MEASUREMENT OF THE PROTON ELECTROMAGNETIC FORM FACTOR RATIO AT BLAST

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The proton's electromagnetic form factors are fundamental quantities related to its underlying electromagnetic structure. Recent measurements of the form factor ratio from recoil proton polarization experiments at JLab indicate a striking departure from previous measurements above $Q^2 \approx 1$ GeV^2. The unique capabilities of the BLAST detector with a polarized internal hydrogen gas target in a polarized electron storage ring will allow us to make precision measurements of the proton form factor ratio in the Q^2 region from 0.1 to 1 GeV^2 which overlaps with the lower Q^2 coverage of the JLab results. Such a measurement is essential since it employs a different experimental technique, with different experimental uncertainties, from the JLab experiments. Projections for the proposed BLAST measurements are presented.

1. Introduction

Form factors are fundamental quantities that describe the underlying structure of a composite particle. The proton's electromagnetic form factors, $G_E^p(Q^2)$ and $G_M^p(Q^2)$, describe the distribution of the proton's electric charge and magnetization, respectively. The form factor ratio G_E^p/G_M^p is equally important and describes the relative distribution of charge and magnetization. Surprisingly, though the proton form factors have been very well studied over the past half-century or so, they are still poorly understood. There has been much excitement recently over results of high precision from recoil proton polarization measurements at JLab by Jones

et al.[1] and Gayou *et al.*[2] These data show a dramatic departure from the Rosenbluth separation data at high Q^2. Figure 1 shows the current state of the world data on the form factor ratio. There is clearly a discrepancy between the JLab data and the earlier world data from Rosenbluth separation methods. This discrepancy has been well noted and analyzed by Arrington[3], and it is clear that further measurements of the proton form factor ratio are needed.

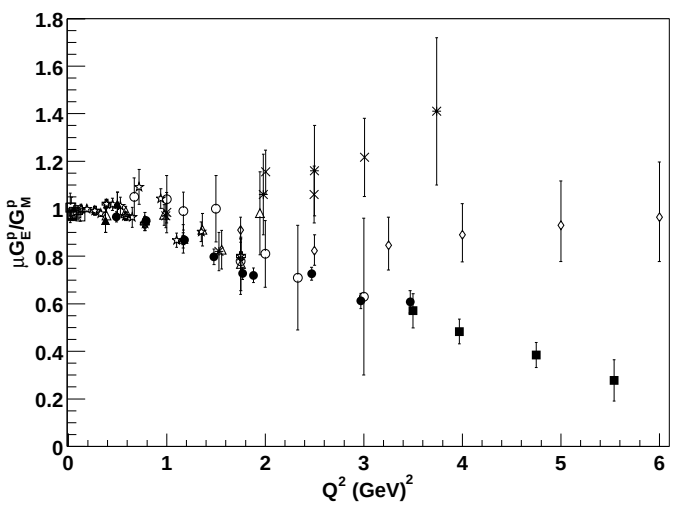

Figure 1. World data for the proton form factor ratio. The solid squares and circles are the Jones *et al.* and the Gayou *et al.* data, respectively.

2. BLAST

The BLAST detector, currently being commissioned at the MIT-Bates Laboratory in Middleton, Massachusetts, will be in a unique position to make high precision measurements of the proton form factor ratio up to $Q^2 \approx 1$ GeV^2. Such an experiment has already been proposed and approved as part of the BLAST program[5]. The technical details of this experiment are beyond the scope of these proceedings, but can be found in the proposal. The discussion below focuses on the proposed method for extracting the form factor ratio from asymmetry measurements and the resulting uncertainty in the form factor ratio. The method takes advantage of the BLAST

geometry by using the ratio of spin-asymmetries to extract the form factor ratio. This super-ratio is insensitive to the beam and target polarizations which are a major source of error in asymmetry measurements. This technique has also been proposed as a way to make a precise measurement of the proton root-mean-square charge radius[4].

