

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

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# 1 Introduction

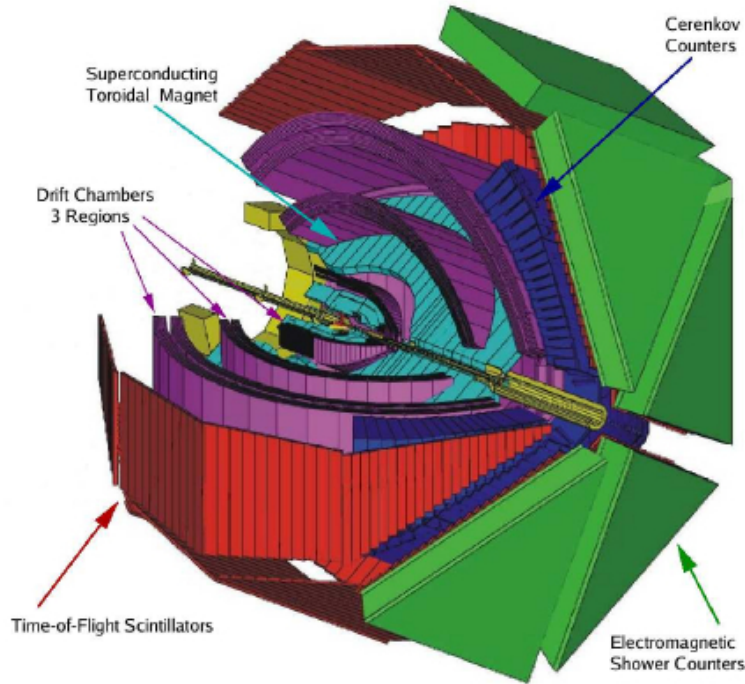


Figure 1: CLAS Detector shown with sub-systems labeled.

## 2 Experiment

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 hundred (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 with the target, and deposit their charge on the Faraday Cup.

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, responsible 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.

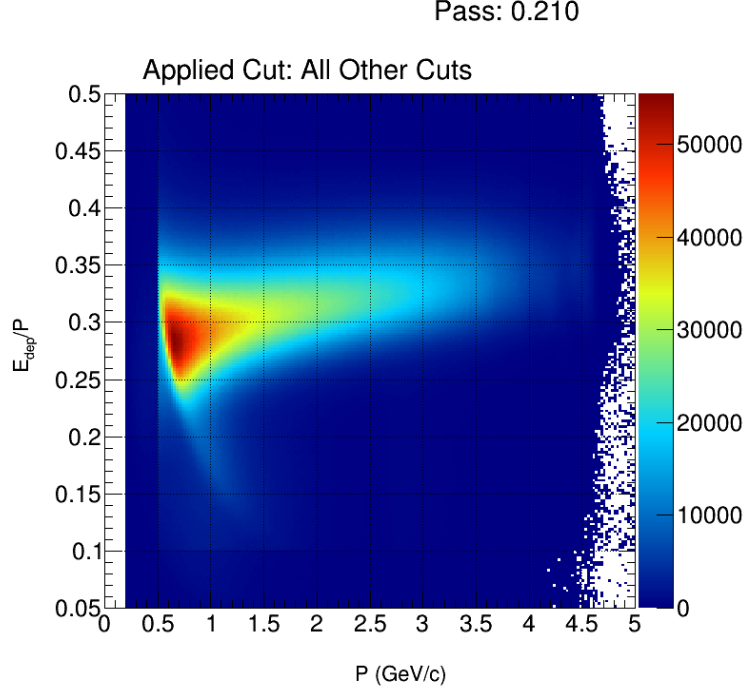


Figure 2: Sampling fraction for electron candidates (all other cuts passed).

## 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  $\mu_i$  and standard deviations  $\sigma_i$  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 ( $E_{inner} > 50\text{MeV}$ ). The Cherenkov Counter (CC) is filled with  $C_4F_{10}$  gas (perfluorobutane), which has a pion threshold of  $p_\pi \approx 2.5\text{GeV}/c$ . Historically, a cut was placed on the minimum number of photo-electrons detected for a track. This cut achieves the desired separation between electrons 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  $\theta = 45^\circ$ . The procedure described above for fitting the momentum dependence of the ratio  $E_{dep}/p$  is applied to the segment dependence of the angle  $\theta_{CC}$ .

