1 Summaries of Experimental Activities

1.1 E02-013: Measurement of the Neutron Electric Form Factor G_E^n at High Q^2

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1.1.1 Introduction

Nucleon form factors contain crucial information on the structure of nucleons, providing insight into the underlying processes of QCD. They are a useful testing ground for fundamental hadron models and are currently a crucial source of information in the development of the parameterization of generalized parton distributions [1, 2].

Traditionally, the electric form factor of the neutron, G_E^n, has been the most difficult to measure of the four nucleon form factors. This is due to the relative smallness of G_E^n as the neutron is an overall neutral particle, and the fact that neutrons to be studied in medium energy electron scattering experiments must be bound in a nucleus, typically deuterium or ^{3}He. Prior to E02-013, precision data on G_E^n was limited to momentum transfers of Q^2 less than 1.5 GeV^2. This missing piece has hindered the reliable separation of the Dirac and Pauli form factors for the neutron, F_1^n and F_2^n, which contain unpolarized and polarized transverse structure of the neutron in the infinite momentum frame [3, 4], and of the u and d valence quark form factors.

The E02-013 experiment is a determination of G_E^n through the measurement of the helicity dependent cross section asymmetry from the reaction $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)pp$, i.e. quasi-elastic scattering from a transversely polarized ^{3}He target. The measurements were performed at four Q^2 points, 1.2, 1.7, 2.5, and 3.5 GeV^2.

This year the G_E^n collaboration continued the analysis of this experiment and released preliminary results for the three highest Q^2 points, presented at several conferences by a number of collaborators. Primary efforts in the analysis included the reliable extraction of quasi-elastic events, studying and improving the method of differentiating recoiling protons and neutrons, and the development of Monte Carlo simulations.

1.1.2 Experiment Overview

Experiment E02-013 measured the electric form factor of the neutron by studying spin asymmetries in quasi-elastic scattering in the reaction $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)pp$ at four values of Q^2 up to 3.5 GeV^2. The scattered electron was detected in coincidence using an open-geometry electron spectrometer, BigBite, (with a solid-angle acceptance of roughly 76 msr). The recoiling nucleon was detected in a large neutron detector which, with an active detection area of around 8 m^2 at a distance $9-12$ m, provides adequate acceptance for quasi-elastic neutrons. A diagram of the physics concept is shown in Fig. 1.

The asymmetry A_{phys} relates to G_E^n through the equation

$$\begin{aligned} A_{\mathrm{phys}} &= -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)G_E^n G_M^n \sin\theta^\star \cos\phi^\star}{(G_E^n)^2+(G_M^n)^2(\tau+2\tau(1+\tau)\tan^2(\theta/2))} \\ &\quad -\frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2)(G_M^n)^2\cos\theta^\star}{(G_E^n)^2+(G_M^n)^2(\tau+2\tau(1+\tau)\tan^2(\theta/2))}, \end{aligned}$$

where $\tau = Q^2/4M^2$, and θ^* and ϕ^* are the polar and the azimuthal angles respectively between the polarization direction of the ^{3}He nucleus and the three-momentum transfer, $\vec{q}$. A missing momentum p_{miss}, ($\vec{q}-\vec{p}_N$, where $\vec{p}_N$ is the momentum of the nucleon) is used for selection quasi-elastic process. The $p_{\mathrm{miss},\perp}$, the component of $\vec{q}-\vec{p}_N$ perpendicular to $\vec{q}$, provides suppression of final state interactions (FSI), allowing for the treatment of quasi-free neutron scattering.

Table 1 shows the kinematics for which data are taken and accumulated beam charge.

Q^2 [GeV^2]	E_{beam} [GeV]	Avg. θ_e [deg]	Q_{beam} [C]
1.2	1.519	56.26	1.2
1.7	2.079	51.59	2.2
2.5	2.640	51.59	5.5
3.5	3.291	51.59	11.4

Table 1: Four kinematics of G_E^n measurements in E02-013 and accumulated beam charge.

