Beam Spin Asymmetries from Exclusive $\pi^+ N$ Electroproduction

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October 2017

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1 Introduction

This section discusses the history of 1-D and 3-D measurement in DIS. It also discusses the cross section for exclusive electroproduction and points out the term we will be accessing with this beam spin asymmetry measurement.

2 Experiment

This section will briefly state facts about the CLAS detector as well as CEBAF. It will then discuss electron and pion identification.

This measurement was conducted at Jefferson Lab in Newport News, Virginia. Jefferson Lab houses the Continuous Electron Beam Accelerator Facility (CEBAF), as well as 4 experimental halls. The current measurement was taken with the CEBAF Large Acceptance Spectrometer (CLAS) in Hall-B.

The CEBAF injector provides a few hundered (get the number and put it here) MeV electrons, where a high voltage Pockels cell is used to switch the polarization of the electrons at a rate of 33 Hz. Electrons are then accelerated via several passes through 2 parallel linear accelerators, before being delivered to Hall-B. For this experimental run (E1-f) the beam energy was 5.5 GeV. The beam polarization was monitored with a Moller polarimeter, and the average value was found to be $\lambda_e = (75 \pm 3)\%$. The electron beam was incident on a liquid hydrogen target, 5 centimeters in length. The vast majority of electrons don't interact, and deposit their charge on the Faraday Cup. Those electrons that are scattered between angles of (put acceptance range here) are collected by the CLAS detector for analysis.

The CLAS detector is composed of several sub-systems that are used together to infer the four momenta of particles that scatter out of the target. A central magnet provides a toroidal magnetic field used to separate charged particles and measure momentum, and divides the spectrometer azimuthally (in the x-y plane if z is taken to be the direction of the beam) into 6 identically constructed sectors. Each sector contains 4 major sub-systems:

- Drift Chambers - Used to detect tracks from charged particles and measure the particle momentum. Also responsible for most of the trajectory tracking of the particles.
- Cherenkov Counter - Used to separate electrons from negative hadrons.
- Electromagnetic Calorimeter - Records the energy deposited by charged and neutral particles, resposible for tracking photons/neutrons.
- Time of Flight Scintillators - A high resolution timing system that is used to calculate the velocity of particles. The time of flight system is the primary means used to separate different hadrons.

2.1 Electron Identification

Electrons are selected for analysis from the candidate tracks by using a cuts based classification algorithm. The dominant background for electron candidates are negative pions. All negative tracks are considered as possible electrons. These candidate electrons are first subject to geometric cuts.
As particles traverse the EC they create an electromagnetic shower, which is not confined within the detector when the particles pass close to the extremes of the detector strips. This mechanism leads to an underestimation of particle energy in the reconstruction phase, for that reason these tracks are discarded. Similarly, the detector efficiency is poorly understood at the extreme edges of the drift chambers, and tracks through these areas are also rejected.
The fractional energy deposition with respect to the particle momentum E_{dep}/p is nearly constant as a function of momentum for electrons, but inversely depends on the momentum of negative pions. This property is exploited by placing a momentum dependent cut on the ratio $E_{dep}(p)/p$ for all negative candidate tracks. The ratio E_{dep}/p is calculated in 60 momentum bins from 0.5 to 2.5 GeV/c (this should be double-checked). The electron signal is then fit with a Gaussian function, and the mean μ_i and standard deviations σ_i are recorded for each momentum bin (above labeled i). These distributions are then fit with a 3rd order polynomial ($\mu(p) = ap^3 + bp^2 + cp + d$) and can be used to create decision boundaries for rejecting tracks from the candidate electron sample.
Unlike electrons, negative pions do not deposit a significant amount of energy in the inner EC, and we apply a minimum energy deposition cut to electron candidates ($E_{inner} > 50 MeV$).
The Cherenkov Counter (CC) is filled with C_4F_{10} gas (perfluorobutane), which has a pion threshold of $p_\pi \approx 2.5 GeV/c$. Historically, a cut was placed on the minimum number of photo-electrons detected for a track. This cut achieves the desired separation between electrions and negative pions, but is known to discard good electron candidates as well. For this analysis, we use a matching condition developed by Osipenko. Using the closest detector (drift chamber region 3) the track polar angle is calculated at the CC. This angle is compared with the CC detection segment for each of the 18 segments which span the polar angle up to $\theta = 45°$. The procedure described above for fitting the momentum dependence of the ratio E_{dep}/p is applied to the segment dependence of the angle θ_{CC}.

