

Longitudinal spin transfer to Λ hyperons in semi-inclusive deep inelastic scattering with the CLAS12 spectrometer

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The polarization of Λ hyperons is preserved in the angular distribution of their decay products. This property allows one to study the spin structure of the Λ . In semi-inclusive deep inelastic scattering where a high energy lepton interacts with a nucleon target and one or more hadrons and the scattered lepton are detected in the final state, the probability for a struck quark to impart the polarization of the lepton to the Λ may be measured. In particular, in electron-proton scattering this quantity may be related to the longitudinal light quark polarization of the Λ . Currently, limited experimental data cannot discriminate between different models of Λ spin structure. This work reports on the measurement of the longitudinal spin transfer D_{LL}^Λ to the Λ using data taken by the CLAS12 spectrometer at Jefferson Lab with a 10.6 GeV longitudinally polarized electron beam and an unpolarized hydrogen target. This measurement is the most precise to date, and, in comparison with theory predictions, it offers valuable insight into the relative dominance of current and target fragmentation in Λ production.

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I. INTRODUCTION

Understanding the internal dynamics of the nucleon and other hadrons remains one of the most complex unsolved challenges in modern physics. The quarks within a hadron are held together by the strong force, one of the four fundamental forces. Quantum chromodynamics (QCD) gives us a theoretical framework that has quite successfully described many physical observations [1]. However, hadrons are strongly coupled systems and, hence, are not perturbatively calculable. Fortunately, the asymptotic freedom of QCD at short distances allows one to analyze the hadron dynamics with a high energy probe such as

an electron since its de Broglie wavelength $\lambda = h/p$ is inversely related to its energy [1].

Processes such as semi-inclusive deep inelastic scattering (SIDIS),

$$\ell(l) + N(P) \rightarrow \ell'(l') + h(P_h) + X, \quad (1)$$

where a high energy lepton ℓ collides with a target nucleon N and one or more hadrons h are detected in the final state are ideally suited to studying nonperturbative quantities in QCD. l , l' , P , and P_h , respectively, denote the 4-momenta of the incoming and outgoing lepton, the target nucleon, and a final state hadron. The 4-momentum of the virtual photon γ^* exchanged between the incoming lepton and the target nucleon is denoted $q = l - l'$. Some kinematic variables used to characterize the interactions are defined as follows:

$$Q^2 = -q^\mu q_\mu, \quad (2a)$$

$$W^2 = (P^\mu + q^\mu)^2, \quad (2b)$$

$$x = \frac{Q^2}{2P^\mu q_\mu}, \quad (2c)$$

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$$y = \frac{P^\mu q_\mu}{P^\mu l_\mu}, \quad (2d)$$

$$z_h = \frac{P^\mu P_{h,\mu}}{P^\mu q_\mu}, \quad (2e)$$

$$x_{Fh} = \frac{2\vec{P}_h \cdot \vec{q}}{W|q|}, \quad (2f)$$

$$\cos \phi_h = \frac{(\vec{q} \times \vec{P}_h) \cdot (\vec{q} \times \vec{l}')}{|\vec{q} \times \vec{P}_h| |\vec{q} \times \vec{l}'|}. \quad (2g)$$

Q^2 is the negative 4-momentum squared of the γ^* momentum and describes the virtuality of the interaction. W is the final state energy in the γ^*N center-of-mass (c.m.) frame, x is the longitudinal light cone momentum fraction of the target nucleon carried by the struck quark, and y is the fraction of the incoming electron energy carried by the virtual photon. The remaining variables are specific to the hadron h of interest detected in the final state. z_h describes the energy fraction of the hadron relative to the struck quark and x_{Fh} is the longitudinal momentum fraction of the hadron relative to the maximum value $W/2$ allowed by momentum conservation in the γ^*N c.m. frame. Finally, ϕ_h is the azimuthal angle of the hadron momentum about the virtual photon momentum in the γ^*N c.m. frame. Importantly, the x_{Fh} variable is used to distinguish between hadrons produced from the struck quark, the current fragmentation region (CFR), and from the remaining quarks within the target nucleon, the target fragmentation region (TFR). Positive x_{Fh} values are associated with hadrons traveling in the forward-going virtual photon direction and negative values are associated with hadrons traveling in the backward-going target nucleon direction in the γ^*N c.m. frame.

While unpolarized SIDIS gives access to unpolarized observables in QCD, there still remain transverse momentum and polarization dependent aspects of hadron structure that can only be accessed through polarized SIDIS measurements. One must consider these aspects of QCD as well in order to construct a complete picture of a hadronic QCD system. In SIDIS, observables dependent on transverse momentum and polarization often manifest in asymmetries between the cross sections produced from opposite initial lepton probe helicity and target nucleon spin configurations. The Λ hyperon lends itself naturally to these studies by virtue of its self-analyzing weak decay $\Lambda \rightarrow p\pi^-$ shown in Fig. 1. In fact, the large spontaneous transverse polarization of Λ hyperons produced in $p + Be$ collisions [2] over 45 years ago was the first indication that transverse spin effects played a significant role in hadron physics. The polarization of the Λ is preserved in the cross section of the decay protons,

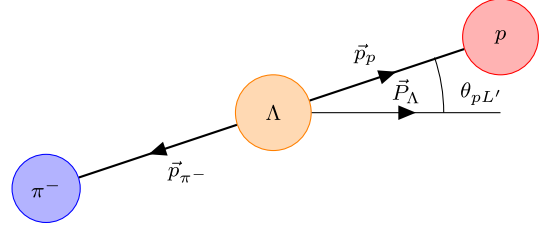


FIG. 1. The $\Lambda \rightarrow p\pi^-$ decay in the Λ rest frame is shown with the Λ spin axis $\vec{P}_\Lambda$ retained from the γ^*N c.m. frame.

$$\frac{dN}{d\Omega_p} \propto 1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{n}_p. \quad (3)$$

$\alpha_\Lambda = 0.747 \pm 0.009$ is the asymmetry parameter for the weak decay of the Λ in its c.m. frame [3] and $\vec{P}_\Lambda \cdot \hat{n}_p$ is the polarization of the Λ along the proton momentum in the Λ rest frame [4,5].

In this paper, we set out to expand upon our previous work [6] and to make a clean and precise measurement of the Λ longitudinal spin transfer coefficient $D_{LL'}^\Lambda$. This quantity describes the probability for a struck quark to impart its longitudinal spin to the Λ in SIDIS, and, as discussed below, for our selected data, this may be assumed to come primarily from scattering off light (u , d) quarks within the target nucleon. Measurement of this quantity also offers a clear test of the dominant Λ production mechanism in the CLAS12 kinematic phase space, which provides significant insight for future studies.

A. The polarized Λ production cross section

As shown in Ref. [7], the only term of the Λ leptoproduction differential cross section with an unpolarized target that is dependent on both the longitudinal helicity state of the incoming lepton beam λ_ℓ and of the Λ longitudinal spin state $S_{\Lambda\parallel}$ is

$$d\sigma_{LUL} \propto S_{\Lambda\parallel} \lambda_\ell \left[y \left(1 - \frac{1}{2}y \right) F_{LUL} + y \sqrt{1-y} \cos \phi_\Lambda F_{LUL}^{\cos \phi_\Lambda} \right]. \quad (4)$$

Here, ϕ_Λ is the azimuthal angle of the Λ momentum about the γ^* momentum in the γ^*N c.m. frame defined by Eq. (2g) and $F_{ABC}^{\text{Mod}} = F_{ABC}^{\text{Mod}}(x, z, P_{h\perp}^2)$ are structure functions of different angular modulations denoted by the superscripts. The subscripts correspond to beam, target, and Λ polarization states, respectively. As shown in Ref. [7], integrating over the transverse momentum $P_{h\perp}$ of the Λ , leaves us with just the first structure function F_{LUL} , which may be expressed in terms of parton distribution functions (PDFs) and fragmentation functions (FFs) as

$$F_{LUL}(x, z) = x \sum_a e_a^2 f_1^a(x) G_1^{\Lambda, a}(z), \quad (5)$$

where the sum runs over the quark flavors a and e_a is the charge of the quark of flavor a . f_1 is the unpolarized PDF and G_1 is the helicity FF, following the notational conventions of Ref. [8]. The only unpolarized differential cross section term that survives the $P_{h\perp}$ integration is given by [9]

$$\begin{aligned} d\sigma_{UUU} &\propto \left(1 - y + \frac{1}{2}y^2\right) F_{UUU} \\ &\propto \left(1 - y + \frac{1}{2}y^2\right) x \sum_a e_a^2 f_1^a(x) D_1^{\Lambda, a}(z), \end{aligned} \quad (6)$$

and contains the unpolarized FF D_1 .

The most basic and extensively studied FF is the unpolarized FF $D_1^{h, a}(z)$ describing the probability for an unpolarized quark of flavor a to fragment into an unpolarized hadron h [10]. However, one may further refine PDFs and FFs by introducing helicity state dependence. For example, we may define the probability for a quark with flavor a of positive helicity $+$ to fragment into a hadron h of the same helicity as $D_1^{h+, a+}$ and to fragment into a hadron of opposite helicity $-$ as $D_1^{h-, a+}$. Assuming these probabilities are symmetric for a quark of negative helicity fragmenting into a hadron of the same or opposite helicity, $D_1^{h-, a-} = D_1^{h+, a+}$ and $D_1^{h+, a-} = D_1^{h-, a+}$, the unpolarized FF may then be expressed as $D_1^{h, a} = D_1^{h+, a+} + D_1^{h-, a+}$, and we may define the helicity-dependent FF $G_1^{h, a} = D_1^{h+, a+} - D_1^{h-, a+}$ [4,8]. $G_1^{h, a}$ describes the probability to produce a longitudinally polarized hadron from a longitudinally polarized quark.

