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Parity Violation in Electron Scattering in the E158 experiment at SLAC

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Abstract: This paper explores strategies for correcting measurements for systematic variations and presents the measurements of the parity violation in electron scattering processed by Jupyter Notebook. The analysis used data from the E158 experiment at SLAC and explored strategies for correcting measurements of systematic variations. It also find the measured correlations that translate between a raw asymmetry and corrected asymmetry using Pearson's correlation method and Multivariate Regression. Factors from weak neutral current interactions, mediated by the Z-boson, that possibly affect the result of the examination of the electroweak theory and the exploration for new dynamics at high-energy scales, are anticipated. The confidence intervals for measured quantities are determined as well.

Keywords: parity violation, electron scattering, E158 experiment.

1. Introduction

Electron scattering is a powerful tool for probing the structure of atomic nuclei. Elastic electron scattering can be divided into parity-conserved electron scattering and parity-violated electron scattering. The electron scattering where parity is conserved only considers the electromagnetic interaction between electrons and nuclei, while the electron scattering where the conservation of parity is violated considers the effects of weak interactions. The E158 experiment at SLAC National Accelerator Laboratory made the first observation of a parity non-conserving asymmetry in Moller (electron-electron) scattering. The experiment was fixed target: longitudinally polarized electrons are scattered off atomic (unpolarized) electrons in a 1.5m liquid hydrogen target with average Q^2 of 0.027 GeV^2. The electron beam in the E158 experiment was generated by photoemission from the Polarized Electron Source. This photoemission process adopted a strained GaAs photocathode and a circularly polarized laser beam. The electron polarization is approximately 90% [1]. The electron beam is accelerated to the desired velocity in the two-mile long Linac and then transported in the A-line that has a 24.5° bend angle to a liquid hydrogen (LH2) target in End Station A (ESA). The DRIP (Damping Ring Intersection Point) region of the Linac has installed pulsed magnets which allow the E158 experiment to be run interleavingly with the BaBar experiment on the PEP-II storage ring [2]. In order to measure the experimental asymmetry, fractional differences are averaged over the cross-sections of complementary beam pulse pairs with opposite helicity [3]. Figure 1 shows the structure of the Target, Spectrometer and Detector in the ESA.

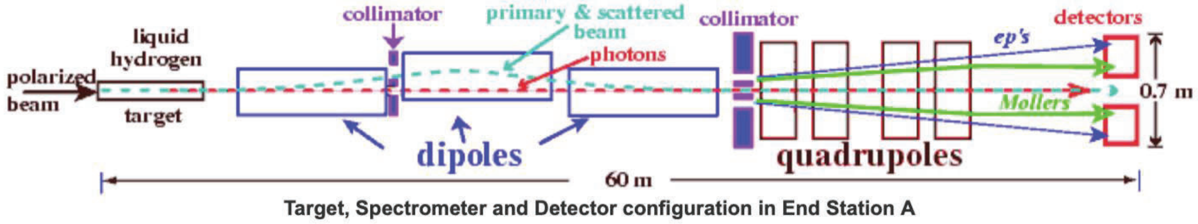

Figure 1. Target, Spectrometer and Detector configuration in End Station A.

2. Theory

Precise measurements of weak neutral current (WNC) interactions mediated by Z bosons have dramatically influenced the testing results of electroweak theory and the search for new dynamics at high energy scales. The E158 experiment, one of the projects in the WNC experiment, involves measuring the fractional difference in the cross-section of longitudinally polarized electrons scattered from a non-polarized nuclear target [4]. A non-zero asymmetry or parity-violating asymmetry (A_{PV}) signifies a parity violation in electron scattering and emerges from the interference between WNC and electromagnetic amplitudes [5].

3. Method

3.1. Variables

The data used was collected over 3 run periods from 2002 to 2003. In this article, the calculation is only applied on a snapshot of 10000 "events" from the E158 experiment. Almost 400 million events are collected over approximately 4 months. Because of the time constrain and instrumentation limit, only 10000 events are taken from the overall events. Each event has two pulses, one pulse for the left-handed electron and one pulse for right-handed electron. The convention is made that the traveling direction of beam is along Z, and there are 4 variables that are recorded for each event:

- Counter: A unique number labeling the event
- Asym: The "raw" cross section asymmetry from one of the 50 detector channels. This equation defines the cross asymmetry [6]:

$$A_{raw} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \tag{1}$$

- ΔX: The beam position at the target in the x-direction in microns.
- ΔY: The beam position at the target in the y-direction in microns.

