Measuring Polarization Transfer from Electron to Lambda in Exclusive K* Electroproduction at CLAS

A Letter of Intent

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Abstract

We propose to use the CEBAF Large Acceptance Spectrometer (CLAS) to study polarization transfer in the electroproduction of $K^{*+}\Lambda$ off a hydrogen target at a beam energy of 5-6 GeV. Our recently published polarization data from CLAS for $K^+\Lambda$ electroproduction has been interpreted through a semi-classical quark model argument that presents evidence that the $s\bar{s}$ quark pair is produced with its spins predominantly anti-aligned. This finding is in contradiction with expectations from the widely-used $^3P_0$ quark-pair creation operator. The same argument predicts that the direction of the Λ's polarization should reverse when the recoil meson is a spin-1 K^{*+}. Thus, study of polarization observables in $K^{*+}\Lambda$ electroproduction can shed light on this important and fundamental question. Important side-issues such as the ratio of K^+ to K^{*+} production can also be studied with the same data.

Although we have only done some of the simulation required for a full proposal we point out that our proposed experiment requires that CLAS be run in an unusual configuration, with reduced and perhaps reversed B-field. We will also need to develop a new (for CLAS) analysis technique: we propose to detect the Λ directly through its decay to a proton and π^- and to detect the recoiling strange meson by its missing-mass rather than by measuring the K and detecting the hyperon by missing-mass. This requirement to detect the π^- is what drives our requirement to run the CLAS at low B-field. We also roughly estimate that we will need about 20 days of beam time.

Our data will have the following impact on the field:

- it will provide data to measure the relative cross sections of $K^{*+}\Lambda$ and $K^+\Lambda$ production, a fundamental and unmeasured quantity;
- it will likely explain why Λ polarizations measured in semi-inclusive reactions (e.g. at HERMES) give much smaller values than those for exclusive reactions, and most importantly,
- it will address the issue of whether the observed polarization can be explained with a semi-classical quark model treatment, and if so, it will greatly strengthen our present assertion that by measuring polarization transfer in exclusive Λ electroproduction we are measuring the spin state of the produced $s\bar{s}$ pair that breaks the flux-tube.

Ultimately, we hope these studies shed light on the question of whether constituent quarks and the flux-tube are the best effective degrees of freedom to describe strong interactions; and if so, what are their physical properties?

1 Physics Motivation

The flux-tube model has been used to explain heavy quarkonia spectra as well as the flavor-dependence of hadronization. The physical reality of the flux-tube is in the process of being established and clarified similar to the way quarks went from being considered merely a catch-word for a complicated mathematical process to being considered physical particles with quantum numbers in the 1970's. Major experimental programs are designed to study mechanical excitations of the flux-tube through spectroscopic searches. We think that it is very interesting to study the process by which the flux-tube is "broken" by quark-pair creation. Fortunately, exclusive hyperon production can isolate the hadronization process to the production of a single $s\bar{s}$ quark pair. Measuring the Λ decay reveals its polarization, and to a good approximation, the spin direction of the produced s quark. This reaction is thus sensitive to the angular momentum state of the produced quark pair.

CLAS has recently published the first measurements of spin transfer in the nucleon resonance region from a longitudinally polarized electron beam to the Λ hyperon produced in the exclusive $p(\vec{e}, e'K^+)\vec{\Lambda}$ reaction [1]. These data have provided interesting, and perhaps surprising, information about the nature of quark-pair production. There is a growing body of evidence that the appropriate degrees of freedom to describe the phenomenology of hadronic decays are constituent quarks held together by a gluonic flux-tube [2]. The non-perturbative nature of the flux-tube gives rise to the well-known linear potential of heavy-quark confinement [3]. Other properties of the flux-tube can be determined by studying $q\bar{q}$ pair production, since this is widely believed to produce the color field neutralization that actually breaks the flux-tube.

Since the 1970's it has been suggested that a quark pair with vacuum quantum numbers is responsible for breaking the color flux-tube (the $^3P_0$ model [4]). The most sensitive experiments to date have measured ratios in certain meson decays of strong amplitudes differing in their orbital angular momenta [5]. Since the $^3P_0$ operator has S=1 and L=1, it implies a different ratio of amplitude strengths than, e.g., a $^3S_1$ operator with S=1 and L=0, corresponding to one gluon exchange.