Recall from Eq. (3) that the Λ decay cross section is itself dependent on the Λ polarization P_Λ which, fortuitously, is an asymmetry we can relate to the $P_{h\perp}$ -integrated cross sections from Eqs. (4) and (6) as

$$P_\Lambda = \frac{N^{\Lambda+} - N^{\Lambda-}}{N^{\Lambda+} + N^{\Lambda-}} \propto \frac{d\sigma_{LUL}}{d\sigma_{UUU}}. \quad (7)$$

Thus, we can express the Λ polarization P_Λ in terms of PDFs and FFs,

$$P_\Lambda = \lambda_e \frac{y(1 - \frac{1}{2}y)}{1 - y + \frac{1}{2}y^2} \frac{\sum_a e_a^2 f_1^a(x) G_1^{\Lambda, a}(z)}{\sum_a e_a^2 f_1^a(x) D_1^{\Lambda, a}(z)}. \quad (8)$$

B. The longitudinal spin transfer coefficient $D_{LL'}^\Lambda$

In SIDIS, the incoming electron interacts with a valence quark in the target nucleon by means of a virtual photon. Since the photon has spin 1, a longitudinally polarized beam will preferentially select a quark of the opposite

polarization. This means that the outgoing quark will have the same helicity as the virtual photon and will have some chance of imparting its polarization to a hadron in fragmentation. With this more intuitive formulation, we can write the Λ polarization from Eq. (8) as

$$P_\Lambda = \lambda_e D(y) D_{LL'}^\Lambda, \quad (9)$$

where λ_e is the helicity of the incident electron and $D(y) = \frac{y(1-\frac{1}{2}y)}{1-y+\frac{1}{2}y^2}$ is a depolarization factor that takes into account the loss of polarization from the incident electron to the virtual photon. The final ratio of PDFs and FFs in Eq. (8) we denote by $D_{LL'}^\Lambda$. This is the longitudinal spin transfer coefficient, which encodes the probability for the struck quark in the target nucleon to impart its polarization to the produced Λ . This means that the angular distribution of protons coming from the Λ decay is

$$\frac{dN}{d\Omega_p} \propto 1 + \alpha_\Lambda \lambda_e D(y) D_{LL'}^\Lambda \cos \theta_{pL'}, \quad (10)$$

where the angle $\cos \theta_{pL'}$ is taken between the proton momentum and Λ spin quantization axis L' in the Λ rest frame. In principle, one may analyze the Λ polarization along any choice of the axis L' . Some authors differ in their definition of the longitudinal axis [8,11,12]. Hence, for our analysis we present results for two different choices of the longitudinal polarization axis: along the virtual photon γ^* momentum and along the Λ momentum direction retained from the $\gamma^* N$ c.m. frame.

We now motivate the interpretation of $D_{LL'}^\Lambda$ as the probability of spin transfer from the struck quark to the produced Λ . Since our CLAS12 data do not span a wide range of Q^2 and exhibit almost no Q^2 dependence, we have assumed that the PDFs and FFs vary slowly with Q^2 . Integrating the spin transfer coefficient as formulated in Eq. (8) over all possible momentum fractions x of the struck quark and inserting an identity, we obtain [4]

$$D_{LL'}^\Lambda(z) \simeq \sum_a \frac{G_1^{\Lambda, a}(z)}{D_1^{\Lambda, a}(z)} p^{\Lambda, a}, \quad (11)$$

where the purity $p^{\Lambda, a}$ is the probability that a Λ was produced at a fractional energy z from a quark of flavor a ,

$$p^{\Lambda, a} = \int \frac{e_a^2 f_1^a(x) D_1^{\Lambda, a}(z)}{\sum_{a'} e_{a'}^2 f_1^{a'}(x) D_1^{\Lambda, a'}(z)} dx. \quad (12)$$

In deep inelastic scattering (DIS), the scattering is predominantly off u and d quarks so $D_{LL'}^\Lambda$ is a measure of the light quark spin contribution to the Λ in this case. Furthermore, because of isospin symmetry, we should naïvely expect that $D_{LL'}^{\Lambda, u} = D_{LL'}^{\Lambda, d}$ [4].

In the naïve quark model (NQM), the s quark carries the entirety of the Λ spin while the u and d quarks are in a spin singlet state. Using SU(3) symmetry considerations to extrapolate measurements of the proton spin structure for the strange baryon octet, Burkardt and Jaffe found indications of a small negative light quark polarization in the Λ [13]. Furthermore, phenomenological models have been applied to DIS data to examine the x -dependence of the longitudinal spin transfer, which is predicted to rise with x [11,12,14].

The longitudinal spin transfer coefficient has been measured previously at OPAL and ALEPH in e^+e^- annihilation near the Z^0 resonance [15,16]. These observations revealed a large negative longitudinal spin transfer coefficient. However, this is associated with the strange quark content of the Λ since the typical production mechanism is $e^+e^- \rightarrow Z^0 \rightarrow s\bar{s}$. The longitudinal spin transfer has also been measured recently in Drell-Yan polarized pp collisions at STAR where it was observed to be small and compatible with zero [17,18]. In the Drell-Yan case, the longitudinal spin transfer coefficient is also sensitive to the strange quark spin contribution in the Λ . In exclusive DIS where all final state particles are identified, the longitudinal spin transfer has been measured in ΛK^+ and ΣK^+ photoproduction [19] and electroproduction [20,21] with the CLAS detector and more recently in electroproduction with the CLAS12 detector [22]. In this context, the spin transfer coefficient offers insight into nucleon resonances in the strange quark s -channel.

In terms of directly comparable measurements from SIDIS, the coefficient has been measured at HERMES [4] and COMPASS [23–25] in e^+ and μ^+ SIDIS respectively, as well as at NOMAD [26,27] in ν_μ charged-current interactions. HERMES and COMPASS both observed small longitudinal spin transfer coefficients in the CFR compatible with 0. NOMAD measurements were concentrated in the TFR where they observed a negative spin transfer, yet in the CFR their measured spin transfer was compatible with zero.

C. The CLAS12 detector

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab delivers a high luminosity polarized electron beam to four experimental halls for fixed target experiments [28]. The CLAS12 (CEBAF Large Acceptance Spectrometer for operation at 12 GeV beam energy) detector is located in experimental Hall B and provides excellent momentum and angular coverage, as well as good particle identification capabilities for both charged and neutral particles produced in high energy electron-nucleus scattering events [29]. The detector is centered around two large superconducting magnets, a solenoid in the central region of the detector and a torus in the forward region. The torus magnet is operated in two different configurations, either bending negatively charged

particles in toward the beamline (inbending configuration), or out away from the beamline (outbending configuration). The detector is also separated into two major detector systems. The forward detector (FD) covers the polar angle region $5^\circ < \theta < 35^\circ$ and the central detector (CD) covers the polar angle region $35^\circ < \theta < 125^\circ$. Both detector regions have symmetric azimuthal coverage about the electron beam direction.

II. DATA

The data used in this study were all taken during the fall 2018 run period in the outbending torus field configuration with a 10.6 GeV longitudinally polarized electron beam and a 5 cm long unpolarized liquid-hydrogen target. This sample corresponds to a total of roughly 35.8 mC accumulated charge, which corresponds to an integrated luminosity of 49 fb^{-1} . The outbending configuration is necessary to identify Λ baryons because the decay π^- typically has much lower momentum than the p . Thus, in the inbending configuration the π^- is bent into the beamline, drastically reducing the acceptance for the $\Lambda \rightarrow p\pi^-$ channel. Before any kinematic cuts were applied to the dataset, a momentum correction [30] for e^- and π^- was first applied to account for biases in the detector reconstruction algorithm. The correction was developed from exclusive events where all final state particles are known and the correct momentum may be inferred from momentum conservation. Our data were all required to have an identified scattered electron (e^-) and a proton-pion ($p\pi^-$) pair in the reconstruction. The electron production vertex was required to be reconstructed within a 12.5 cm interval within the scattering chamber excluding the scattering chamber exit window but allowing for some spread in the reconstructed value due to imperfections in alignment. The scattered electron was also required to have a momentum $p_{e^-} > 2 \text{ GeV}$. The proton and pion were both also required to be detected in the FD ($\theta < 35^\circ$).

Our sample of Monte Carlo (MC) simulation events was produced with the same run configuration as the actual data from the fall 2018 run period. Events were generated with an MC algorithm based on the PEPSI (polarized electron proton scattering interactions) Lund program [31], which computes the photon-parton hard scattering to first order in the strong coupling constant α_s and uses the JetSeT [32] routines to simulate the hadronic fragmentation. While the statistics of the MC sample are significantly lower than that of the data sample, this is not considered an issue because there is such a preponderance of data and the MC only enters the results through fractional corrections and in the systematic uncertainties, where it is one of the smallest contributions.