BLAST is a large acceptance spectrometer composed of two detector packages operating in a toroidal magnetic field. The detector packages are situated symmetrically about the beam line such that each package is the mirror image of the other. This geometry is well-suited for measuring asymmetries formed between either the two different helicity states of the electrons in the polarized beam or the two anti-aligned states of the proton spins in the target. We turn now to a discussion of these asymmetries and the extraction of the proton form factor ratio. The discussion below follows the formalism of Donnelly and Raskin[6].

The spin-dependent cross section for a longitudinally polarized electron scattering off a polarized proton target can be written as a sum of two pieces:

$$\left(\frac{d\sigma}{d\Omega}\right)_{pol} = \Sigma + h\Delta, \tag{1}$$

where Σ is the unpolarized electron-proton elastic scattering cross section, and Δ is the spin-dependent piece. The spin-dependent asymmetry[6] is just the relative difference between the scattering cross sections for the two helicity states of the beam (for a constant target configuration), or the two spin states of the target (for a constant helicity). This is expressed in the following way:

$$A = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}, \tag{2}$$

where the arrow represents the state of the beam or target, and σ is shorthand for $(d\sigma/d\Omega)_{pol}$. Using Eq. (1) we can write the asymmetry as

$$A = \frac{\Delta}{\Sigma}. \tag{3}$$

The asymmetry can also be expressed in terms of the proton form factors:

$$A = -\frac{2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}, \tag{4}$$

where the angles θ^* and ϕ^* are the coordinates of the target spin vector in the frame where the outgoing proton's 3-momentum, $\vec{q}$, defines the z axis.

The definitions for the other kinematic factors can be found in Donnelly and Raskin[6].

In practice, the beam and target are not 100% polarized, so the physics asymmetry is diluted by the beam and target polarizations. The measured asymmetry is then

$$A^{meas} = P_t P_b A. \tag{5}$$

The symmetry of the BLAST detector allows us to measure an independent asymmetry in each half of the detector simultaneously since the asymmetry depends only on θ^*, ϕ^*, θ, and Q^2; and because θ^* and ϕ^* are different for electrons that scatter to the right from θ^* and ϕ^* for electrons that scatter to the left. This is an extremely important feature of the experiment since the ratio of the two *measured* asymmetries will be equal to the ratio of the two *physics* asymmetries,

$$\frac{A^1_{meas}}{A^2_{meas}} = \frac{A^1}{A^2} = R_A, \tag{6}$$

where A^1 is the asymmetry formed in one half of the detector, and A^2 is the asymmetry formed in the other half. Then from Eq. (4) the super ratio is

$$R_A = \frac{2\tau v_{T'} \cos\theta_1^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta_1^* \cos\phi_1^* G_M^p G_E^p}{2\tau v_{T'} \cos\theta_2^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta_2^* \cos\phi_2^* G_M^p G_E^p}. \tag{7}$$

Then by factoring out ${G_M^p}^2$ and rearranging, we can solve for the form factor ratio,

$$R = k \frac{\cos\theta_1^* - R_A \cos\theta_2^*}{R_A \sin\theta_2^* \cos\phi_2^* - \sin\theta_1^* \cos\phi_1^*}, \tag{8}$$

where the constant k contains the kinematic factors,

$$k = \frac{\tau v_{T'}}{\sqrt{2\tau(1+\tau)} v_{TL'}}. \tag{9}$$

3. Uncertainties

The projected uncertainties for the experiment at BLAST were calculated using an analytic code that calculated the errors from Eq. (8). The code is not a monte-carlo simulation. Rather, it computes the uncertainties in R due to the measured quantities R_A, θ_1^*, and θ_2^* from the relevant derivatives of Eq. (8) and the experimental uncertainties ΔR_A, k, $\Delta\theta_1^*$ and $\Delta\theta_2^*$. The error in R_A is found from the statistical error in the two asymmetries. This

is estimated using the scattering cross section (where we used the Höhler parameterization to estimate the form factors) and the proposed luminosity and beam time. We refer to this part of the uncertainty as the 'statistical' error. The errors on k, θ_1^* and θ_2^* depend on the scattered electron momentum, the electron scattering angle, the target spin direction, and the associated resolutions of these quantities. We refer to these as 'systematic' uncertainties. BLAST has a large continuous acceptance and an extended gas target. In order to take these features into account, the statistical error is averaged appropriately over the length of the target and the extent of the acceptance, and then binned accordingly. The systematic error depends on the target spin direction so the overall error was minimized with respect to this parameter. The relative contributions from the statistical and systematic error are shown in Figure 2.

