Measuring Double-Spin Asymmetry in Jefferson Lab's EG4 Experiment

Ryan Loving

Faculty Adviser: Dr. Robert Fersch

Christopher Newport University

Table of Contents

1. Abstract
2. Introduction
3. Theory
    - 3.1. Primary Quantities of Interest
    - 3.2. Systems Used for Analysis
    - 3.3. Mathematical Motivation
4. Methods
5. Data
6. Discussion
7. Appendices
8. Bibliography

1) Abstract

This project is based on data from Jefferson Lab's EG4 accelerator experiment from 2006. The goal is the development of a system to measure longitudinal double-spin asymmetry, a ratio measure between the two quantized spin states of a proton that's normalized to account for inherent quantities in the experiment. The reason for pursuing this is that asymmetry has applications in the analysis of proton spin structure, which presents a potential path for continuation of this research. This system is made to work with minimal user input, in order to increase its versatility and applicability as well as to reduce potential error when processing the large amounts of data necessary to achieve accurate results. Secondary goals include applying data cuts and kinematic corrections that improve the viability of the data, as well as comparing the results to existing fits to global data generated by Jefferson Lab's experimental spin-physics group to verify the former's accuracy.

2) Introduction

This project makes use of data from the CLAS EG4 experiment performed at Jefferson Lab in 2006. The goal of the experiment was to take measurements at very low Q^2 levels, where virtual photons exchanged between the electron beam and the target closely mimic real photons. This was done with the goal of testing quantum chromodynamic models. Another useful application of this data, and the focus of this project, is the calculation of longitudinal double-spin asymmetry.

Asymmetry is a ratio measure between the two quantized spin states of a proton. This ratio is not one-to-one, and the resultant patterns are useful in investigating the spin structure of a proton using structure functions. While analysis of one of these structure functions is beyond the scope of what is achievable in this project, it provides a compelling reason to pursue asymmetry calculation.

Furthermore, asymmetry calculation is a pursuit that demands a degree of automation. To receive useful results, it is necessary to analyze the entirety of the data collected during the accelerator test run in question. This involves millions of data points across thousands of files, necessitating an efficient analysis system that can run with minimal user input. As such, the secondary goal of this project was to create a sufficiently independent and efficient analysis code. The result is an automated system that can perform a full analysis of any file set it is presented with.

3) Theory

3.1 - Primary quantities of interest

The quantities that this experiment focuses on are the positive definite square of virtual photon 4-momentum, Lorentz-invariant missing mass, and asymmetry. These quantities are commonly abbreviated as Q^2, W, and A, respectively.

Q^2's role in the scattering event is shown in Figure 1. It can also be referred to as the energy of the interaction or as the mass of the virtual photon exchanged between the incident electron from the beam and the proton from the polarized target. Q^2 is calculated using this formula:

$$Q^2 = 2EE'(1 - cos(\theta)) \qquad \text{(Eq. 1)}$$

where E is the beam energy, E' is the momentum of the scattered electron in GeV, and {theta} is the angle from the z-axis (beam axis).