The kinematic cuts to select SIDIS events for our analysis were $Q^2 > 1 \text{ GeV}^2$, $W > 2 \text{ GeV}$, $p_{e^-} > 2 \text{ GeV}$, $y < 0.8$, $z_{p\pi^-} < 1$. We also required $x_{Fp\pi^-} > 0$ for the $p\pi^-$ pair to cut out backward-traveling particles in the γ^*N c.m.

frame and reduce TFR contributions. Additionally, the invariant mass of the $p\pi^-$ pair was restricted to $M_{p\pi^-} < 1.24$ GeV so that events were sufficiently close to the Λ mass peak. After cuts, our dataset contains roughly 3.4×10^6 events. While previous experiments [4,23,24] have relied on looking for the extended Λ decay vertex to isolate the Λ signal and reduce combinatorial background, we did not apply such an approach in our final analysis. This could be investigated in future analyses of this sort. Some effort was made to use Armenteros-Podolanski plots [33] to isolate the Λ signal; however, cuts based on this method were found to make the invariant mass distribution too complex to perform a reliable fit of signal and background distributions.

A. Signal extraction

The invariant mass spectrum of reconstructed $p\pi^-$ pairs passing kinematic cuts is shown in Fig. 2 for both the data and MC simulation. A peak around the nominal Λ mass $M = 1.1157$ GeV is apparent, but the background contribution is very high, especially in data. The main background contribution comes from combinatorics of $p\pi^-$

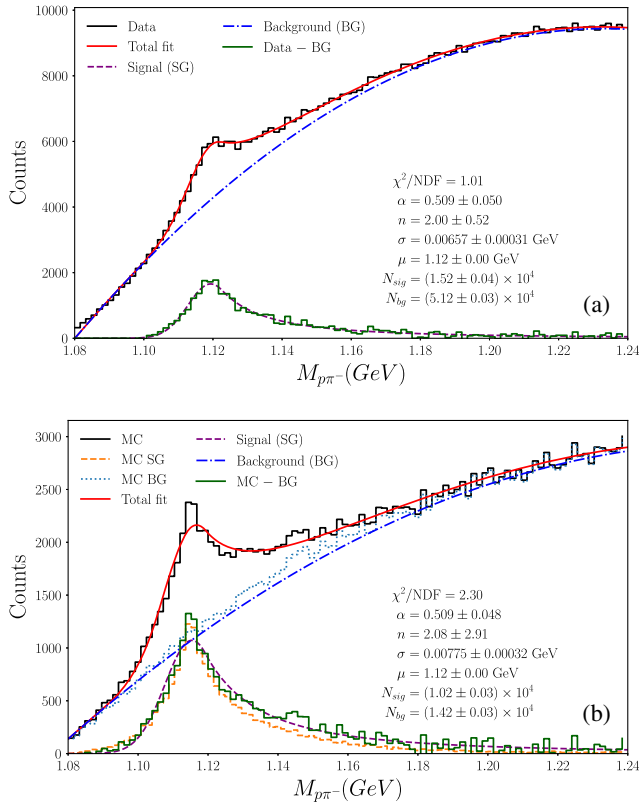


FIG. 2. Fits to the invariant mass spectrum $M_{p\pi^-}$ of reconstructed $p\pi^-$ pairs in data (a) and MC (b) are similar up to scale factors. These distributions are from the middle bin 3 in our $z_{p\pi^-}$ bin scheme. The histogram counts over the fitted background are shown in the black histograms at the bottom of each plot for comparison with the fitted signal function.

pairs that do not originate from a Λ decay. A Crystal Ball function [34] was used to fit the signal in order to accurately capture the tail of the signal distribution towards higher $M_{p\pi^-}$ events, while the background spectrum was modeled with a simple quadratic function or a fourth-order polynomial depending on the bin. The Crystal Ball function f is defined such that both the function and its first derivative are continuous,

$$f(x; \alpha, n, \sigma, \mu) = N \begin{cases} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), & \frac{x-\mu}{\sigma} \leq \alpha \\ A\left(B - \frac{x-\mu}{\sigma}\right)^{-n}, & \frac{x-\mu}{\sigma} > \alpha \end{cases}, \quad (13)$$

where N , A , and B are constants that are defined by the function parameters and satisfy the continuity requirements and normalization. Before settling on the Crystal Ball signal shape, we experimented with several other shapes including a simple Gaussian and a sum and a convolution of Gaussian and Crystal Ball functions. While not perfect, as we will discuss in the following paragraph, the Crystal Ball function provided the best option in terms of fit stability and minimum χ^2 values across our kinematic bins.

The signal is more pronounced in MC but the fit parameters are consistent up to scale factors between MC and data. Since the yields from the MC do not enter directly into the final results, the difference in relative signal and background yields between MC and data should not affect our measurements. However, as one may notice, the peak of the signal distribution exceeds the Gaussian peak of the Crystal Ball function in both MC and data. Thus, to minimize the effect of this excess peak, rather than integrating the fitted signal distribution, we estimated the signal events N_{sig} by subtracting from the counts of the total spectrum the counts N_{bg} of the integrated background function in the signal region. One may also observe that the Crystal Ball signal shape is broad, while we know the raw Λ spectrum before detector acceptance is extremely narrow since the Λ has a relatively long lifetime of $(2.617 \pm 0.0010) \times 10^{-10}$ s [3]. This is due to the poor reconstruction of the π^- for the $\Lambda \rightarrow p\pi^-$ channel because it tends to have low momentum. For the final results, the signal region limits were optimized so as to maximize the signal purity and minimize the signal uncertainty, which gave a signal region of $\pm 2\sigma$ centered about the signal mean μ at roughly the nominal Λ mass. This gave us a signal region of roughly 1.11–1.13 GeV.

III. METHODS

A. Extraction of $D_{LL'}^{\Lambda}$

To extract the spin transfer coefficient $D_{LL'}^{\Lambda}$, one may use the naïve method of simply fitting the acceptance-corrected $\cos \theta_{pL'}$ distribution to a linear function and using the fitted slope to compute $D_{LL'}^{\Lambda}$. However, this method we found to

systematically undershoot injected asymmetries, and hence, for our analysis we used a slightly more sophisticated method that we refer to as the helicity balance (HB) method. A detailed derivation of this method may be found in Ref. [35]. It is based on the method of maximum likelihood and relies on the assumption that the luminosity averaged beam polarization $\overline{\lambda}_\ell$ is consistent with zero. This allows the acceptance function to cancel out in the derivation since it couples to $\overline{\lambda}_\ell$ for computing quantities that are linearly dependent on λ_ℓ . Following this method, one may calculate the spin transfer coefficient with a simple numerical formula,

$$D_{LL'}^\Lambda = \frac{1}{\alpha_\Lambda \overline{\lambda}_\ell^2} \frac{\sum_{i=1}^{N_\Lambda} \lambda_{\ell,i} \cos \theta_{pL'}^i}{\sum_{i=1}^{N_\Lambda} D(y_i) \cos^2 \theta_{pL'}^i}, \quad (14)$$

where $\overline{\lambda}_\ell^2$ is the luminosity-averaged squared beam polarization, which was $(89.22 \pm 2.51)\%$ for our dataset. The sums run over the events in a given kinematic bin.

Of course, this method has its limitations. We observed this by injecting an artificial asymmetry in MC simulation to see the difference between the true, injected value and the extracted value of the asymmetry. We applied a correction in each kinematic bin from the fractional difference of the extracted to the injected asymmetry in MC scaled to the asymmetry extracted in data. The corrections are computed as follows. We first take the difference between reconstructed and injected asymmetry $\Delta A_{MC} = A_{Rec} - A_{Inj}$ in MC for each data point. We then scale this difference to the measured asymmetry to obtain the correction $\Delta A_{Data} = \Delta A_{MC} \cdot \frac{A_{Data}}{A_{MC}}$. The corrected value is then $A_{Data}^{Cor} = A_{Data} - \Delta A_{Data}$. The underlying assumption, which generally holds true for asymmetries, is that the extracted asymmetry should scale proportionally to the true asymmetry. The asymmetry we injected was 0.1 for these corrections since this was on par with the average asymmetry. The average value of the corrections was +23% for $\cos \theta_{LL'}$ along P_Λ and +25% for $\cos \theta_{LL'}$ along P_{γ^*} . The corrections have a nontrivial kinematic dependence which is why we apply them independently in each bin.

B. Background correction

Since there is still an irreducible background underneath our Λ signal due to combinatorics of particles not originating from the same Λ decay or any Λ decay at all, we have to correct our results to subtract away any background contributions. To do this we use the method of sideband subtraction. Assuming that the background polarization does not vary much as a function of the invariant mass $M_{p\pi^-}$ we can calculate the polarization in the signal region and in a sideband region away from the signal.

