signal [2] and the total polarization in inclusive processes should average to 0 in a naive expectation [3]. This observation indicates that the Λ hyperon polarization has to originate from nonperturbative processes in a nontrivial way. Since then, transverse Λ polarization has been found in many different collision systems, e.g., electron-proton and electron-nucleus deep-inelastic scattering (DIS) [4–7], hadron-hadron and hadron-nucleus collisions [1,8], heavy-ion collisions [9], and recently even electron-positron collisions [10].

Apart from the Λ polarization in heavy-ion collisions, which seems to be understood in the context of a strongly rotating quark-gluon plasma [9,11], the origin of all other observed polarization remains inconclusive to date. Many theoretical models [3,12–15] have attempted to explain this phenomenon, and some have been quite successful [12,13], but there is no model that can explain the global data at the same time. Although all models point to a common direction, which is the hadronization process or final-state effects in general, the quantitative description of how Λ obtains its spin in unpolarized collisions is still unknown.

What makes this problem even more interesting is when experiments have attempted to measure Λ polarization in a polarized target [16–20]. Thanks to the self-analyzing weak decay of Λ hyperons, the Λ polarization measurement has been a common experimental tool to access the initial-state spin effect, e.g., the strange quark helicity and transversity distributions. However, no Λ polarization has ever been found with respect to the initial spin direction of the target.[1] It is expected that the Λ polarization asymmetry measurement is a convolution of parton distributions (e.g., helicity), parton-scattering cross sections, and polarized fragmentation functions [21]. Without understanding quantitatively the role of fragmentation, it is both experimentally and theoretically difficult to access the initial-state parton distributions. In other words, the hadronization process could be responsible for *not* seeing the Λ polarization in a polarized target [21]. Recently, there are new proposals to measure Λ spin-spin correlation in both polarized and unpolarized DIS and hadron-hadron collisions [22–24], where final-state effects are expected to be suppressed. This is similar to the long-range two-particle momentum correlation in heavy-ion collisions [25]. There are other related studies based on Λ and its polarization at the Electron-Ion Collider (EIC), e.g., leading Λ production [26] and inclusive transverse Λ polarization [27].

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[1]Note that a nonzero polarization signal was found for Λ̄ [16], which makes the whole picture more complex.

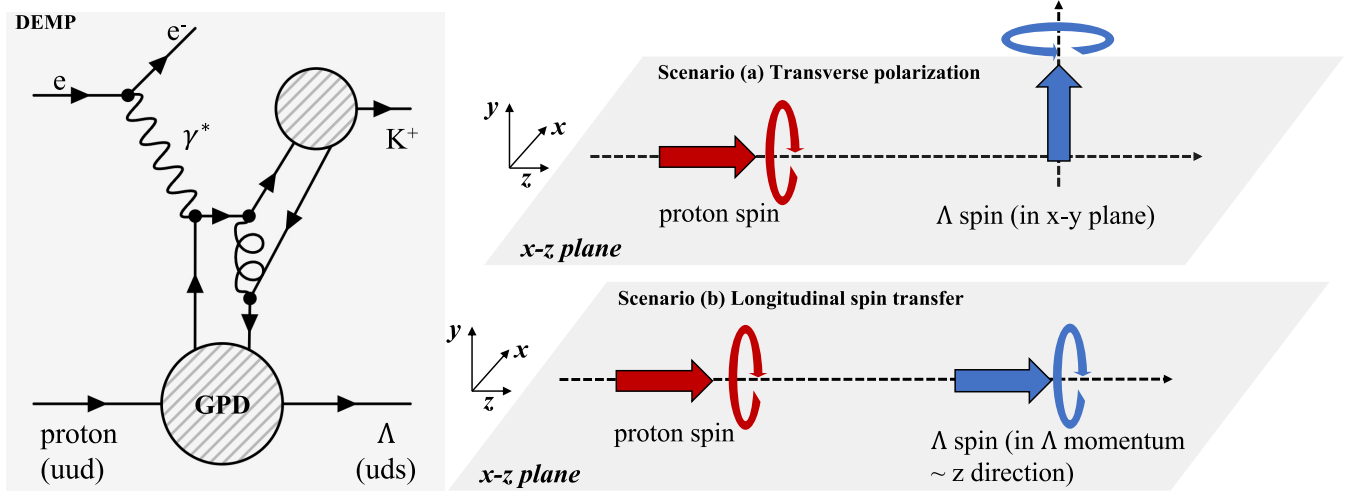## Λ hyperon polarization in DEMP with longitudinally-polarized protons

FIG. 1. Illustration of deep exclusive meson production (DEMP) in a longitudinally polarized electron-proton scattering at the Electron-Ion Collider. The proton beam momentum can be between 41 and 275 GeV/c, and the longitudinal polarization can be either positive or negative helicity. The Λ decay products do not need to be in the production plane, which is not shown.