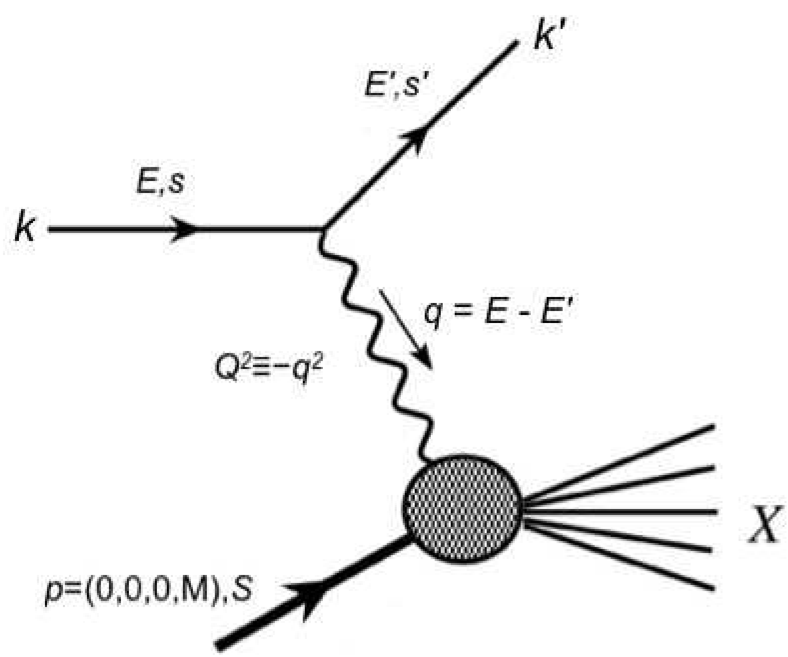

Figure 1: Diagram of a scattering event from the EG4 experiment. A virtual photon is exchanged between an electron from the beam and a proton from the target. The mass of this virtual photon, in GeV, is Q^2

W refers to the mass of the scattered products from the interaction. The label "Lorentz-invariant" means that it is unaffected by Lorentz transformations and remains constant in different reference frames. *W* is calculated as follows:

$$W = \sqrt{M^2 + 2M(E - E' - Q^2)} \qquad \text{(Eq. 2)}$$

where *M* is the mass of the particle in GeV. *W* peaks at 0.938 GeV, equivalent to the mass of a proton.

Both Q^2 and *W* are used in the final determination of asymmetry. The full calculation of asymmetry is explored further in the "Mathematical motivation" section. In essence, asymmetry is a ratio of positive and negative helicity, and these ratios are counted within bins of *W* and Q^2. Helicity is a measure of spin alignment between the beam and the target. The spins of the incident electron and polarized target proton can either be parallel (positive helicity) or antiparallel (negative helicity). Longitudinal double-spin asymmetry ($A_{//}$), which accounts for the beam polarization and dilution factor, is the final result of this project. This normalization makes the results comparable with results from other experiments, independent of background noise and other inherent factors.

3.2 - Systems used for analysis

The analysis performed for this project was done using a C++ program that implemented the ROOT framework. ROOT is a set of tools and systems developed by CERN for use in large-scale data analysis. Not only does ROOT provide the means necessary for a large portion of the operations this project requires, the data from the EG4 experiment also exists in ROOT TTree files.

A TTree is a type of file typically used to store large amounts of data points. The structure of a TTree consists of internal branch nodes that each contain an ordered series of leaf nodes. In this case, the leaf nodes correspond to the measurements of various quantities from each event in the EG4 experiment, where an event is a single collision between an electron from the accelerator beam and a proton from the polarized target. The measurements of momentum, beam angle, and helicity are among those necessary for the calculations at hand, while some others are used in identifying events to be cut from the final results.

The involvement of ROOT in the calculations is largely confined to the beginning and ending of the operation. ROOT's tools are used to access the EG4 data in the TTree files. The calculations, shown in greater detail in the next section, are performed using basic C++ functionality. Once complete, ROOT has several pre-built classes that can be used for graph generation. In this case, the result uses a line graph will vertical error bars to show uncertainty levels in the results.

3.3 - Mathematical Motivation

The fundamental analysis operation in this project is the calculation of raw spin asymmetry. Further operations are either adjustments to the final result or adjustments to the basic quantities that are used in various calculations.

The first step is to separate all events into both W and Q^2 bins. The W bins are uniform subdivisions of the 0-3 GeV range. The Q^2 bins are logarithmic, with their sizes calculated beforehand. The final graphs plot asymmetry on the y-axis, with the W bins serving as the x-axis. The data is further separated into multiple graphs that each represent a single Q^2 bin.