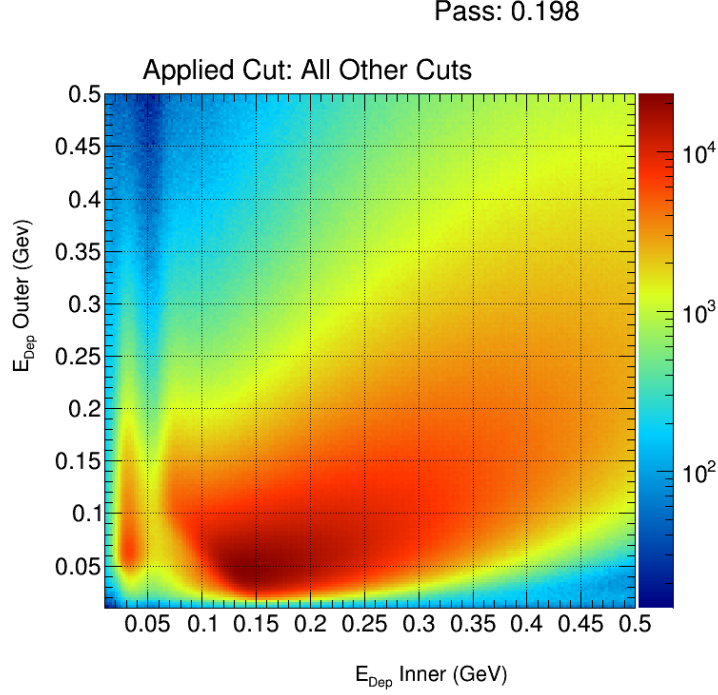


Figure 3: Calorimeter energy deposition for electron candidates (all other cuts passed).

## 2.2 Pion Identification

After electron identification, all positive tracks are subject to two constraints. First, events which pass close to the torus coils are removed by cutting on the hit positions reported by the region 1 drift chambers, this is shown in figure 2.2. Such events are often poorly reconstructed or have poorly understood acceptances and are discarded from analyses. Then, the distance between the electron vertex and the positive track vertex is computed ( $\delta v_z = v_z^e - v_z^+$ ). This distance is constrained to be within the length of the target (5 cm) see figure 2.2.

### 2.2.1 Likelihood Method

For each particle species considered, a normalized probability density function  $P(x; p, h)$  is constructed for each input into the likelihood analysis. Here,  $x$  corresponds to the feature being used to categorize different particles (in our case,  $x$  is the  $\beta$  value measured by CLAS time-of-flight),  $p$  is the particle momentum, and  $h$  is the hadron being hypothesized (eg: in our case the possible values for  $h$  are pion, kaon, proton). In general if one uses a set of  $N$  variables  $x = (x_1, x_2, \dots, x_N)$ , the likelihood for a hypothesis  $h$  is defined below.

$$\mathcal{L}_h = \prod_{i=1}^N P_i(x_i; p, h) \quad (1)$$

In our case, the only random variable we consider is  $\beta$ , and the likelihood is just the PDF. Here, and in many cases where the choice is statistically appropriate, it is possible to use a Gaussian PDF for the variable  $x_i$  ( $\beta$ ).

$$P(\beta; p, h) = \frac{1}{\sqrt{2\pi}\sigma_\beta(p, h)} \exp \left\{ -\frac{1}{2} \left( \frac{\beta - \mu_\beta(p, h)}{\sigma_\beta(p, h)} \right)^2 \right\} \quad (2)$$

The identity is assigned by choosing the particle hypothesis  $h$  which maximizes the likelihood ratio.