In recent years, deep exclusive meson production (DEMP) has been proposed to be sensitive to generalized parton distributions (GPDs) and meson form factors [28,29]. The process is as follows, $e + p \rightarrow e' + K^+ + \Lambda$, where the cross section of this process and its momentum transfer $-t$ are closely related to GPDs [28], thanks to the large Q^2 and high center-of-mass energy to ensure factorization in such a process. However, Λ polarization has never been considered in this context. Although this process was not initially intended for measuring the Λ polarization, it has a few advantages: (i) an exclusive process with well-defined final states and kinematics; (ii) a large Λ momentum that is close to the beam direction, where the Λ unambiguously carries valence quarks from the incoming proton; and (iii) no feed-down from higher mass resonance and no fragmentation process involved. Therefore, this process would significantly simplify the picture of Λ polarization, which could potentially pin down its nonpertubative origin.

In this paper, a new Λ polarization measurement is proposed in the polarized ep DEMP process at the upcoming EIC. See Fig. 1 for an illustration. The measurement is designed to find out in which direction the Λ hyperon is polarized: (a) transverse polarization with respect to the production plane, or (b) a large longitudinal spin transfer from proton to Λ, which is close to the direction of the incoming beams. Note that the spin directions of scenarios (a) and (b) are by definition orthogonal to each other. In this process, both scenarios are expected to have its possible maximum strength. However, only one scenario can be correct.

II. EXPERIMENTAL TECHNIQUES

Experimental measurement of the Λ polarization is via its self-analyzing weak decay, $\Lambda \rightarrow p + \pi^-$. In the Λ rest frame, the momentum direction of the daughter proton (or π^-) exhibits a cosine distribution relative to the Λ polarization direction, as follows,

$$\frac{dN}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta. \qquad (1)$$

Here α is the weak-decay constant [30], θ is the opening angle between the proton daughter in the Λ rest frame with respect to the Λ spin direction, and P_Λ is the polarization magnitude of the Λ particle. The spin direction, however, can vary in different studies depending on the underlying mechanism of Λ polarization. In this study, I focus on two possible directions of Λ polarization: (a) with respect to the production plane and (b) with respect to the beam polarization (or Λ momentum) direction.

Production plane. The normal vector of the production plane is defined by $\vec{p}_{beam} \times \vec{p}_\Lambda$. In this study, the proton beam is used instead of the electron beam momentum as the $\vec{p}_{beam}$.

Beam polarization. For the longitudinal spin transfer, the expected Λ polarization is the direction of the Λ momentum. Some studies have tried to measure in the direction of the beam polarization, which is the same (or opposite) as the $\vec{p}_{beam}$ of the longitudinally polarized proton. In this study of DEMP, the directions of $\vec{p}_\Lambda$ and $\vec{p}_{beam}$ are very similar.

Therefore, it is by definition that the two spin polarization directions mentioned above are orthogonal to each other. Note that in the spin transfer measurement of polarized targets, it is common to use both helicity configurations to perform an asymmetry measurement, where most detector effects cancel. See Ref. [19] for an example.

III. EIC EXPERIMENTS

The upcoming EIC is designed to be an accelerator facility that can provide high-energy and high-luminosity electron-proton and electron-ion collisions, where proton and light ions can be also polarized [31]. It will enable a comprehensive DIS measurements across a wide range of processes, including rare

reactions that previously were impossible to be measured at ep collider experiments.

The current EIC project includes the accelerator facility and only one interaction region with one experiment—ePIC [32]. However, it is not excluded that there can be a second detector at the EIC. In fact, the EIC physics community favors two experiments [33]. One potential difference of the second detector, among many other possibilities, can be the tagging capability in the hadron-going far-forward (FF) region [34].