2.2 Pion Identification

Identification of charged hadrons in CLAS depends on time-of-flight information. First, candidate tracks are subject to a geometric cut in the region 1 drift chambers, for the same reasons described above. Next, the vertex position of the pion is compared to the vertex position of the electron. For a process with a detached vertex (pion comes from a decaying mother particle) this type of cut would discard events of interest, but for this process we expect the pion to originate from the point of collision. With this motivation, the vertex difference Δv_z is required to be on the order of the target ($|\Delta v_z| < 5\ cm$). Finally, we use a timing cut suggested by Dan Carman (reference to some paper where he uses it?) that does not discard any tracks which have passed the first two cuts. Using momentum information from the drift chambers, the value for β can be calculated for a particle of mass m as shown below:

$$\beta_{calc} = \frac{p}{\sqrt{p^2 + m^2}} \tag{1}$$

This quantity is calculated for the pion mass, kaon mass, and proton mass (in the positive case that we consider in this note). The mass value $\beta_{calc}(m)$ which produces a value closest to β_{TOF} is chosen as the identity of the particle.

3 Data Analysis

This section is dedicated to the description of data analysis techniques used to identify events, correct kinematics, and calculate the beam spin asymmetries.

3.1 Corrections, Event Selection, & Binning

For this analysis $ep \rightarrow e\pi^+ N$ events will be identified by directly identifying the scattered electron and positive pion, and inferring the presence of the neutron.
After electron and pions have been identified, their momenta are corrected using momentum corrections developed for the E1-F dataset by Marco Mirazita (check spelling of name, and put reference to note here). Time of flight corrections are also implemented based on work by Nathan Harrison (provide reference here), including removal of non-functional TOF paddles on a run-by-run basis. Do we need to discuss corrections here at all, is this level of detail sufficient, should we elaborate?
After the particle identification and kinematic correction, kinematic restrictions of $Q^2 > 1.0$ and $W > 2.0$ are implemented to confine our measurement to the commonly accepted DIS region. The rest of the final state can be calculated for each event simply by comparing initial and final state four-vectors.

$$X^\mu = e'(k'^\mu) + \pi^+(h^\mu) - e(k^\mu) - p(P^\mu) \tag{2}$$

The missing neutron can be inferred by asking that $M_X = \sqrt{X^\mu X_\mu} \approx M_N$, in particular it is required that $0.89 < M_X < 1.01$. Events passing these criteria are considered to be the final event sample.
These events are binned in 15 bins (in the variable $\cos\theta_h$, the cosine of the polar angle between the virtual photon and the hadron) of variable size which are chosen based on the statistical content in each bin, and the acceptance in that bin. The most extreme backward angle was not used due to a large acceptance hole in the central phi regions, shown in figure (put figure and reference). The ϕ_h distributions are binned for fitting in 12 symmetric bins of width 30 degrees. (Add figure which shows the binning drawn over the phi vs. theta histogram).

3.2 Beam Spin Asymmetry

Beam spin asymmetry (BSA) measurements are a go-to tool for Nuclear/Particle Physics, and will now be briefly introduced. The cross section difference $d\sigma_+ - d\sigma_-$, where the subscript refers to the lepton (electron) helicity projection along the beamline direction, is just the part of the cross section which depends on the electron spin state. This quantity (interesting in itself) is not usually measured. Instead the ratio,

$$BSA = \frac{1}{P_e}\frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \approx \frac{1}{P_e}\frac{N_+ - N_-}{N_+ + N_-} \tag{3}$$

is presented, due to convenient cancellations in detector efficiency and acceptances in each cross section term. Where the fractional polarization of the beam is denoted as P_e. As mentioned in section 2, the beam spin is flipped at a rate of 33 Hz to minimize systematic errors arising due to differences in detector position and calibration.

3.3 Fitting Procedure

The distributions for ϕ_h are binned and fit with the function $f(\phi_h) = A\sin\phi_h$ using χ^2 minimization. This is accomplished using the python implementation of gradient descent provided in `scipy.optimize.minimize`, which by default uses the `BFGS` method. Parameter errors are calculated using two methods, first the common Hessian method, and second the bootstrap replica method. These two methods are found to be consistent, and the parameter errors estimated obtained by bootstrap methods are used throughout this report.

4 Systematic Errors

This section will discuss systematic errors in the measurement.

4.1 Summary

In this section there will be a table displaying the fractional shift of the result for each systematic error source that was considered in this analysis.

4.2 Cut Variations

In this section we describe the results of cut variations on the analysis.

4.3 Random Subset/Helicity

Two additional studies are performed which involve randomization of the input data in some way. In the first study, the helicity of each event is assigned a random value of ± 1. This randomization destroys the correlation between beam spin and the ϕ_h distributions. Therefore, one expects to find zero asymmetries as a result of this randomization. In the second study, the full analysis is run on a subset of 80

5 Results

This section will display the final results for the BSA. We will also compare to previously measured results, as well as compare to theory if any is available.

5.1 Summary of Results

These are the results of this study.

5.2 Comparison to Other Measurements

Here we are comparing to E1-6.