In our recent Letter [1], we argue that the spin properties of the quark-pair creation operator might be responsible for the observed trends in the Λ polarization, which indicate that the relevant operator dominating our reaction produces the $s\bar{s}$ pair with spins anti-aligned. This finding, if confirmed by further calculations, brings into question the universal applicability of the $^3P_0$ model. This has important implications since many, if not most, calculations of hadronic spectroscopy use the $^3P_0$ operator to calculate the transition to the final-state particles [6]. On a more fundamental level, if we really take the physical existence of the flux-tube seriously, we should not only search for dynamical excitations of the flux-tube, as in hybrid searches, we should also study the angular-momentum dynamics of the quark-pair creation process.

In our recent Letter, we also attempted to interpret our data in terms of the quark-pair spin alignment because we think such a physical interpretation will both encourage and constrain model calculations of strong decays and flux-tube properties. We cite only a few:

Kokoski and Isgur [7], Geiger and Swanson [5] and Ackleh, Barnes, and Swanson [8]. Newer calculations might drastically change our concept of the quark-pair creation process; for example, the pair might be produced in a spectrum of angular momentum states and not just in the $^3P_0$ state alone. We acknowledge that our polarization data could be explained as an interference between s, t and u-channel hadronic amplitudes with no mention of quark degrees of freedom at all. It is very important to decide which picture is favored by the test of Occam's razor [9]. Our simple, semi-classical argument predicts that the Λ polarization should flip sign when the recoiling meson is a K^{*+}, independent of W.

Similarly, our simple quark model picture predicts that the K^{*+}/K^+ ratio is a constant ratio once phase-space has been taken into account. The cross-section ratio is a fundamental quantity that also should have great value for theorists tuning up hadrodynamic models. We note in passing that semi-inclusive measurements at HERMES have measured a substantially smaller value for the electron to Λ polarization transfer. This is not surprising if the semi-inclusive results are considered to be a sum over exclusive states with alternating signs; a positive term for recoiling K^+ plus a negative term for recoiling K^{*+}, etc.

2 Polarization Extraction

The details of our analysis methods are given in our recent Letter [1]. Briefly, we analyze our events as follows. We find events with at least three reconstructed and identified charged particles: an electron, a proton, and a K^+. We isolate a sample of ΛK^+ events by cutting on the epK^+ missing mass. We sort the ΛK^+ events into bins of Q^2, W, $\cos\theta_K^*$, and $\cos\theta_p^{RF}$, where $\cos\theta_p^{RF}$ is the cosine of the decay angle of the proton in the Λ center-of-mass frame (i.e. the Λ decay rest frame) relative to a particular z-axis. In one case the z-axis was along the direction of the virtual photon's 3-momentum in the hadronic production center-of-mass (the "unprimed" system), while another choice of z-axis that we used was along the Λ momentum direction (the "primed" system). Note, we summed over Φ, the azimuthal angle between the leptonic and hadronic planes.

Our analysis consisted of doing a beam helicity asymmetry in the space of these 4-dimensional bins. We showed in our paper that such an asymmetry, $(N^+ - N^-)/(N^+ + N^-)$, should yield a distribution of shape and magnitude, $\alpha P' \cos\theta_p^{RF}$, when plotted versus $\cos\theta_p^{RF}$. In this case, $\alpha = 0.642$ is the analyzing power of the Λ decay, while P' is the value of the polarization transfer. Please refer to our published Letter (attached) for details.

3 Recently Published Physics Results

Our results are shown in Figs. 1 and 2 compared to several hadrodynamic model calculations. The error bars in these figures include statistical but not systematic uncertainties for P', which we estimate to be ≤ 0.084 on the polarization [10]. The dominant source of systematic effects comes from the acceptance correction (0.07). Other contributions include effects associated with binning, polarization extraction methods, and the beam polarization uncertainty.

Fig. 1 shows the W dependence of P' summed over all Q^2 and $d\Omega_K^*$ for our two choices of spin axes. The data indicate sizeable Λ polarizations. The average polarization magnitude is roughly the same along the z' and x' axes, indicating equal strength in the $R_{TT'}^{z'0}$ and $R_{TT'}^{x'0}$ responses. For the other choice of axes, the polarization is maximal when projected along the z-axis (the virtual photon direction), while the component along the x-axis is consistent with zero.