Based on the current ePIC design, there are four detector subsystems in the FF region—the B0 spectrometer, the Roman pots (RP), the off-momentum detector (OMD), and the zero-degree calorimeter (ZDC). For details, see previous studies in Refs. [35–37]. Although the exact design has not been finalized yet, the general acceptance and performance are understood. Specifically, the B0 spectrometer can detect charged particles for scattering angles between 5.5 to 22.0 mrad. The RP detects the scattered proton in ep collisions for small scattering angles, while the OMDs can detect breakup protons from nuclei with small scattering angles due to the change of the magnetic rigidity. Finally, the ZDC can detect neutral particles, e.g., the neutrons and maybe high-energy photons.

For the process of interest in this study, the final-state particles are the kaon and the Λ, where the Λ decays to a pion and proton. The Λ will be close to the beam momentum with a small scattering angle. The challenge of detecting the Λ from its decay is its long lifetime. From a current estimate [31], the acceptance of the Λ decay products in the FF system is small for high-energy configurations, e.g., 18×275 GeV ep collisions, but is feasible for 5×41 GeV (see a ePIC-like B0 simulation in Sec. V). For Λ particles with an energy range of 30 to 41 GeV, the mean displaced vertex is at 2.7 m downstream, which is before the location of the B0 spectrometer. The B0 spectrometer is designed and expected to detect charged particles, e.g., protons and pions from the Λ decays. Quantitative estimation is needed and full detector simulations are being prepared in ePIC and at the EIC second interaction point (IP). In addition, the kaon can be detected in the ePIC main detector with the barrel and the forward tracker, together with particle identification systems. An interesting direction for the EIC second detector is whether the acceptance of this measurement can be improved for a high-energy configuration, which allows access to the low-x region.

IV. PREDICTIONS

A. Transverse Λ polarization with respect to the production plane

From the measured data in the past decades, the transverse Λ polarization with respect to the production plane has been found with the following features:

  (i)   independent of the center-of-mass energy;
  (ii) strongly dependent on x_F and p_T of the Λ particle, and most data show a linear or quadratic dependence;
  (iii) the polarization is negative with respect to the production plane.

Note that the sign of the polarization signal depends on the definition of the production plane, which is usually $\vec{p}_{\mathrm{beam}} \times \vec{p}_{\Lambda}$, where $\vec{p}_{\mathrm{beam}}$ is the momentum of the incident beam that carries valence up and down quarks. The polarization signal is found to have an opposite sign in lepton-nucleon (or nucleus) scattering (e.g., Ref. [6]), and the natural explanation is that the incident beam is a lepton, which does not carry valence quarks. Therefore, the polarization signal is positive. It should also be noted that the transverse direction in the low-energy measurements within the resonance region [38] has a different definition of the projected spin axis.

For hadron-hadron colliders, e.g., proton-proton collisions at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider, both beams can be target and projectile, the choice is not unique. However, no polarization signal has been observed either [39]. Another feature to note is that the $\bar{\Lambda}$ polarization signal has never been observed in unpolarized hadron-hadron or lepton-hadron scatterings.

In this proposed measurement, Λ particles are mostly in an extreme phase space. Specifically, the x_F of Λ is close to -1, as the Λ will move forward close to the incoming proton beam momentum in the DEMP process. Note that the positive x_F is defined as the longitudinal momentum fraction of a particle with respect to the incoming photon in the hadronic center-of-mass frame. However, to compare with previous proton-proton and proton-nucleus fixed target data [1,8], the sign of x_F is flipped in order to be compared properly. The naive picture is as follows: (i) the proton has two up quarks and one down quark, together with sea quarks and gluons; (ii) the strange and antistrange pair provides one strange quark to combine with one up quark and one down quark to form a Λ particle, while one valence up quark and the antistrange quark form a positively charged kaon (K^+); both particles are moving forward, with Λ closer to the beam momentum.

In Fig. 2, data taken from ATLAS [39], HERA-B [4], and M2 [8] are shown as a function of x_F of Λ particles. The data are fitted with a quadratic form, which describes the data really well with $\chi^2/ndf = 1.42$. Based on this extrapolation, the predicted P_Λ value at $x_F = 1$ is -0.58, which would suggest the dominant mechanism of Λ polarization is formed at the final state.