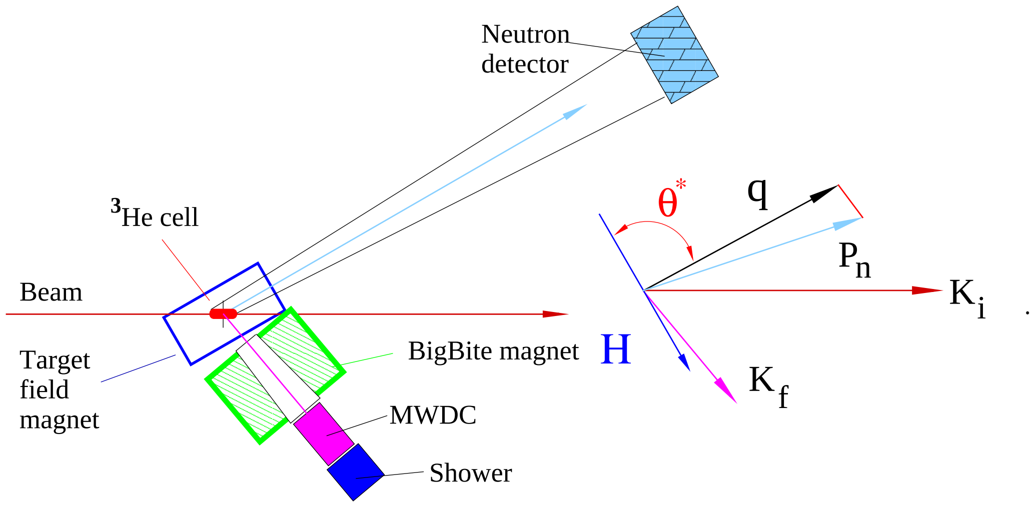

Figure 1: Conceptual layout of the E02-013 experiment. Here H shows the target holding magnetic field; K_i and K_f are the initial and a final electron momenta; $\vec{q} = \vec{K}_i - \vec{K}_f$ is the momentum transfer; P_n is the neutron momentum, θ^* is the angle between directions of the magnetic field and the momentum transfer.

1.1.3 Progress of Analysis

Analysis of the G_E^n data continues from last year and we have released preliminary results for our three highest Q^2 points. Detector calibrations substantive to the analysis have been completed for these points. Most efforts in the analysis have gone to the extraction of quasi-elastic events from the data, understanding the identification of recoiling protons and neutrons, and in the development of Monte Carlo simulations.

Quasi-elastic Selection The selection of quasi-elastic events is performed by placing cuts on (pseudo-)invariant mass, components of missing momentum, and the missing mass of the reaction $e^3\text{He} \rightarrow e'nX$. This allows us to suppress final state interactions, inelastic processes such as pion electroproduction, and treat electron the interaction as with an effectively free neutron. Due to finite detector resolution there is some choice in where these cuts are placed, trading quantity of statistics for the purity of quasi-elastic sample. In practice, simulations can provide quantification background to provide corrections, but due to the present early development of these simulations, our analysis takes a conservative approach biasing towards results requiring minimal corrections. This becomes particularly important at the highest Q^2 points where pion electroproduction plays a more significant role.

In Fig. 2 and 3 the quasi-elastic peaks can be clearly seen for two of our Q^2 points, with the selected cuts shown in red. In particular, the degraded momentum resolution at the higher Q^2 point is apparent, due to the higher nucleon momentum measured through time of flight. This degraded resolution complicates the separation of inelastic events. We have made compensations for this by placing the upper limit of the invariant mass cut at a lower value. This change in the invariant mass cut combined with the missing mass cut reduces our statistics by a factor of two without further support from simulations.