Once both W and Q^2 bins are identified for an event, it is then checked for its helicity, a value of either 1 or 0. A tally is kept of the total number of both results for every combination of bins, referred to as n_+ and n_-. Once all events have been counted, Eq. 3 is used to calculate the asymmetry value of each bin combination A_{raw} and Eq. 4 is used to calculate the size of the error bars σ. Note that the error bars are solely depended on the number of events recorded - reducing them is a matter of processing larger amounts of data.

$$A_{Raw} = \frac{n^+ - n^-}{n^+ + n^-} \quad \text{(Eq. 3)}$$

$$\sigma = \frac{1}{\sqrt{n^+ + n^-}} \quad \text{(Eq. 4)}$$

From there, the results must be normalized and adjusted according to beam polarization $P_b P_t$ and dilution factor F_{DF}. The result is longitudinal double-spin asymmetry, shown in the formula below.

$$A_{/\!/} = \frac{1}{F_{DF}} \frac{A_{Raw}}{P_b P_t} \quad \text{(Eq. 5)}$$

4) Methods

The ultimate goal of this experiment is to develop a system to efficiently measure double-spin asymmetry $A_{/\!/}$ with minimal user input. This requires analysis code that is developed in a series of distinct steps. This development was performed on a personal computer running Ubuntu, using C++ and implementing the ROOT framework.

The first step is the development of a program called a skimmer, intended to perform the asymmetry calculation on single test run and output the results into a text file. The reason for performing the operation this way, rather than performing the calculations and immediately graphing the results, is twofold. First, the skimmer can function much more efficiently than the complete program on the scale this project requires. Secondly, separating the results by run and putting them in a more easily machine-readable format makes debugging easier, which was essential over the course of this project.

For each run, the skimmer performs the asymmetry calculation operation as described in Section 3.3. An additional step at this point was using cuts and kinematic corrections. This step, which uses external files that test certain variables from each event, eliminate various undesirable parts of the data, such as faulty hits on the target or scattering events involving particles other than protons. The development of entirely new cuts was beyond the scope of this project, and as such this was the first of two elements using resources developed by others. In this case, the cuts were adapted for use from those written by Dr. Krishna Adhikari from Jefferson Lab.

The next step is using the skimmer over all available test data. Because of the large amount of data used, and the secondary goal of this project being the development of an automated system, this step made use of Jefferson Lab's scientific computing batch system. This system allows computing jobs to submitted and handled automatically by the lab's servers. By submitting the full asymmetry skim as a series of single-run skimming jobs, this part of the operation was completed with minimal user input.

The second part of the skimming operation is graphing, which is performed by a second program. While this part mostly consists of retrieving skims and producing graphs, the size of each run must be accounted for. Because σ is the inverse square root of the total count of all events in that bin, it can be used to weight the results. The following formulas are used to calculate the final results, keeping in mind that each summation is done across all test runs for that particular value.