3.2. Calculation

3.2.1. Distribution of the Unprocessed Data. Figure 2, 3, and 4 demonstrate the original distribution of ΔX, ΔY, and unprocessed A, all peaking around zero. The mean of the raw asymmetry (A_{PV}) distribution is 0.44301 PPB, and its statistical uncertainty is 8.48896. It is difficult to confirm the parity-violating asymmetry from the raw A_{PV} data since the mean of A_{PV} is extremely close to 0. Only when A_{PV} is distinctly greater than 0, the raw cross section asymmetry can indicate a parity violation in electron scattering.

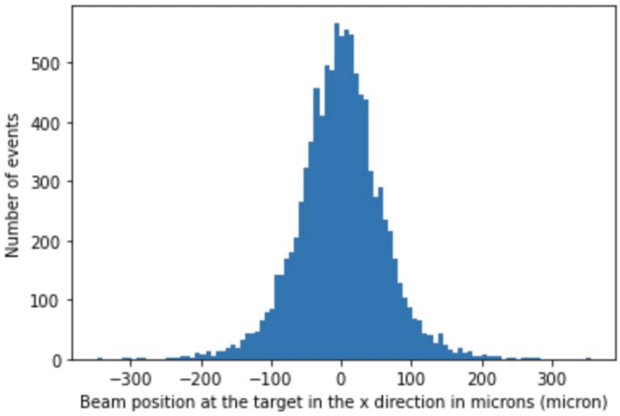

Figure 2. ΔX distribution.

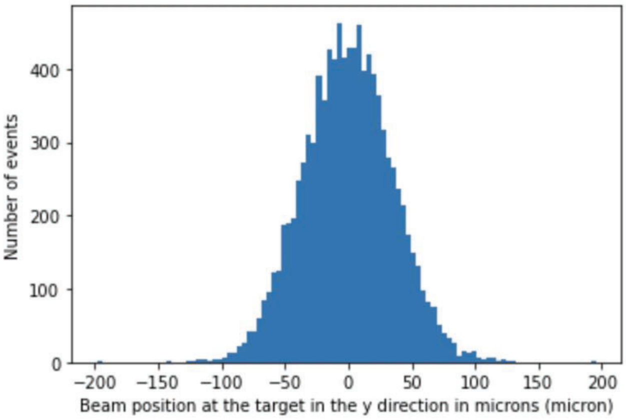

Figure 3. ΔY distribution.

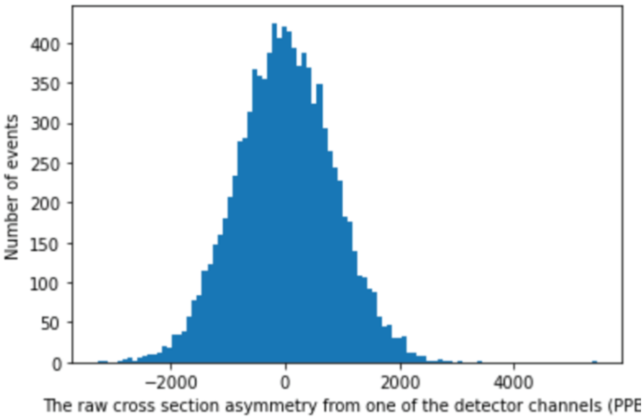

Figure 4. A_{raw} distribution.

3.2.2. Correlation Coefficients. Using Pearsons correlation method [7], the correlation of Dx and A, Dy and A, and Dx and Dy can be computed with the equation

$$cov(X,Y) = \frac{\sum_{i=1}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}(X_i - \bar{X})^2 \sum_{i=1}(Y_i - \bar{Y})^2}} \tag{2}$$

These correlations correspond to figure 5, 6, and 7 respectively. The correlation of Dx and A is 0.056393. The correlation of Dy and A is 0.64754. The correlation of Dx and Dy is 0.40213.

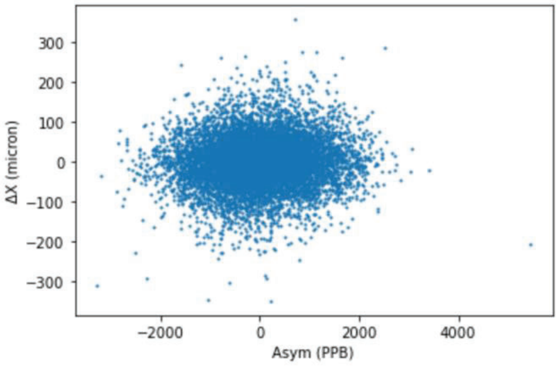

Figure 5. ΔX and Asym scatter plot.