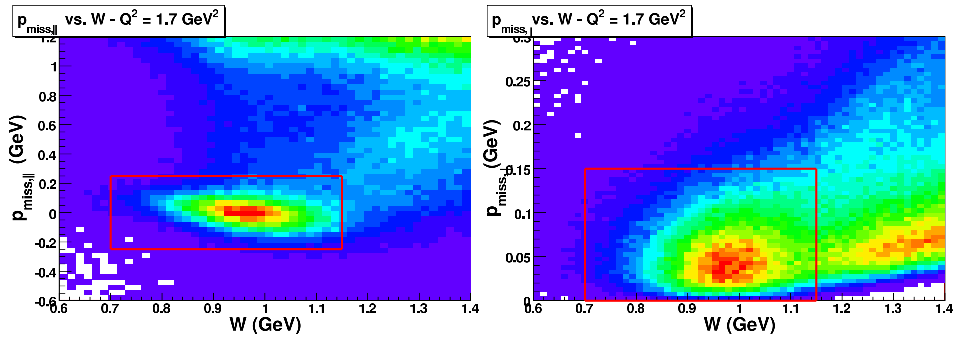

Figure 2: $p_{\mathrm{miss},\|}$ and $p_{\mathrm{miss},\perp}$ vs. invariant mass for $Q^2 = 1.7$ GeV^2. The quasi-elastic cut selection is outlined in red.

Nucleon Charge Identification For a given quasi-elastic scattering event, the detected nucleon in the neutron arm is assigned a charge based on signals in two front-most scintillator planes, known as the veto planes. Several effects may cause charge misidentification which need to be accounted for to properly calculate the neutral sample asymmetry. The dominant effects are natural detector inefficiencies in the veto planes, the interaction of the nucleon while in flight with materials such as the target cell wall and neutron arm shielding, accidental background producing a false signal in the veto planes, and charge exchange through final state interactions.

For all but the last effect, we have developed a technique that allows us to determine the relevant overall conversion probabilities directly from the data, providing knowledge of the purity of our sample. To perform this analysis, we utilize

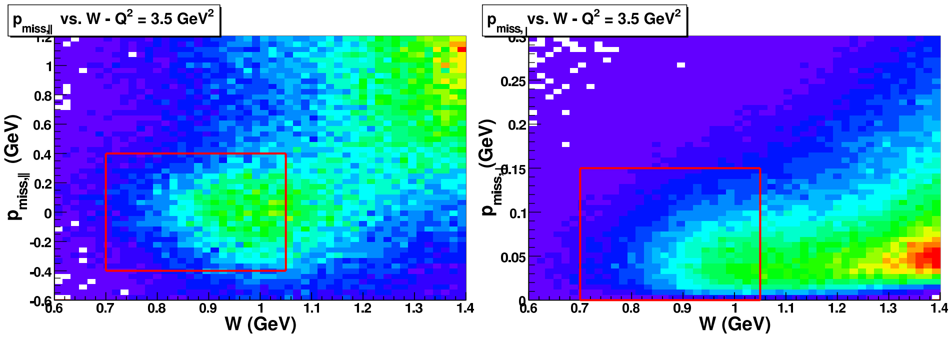

Figure 3: $p_{\text{miss},\parallel}$ and $p_{\text{miss},\perp}$ vs. invariant mass for $Q^2 = 3.5$ GeV^2. The quasi-elastic cut selection is outlined in red. The upper limit on the invariant mass cut has been reduced to help suppress inelastic background contributions.

three targets with different nuclear ratios of protons and neutrons, H_2, ^{3}He, and N_2, and examine the response of the neutron arm. By looking at the ratio of the number of identified uncharged to charged nucleons for each of the three targets, it is then possible to sufficiently constrain these conversion rates using the uncharged to charged ratios without misidentification.

Due to the differences in the initial momentum distributions of protons and neutron in ^{3}He, placing cuts on missing momentum will produce changes in the relative rates between protons and neutrons. To calculate this, we developed a simulation utilizing realistic nucleon momentum distributions bound in ^{3}He and simulate the final measured momentum distributions for quasi-elastic scattering. By placing cuts on these final momenta, the effective ratio of protons to neutrons can be determined. This analysis was determined to be unnecessary for N_2 due to isospin symmetry considerations and is irrelevant for H_2. For our analysis, the ratio of protons to neutrons for our cuts is generally near 2.15, higher than the naive expectation of 2, Fig. 4.