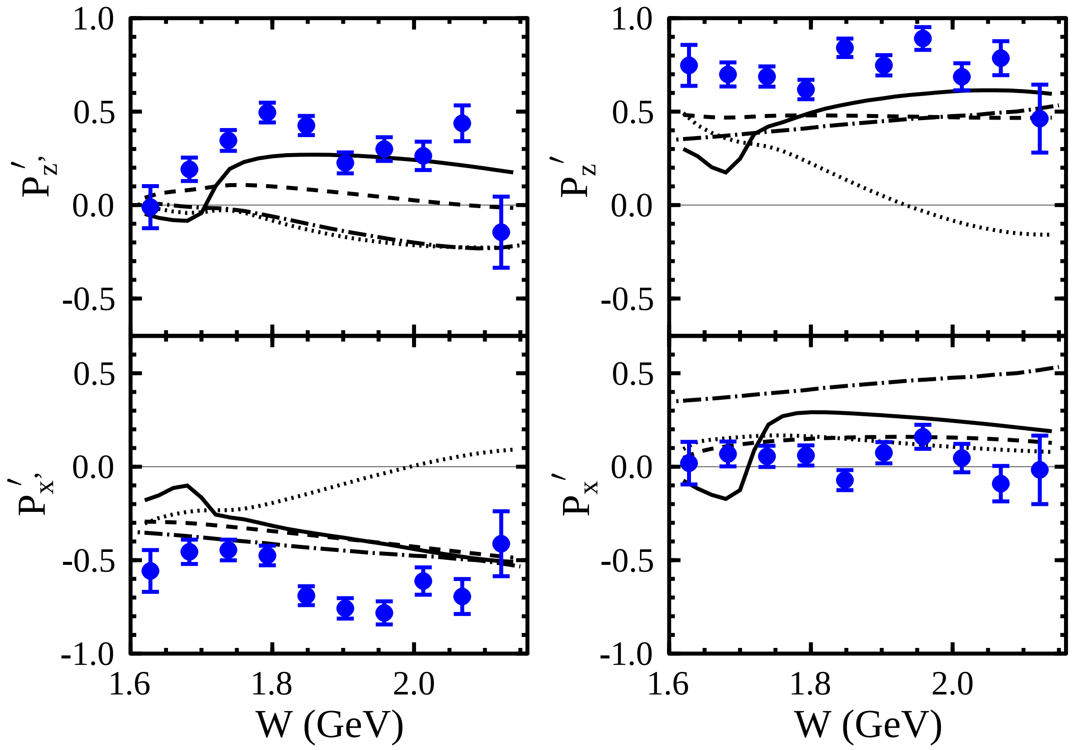

Figure 1: Transferred Λ polarization components $P'_{z'}$ and $P'_{x'}$ (left) and P'_z and P'_x (right) at 2.567 GeV vs. W summed over all Q^2 and $d\Omega_K^*$. Curves correspond to the hadrodynamic models: WJC92 [11] (dotted), BM98 [12] (dashed), BM02 [13] (solid), J02 [14] (dot-dash), averaged over the experimental bins.

Fig. 2 shows the angular dependence of P' summed over all Q^2 for three different W bins from just above threshold to 2 GeV. The polarization $P'_{z'}$ decreases with increasing θ_K^*. $P'_{x'}$ is constrained to be zero at $\cos\theta_K^* = \pm 1$ due to angular momentum conservation, and reaches a minimum at $\theta_K^* \sim 90°$. Again, the maximum Λ polarization occurs along the virtual photon direction. This component, P'_z, is roughly constant with respect to $\cos\theta_K^*$ and W. The component P'_x in the electron-scattering plane is again consistent with zero. The Φ-integrated $P'_{y'}$ and P'_y components (not shown) are statistically consistent with zero with respect to W and $\cos\theta_K^*$ as expected [10].