$$Numerator = \Sigma\frac{A}{\sigma^2} \quad \text{(Eq. 6)}$$

$$Denominator = \Sigma\frac{1}{\sigma^2} \quad \text{(Eq. 7)}$$

$$A_{final} = \frac{Numerator}{Denominator} \quad \text{(Eq. 8)}$$

$$\sigma_{final} = \frac{1}{\sqrt{Denominator}} \quad \text{(Eq. 9)}$$

5) Data

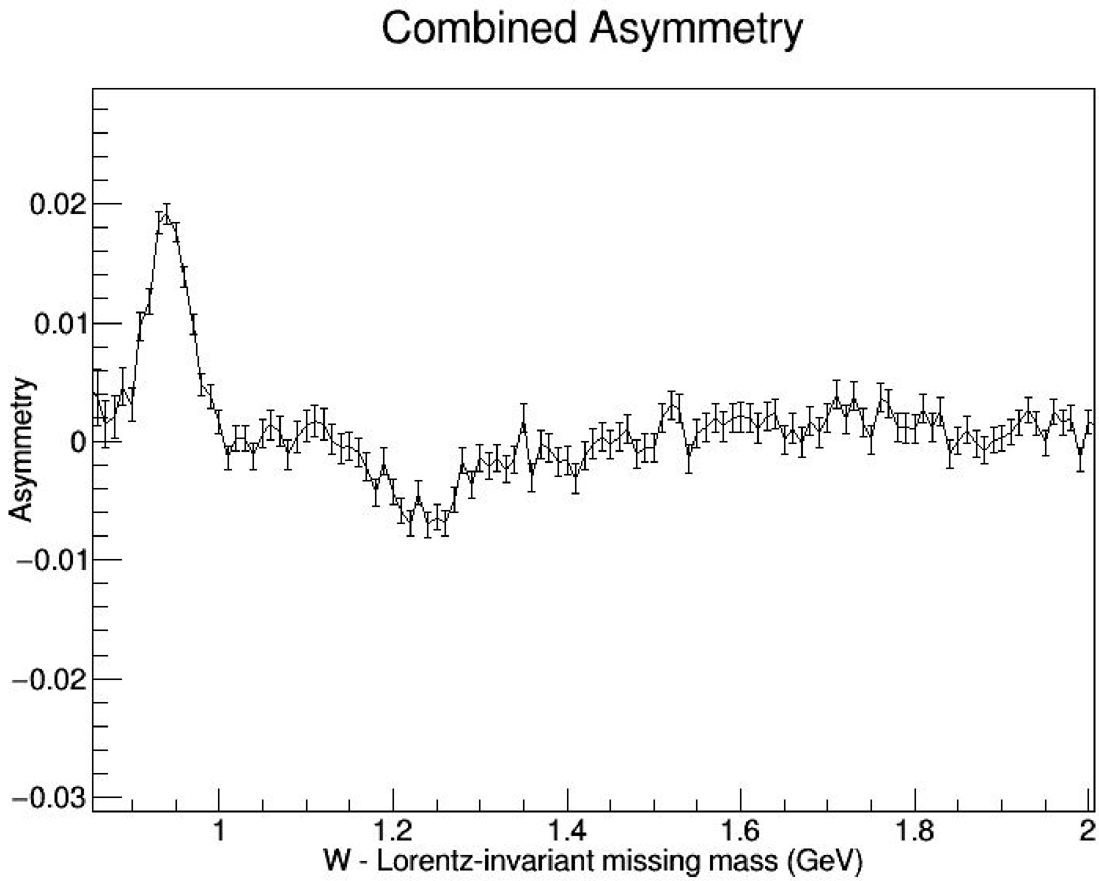

Figure 2: Raw Asymmetry, with all Q^2 bins combined into a single graph

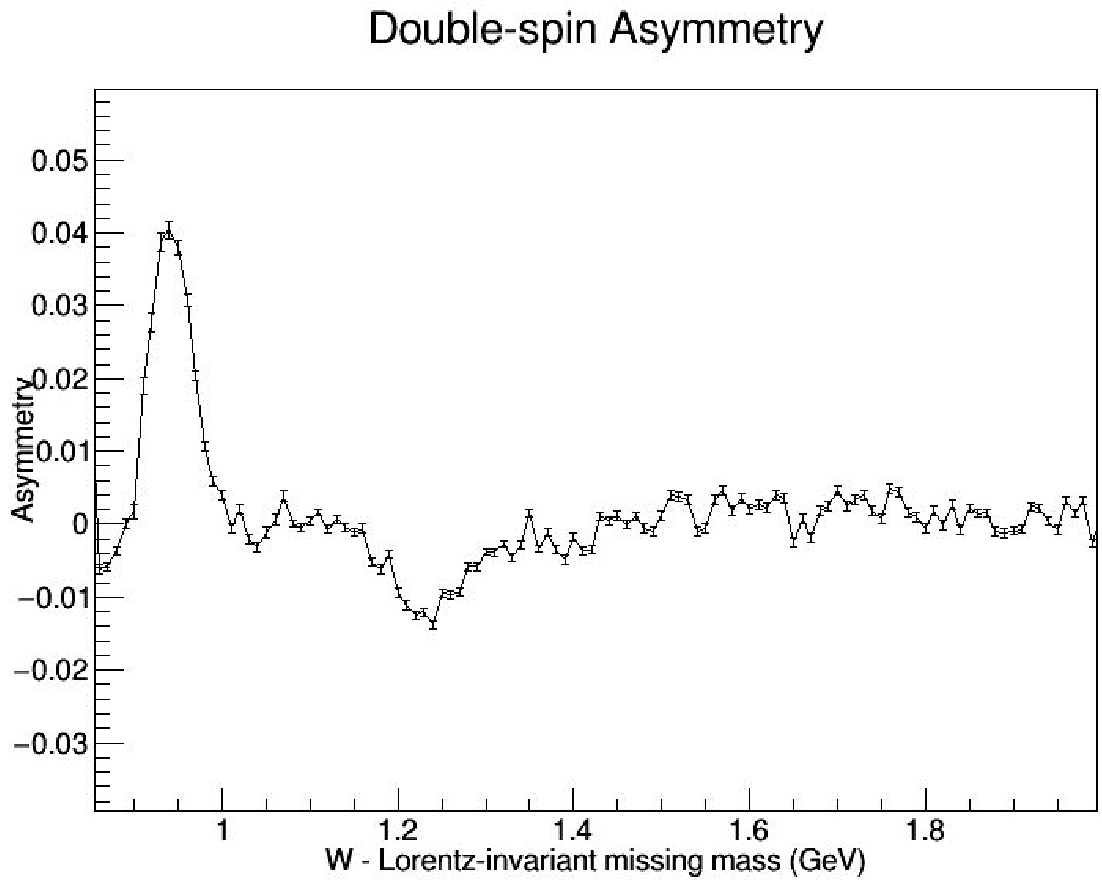

Figure 3: Double-Spin Asymmetry, normalized using beam polarization and dilution factor

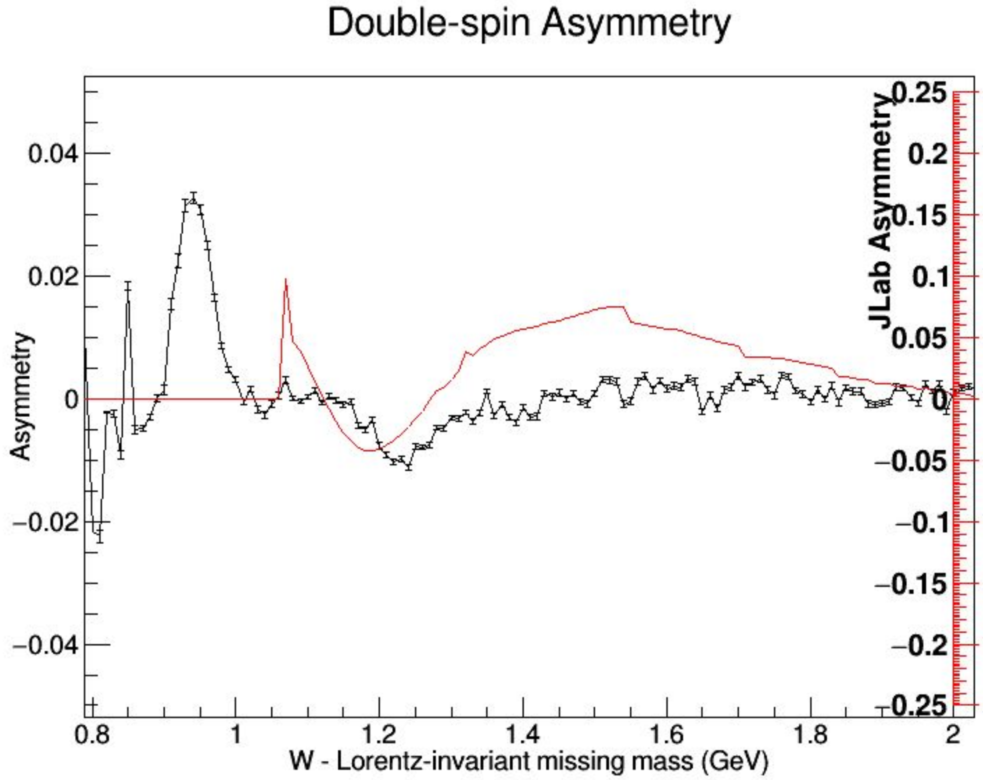

Figure 4: Double-Spin Asymmetry calculated in this project (black) versus the fit produced by JLab's experimental spin physics group (red). Note the altered scale - dilution factor can greatly affect the scaling of the results

6) Discussion

The primary signifier of successful asymmetry calculation is the elastic peak - the positive asymmetry spike at *W* = 0.938 GeV. This means that when the scattered product of the interaction is only a proton - unchanged by the collision, hence "elastic" - there is a greater chance of positive helicity.