Although the parametrization of a quadratic function is only to describe the data, the strong x_F dependence is well established. There are many models that have claimed to qualitatively describe this phenomenon, and some have even claimed quantitative description. The one that has been most successful is the semiclassical quark recombination approach with the "Thomas precession" [12,13]. In this model, the polarization of the Λ particle is generated by accelerating the strange sea quark from low momentum (x_s) to roughly $1/3$ of the Λ momentum. If the strange quark has a nonzero intrinsic transverse momentum k_T, the acceleration will naturally generate spin, e.g.,

$$\omega_{\mathrm{T}} = \mathbf{a} \times \mathbf{v}_{\mathrm{T}}. \tag{2}$$

Here ω_{T} is the Thomas precession frequency, $\mathbf{a}$ is the acceleration of the strange quark, and $\mathbf{v}_{\mathrm{T}}$ is the transverse velocity of the strange quark. For high-energy scatterings, the longitudinal momentum fraction of the strange quark can be very small,
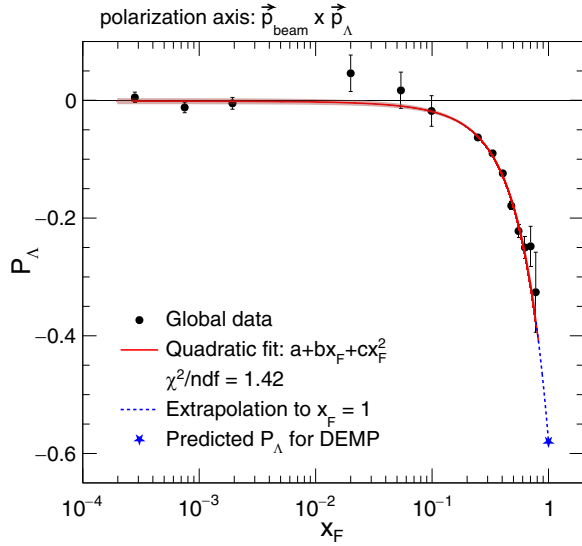
FIG. 2. Transverse Λ polarization signal, $\vec{p}_\Lambda$, as a function of Feynman x, x_F, from the ATLAS [39], the HERA-B [4], and the M2 [8] experiments. A quadratic fit and the polarization signal extrapolated to $x_F = 1$ are shown. The sign of x_F is flipped for the DEMP process for proper comparison.

$x_s < 10^{-2}$, which corresponds to momenta less than 1 GeV. However, the Λ in DEMP can be produced up to hundreds of GeVs close to the beam momentum, where $1/3$ of the beam momentum can be on the order of ≈ 100 GeV. Therefore, the expected acceleration of the strange quark is large at high energy and so are the ω_T and polarization of the Λ particle.

There are other models that have claimed to describe the transverse polarization of Λ in unpolarized lepton-lepton, lepton-hadron, and hadron-hadron collisions. In the DEMP process, it is expected that those based on the production of high-spin baryon resonances [14], single-pion exchange [3], and polarizing fragmentation function [40] should not play a role in this process. Based on all this information, the prediction is as follows.

Prediction (a). For scenario (a), the Λ polarization would be as large as negative 60% with respect to the production plane.

B. Longitudinal spin transfer via Λ polarization

From polarized lepton-hadron and hadron-hadron collisions, the parton helicity distributions of quarks are well understood in the valence region. There are two general spin sum rules, known as tje "Ji sum rule" and the "Jaffe-Manohar sum rule," respectively, as follows:

$$1/2 = \Delta\Sigma/2 + L_q + J_g \qquad (3)$$

and

$$1/2 = \Delta\Sigma/2 + \Delta G + l_q + l_g. \qquad (4)$$

Despite the difference in their approach, there is no ambiguity in counting spin contributions from quarks. Other terms are related to angular and orbital angular momentum of quarks and gluons.