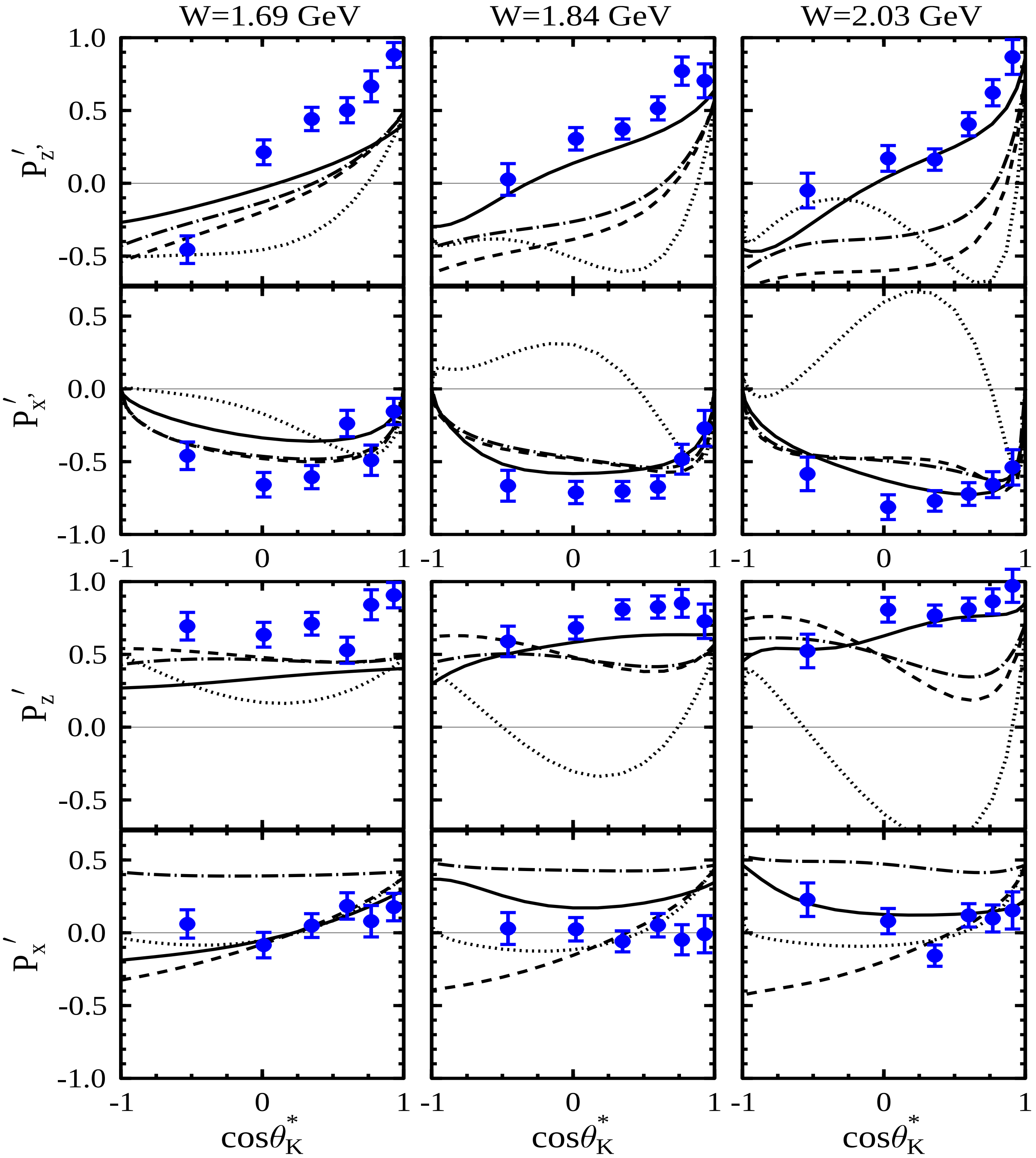

Figure 2: Transferred Λ polarization components $P'_{z'}$ and $P'_{x'}$ (upper) and P'_z and P'_x (lower) at 2.567 GeV vs. $\cos\theta_K^*$ summed over all Q^2 and Φ for three W bins centered at 1.69, 1.84, and 2.03 GeV. The curves are the same as Fig. 1.

Recent calculations have been guided by coupled-channels analyses [15, 13] that recognize the importance of the $S_{11}(1650)$, $P_{11}(1710)$, and $P_{13}(1720)$ s-channel resonances, which are the only ones with a known significant branching into strange channels [16]. The $p(e, e'K^+)\Lambda$ cross section data exhibit a forward peaking in θ^*_K that has been attributed to t-channel exchanges [17]. For this reason the two lowest vector meson resonances $K^*(892)$ and $K_1(1270)$ are typically included. Some models also include Y^* resonances in the u channel.