Since we can compute the relative background fraction ϵ in the signal region from our signal fit we can then use a

properly weighted subtraction of the sideband polarization to correct for any background polarization in the signal region,

$$D_{LL'}^\Lambda = \frac{D_{LL'}^{\text{sig}} - \epsilon D_{LL'}^{\text{sb}}}{1 - \epsilon}, \quad (15)$$

where $D_{LL'}^{\text{sb}}$ is the background contribution from the sideband region and $D_{LL'}^{\text{sig}}$ is the contribution in the signal region. For our purposes we define our signal region as the $\pm 2\sigma$ window about the signal mean μ , where σ is the signal width obtained from the fit to the invariant mass spectrum. For the unbinned mass spectrum this region is $1.11 \text{ GeV} < M_{p\pi^-} < 1.13 \text{ GeV}$. The sideband regions for this analysis were chosen to be $1.08 \text{ GeV} < M_{p\pi^-} < 1.10 \text{ GeV}$ and $1.15 \text{ GeV} < M_{p\pi^-} < 1.18 \text{ GeV}$. We use the same signal and sideband regions across all bins.

The sideband subtraction depends on the validity of the assumption that the background polarization does not strongly depend on $M_{p\pi^-}$ near the Λ signal region. Figure 3 shows the raw polarization extracted using the

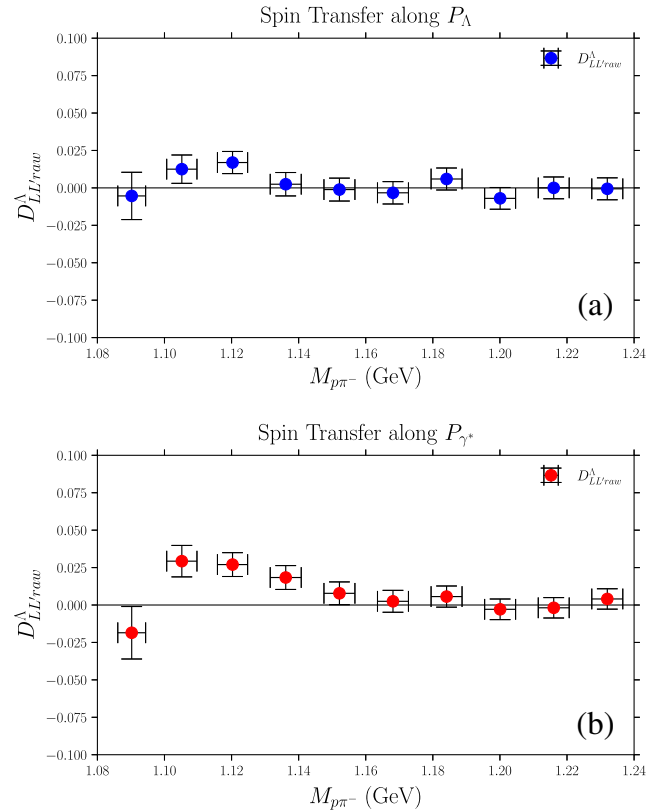


FIG. 3. Raw spin transfer results obtained with the HB method, before background correction, as a function of the mass spectrum $M_{p\pi^-}$ over the entire dataset. The insets show results for Λ polarization along the Λ momentum (a) and along the virtual photon γ^* momentum (b) in the γ^*N c.m. frame. Vertical uncertainties are statistical and horizontal uncertainties are given by the standard deviation within each bin.

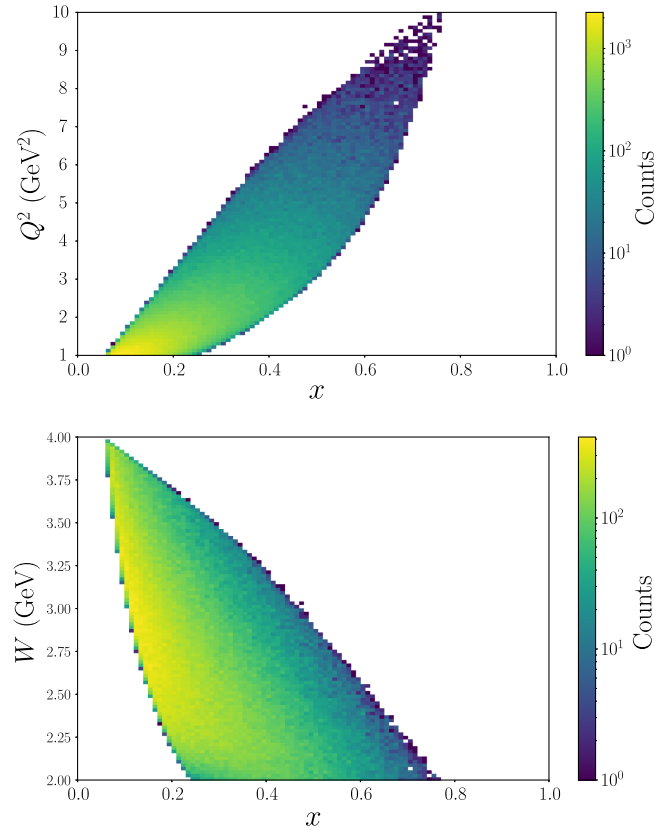
TABLE I. Bin limits used for kinematically binned results.

Bin	$z_{p\pi^-}$ bins	$x_{Fp\pi^-}$ bins
1	$0.346 \leq z_{p\pi^-} < 0.593$	$0.000 \leq x_{Fp\pi^-} < 0.050$
2	$0.593 \leq z_{p\pi^-} < 0.686$	$0.050 \leq x_{Fp\pi^-} < 0.108$
3	$0.686 \leq z_{p\pi^-} < 0.770$	$0.108 \leq x_{Fp\pi^-} < 0.178$
4	$0.770 \leq z_{p\pi^-} < 0.860$	$0.178 \leq x_{Fp\pi^-} < 0.278$
5	$0.860 \leq z_{p\pi^-} < 1.000$	$0.278 \leq x_{Fp\pi^-} < 0.805$

HB method *before* any background correction as a function of $M_{p\pi^-}$. As one would hope, we see some slight dependence near the Λ signal region and essentially a flat distribution close to zero elsewhere.

C. Kinematic bins and coverage

We divided our dataset into *separate* 1D binning schemes in the kinematic variables $z_{p\pi^-}$ and $x_{Fp\pi^-}$. The bin definitions in both variables are given in Table I. Five bins were chosen in each bin variable to cover the range of the variable and also to maintain reasonable statistics in each bin. The kinematic coverage of our dataset in Q^2 , x , and W is shown in Fig. 4.

FIG. 4. Kinematic coverage in Q^2 , x , and W of our dataset.

D. Bin migration

Due to the smearing of our reconstructed kinematic variables introduced by detector resolution, there is inevitably some migration of the reconstructed values between the true kinematic bins. Naturally, one may unfold the distribution using the bin migration matrix $f_{i \rightarrow j} = f_{ij}^T$, i.e., the fraction of true Λ s generated in bin i that are reconstructed in bin j , estimated from MC. Assuming the measured results A_j are related to the true results by the matrix equation,

$$A_j = f_{ij}^T A_{i,\text{true}}, \quad (16)$$

one can simply compute the inverse of this matrix and correct for this effect,

$$f_{ij}^{T-1} A_j = A_{i,\text{true}}. \quad (17)$$

We use this method to unfold our results, but in general the bin migration fractions are $<10\%$, and at most they are $\sim 18\%$.

IV. SYSTEMATIC UNCERTAINTIES

We estimated our systematic uncertainties based on several sources. A summary of average systematic values is shown in Table II, and breakdowns of the systematic uncertainties in each kinematic bin are shown in the Appendix. We folded in the uncertainty in the Λ decay asymmetry parameter $\delta\alpha_\Lambda = 0.009$ [3] as a systematic scale uncertainty. A scale uncertainty of 2.51% from our beam polarization was also included.

We estimated bin-dependent uncertainties from the variation in results due to the choice of the signal fit function for identifying the Λ invariant mass peak by comparing the difference in results corrected with the background fraction ε taken from a Gaussian signal fit and our chosen Crystal Ball signal. In general, this was our dominant source of systematic uncertainty, and the Gaussian comparison was intentionally used as a conservative estimate of this systematic since any choice of signal shape was not an exact match to the actual signal distribution. However, our overall systematics tend to be much smaller than

TABLE II. Systematic uncertainties by source averaged over all kinematic bins for each choice of Λ spin axis.

Source	P_Λ	P_{γ^*}
Decay parameter α_Λ	0.001	0.002
Beam polarization λ_c^2	0.003	0.005
MC injection	0.007	0.011
Mass fit	0.008	0.013
$\cos\phi_\Lambda$ effects	0.022	0.024
Total	0.0246	0.0300

the statistical uncertainties even with this conservative estimate.

We also estimated a bin-dependent systematic uncertainty on our extraction via the HB method from the variation in the deviation of results from an injected asymmetry for several values of the injected asymmetry, which we assessed using MC simulated events. We included a final bin-dependent systematic also based on asymmetry injections of $D_{LL'}^\Lambda$ with an additional $\cos\phi_\Lambda$ -dependent cross section term. This additional term cancels out with integration over $P_{\Lambda\perp}$ [7]; however detector acceptance introduces a lingering effect. We quantified the extent of this effect based on the variation in results when several different values for the additional asymmetry associated with this modulation. We scaled this variation to data by using the ratio between data and MC of the maximum difference in the results, i.e., the difference in results between the regions where the $\cos\phi_\Lambda$ term is positive— $\phi_\Lambda \in (0, \pi/2]$ or $\phi_\Lambda \in (3\pi/2, 2\pi]$ —or negative— $\phi_\Lambda \in (\pi/2, 3\pi/2]$. To get the final systematic uncertainty scales for each kinematic bin, we added all systematic uncertainties for the bin in quadrature assuming all systematic uncertainties were completely uncorrelated.