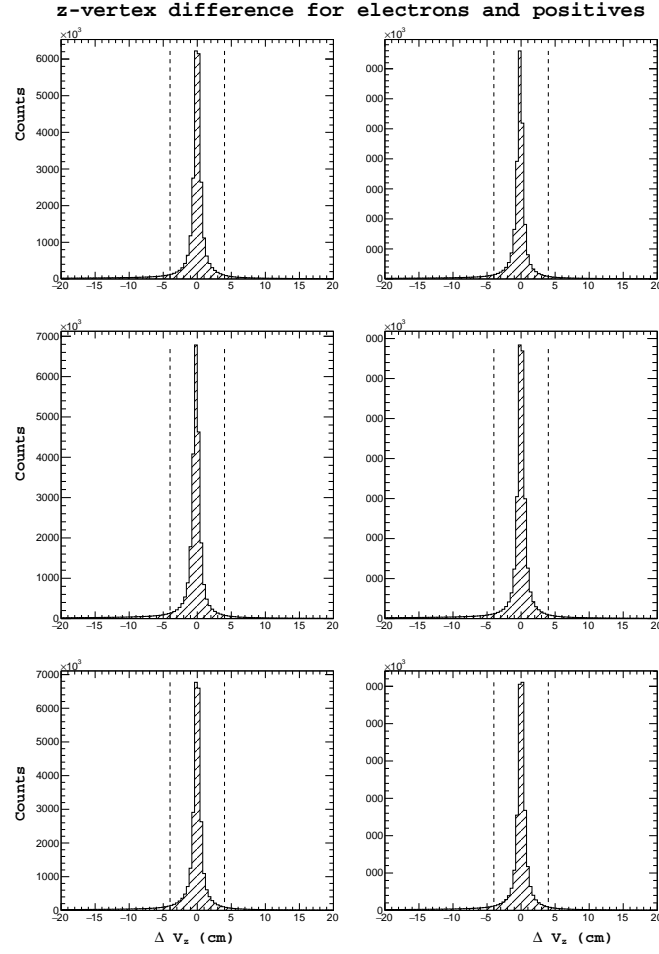


Figure 4: Shown above: The difference between the z-vertex position between detected electrons and positive tracks.

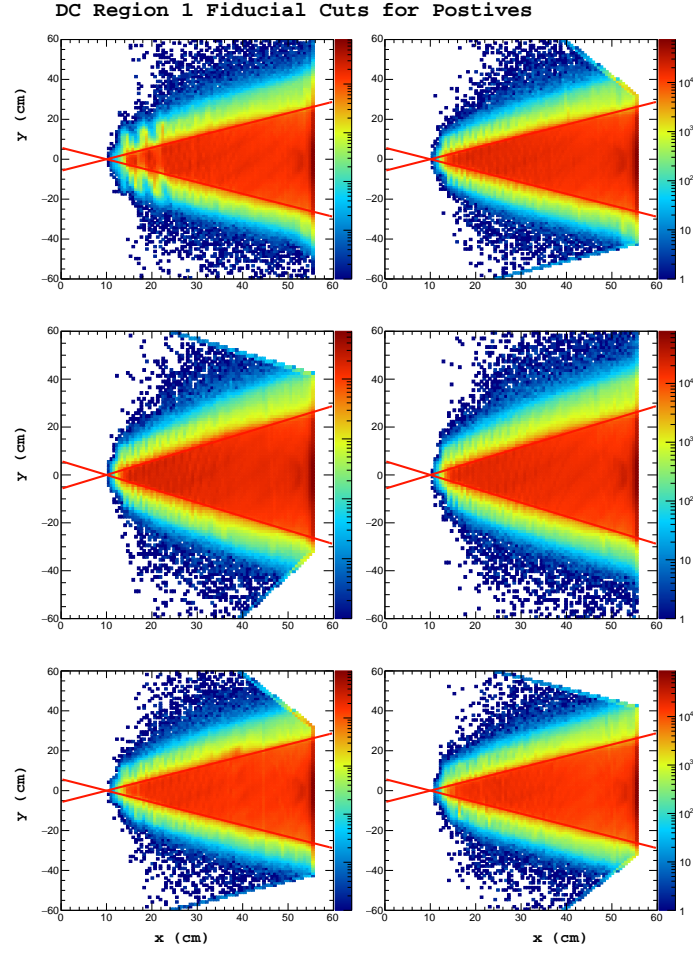
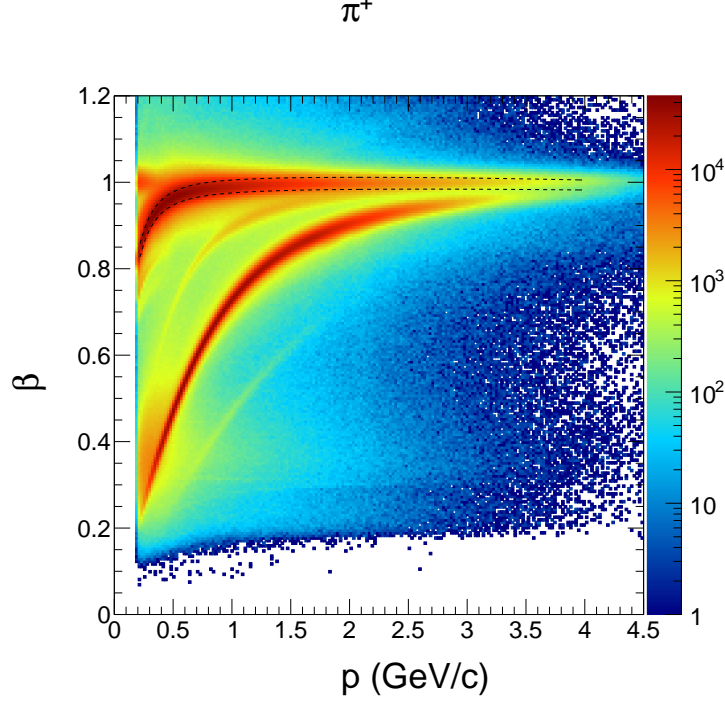


Figure 5: Shown above: Positive track hits on the region 1 drift chamber, events falling between the red lines are kept for analysis.