These data reveal a simple phenomenology that indicates the transferred Λ polarization is maximal along the virtual photon direction. Here, we have not included the virtual photon depolarization factor. For our data sample this factor is $\sim$0.8, which if divided out, would push P' even closer to unity. We note that the lack of a strong W dependence is an indication that the data might be economically described in a flux-tube strong-decay framework. In this picture we expect that the cross section is dominated by photo-absorption by a u quark. When viewed in the γ^*-p Breit frame, after a u quark has absorbed the virtual photon, there is an intermediate u-(ud) system with the u quark polarized along the photon direction ($+z$) due to the helicity-conserving vector interaction. Hadronization into the K^+-Λ final state proceeds with the production of an $s\bar{s}$ pair that breaks the color flux-tube. Because the u quark hadronizes as a pseudoscalar K^+, the $\bar{s}$ quark spin is required to be opposite to that of the u quark, i.e. in the -z direction. In the non-relativistic quark model the entire spin of the Λ is carried by the s quark. Since we observe the Λ polarization to be in the $+z$ direction, we conclude that the s and $\bar{s}$ spins were anti-aligned when they were created, if the hadronization did not flip or rotate their spins. We note that the authors of Ref. [18] also posit a two-step process for the production of transversely polarized Λ hyperons in the exclusive $pp \to pK^+\Lambda$ reaction, and come to the similar conclusion that the s and $\bar{s}$ quark pair must also have been produced with spins anti-aligned.

A dominance of spin anti-alignment for the s and $\bar{s}$ quarks is not consistent with the S=1 $^3P_0$ operator, which predicts a 2:1 mixture of $s\bar{s}$ quarks produced with spins aligned vs. anti-aligned if the orbital substates are equally populated. Along with other observations of failure of the $^3P_0$ model (e.g. explaining $\pi_2 \to \rho\omega$ decay [6]), the applicability of the $^3P_0$ model in describing all hadronic decays is brought into doubt. We await theoretical investigations on the effect of the functional form of the quark-pair-creation operator on hyperon polarizations when a single $s\bar{s}$ pair is produced.

Note that a major part of the semi-classical argument rested on the assumption that the aligned u quark selected an anti-aligned $\bar{s}$ quark in order to produce a pseudoscalar kaon. If the final state meson were a vector K^{*+}, the argument would be inverted and presumably the Λ polarization would flip sign. We plan to measure this process.

4 Experimental Issues

Directly detecting the K^{*+} is more difficult than detecting the K^+ because the K^{*+} decays promptly to $K^+\pi^0$ or to $K^0\pi^+$ with the K^0 decaying within centimeters to $\pi^+\pi^-$. Detection of the three charged pion decay has very low efficiency in CLAS. Also, it does get more difficult to separate Λ's from Σ's cleanly using the missing-mass technique since the momentum resolution for the K^{*+} is worse than that for the single-particle K^+. Detecting a Λ directly requires measuring three particles in the final state: $ep\pi^-$. The $e\pi^+\pi^+\pi^-$ final-state required for detecting the charged decay of the K^{*+} will have even smaller acceptance than that for direct detection of the Λ by another factor of 5-7.

For these reasons, it is simpler to detect the Λ directly from its $p\pi^-$ decay mode. This also has the advantage of having similar acceptance for detecting the recoil K (or K^*) by missing mass. The main weakness of the CLAS detector for this approach is its low acceptance for the π^-. For this reason, we propose to take data with a reduced B-field, and to study systematics, to alternate the polarity of the CLAS torus.

We have tested our methods on two of our current data samples: one at 5.754 GeV beam energy with the CLAS torus at 90% maximum field and the other at 4.247 GeV with the torus at 60% maximum field. We selected events with at least an electron, proton, and π^- candidate in the final state. We calculated the invariant mass of the proton and π^-. A small Λ signal is observed above the background. We have made a crude vertex cut to enhance Λ candidates by demanding that the apparent z-vertex of the π^- track be downstream of the apparent proton z-vertex by 1 cm or more. This reduces the background under the Λ candidate by a factor of three or so, while reducing the Λ signal by roughly 20% (see Fig. 3).