V. RESULTS AND DISCUSSION

All final results were calculated with the helicity balance method and may be accessed from the CLAS physics database [36]. Results over the full dataset are listed in Table III, and results binned in $z_{p\pi^-}$ and $x_{Fp\pi^-}$ are shown in Figs. 5 and 6 and listed in the Appendix. Uncertainties on the kinematic variables are taken as the standard deviation of the values in a given bin.

We have extracted the longitudinal spin transfer $D_{LL'}^\Lambda$ to Λ hyperons in the CFR with SIDIS events at CLAS12. In general, our results indicate a small positive light quark polarization in the Λ hyperon. This is as one would expect for Λ s coming primarily from u and d quark fragmentation. Our results are consistent with and improve on the statistical uncertainties of previous measurements from HERMES [4], COMPASS [23,24], and NOMAD [26,27]. A comparison of some of these previous measurements with the results of this work is shown in Fig. 7. In general, our results are also similar between the two different choices of polarization axis, as one would expect since Λ s from the CFR should carry away most of the momentum of the γ^* considering the modest beam energy of our dataset.

TABLE III. Results for $D_{LL'}^\Lambda$ over the full dataset.

Λ spin axis	Extracted asymmetry
P_Λ	0.071 ± 0.029 (stat) ± 0.025 (syst)
P_{γ^*}	0.130 ± 0.031 (stat) ± 0.031 (syst)

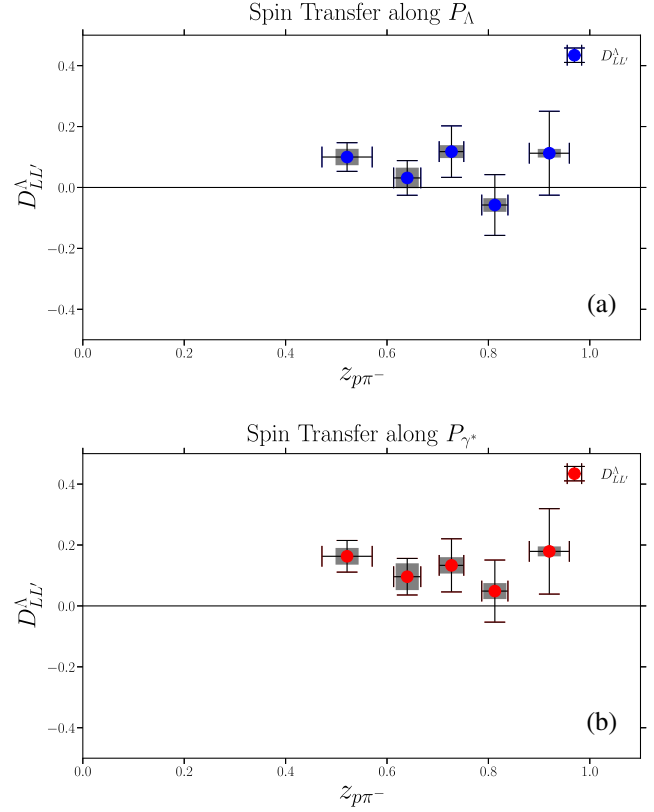


FIG. 5. Results for $D_{LL'}^\Lambda$ binned in $z_{p\pi^-}$. The insets show results for Λ polarization along the Λ momentum (a) and along the virtual photon γ^* momentum (b) in the γ^*N c.m. frame. Vertical uncertainties are statistical and horizontal uncertainties are given by the standard deviation within each bin. Gray boxes show the systematic uncertainties.

One must also consider that our Λ sample contains some Λ s produced from the decays of heavier hyperons. Our MC simulation sample shows that these are primarily from Σ baryons, for example from the channel $\Sigma^0 \rightarrow \Lambda\gamma$ as shown in Fig. 8. These decays account for $\simeq 33\%$ of the true Λ baryons in our signal region for our MC events. We expect the Λ polarization to be $P_\Lambda = -\frac{1}{3}P_{\Sigma^0}$ [37,38] and for $\Sigma^* \rightarrow \Lambda\pi$ we expect $P_\Lambda = \frac{5}{3}P_{\Sigma^*}$ [38]. However, there is yet no clean way to separate these feed-down Λ s from prompt Λ s originating directly from the struck quark in SIDIS.

There is also a dilution effect from TFR Λ s that form from the remnant diquark system in the target nucleon. Λ s originating from the TFR should not carry any spin transfer since the electron spin is only imparted to the struck diquark. Hence, one expects TFR contributions to have zero spin transfer and to dilute any spin transfer from the CFR. Since the $x_{Fp\pi^-} > 0$ cut does not guarantee that the sample is purely CFR Λ s, our results may be affected by some inevitable contamination from the TFR, and this is in fact observed by comparison with theory predictions [39] including both CFR and TFR contributions as shown in Figs. 9 and 10. The CFR predictions were obtained with

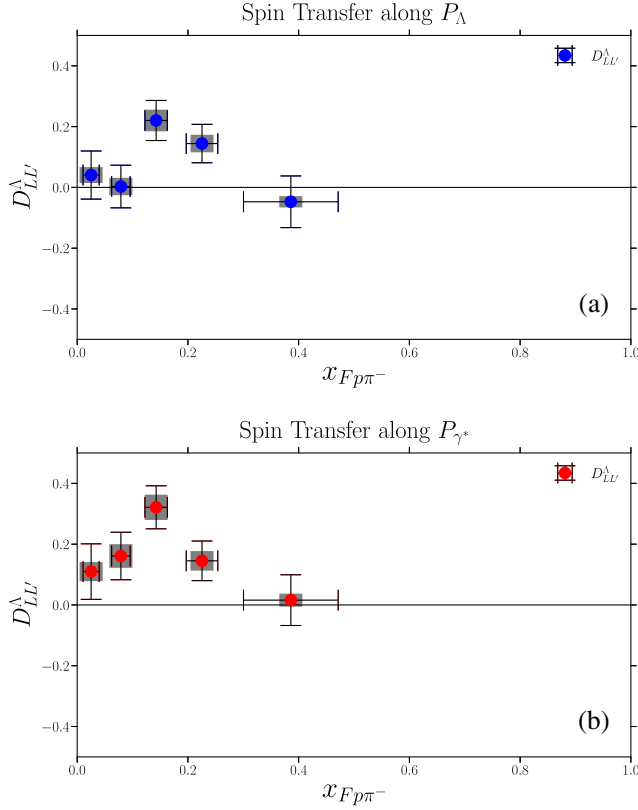


FIG. 6. Results for $D_{LL'}^\Lambda$ binned in $x_{Fp\pi^-}$. The insets show results for Λ polarization along the Λ momentum (a) and along the virtual photon γ^* momentum (b) in the γ^*N c.m. frame. Vertical uncertainties are statistical and horizontal uncertainties are given by the standard deviation within each bin. Gray boxes show the systematic uncertainties.

parametrizations of the Λ FFs $D_{1,a}^\Lambda$ and $G_{1,a}^\Lambda$ inferred from a perturbative QCD (pQCD) fit to e^+e^- annihilation data [40], while a spectator quark-diquark model calculation was used to obtain the TFR predictions [39]. Predictions were calculated for the mean kinematic values of our dataset at $Q^2 = 2.13 \text{ GeV}^2$ and $x = 0.25$.

The comparison of our observations with the combined CFR and TFR model predictions indicates firstly that our data contains a large TFR contribution even at high $x_{Fp\pi^-}$ and hence the TFR and CFR contributions are not cleanly separable by a simple cut on $x_{Fp\pi^-}$. Furthermore, looking at the $x_{Fp\pi^-}$ distribution, one may also notice a peak in the data around $x_{Fp\pi^-} \simeq 0.2$ which is not captured by the model. This indicates that the possibility that there is more nuanced physics underlying our data than is described by the simple parametrizations of the polarized FF $G_{1,a}^\Lambda$ from measurements of the unpolarized FF $D_{1,a}^\Lambda$ employed in Ref. [40].