Monte Carlo Developments Presently work is underway to develop a Monte Carlo simulation of the experiment. From these simulations we are particularly interested in pion electroproduction process rates and asymmetries and the neutron arm response to protons and neutrons with varying momenta. From this it is our plan to increase our quasi-elastic statistics, possibly by a factor of 2, by widening our cuts and correcting using calculations of inelastic background contributions. We also hope to reduce the systematic uncertainty present in our charge

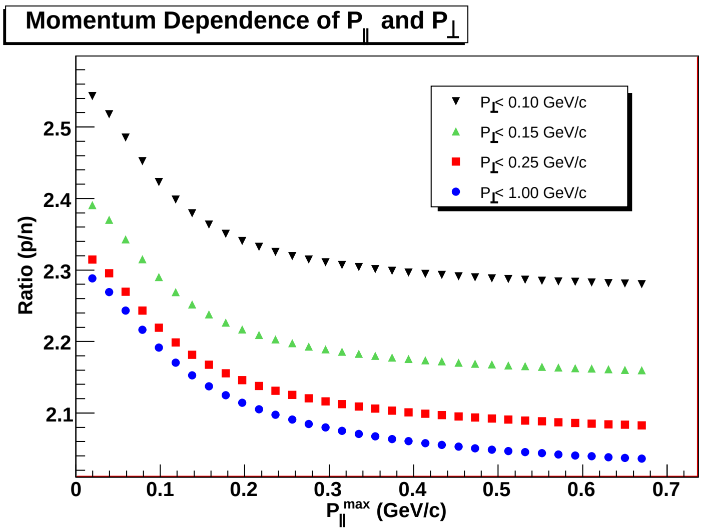

Figure 4: Effective proton to neutron ratios for a ^{3}He target with varying cuts on $p_{\mathrm{miss},\|}$ and $p_{\mathrm{miss},\perp}$.

identification analysis by augmenting it with results from the simulated response.

At this point we have developed a simulation which can reproduce the cross sections and asymmetries for elastic H_2 and quasi-elastic ^{3}He scattering, as well as for pion electroproduction from these targets using data from the MAID project. This simulation has provided somewhat accurate results up to invariant masses of about 1.4 GeV. Currently missing is an accurate representation of the neutron arm response, however, agreement between the data and simulation in the invariant mass spectrum and asymmetry vs. invariant mass is quite good, Fig. 5 and Fig. 6. From this we have evaluated that the inelastic contributions to the asymmetry for our present cuts are less that 1% for our highest three points.

Preliminary Results We have release preliminary results for our three highest Q^2 points ranging from $Q^2 = 1.7$ to 3.5 GeV^2, Fig. 7. These have been present at several conferences, most recently at SPIN 2008 in Charlottesville, the 2008 fall APS/DNP meeting in Oakland, and PANIC08 in Tel Aviv. For these results we have omitted the model dependent FSI corrections, which based on preliminary calculations [5, 6], increase the G_E^n results by about 5%. The lowest Q^2 point is in agreement with the highest Q^2 point from the Madey results [7]. Our higher Q^2

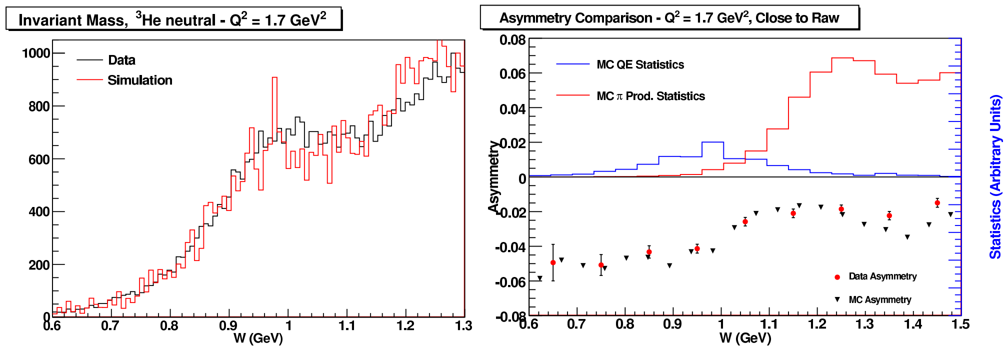

Figure 5: Agreement between data and simulation for the invariant mass spectrum and asymmetry vs. invariant mass with broad cuts for ^{3}He data at $Q^2 = 1.7$ GeV^2.