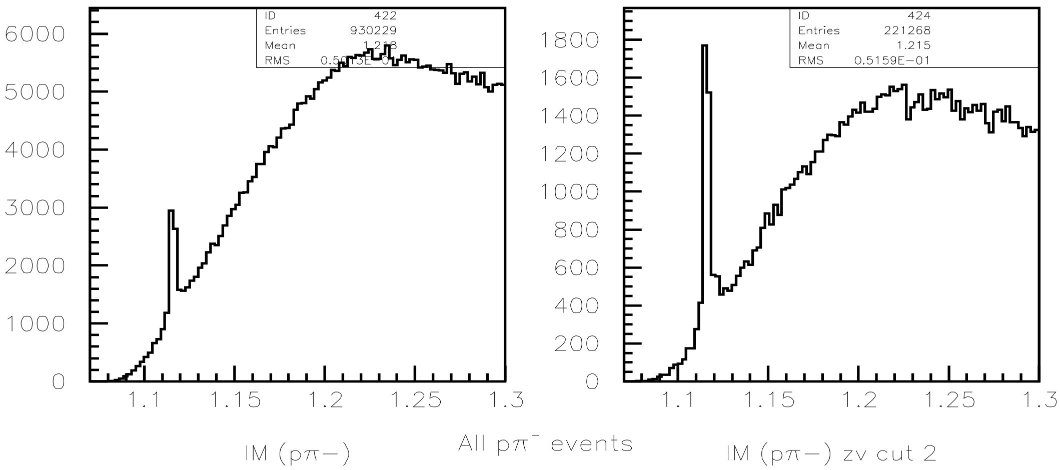

Figure 3: Analysis for 4.247 GeV/2250 A CLAS data showing the reconstructed $p\pi^-$ invariant mass without (left) and with (right) the z-vertex cut in place.

For $p\pi^-$ pairs with mass consistent with a Λ, we calculate the missing mass recoiling from the scattered electron and the Λ. Our preliminary results are shown in Fig. 4 for the 4.247 GeV/2250 A analysis. These results show the missing mass recoiling from the $e'p\pi^-$ final state. The background is cleaned up significantly with cuts on the reconstructed z-vertex as well as a cut on the Λ peak in the $p\pi^-$ invariant mass. The lower sub-graphs shows the same missing mass quantity, but with increasing cuts on W. As the cut on W increases, the K^+ peak decreases more rapidly than events in the region of the K^{*+}. Events in the K^{*+} mass region are apparent with the cut on W >2.2 GeV.