The second identifiable feature is the delta resonance, seen at *W* = 1.2 GeV. In this range, there is a greater chance of negative helicity if the products consist of a proton and a delta particle.

The primary source of error in these results is the dilution factor. Normally, each dilution factor is unique to its experiment, and calculating it is a complicated process involving many different quantities from the results. At the time of the project proposal, this was deemed out of scope for what was achievable over the course of one year, so a dilution factor from another experiment was used. The results provided are adequate, but not precise. In future continuations of this research, calculating a dilution factor for EG4 will be an early priority.

The second way the results could be improved is by adding more data to the calculations. This project was done on one beam energy level, but there are multiple other energy levels available. Adding the ability to handle multiple energy levels would require some adjustments to the skimming code, but once completed the amount of data processed would be greatly increased, which would reduce the uncertainty of the results.

7) Conclusions

The project's primary goal, the development of a system that can measure double-spin asymmetry with accuracy and efficiency, is considered to be achieved. While the accuracy is not ideal due to compromises made in response to time constraints, the efficiency of the system makes it viable for use in future projects. In particular, the minimum input required for operation makes it a useful system for testing new algorithms or refining existing ones.

The secondary goal of gaining experience with the systems used for this project - Ubuntu, C++, ROOT, and JLab scientific computing - was also achieved. These are all systems that are anticipated to be used in future continuations of this research. These skills are also applicable in the field of nuclear physics as well as many other fields.

8) Appendices

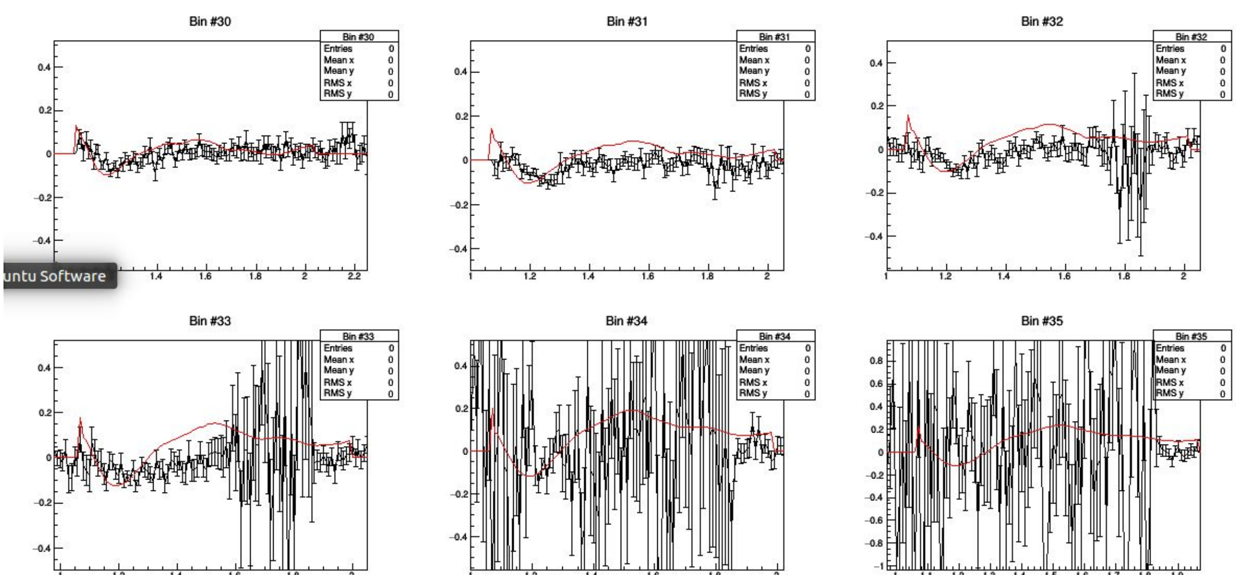

Figure 5: Double-spin asymmetry graphs separated by Q^2 bin, compared against the JLab fit (red). The error bars are much larger due to fewer data points in each bin, but the general trend can still be observed.

9) Bibliography

Fersch, Robert G. “Measurement of Inclusive Proton Double-Spin Asymmetries and Polarized Structure Functions.” *College of William and Mary*, 2008.