In the process of DEMP, the production of Λ from the incoming proton beam can be viewed as a result of knocking out a valence up quark and the addition of a strange quark from the sea. In the valence region, the data have shown that the two up quarks account for 60%, down quark accounts for -30%, and strange quarks and antiquarks account for a very small fraction of the total nucleon spin [41]. Therefore, removing one up quark and adding one strange quark naively would result in a 30% reduction of the total spin. In other words, for a longitudinal polarized proton target with 70% initial polarization,

$$\text{proton[uud]}(70\% \text{ polarized}) \rightarrow \Lambda\text{[uds]}(\sim 50\% \text{ polarized}). \qquad (5)$$

To measure this polarization, the spin axis is the momentum direction of the Λ particle, which is close to the beam momentum and initial polarization direction (e.g., positive helicity configuration). There are models, e.g., Ref. [42], that predict similar results of the longitudinal Λ polarization in the target fragmentation region; however, it is not in the exclusive channel that the x_F is much smaller.

Most of longitudinal and transverse spin transfer measurements using Λ particles were measured at small x_F or midrapidity. In DEMP, the Λ momentum is close to the initial polarization direction, which is expected to maximize the spin transfer. In addition, similar to the case of polarization with respect to the production plane, the fragmentation process does not play a role here, and thus, a clearer picture of the spin transfer from nucleon to parton can be obtained. Based on these expectations, the prediction is as follows.

Prediction (b). For scenario (b), the Λ polarization would be as large as positive 50% with respect to the Λ momentum or the beam polarization direction.

V. STAND-ALONE DETECTOR SIMULATION

In order to show the experimental feasibility of this proposed measurement, the stand-alone GEANT simulation [43] study is performed to evaluate the acceptance of Λ reconstruction in the planned B0 detector in the EIC far-foward region. Although this is not the exact B0 simulation in ePIC, this framework has been used in previous publications [35,37] before the ePIC Collaboration was formed and it is sufficient to show experimental feasibility. For details see Refs. [35,37].

Specifically, the B0 spectrometer consists of silicon tracking planes (four layers) embedded in the first dipole magnet after the IP, which is about 5 m downstream. The angular acceptance of the B0 spectrometer is designed for reconstructing charged particles with angles $5.5 < \theta < 20.0$ mrad, such as the proton and the pion decayed from the Λ particle from DEMP. The GEANT simulation describes the Λ particle decays and their secondaries that propagate through the predefined detector volume of the B0 detector. The decay daughters, protons and pions in this study, would go through different layers of the silicon planes and leave signals, regarded as hits. By requiring at least three out of four hits, tracking reconstruction uses the EicRoot [44] (which uses the GENFIT package with the Kalman filter algorithm [45]) to obtain the
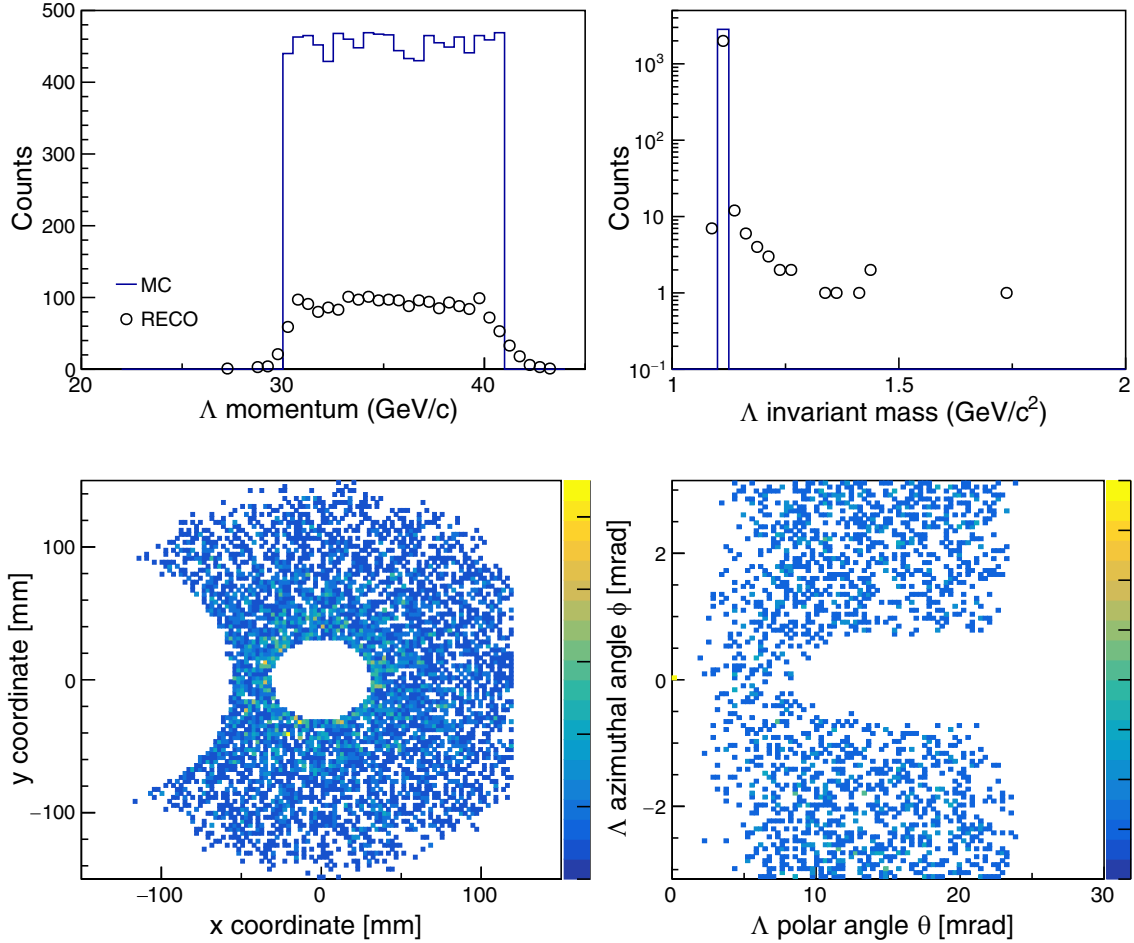
FIG. 3. Stand-alone GEANT simulation of the B0 spectrometer for Λ reconstruction with a particle gun input between 30 and 41 GeV.