This will require future measurements of SIDIS CFR and TFR quantities at these energy scales to carefully account

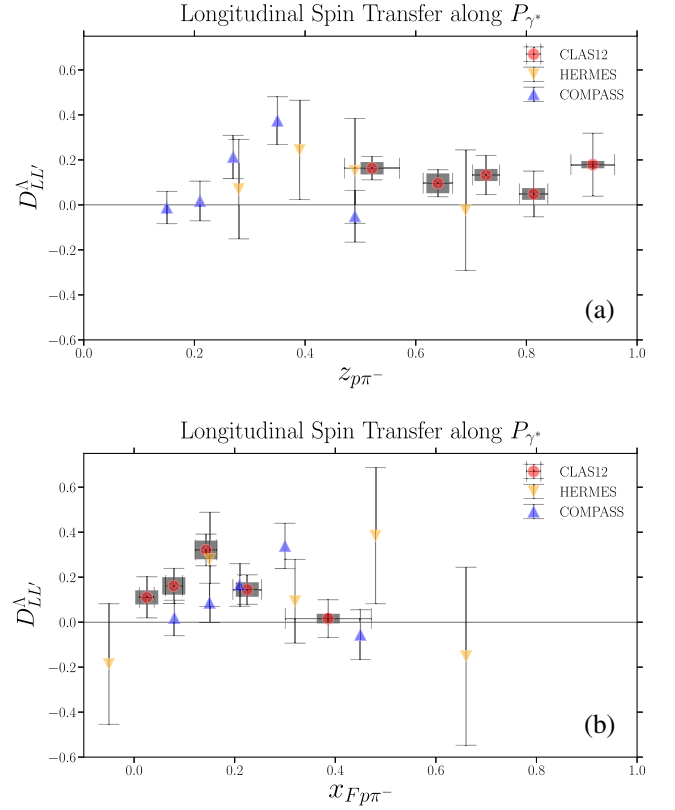


FIG. 7. Comparison of the extracted $D_{LL'}^\Lambda$ along P_{γ^*} with previous results from HERMES [4] and COMPASS [24]. The insets show results binned in $z_{p\pi^-}$ (a) and $x_{Fp\pi^-}$ (b) for Λ polarization along the virtual photon momentum in the γ^*N c.m. frame. Vertical uncertainties are statistical and horizontal uncertainties are given by the standard deviation within each bin. Gray boxes show the systematic uncertainties.

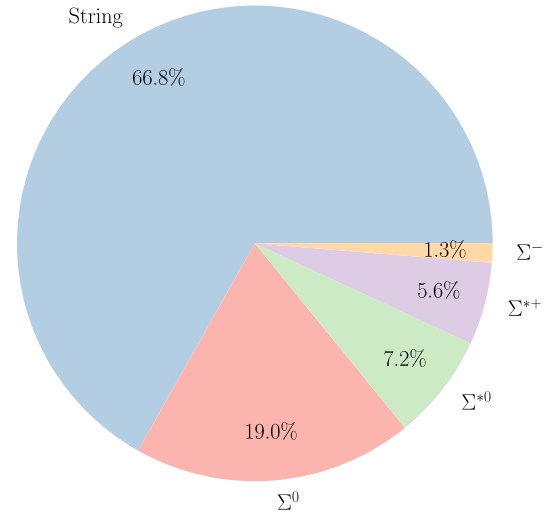


FIG. 8. Distribution of Λ parents from MC [31] for Λ s in the signal region with $x_{Fp\pi^-} > 0$.

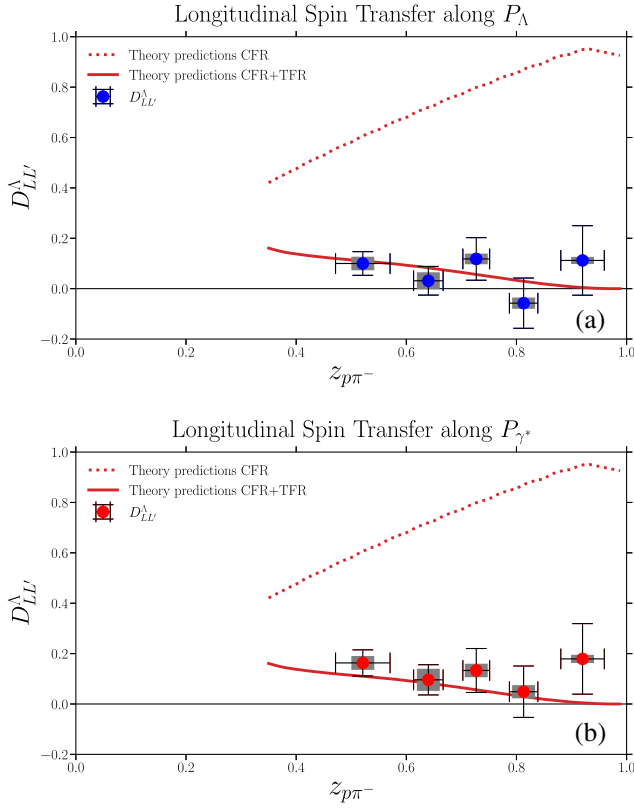


FIG. 9. Comparison of the extracted $D_{LL'}^\Lambda$ binned in $z_{p\pi^-}$ with predictions computed from FF parametrizations from pQCD [40] for the CFR and from a spectator quark-diquark model calculation for the TFR [39]. Dashed curves represent CFR only and solid curves represent the sum of CFR and TFR contributions [41]. The insets show results for Λ polarization along the Λ momentum (a) and along the virtual photon γ^* momentum (b) in the γ^*N c.m. frame. Vertical uncertainties are statistical and horizontal uncertainties are given by the standard deviation within each bin. Gray boxes show the systematic uncertainties.

for the relative contributions from each production mechanism. Our measurement also constrains the extraction of related Λ fracture functions (FrFs) [42,43], which describe the TFR production mechanism. A FrF is typically expressed as a function of x and $\zeta_h = \frac{P_h^-}{P^-}$, which is the negative light cone momentum component fraction for a hadron h with 4-momentum P_h produced off a nucleon target with 4-momentum P . The reason ζ is introduced is that z_h cannot distinguish between soft hadron emission and the target fragmentation region since it vanishes in the soft emission limit (hadron energy $E_h \rightarrow 0$) and in target fragmentation ($\theta_h = 0$ where θ_h is the γ^*N c.m. frame angle between $\vec{P}$ and $\vec{P}_h$), whereas ζ does not vanish in target fragmentation [43]. Comparison with measurements of FFs from e^+e^- annihilation, which obviously receives no TFR contribution, would allow one to deduce the FrFs. Furthermore, because the spin transfer $D_{LL'}^\Lambda$ observable is sensitive to the production mechanism of the Λ , one may

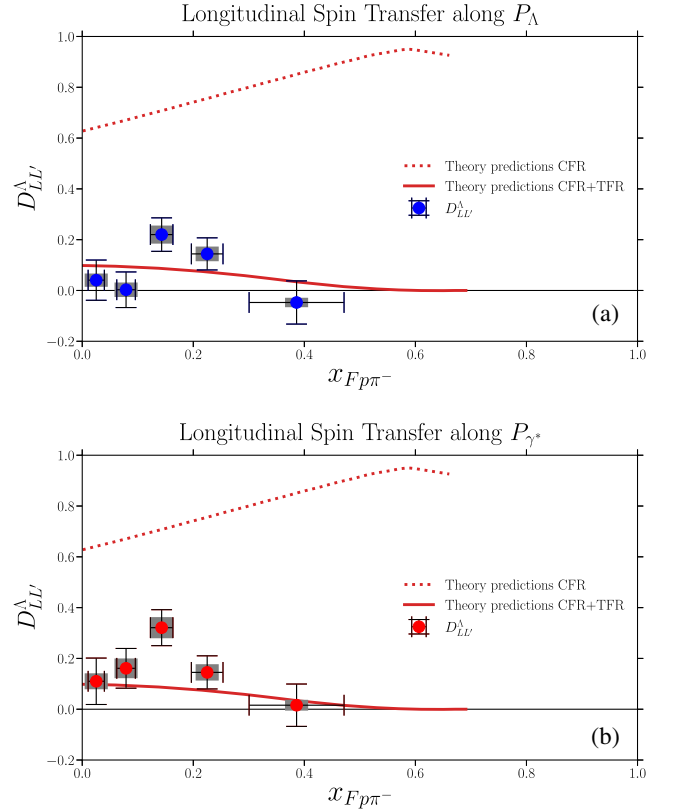


FIG. 10. Comparison of the extracted $D_{LL'}^\Lambda$ binned in $x_{Fp\pi^-}$ with predictions computed from FF parametrizations from pQCD [40] for the CFR and from a spectator quark-diquark model calculation for the TFR [39]. Dashed curves represent CFR only and solid curves represent the sum of CFR and TFR contributions [41]. The insets show results for Λ polarization along the Λ momentum (a) and along the virtual photon γ^* momentum (b) in the γ^*N c.m. frame. Vertical uncertainties are statistical and horizontal uncertainties are given by the standard deviation within each bin. Gray boxes show the systematic uncertainties.

also infer loose constraints on the relative dominance of the CFR and TFR mechanisms in specific kinematic regions. For example, due to helicity conservation the Λ should carry the same helicity as the fragmenting quark as $z \rightarrow 1$, giving one a clear idea of the CFR contribution. Conversely, in the valence region $x \rightarrow 1$ and $\zeta \rightarrow 1$, the TFR production mechanism highly favors unpolarized Λ production due to the spin and flavor structure of the Λ where the strange quark produced during fragmentation carries most of the Λ spin.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

APPENDIX: TABLES

Here we present breakdowns of our systematic uncertainties according to their various sources in Tables IV–VII, our final results for $D_{LL'}^\Lambda$ in Tables VIII–XI, and the kinematic means in Tables XII–XIV for each of our binning

TABLE IV. Systematic uncertainties on $D_{LL'}^\Lambda$ for $\cos\theta_{pL'}$ along P_Λ binned in $z_{p\pi^-}$.