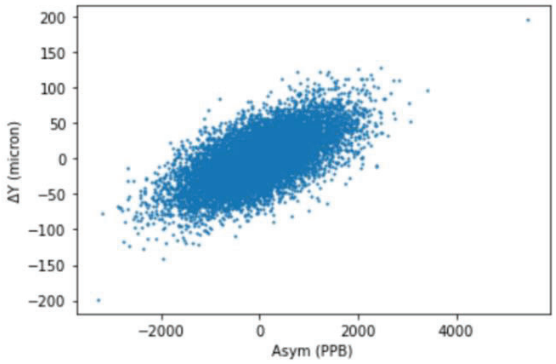

Figure 6. ΔY and Asym scatter plot.

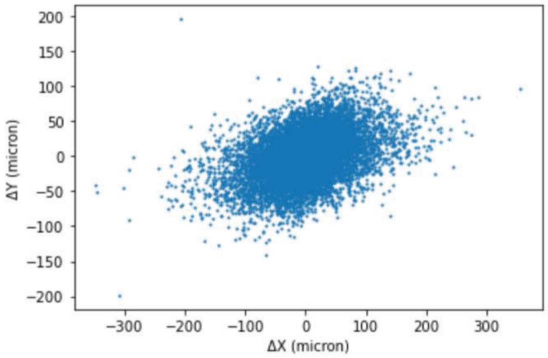

Figure 7. ΔX and ΔY scatter plot.

Based on the graphs, it is reasonable to assume that A is more correlated with the value of Dy than Dx.

3.2.3. Linear Regression. The parity-violating asymmetry can be more effectively estimated with the quantity of corrections for possible differences in right- and left-handed electron pulses. With the condition that A_{pv} is independent of ΔX and ΔY, the coefficients are defined as a_i and b_i. The parity-violating asymmetry is defined as

$$A_{PV} = A_{raw} - (a_x \Delta X + b_x) - \left(a_y \Delta Y + b_y\right) \tag{3}$$

with coefficients a_i and b_i defined in such a way that A_{PV} is independent of ΔX and ΔY. The lines $A_{raw} = a_y \Delta Y + b_y$ and $A_{raw} = a_x \Delta Y + b_x$ are the lines of best fit to the data for the two spatial parameters [8]. After the ΔY dependence is removed, the mean of the regressed asymmetry distribution A_{PV} is 5.12334 PPB, and its statistical uncertainty is 6.46882. Then, removing the ΔX dependence by repeating the same regression technique, the mean and uncertainty of A_{PV} are respectively 4.59763 PPB and 6.23271. The corresponding scatter plot is figure 8. It shows the relation between ΔX and A_{PV} before removing the correlation of ΔX and ΔY but after removing the correlation of ΔX and A_{PV} and the correlation of ΔY and A_{PV}.

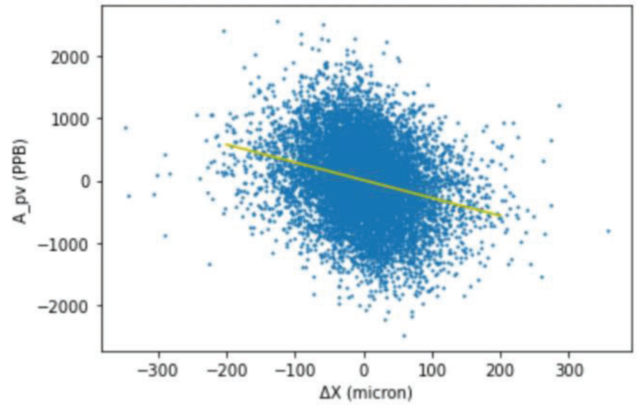

Figure 8. Scatter Plot of ΔX and A_{PV} before removing the correlation of ΔX and ΔY but after removing the correlation of ΔX and A_{PV} and the correlation of ΔY and A_{PV}.

3.2.4. Multivariate Regression. It is also necessary to consider the possibility that Δx and Δy is not independent. Then, AP V becomes

$$A_{PV} = A_{raw} - (a_x \Delta X + b_x) - \left(a_y \Delta Y + b_y\right) - \left(a_{xy} \Delta X \Delta Y + b_{xy}\right) \tag{4}$$

Apply the regression technique to $\Delta X \Delta Y$, the work removes the correlation between ΔX and ΔY [9]. Now, the final new mean of A_{PV} is 7.95549 PPB with an uncertainty of 6.23196. The uncertainties of the final A_{PV} and the A_{PV} with only ΔX and ΔY correlation removed are nearly the same. However, the resolution is highly improved undergoing regression processing. It is clear to observe that the distribution of A_{PV} is Gaussian, and the goodness-of-fit (or p) value for the Gaussian distribution is 1.069821. Figure 9 gives the scatter plot of ΔY and A_{PV} after removing the correlation of ΔX, ΔY, and $\Delta X \Delta Y$.