Figure 6:  $\beta(p)$  resolution for positive pions shown.

$$\frac{\mathcal{L}_h}{\mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p} \quad (3)$$

Using this method, every positive track is assigned a particle identification. However, at times the likelihood value is quite small when compared with the maximum likelihood for that species. This is the case for positrons which are classified by this method as positive pions, because they are the closest particle for which a hypothesis has been provided. To avoid these situations, the significance level  $\alpha$  of each track is calculated and a cut is placed on the minimum significance. This cut can be easily varied to see how it changes the analysis result.

$$\alpha = 1 - \int_{\mu - \beta_{obs}}^{\mu + \beta_{obs}} P(\beta; p, h) d\beta \quad (4)$$

Pions are chosen using this method and we apply a cut on  $\alpha > 0.05$ .



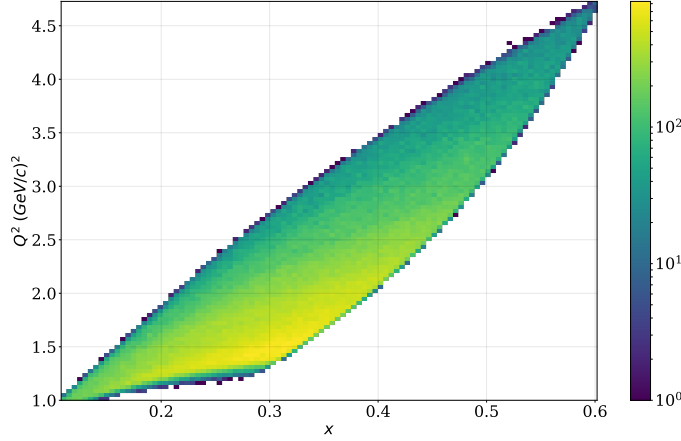


Figure 7: Kinematic distribution after event selection.

### 3 Data Analysis

#### 3.1 Corrections, Event Selection, & Binning

For this analysis  $ep \rightarrow e\pi^+N$  events are identified by directly identifying the scattered electron and positive pion, and inferring the presence of the neutron.

After the electron and pion have been identified, their momenta are corrected using momentum corrections developed for the E1-F dataset by Marco Mirazita [2]. Time of flight corrections are also implemented based on work by Nathan Harrison [1], including removal of non-functional TOF paddles on a run-by-run basis.

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.

$$X^\mu = e'(k'^\mu) + \pi^+(h^\mu) - e(k^\mu) - p(P^\mu) \quad (5)$$

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  $\phi_h$  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,

$$BSA = \frac{1}{P_e} \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \approx \frac{1}{P_e} \frac{N_+ - N_-}{N_+ + N_-} \quad (6)$$

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.

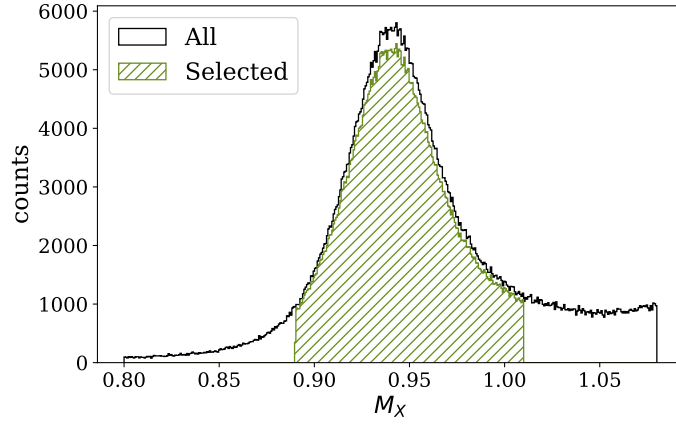
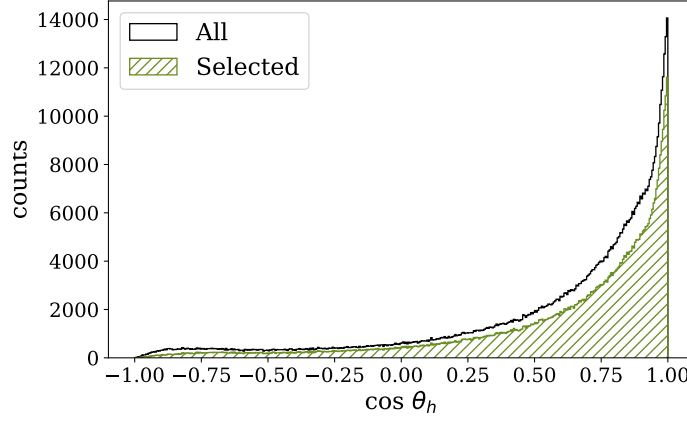
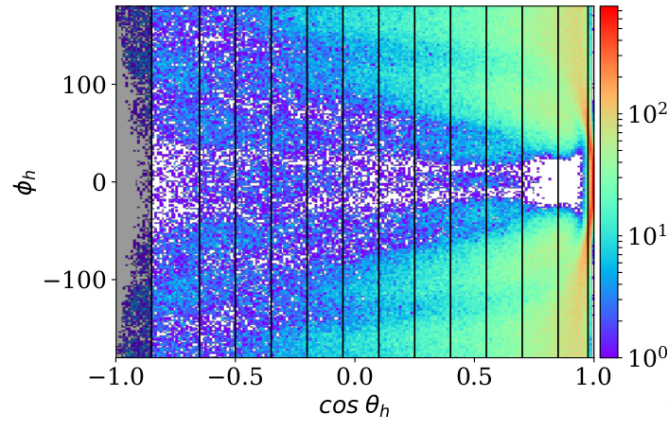