momentum of particles. In a single event, if two oppositely charged tracks are reconstructed and combined to a Λ particle, this event is considered as accepted.

In Fig. 3, the Λ Monte Carlo (MC) truth and reconstructed momentum (top-left panel), invariant mass (top-right panel), hit signals detected in the B0 detector from Λ decays (bottom-left panel), and the azimuthal verse polar angle of Λ (bottom-right panel) are shown. The events are generated via a particle gun with flat distributions between 30 and 41 GeV/c in momentum as well as in scattering angle θ and azimuthal angle ϕ. The reconstructed invariant mass distribution is peaked at the PDG Λ mass value but with a tail distribution at higher masses. This is caused mostly by the detector resolution. In addition, the reconstruction efficiency and acceptance are found to be $\approx$20%, largely due to the geometrical acceptance loss from electron and hadron beam pipes, the quadruple magnet, and shielding. This can be seen from the bottom left panel of Fig. 3, which shows the local coordinate of the B0 detector that the origin (0,0) is the center of the hadron beam pipe. The acceptance losses from the negative x direction are due to the electron beam pipe, the quadruple magnet, shielding, etc. These acceptance losses can be seen from the polar angle and azimuthal angle distributions, which are shown in the bottom right panel of Fig. 3. Note that the 20% acceptance includes contributions from all

decay channels. Furthermore, most of the displaced vertices are within 5 m from the IP, which is before the location of the B0 detector. From the same study with higher energy Λ particles, the acceptance is found to be significantly reduced because the positions of the displaced vertices are largely beyond the B0 detector. Nevertheless, the Λ reconstruction in the B0 detector at the low-energy configuration, e.g., 5×41 GeV, is found to be feasible.