Bin	$\langle z_{p\pi^-} \rangle$	Δ_{α_Λ}	Δ_{pol}	Δ_{Fit}	Δ_{Inj}	$\Delta_{\cos\phi_\Lambda}$
1	0.521 ± 0.050	0.00120	0.00360	0.0010	0.0083	0.0253
2	0.640 ± 0.027	0.00038	0.00113	0.0132	0.0036	0.0308
3	0.727 ± 0.024	0.00141	0.00424	0.0085	0.0072	0.0175
4	0.813 ± 0.026	0.00069	0.00207	0.0019	0.0090	0.0203
5	0.920 ± 0.040	0.00135	0.00405	0.0000	0.0044	0.0128

TABLE V. Systematic uncertainties on $D_{LL'}^\Lambda$ for $\cos\theta_{pL'}$ along P_{γ^*} binned in $z_{p\pi^-}$.

Bin	$\langle z_{p\pi^-} \rangle$	Δ_{α_Λ}	Δ_{pol}	Δ_{Fit}	Δ_{Inj}	$\Delta_{\cos\phi_\Lambda}$
1	0.521 ± 0.050	0.00196	0.00587	0.0013	0.0116	0.0241
2	0.640 ± 0.027	0.00115	0.00345	0.0276	0.0087	0.0329
3	0.727 ± 0.024	0.00160	0.00479	0.0113	0.0107	0.0214
4	0.813 ± 0.026	0.00058	0.00175	0.0071	0.0166	0.0189
5	0.920 ± 0.040	0.00215	0.00645	0.0000	0.0066	0.0133

TABLE VI. Systematic uncertainties on $D_{LL'}^\Lambda$ for $\cos\theta_{pL'}$ along P_Λ binned in $x_{Fp\pi^-}$.

Bin	$\langle x_{Fp\pi^-} \rangle$	Δ_{α_Λ}	Δ_{pol}	Δ_{Fit}	Δ_{Inj}	$\Delta_{\cos\phi_\Lambda}$
1	0.025 ± 0.015	0.00049	0.00146	0.0029	0.0056	0.0254
2	0.079 ± 0.017	0.00003	0.00010	0.0041	0.0085	0.0270
3	0.143 ± 0.020	0.00264	0.00793	0.0192	0.0041	0.0284
4	0.225 ± 0.029	0.00173	0.00519	0.0188	0.0105	0.0185
5	0.386 ± 0.086	0.00057	0.00170	0.0066	0.0108	0.0135

TABLE VII. Systematic uncertainties on $D_{LL'}^\Lambda$ for $\cos\theta_{pL'}$ along P_{γ^*} binned in $x_{Fp\pi^-}$.

Bin	$\langle x_{Fp\pi^-} \rangle$	Δ_{α_Λ}	Δ_{pol}	Δ_{Fit}	Δ_{Inj}	$\Delta_{\cos\phi_\Lambda}$
1	0.025 ± 0.015	0.00132	0.00395	0.0070	0.0082	0.0292
2	0.079 ± 0.017	0.00193	0.00580	0.0187	0.0129	0.0310
3	0.143 ± 0.020	0.00386	0.01160	0.0257	0.0045	0.0301
4	0.225 ± 0.029	0.00174	0.00522	0.0189	0.0150	0.0206
5	0.386 ± 0.086	0.00019	0.00057	0.0093	0.0128	0.0143

TABLE VIII. $D_{LL'}^\Lambda$ binned in $z_{p\pi^-}$ for $\cos\theta_{pL'}$ along $\vec{P}_\Lambda$.

Bin	$\langle z_{p\pi^-} \rangle$	Extracted asymmetry
1	0.521 ± 0.050	0.100 ± 0.047 (stat) ± 0.027 (syst)
2	0.640 ± 0.027	0.031 ± 0.057 (stat) ± 0.034 (syst)
3	0.727 ± 0.024	0.118 ± 0.085 (stat) ± 0.021 (syst)
4	0.813 ± 0.026	0.000 ± 0.100 (stat) ± 0.022 (syst)
5	0.920 ± 0.040	0.112 ± 0.138 (stat) ± 0.014 (syst)

TABLE IX. $D_{LL'}^\Lambda$ binned in $z_{p\pi^-}$ for $\vec{P}_\Lambda$ along $\vec{P}_{\gamma^*}$.

Bin	$\langle z_{p\pi^-} \rangle$	Extracted asymmetry
1	0.521 ± 0.050	0.163 ± 0.052 (stat) ± 0.028 (syst)
2	0.640 ± 0.027	0.096 ± 0.060 (stat) ± 0.044 (syst)
3	0.727 ± 0.024	0.133 ± 0.087 (stat) ± 0.027 (syst)
4	0.813 ± 0.026	0.049 ± 0.102 (stat) ± 0.026 (syst)
5	0.920 ± 0.040	0.179 ± 0.140 (stat) ± 0.016 (syst)

TABLE X. $D_{LL'}^\Lambda$ binned in $x_{Fp\pi^-}$ for $\cos\theta_{pL'}$ along $\vec{P}_\Lambda$.

Bin	$\langle x_{Fp\pi^-} \rangle$	Extracted asymmetry
1	0.025 ± 0.015	0.041 ± 0.079 (stat) ± 0.026 (syst)
2	0.079 ± 0.017	0.003 ± 0.070 (stat) ± 0.029 (syst)
3	0.143 ± 0.020	0.220 ± 0.066 (stat) ± 0.036 (syst)
4	0.225 ± 0.029	0.144 ± 0.063 (stat) ± 0.029 (syst)
5	0.386 ± 0.086	0.000 ± 0.085 (stat) ± 0.019 (syst)

TABLE XI. $D_{LL'}^\Lambda$ binned in $x_{Fp\pi^-}$ for $\cos\theta_{pL'}$ along $\vec{P}_{\gamma^*}$.

Bin	$\langle x_{Fp\pi^-} \rangle$	Extracted asymmetry
1	0.025 ± 0.015	0.110 ± 0.091 (stat) ± 0.031 (syst)
2	0.079 ± 0.017	0.161 ± 0.078 (stat) ± 0.039 (syst)
3	0.143 ± 0.020	0.321 ± 0.071 (stat) ± 0.042 (syst)
4	0.225 ± 0.029	0.145 ± 0.065 (stat) ± 0.032 (syst)
5	0.386 ± 0.086	0.016 ± 0.083 (stat) ± 0.021 (syst)

TABLE XII. Kinematic means in the Λ signal region averaged over the entire dataset.

Bin	$\langle M_{p\pi^-} \rangle$ (GeV)	$\langle Q^2 \rangle$ (GeV ²)	$\langle W \rangle$ (GeV)	$\langle y \rangle$	$\langle x \rangle$	$\langle z_{p\pi^-} \rangle$	$\langle x_{Fp\pi^-} \rangle$
1	1.12 ± 0.01	2.21 ± 1.18	2.79 ± 0.47	0.469 ± 0.139	0.247 ± 0.117	0.705 ± 0.143	0.199 ± 0.140

TABLE XIII. Kinematic means in the Λ signal region for the $z_{p\pi^-}$ binning.

Bin	$\langle M_{p\pi^-} \rangle$ (GeV)	$\langle Q^2 \rangle$ (GeV ²)	$\langle W \rangle$ (GeV)	$\langle y \rangle$	$\langle x \rangle$	$\langle z_{p\pi^-} \rangle$	$\langle x_{Fp\pi^-} \rangle$
1	1.12 ± 0.01	2.17 ± 1.14	3.27 ± 0.33	0.607 ± 0.103	0.182 ± 0.091	0.521 ± 0.050	0.091 ± 0.066
2	1.12 ± 0.01	2.32 ± 1.28	2.89 ± 0.35	0.499 ± 0.105	0.236 ± 0.113	0.640 ± 0.027	0.158 ± 0.095
3	1.12 ± 0.01	2.31 ± 1.25	2.68 ± 0.36	0.439 ± 0.106	0.267 ± 0.120	0.727 ± 0.024	0.208 ± 0.117
4	1.12 ± 0.01	2.21 ± 1.15	2.51 ± 0.34	0.390 ± 0.101	0.287 ± 0.117	0.813 ± 0.026	0.260 ± 0.133
5	1.12 ± 0.01	2.02 ± 1.03	2.37 ± 0.30	0.345 ± 0.091	0.294 ± 0.107	0.920 ± 0.040	0.339 ± 0.147

TABLE XIV. Kinematic means in the Λ signal region for the $x_{Fp\pi^-}$ binning.

Bin	$\langle M_{p\pi^-} \rangle$ (GeV)	$\langle Q^2 \rangle$ (GeV ²)	$\langle W \rangle$ (GeV)	$\langle y \rangle$	$\langle x \rangle$	$\langle z_{p\pi^-} \rangle$	$\langle x_{Fp\pi^-} \rangle$
1	1.12 ± 0.01	2.27 ± 1.21	2.87 ± 0.49	0.495 ± 0.143	0.242 ± 0.121	0.588 ± 0.123	0.025 ± 0.015
2	1.12 ± 0.01	2.24 ± 1.20	2.83 ± 0.48	0.482 ± 0.142	0.245 ± 0.119	0.625 ± 0.122	0.079 ± 0.017
3	1.12 ± 0.01	2.20 ± 1.17	2.78 ± 0.48	0.468 ± 0.141	0.248 ± 0.117	0.669 ± 0.120	0.143 ± 0.020
4	1.12 ± 0.01	2.20 ± 1.18	2.75 ± 0.47	0.456 ± 0.138	0.252 ± 0.117	0.726 ± 0.114	0.225 ± 0.029
5	1.12 ± 0.01	2.18 ± 1.16	2.76 ± 0.44	0.458 ± 0.130	0.247 ± 0.114	0.825 ± 0.101	0.386 ± 0.086

schemes and each choice of Λ polarization axis. The sources of systematic uncertainty are denoted as follows: Δ_{α_Λ} refers to the systematic from the Λ decay asymmetry parameter, Δ_{pol} refers to the systematic from the beam polarization, Δ_{Fit} refers to the systematic from the mass fit,

Δ_{Inj} refers to the systematic from the asymmetry injection study, and $\Delta_{\cos\phi_\Lambda}$ refers to the systematic from the additional injection study in different regions of ϕ_Λ . Uncertainties on the kinematic variables are taken as the standard deviation of the values in a given bin.