Figure 8: Missing mass cut used to select neutrons.

Figure 9: Distribution of  $\cos\theta_h$  for positive pions before and after missing mass and pion significance cuts.Figure 10: Distribution of events in the center of mass of the  $\gamma^*p^+$  system. The extreme backward angles are removed for lack of data at central values of  $\phi_h$ .

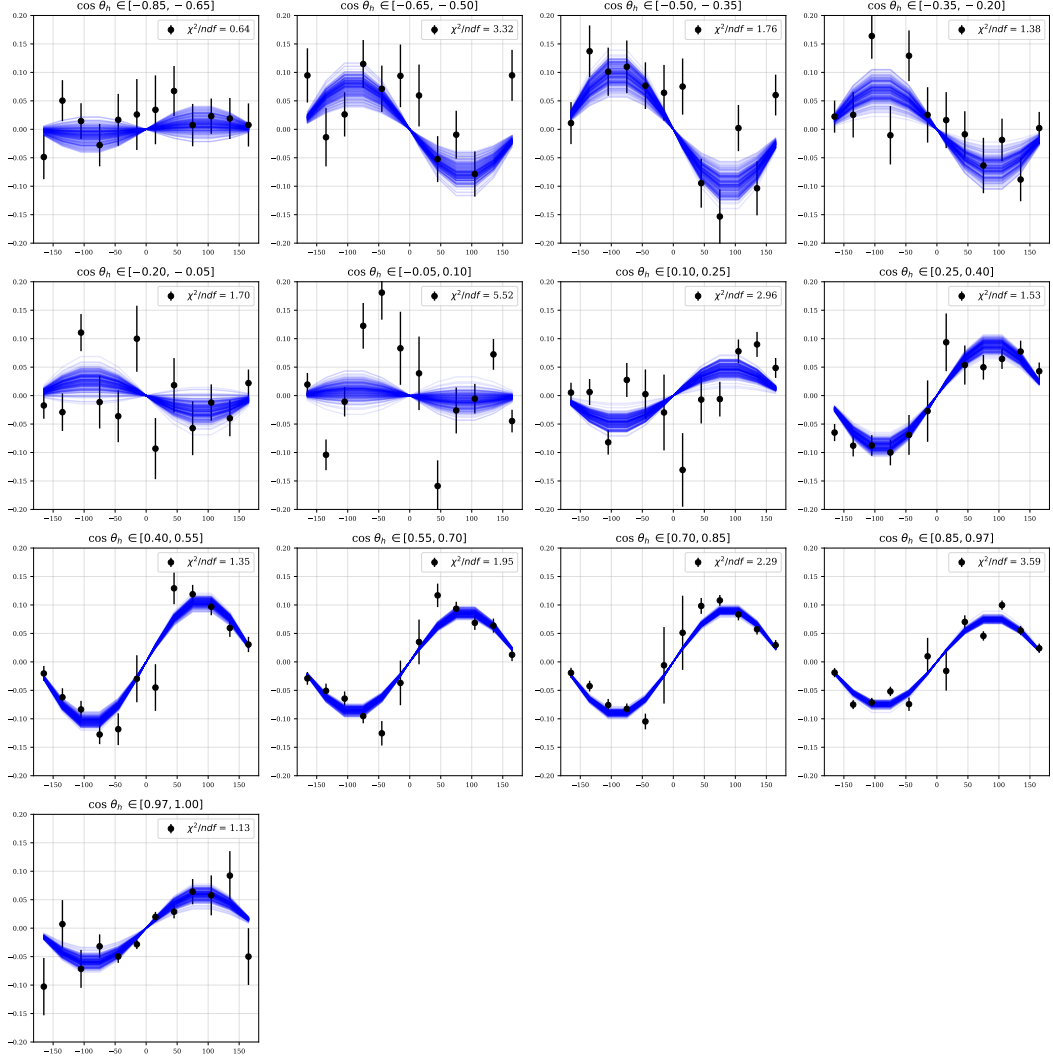


Figure 11: The BSA shown as a function of  $\phi_h$  for different bins of  $\cos \theta_h$ . Overlaid are the 200 bootstraps performed for each  $\cos \theta_h$ -bin.

### 3.3 Fitting Procedure

The distributions for  $\phi_h$  are binned and fit with the function  $f(\phi_h) = A \sin \phi_h$  using  $\chi^2$  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.

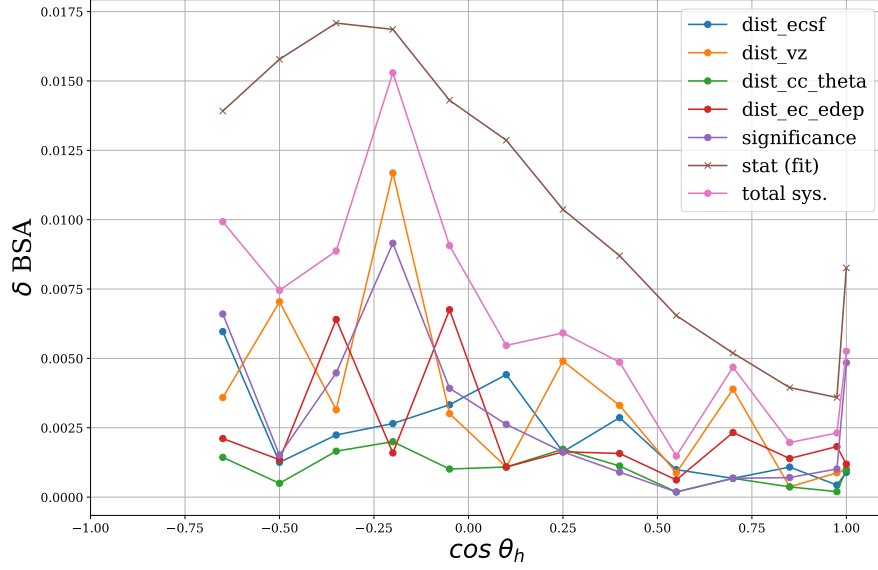


Figure 12: The largest shift resulting from all variations of each analysis cut parameter. Shown also is the statistical error. All resulting cut variations remained within statistical error.

## 4 Systematic Errors

The error on our measured values is considered in two categories. First, statistical errors are calculated for the beam spin asymmetry measurement for every phi-bin. During the fitting procedure, these statistical errors are mapped into errors on the fit parameters. This first class of errors we consider as the statistical error on the result. Second, the authors consider all other possible sources of error which do not depend on statistical effects. Those effects which have been identified are:

Source	Relative Error
Cut: z-vertex	0.0019
Cut: EC edep	0.0027
Cut: sampling fraction	0.0010
Cut: $\theta_{CC}$ matching	0.0022
Cut: pion significance $\alpha$	0.0049
Beam Polarization	0.03

### 4.1 Cut Variations

In some cases, the direct variation of analyses parameters is the only way to try and understand the dependence of the result on the input parameters. Ideally, the analysis result shouldn't vary outside of the errors which arise from statistical fluctuations.

### 4.2 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  $\pm 1$ . This randomization destroys the correlation between beam spin and the  $\phi_h$  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% of the events in the full dataset. This study is designed to identify if there is internal inconsistency in the dataset.