points are in disagreement with favored models, such as Miller's light front cloudy bag model [8]. Our curve is in better agreement with the Galster parameterization performed in 1971 with some of the earliest G_E^n data. Also interesting is to look at the expected perturbative QCD (pQCD) scaling behavior determined by Belitsky et al. [9], which in the case of the proton, appears to set in surprisingly early at about 2 GeV^2. Scaling a curve of the same form to our lowest Q^2 point, we do not see such behavior implying that we are not yet in the pQCD regime for this range of momentum transfer.

References

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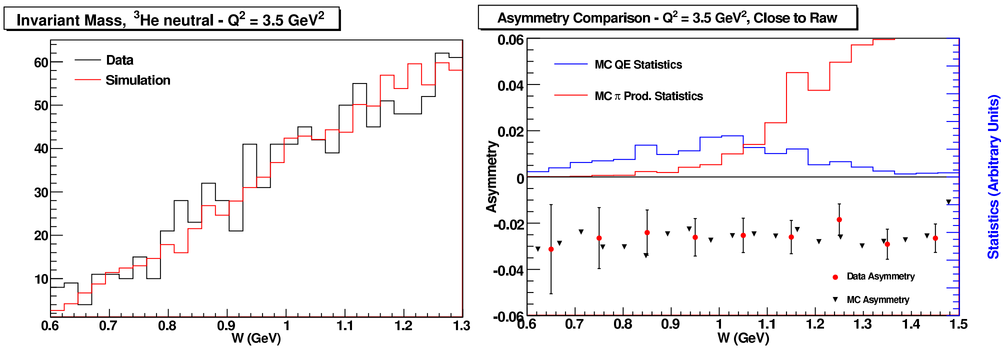

Figure 6: Agreement between data and simulation for the invariant mass spectrum and asymmetry vs. invariant mass with broad cuts for ^{3}He data at $Q^2 = 3.5$ GeV^2.

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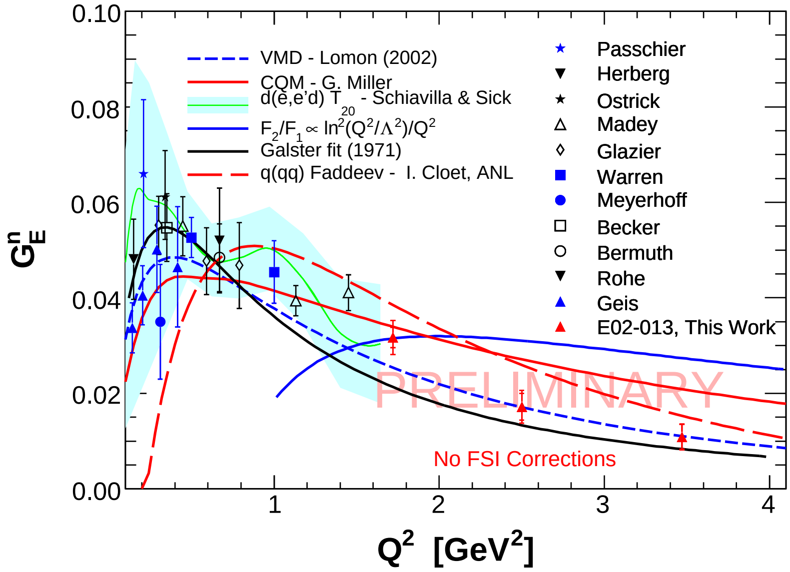

Figure 7: Preliminary results for the three highest Q^2 points for E02-013.