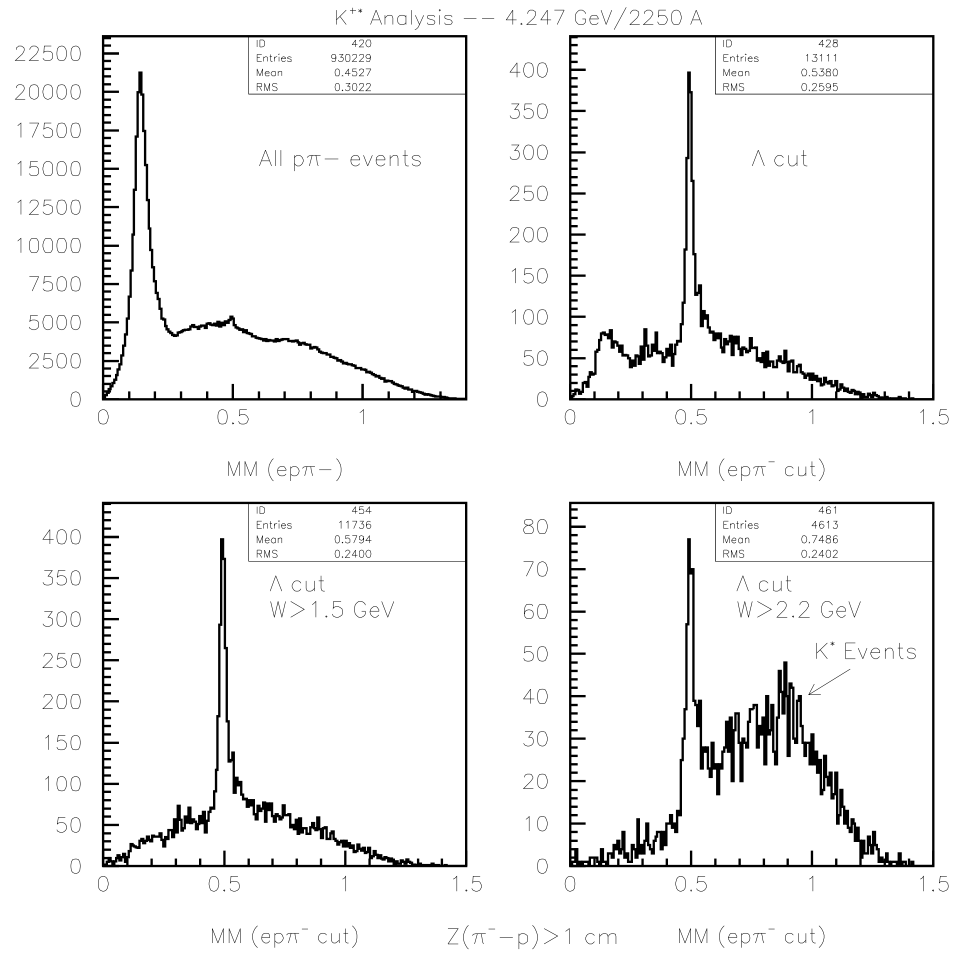

Figure 4: Data analysis for 4.247 GeV/2250 A CLAS data. (Upper-left): The $e'p\pi^-$ missing mass spectra for all events. The remaining plots include a cut on the $(p - \pi^-)$ z-vertex distribution (the 1 cm cut) and the Λ mass peak. (Upper-right): All W, (Lower-left): Cut on W >1.5 GeV, (Lower-right): Cut on W >2.2 GeV.

We note that $K^{*+}\Lambda$ yields are suppressed by two effects relative to $K^+\Lambda$ yields: at a given W there is less phase space to produce the heavier K^{*+}, and at a given W, the Λ associated with the heavier K^{*+} is moving slower in the lab; thus, its daughter π^- has less momenta also, and thus, a smaller acceptance. This argues that we should see more $K^{*+}\Lambda$ events for higher beam energy and for a lower B-field setting. We did the same analysis for 5.754 GeV beam energy data with the CLAS torus at 90% maximum field. We see a similar K^+ peak but the spectra in the K^{*+} mass region is even more depleted than for the 4.247 GeV/2250 A data; most likely because the higher torus setting at 5.754 GeV cuts into the $K^{*+}\Lambda$ acceptance, more than offsetting the extra phase-space available at the higher energy.

We don't think there are any show-stoppers for this experiment. We need to study the event acceptance in some detail because we have to detect both the p and π^-, and thus we will not, in general, have complete coverage in the center-of-mass angle ($\cos\theta_p^{RF}$) of the proton. For example, we will lose some of the region near $\cos\theta_p^{RF} = 1$, because in this case the π^- goes backward in the Λ rest-frame and thus has lower than normal laboratory momentum. The necessity to exactly understand the acceptance will be obviated somewhat because we will be doing an asymmetry analysis to extract the Λ polarization. We also plan to do simulations to understand the source of the background in the K^{*+} missing-mass region. We think that it is mainly caused by Σ^0, $\Sigma(1385)$, and $\Lambda(1405)$ production and subsequent decays to Λ's as well as some contribution from multi-pion production.

5 Conclusions

To summarize, we state our intention of submitting a proposal to the next PAC to measure transferred Λ polarization in $K^{*+}\Lambda$ events. These measurements will test the validity of our semi-classical argument that the $s\bar{s}$ pair is produced with spins anti-aligned. These results should inspire detailed calculations of the spin-dependence of strong decays which will illuinate the nature of flux-tube breaking. As a by-product, the experiment will measure the ratio of $K^* - \Lambda$ to $K^+ - \Lambda$ cross sections. The CLAS will be operated at low values of B-field, allowing us to measure Λ production by a direct-detection technique. Our study will require about 20 days of beam time at the highest available energy and polarization.

We solicit the advice of the PAC regarding our impending preparation of the proposal.

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