VI. DISCUSSION

Based on the DEMP generator (Ref. [46]), the rate of this process for 5×41 GeV at the EIC is around 18 Hz for the kaon-Λ final state. In other words, it is only about 10 pb^{-1} for generating 5×10^5 Λ for this study. See Fig. 4 for the kinematic distributions of this process. The physics model is based on the exchange of Regge trajectories in the t channel and constrained by the Vanderhaeghen-Guidal-Laget model [47–50] that describes exclusive hadronic reactions in the DIS region with low-momentum transfer. The model has been compared with another by Tom Vrancx and Jan Ryckebusch (the VR model) [51], which was found to be reasonably close in describing the differential cross section in momentum transfer. A quantitative estimate of the model uncertainty is currently unavailable.
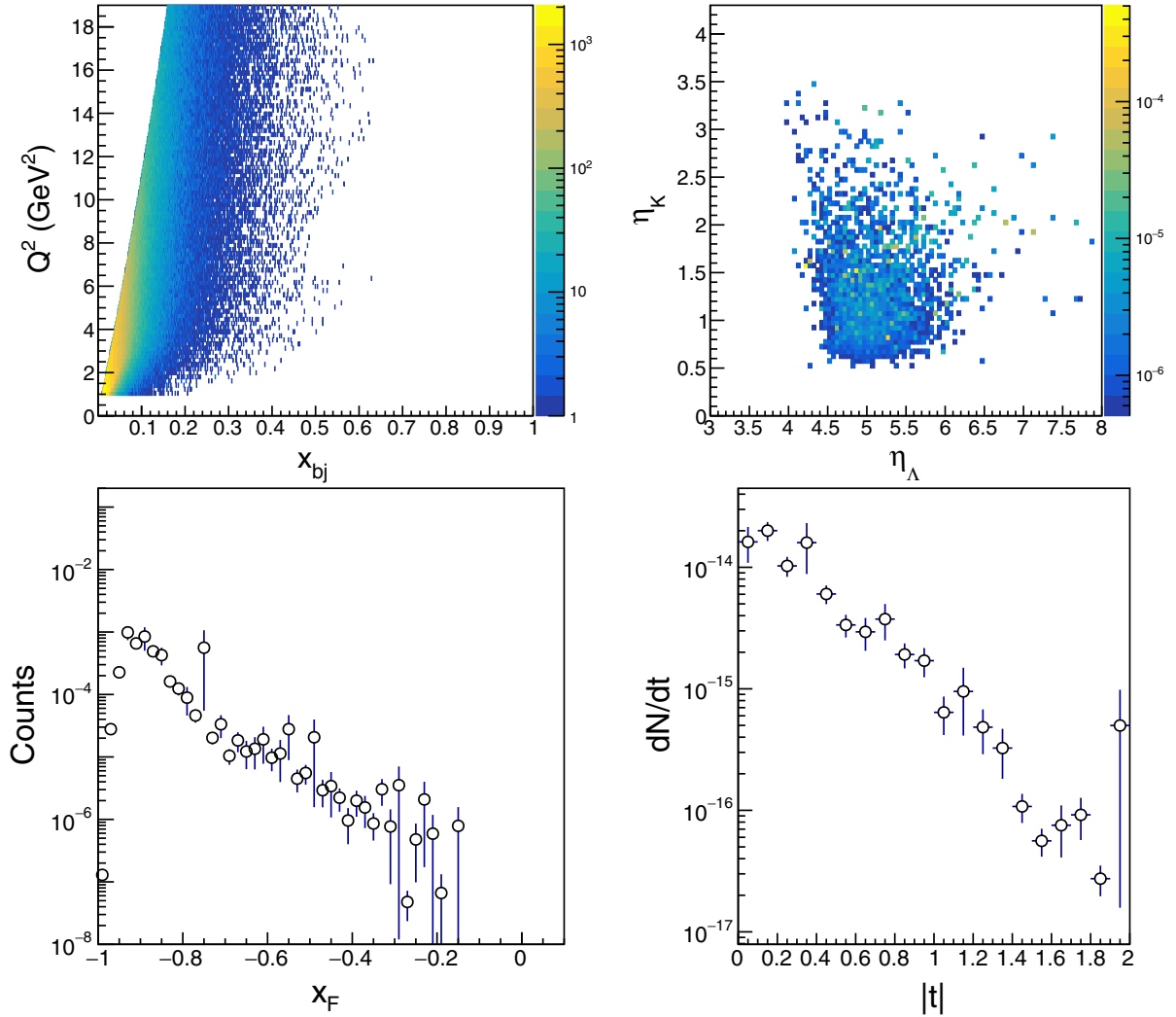
FIG. 4. Kinematic distribution of deep exclusive meson production in the $e + p \rightarrow e' + K^+ + \Lambda$ process, generated by the event generator DEMPgen [46].