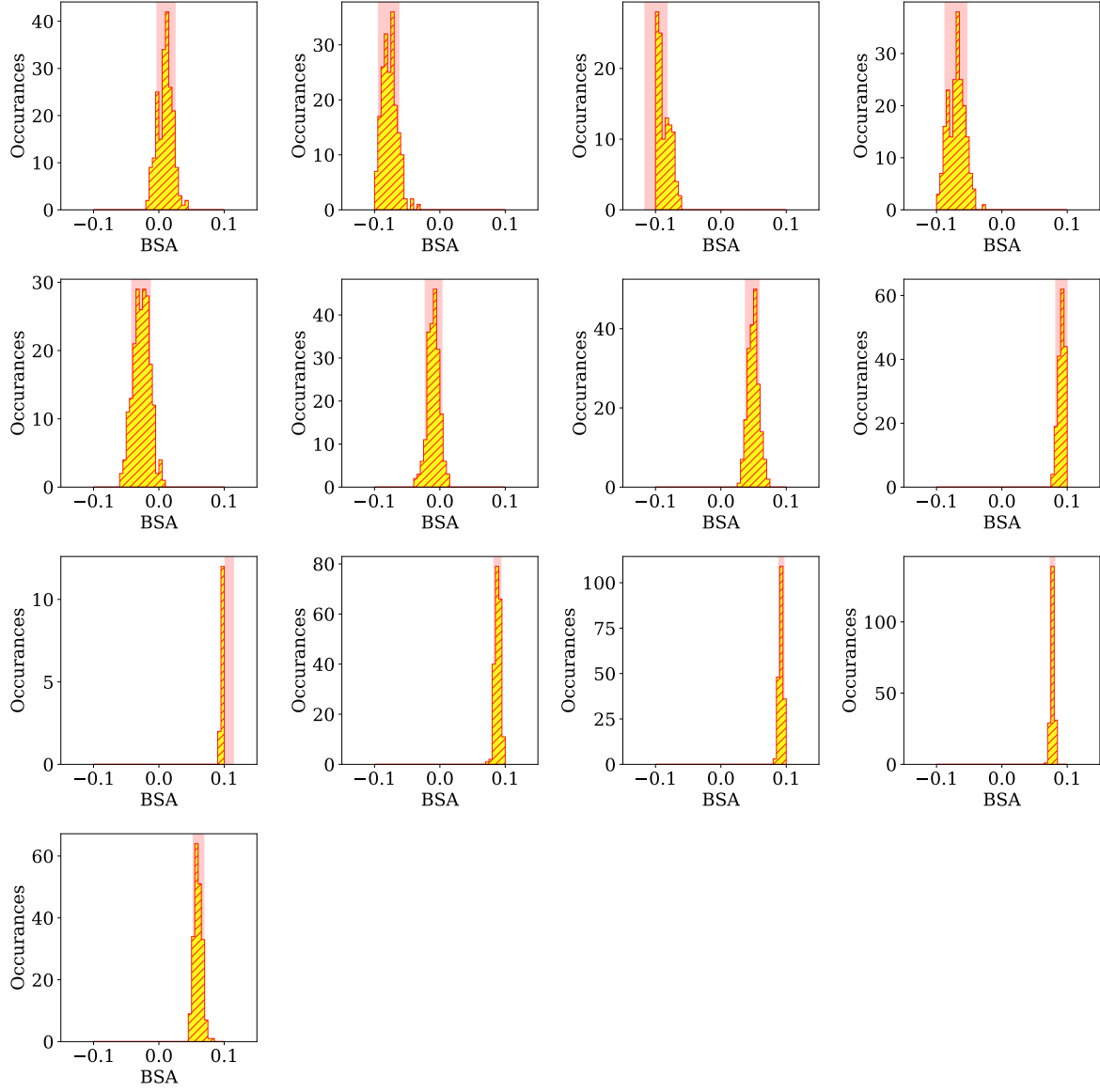


Figure 13: PPPP

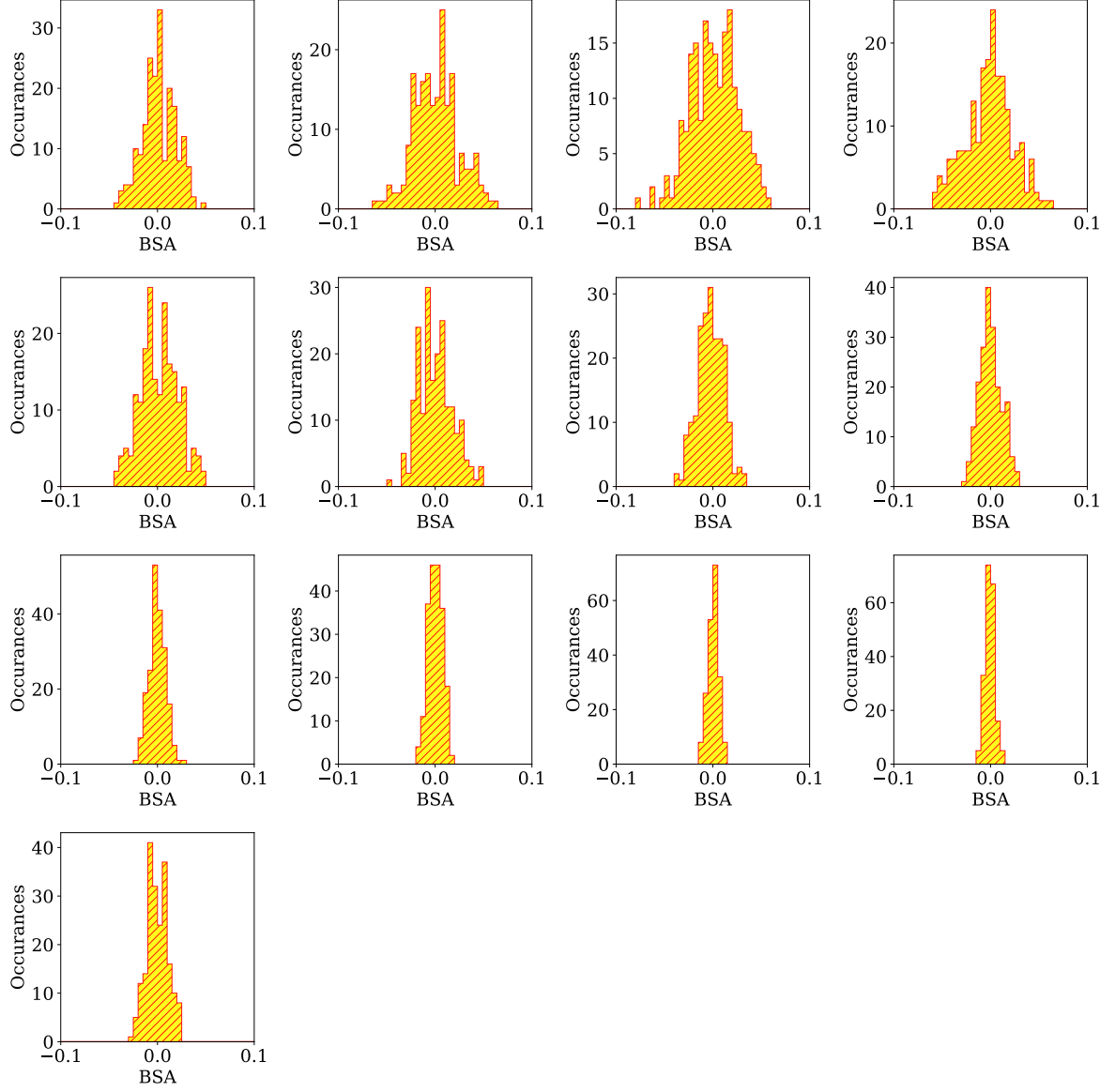


Figure 14: XGDFG

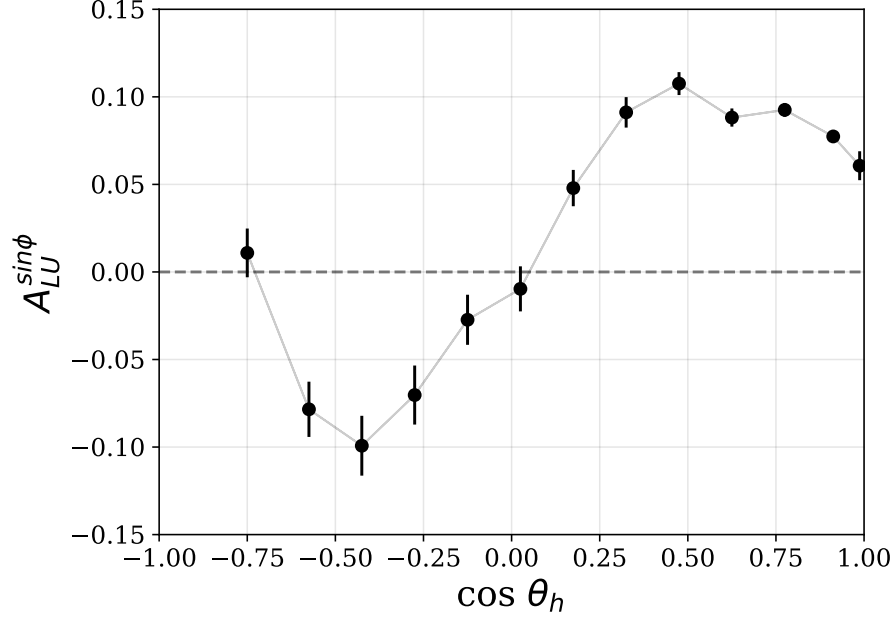


Figure 15: BSA shown with systematic errors in blue.

## 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

adf asdf

### 5.2 Comparison to Other Measurements

Here we are comparing to E1-6.



## References

- [1] Nathan Harrison. “Semi-Inclusive Pion Electronproduction on the Proton”. In: ().
- [2] Marco Mirazita. “Momentum Corrections for E1-F”. In: ().