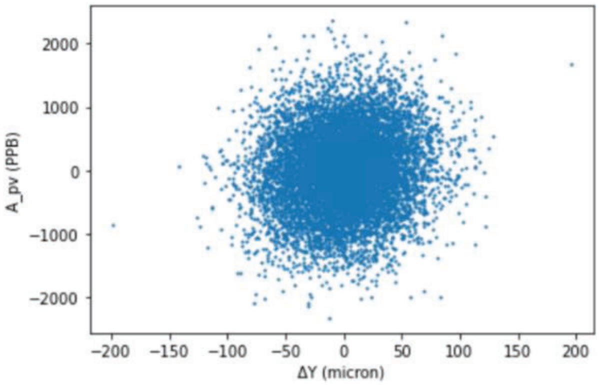

Figure 9. Scatter Plot of ΔY and A_{PV} after removing the correlation of ΔX, ΔY, and $\Delta X\Delta Y$.

3.2.5. Time Dependence. One worry when experiments are making sensitive measurements is that the detector response might change with time. This step is to check if there is any time dependence in the measured cross section or asymmetry. Since the order in which the events are recorded above is the order in which they were collected, the data can be split to five different groups with same number of events but different time. In figure 10, the histograms, representing five time intervals, overlap each other. For event number $0-1999$, $2000-3999$, $4000-5999$, $6000-7999$, and $8000-9999$, the means are 11.83838 with statistical uncertainty 13.93102, 29.19639 with uncertainty 13.71236, 5.074712 with uncertainty 13.92791, -15.71346 with uncertainty 13.61636, and 5.26219 with uncertainty 14.11794 respectively. Therefore, the detector response does seem to have a shift with time. The data seems to follow a sinusoidal pattern, but it was known that the data should come from a period where there is no reversal. Thereby, there are some systematic errors that cannot be determined by the given data set.

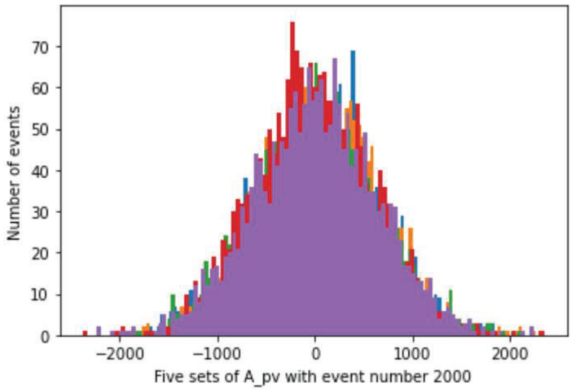

Figure 10. Histogram of five sets of A_{PV}, each has event number of 2000.

4. Result

The 158 experiment essentially measures the parity violation in electron-electron scattering. The result is used to resolve the weak charge of electrons and the weak mixing angle parameter. The A_{PV} histogram is shown in figure 11. From the 10000 number of data, the parity violation asymmetry is

$$A_{PV} = 7.95549 \pm 6.23196(stat)\ ppb$$

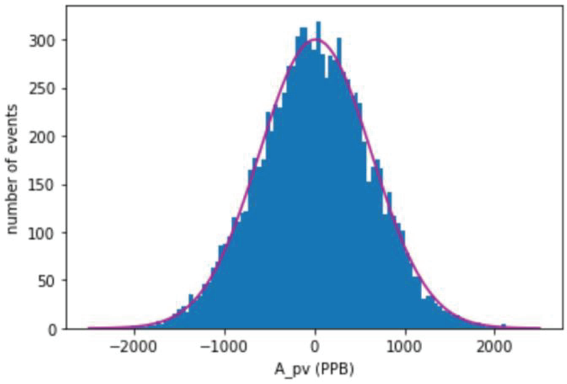

Figure 11. A_{PV} histogram.

5. Conclusion

This result is not very convincing to demonstrate the parity violation in electron scattering. In the SLAC E158 experiment, the result with the full data set collected in three production runs is

$$A_{PV} = -131 \pm 14(stat) \pm 10(syst)$$

parts per billion [10]. This is much greater than the value calculated from only 10000 data sets. Thus, it is crucial to increase the number of events to determine the parity violation. In addition, the experiment instrument has systematic error that cannot be estimated because of the missing of necessary information.

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