- [1] F. Halzen and A. D. Martin, *Quarks and Leptons: An Introductory Course in Modern Particle Physics* (John Wiley & Sons, Inc., 1984), <https://www.osti.gov/biblio/6014092>.
- [2] G. Bunce *et al.*, Λ^0 hyperon polarization in inclusive production by 300-GeV protons on beryllium, *Phys. Rev. Lett.* **36**, 1113 (1976).
- [3] S. Navas *et al.*, Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).

- [4] A. Airapetian *et al.*, Longitudinal spin transfer to the Λ hyperon in semi-inclusive deep-inelastic scattering, *Phys. Rev. D* **74**, 072004 (2006).
- [5] Y. Guan, A. Vossen *et al.*, Observation of transverse $\Lambda/\bar{\Lambda}$ hyperon polarization in e^+e^- annihilation at Belle, *Phys. Rev. Lett.* **122**, 042001 (2019).
- [6] M. McEneaney, Longitudinal spin transfer to Λ hyperons in CLAS12, *J. Phys. Soc. Jpn. Conf. Proc.* **37**, 020304 (2022).

- [7] Y. Yang and Z. Lu, Polarized Λ hyperon production in semi-inclusive deep inelastic scattering off an unpolarized nucleon target, *Phys. Rev. D* **95**, 074026 (2017).
- [8] P. J. Mulders and R. D. Tangerman, The complete tree-level result up to order $1/Q$ for polarized deep-inelastic lepton production, *Nucl. Phys.* **B461**, 197 (1996).
- [9] D. Boer and P. J. Mulders, Time-reversal odd distribution functions in lepton production, *Phys. Rev. D* **57**, 5780 (1998).
- [10] A. Metz and A. Vossen, Parton fragmentation functions, *Prog. Part. Nucl. Phys.* **91**, 136 (2016).
- [11] C. Boros, J. T. Londergan, and A. W. Thomas, Structure and production of Λ baryons, *Phys. Rev. D* **61**, 014007 (1999).
- [12] B. Q. Ma, I. Schmidt, J. Soffer, and J. J. Yang, Quark distributions of octet baryons from $SU(3)$ symmetry, *Phys. Rev. D* **65**, 034004 (2002).
- [13] M. Burkardt and R. L. Jaffe, Polarized $q \rightarrow \Lambda$ fragmentation functions from $e^+e^- \rightarrow \Lambda + X$, *Phys. Rev. Lett.* **70**, 2537 (1993).
- [14] L. Chun-xiu and L. Zuo-tang, Spin structure and longitudinal polarization of a hyperon in e^+e^- annihilation at high energies, *Phys. Rev. D* **62**, 094001 (2000).
- [15] K. Ackerstaff *et al.*, Polarization and forward-backward asymmetry of Λ baryons in hadronic Z^0 decays, *Eur. Phys. J. C* **2**, 49 (1998).
- [16] D. Buskulic *et al.*, Measurement of Λ polarization from Z decays, *Phys. Lett. B* **374**, 319 (1996).
- [17] M. I. Abdulhamid *et al.*, Longitudinal and transverse spin transfer to Λ and $\bar{\Lambda}$ hyperons in polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV, *Phys. Rev. D* **109**, 012004 (2024).
- [18] J. Adam *et al.*, Improved measurement of the longitudinal spin transfer to Λ and $\bar{\Lambda}$ hyperons in polarized proton-proton collisions at $\sqrt{s} = 200$ GeV, *Phys. Rev. D* **98**, 112009 (2018).
- [19] R. K. Bradford *et al.* (CLAS Collaboration), First measurement of beam-recoil observables C_x and C_z in hyperon photoproduction, *Phys. Rev. C* **75**, 035205 (2007).
- [20] D. S. Carman *et al.* (CLAS Collaboration), First measurement of transferred polarization in the exclusive $\bar{e}p \rightarrow e'K^+\bar{\Lambda}$ reaction, *Phys. Rev. Lett.* **90**, 131804 (2003).
- [21] D. S. Carman *et al.* (CLAS Collaboration), Beam-recoil polarization transfer in the nucleon resonance region in the exclusive $\bar{e}p \rightarrow e'K^+\bar{\Lambda}$ and $\bar{e}p \rightarrow e'K^+\bar{\Sigma}^0$ reactions at the CLAS spectrometer, *Phys. Rev. C* **79**, 065205 (2009).
- [22] D. S. Carman *et al.* (CLAS Collaboration), Beam-recoil transferred polarization in K^+Y electroproduction in the nucleon resonance region with CLAS12, *Phys. Rev. C* **105**, 065201 (2022).
- [23] D. Kang, Longitudinal Λ and $\bar{\Lambda}$ Polarization in the COMPASS experiment, *Nucl. Phys. B, Proc. Suppl.* **167**, 106 (2007).
- [24] D. Kang, Longitudinal Λ and $\bar{\Lambda}$ polarization at the COMPASS experiment, Ph.D. thesis, Freiburg University, 2007.
- [25] M. Alekseev *et al.*, Measurement of the longitudinal spin transfer to Λ and $\bar{\Lambda}$ hyperons in polarised muon DIS, *Eur. Phys. J. C* **64**, 171 (2009).
- [26] P. Astier *et al.*, Measurement of the Λ polarization in ν_μ charged current interactions in the NOMAD experiment, *Nucl. Phys.* **B588**, 3 (2000).
- [27] D. V. Naumov, Measurement of Λ^0 polarization in ν_μ CC interactions in NOMAD, *AIP Conf. Proc.* **570**, 489 (2001).
- [28] C. W. Leemann, D. R. Douglas, and G. A. Krafft, The continuous electron beam accelerator facility: CEBAF at the Jefferson Laboratory, *Annu. Rev. Nucl. Part. Sci.* **51**, 413 (2001).
- [29] V. D. Burkert *et al.* (CLAS Collaboration), The CLAS12 Spectrometer at Jefferson Laboratory, *Nucl. Instrum. Methods Phys. Res., Sect. A* **959**, 163419 (2020).
- [30] R. Capobianco *et al.*, CLAS12 momentum corrections, Internal note, Available at: <https://misportal.jlab.org/mis/physics/clas12/viewFile.cfm/2023-001.pdf?documentId=83> (2023).
- [31] L. Mankiewicz, A. Schäfer, and M. Veltri, PEPSI—A Monte Carlo generator for polarized lepton production, *Comput. Phys. Commun.* **71**, 305 (1992).
- [32] T. Sjöstrand and M. Bengtsson, The Lund Monte Carlo for jet fragmentation and e^+e^- physics—JetSet version 6.3—An update, *Comput. Phys. Commun.* **43**, 367 (1987).
- [33] J. Podolanski and R. Armenteros, Analysis of V-events, *Philos. Mag. Ser. 5* **45**, 13 (1954).
- [34] J. E. Gaiser *et al.*, Charmonium spectroscopy from inclusive ψ' and J/ψ radiative decays, *Phys. Rev. D* **34**, 711 (1986).
- [35] G. Schnell, Longitudinal polarization of the Λ in deep inelastic scattering of polarized positrons from nucleons, ProQuest Dissertations and theses, New Mexico State University, 1999.
- [36] CLAS Physics Database, <http://clasweb.jlab.org/physicsdb>.
- [37] R. Gatto, Relations between the hyperon polarizations in associated production, *Phys. Rev.* **109**, 610 (1958).
- [38] D. Ashery and H. J. Lipkin, Expected polarization of Λ particles produced in deep inelastic polarized lepton scattering, *Phys. Lett. B* **469**, 263 (1999).
- [39] X. Zhao, Z. Liang, T. Liu, and Y. Zhou, Suppression of spin transfer to Λ hyperon in deep-inelastic scattering, *Phys. Rev. Lett.* **134**, 231901 (2025).
- [40] D. de Florian, M. Stratmann, and W. Vogelsang, QCD analysis of unpolarized and polarized Λ -baryon production in leading and next-to-leading order, *Phys. Rev. D* **57**, 5811 (1998).
- [41] X. Zhao (private communication).
- [42] L. G. Trentadue and G. Veneziano, Fracture functions. An improved description of inclusive hard processes in QCD, *Phys. Lett. B* **323**, 201 (1994).
- [43] M. Anselmino, V. Barone, and A. M. Kotzinian, SIDIS in the target fragmentation region: Polarized and transverse momentum dependent fracture functions, *Phys. Lett. B* **699**, 108 (2011).