The top-left panel of Fig. 4 shows the kinematic distribution Q^2 versus x_{bj}, where the large lever arm in Q^2 is one of the advantages of this process at the EIC. The top-right panel of Fig. 4 shows the pseudorapidity (η) distribution of the kaon and the Λ particle in the laboratory frame. The forward-going Λ is concentrated around 4–6 in η, which is within the acceptance of the EIC far-forward detector system in general (both ePIC and the conceptual design of a second detector). The bottom-left and bottom-right panels show the longitudinal momentum fraction with respect to the virtual photon momentum in the hadronic center-of-mass frame (x_F) and the momentum transfer $-t$. The x_F distribution shows that the Λ is carrying most of the momentum of the proton beam going in the forward direction.

Based on requirements of measuring Λ polarization in DEMP via its decay and the beam polarization, this measurement can be best, if not only, performed at the EIC. In terms of the luminosity requirement for 5×41 GeV of ep collisions, an integrated luminosity of ≈ 10 pb^{-1} can result in a measurement with statistical precision better than 2%, which is based on an estimate of the branching ratio of Λ decaying

to the proton-pion final state and the reconstruction efficiency and acceptance of Λ and kaon detection. This requirement is orders of magnitude lower than GPD measurements based on the same channel [46].

Based on the GEANT simulation study above, it would be challenging to perform this measurement at higher-energy configurations, e.g., 18×275 GeV ep collisions, in ePIC given the location of the B0 detector. From the perspective of a EIC second detector, where the design of the detector and technology choice are not decided yet, a more downstream spectrometer away from the IP can benefit the higher-energy Λ reconstruction in the far-forward region. In addition to the acceptance, the momentum and the spatial resolution are expected to be good enough based on the current B0 design in ePIC to determine the direction of the Λ momentum reasonably well [35,37]. Quantitative feasibility studies at ePIC and the EIC second detector are needed and have been planned.

Taking one step further, this measurement can be extended to (i) transverse polarized ep DEMP and (ii) the incoherent electron-deuteron or electron-helium-3 DEMP on the bound nucleon target. For case (i), the transverse spin direction is

not always perpendicular to the production plane direction. One could vary the relative angle between them by selecting different azimuthal angles of the Λ particle in the forward direction. For case (ii), with helium-3 polarization and the proton spectators tagging technique [35,37,52], one could measure a similar process on the polarized neutron target to understand the role of valence quarks, e.g., $e + \mathrm{He}^3(d) \rightarrow e' + 2p'(p') + K^0 + \Lambda$, where the neutral kaon decays weakly (e.g., K_s^0 to two pions). Experimentally, this is much more challenging than the proton case. In addition, one of the possible upgrades at the EIC is to polarize deuterons, where similar measurements can be done using the deuteron target.

Finally, experiments in Ref. [28] and CLAS12 at Jefferson Lab with the 12-GeV electron beam program can measure the momentum transfer cross section of DEMP, based on a technique by utilizing the missing mass of the Λ particle. However, dedicated studies are needed to investigate the feasibility of measuring the Λ polarization in this process. Note that similar measurements in the resonance region with electron beam polarization have been done at CLAS before [38,53], while longitudinal polarized target data were not available until recently. A potential measurement with these data in CLAS12 is also interesting. At both the Jefferson Lab 12-GeV program and at the EIC, this experimental measurement may be sensitive to chiral-odd GPDs [54], which may shine new light on the problem of Λ polarization.

VII. CONCLUSIONS

In conclusion, a new experimental measurement of Λ polarization in the process of deep exclusive meson production in polarized ep collisions at the upcoming Electron-Ion Collider is proposed. This measurement is expected to probe directly the underlying mechanism of how Λ acquires its spin in high-energy particle-scattering processes. Specifically, this proposal has a number of advantages: (i) a clean exclusive reaction with only a kaon and an Λ particle in the final state; (ii) the Λ particle carries the *maximal* longitudinal momentum, where maximum polarization with respect to both the production plane and the beam polarization direction are expected; however, only one can be correct; (iii) no feed-down from higher mass resonance and no fragmentation involved in this process, which automatically rules out many theoretical models on transverse Λ polarization. The result of this measurement will significantly broaden the experimental program at the Electron-Ion Collider, e.g., using the Λ hyperon as a probe to study transverse-momentum-dependent parton distribution functions and generalized parton distributions. Most importantly, it may also provide a clear path forward towards solving the almost 50-year puzzle of Λ polarization.

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