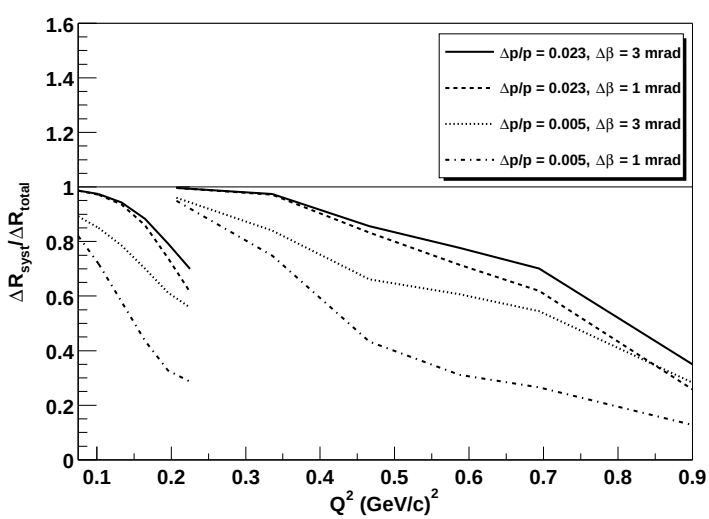

Figure 2. Relative contributions from systematic error for beam energies 440 MeV ($0 < Q^2 < 0.25$ (GeV/c)^2) and 880 MeV ($0.2 < Q^2 < 0.9$ (GeV/c)^2). The systematic error is most sensitive to the momentum resolution ($\Delta p/p$) and the uncertainty in the target spin direction ($\Delta\beta$). This plot shows the relative contribution of the systematic error to the total error for different values of these quantities. A study is currently underway to determine the values of $\Delta p/p$ and $\Delta\beta$ so that we may make more accurate projections for the total uncertainty in the form factor ratio.

The systematic error dominates the total error (for a given beam energy)

at low Q^2 and the statistical error dominates at high Q^2. The increase in the statistical error is simply due to the drop off of the scattering cross section at high Q^2. The systematic error is dominated by the momentum resolution and the uncertainty in the target spin angle. Figure 2 shows the contributions to the total error for the extreme values expected for $\Delta p/p$ and $\Delta\beta$. The total error clearly depends very strongly on the values of these resolutions and a detailed monte-carlo study is currently underway to determine the expected values for these quantities so that we can make more accurate projections of the total error.

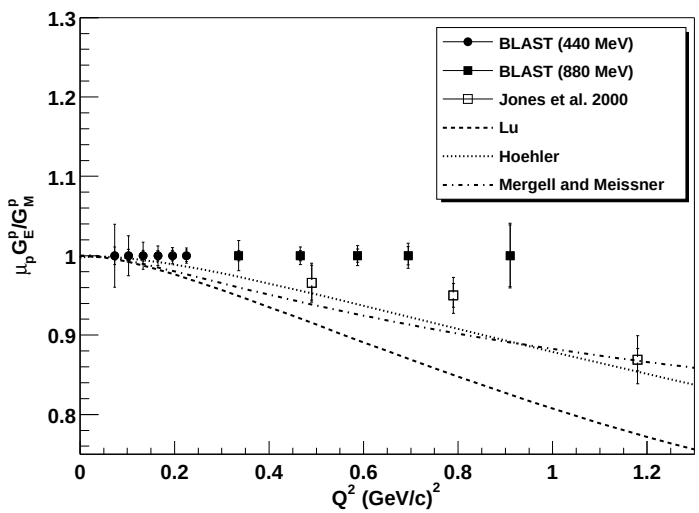

Figure 3. This plot shows the projected errors for the BLAST measurement of the proton form factor ratio along with some theoretical models and the Jones *et al.* data. Note that there are two error bars shown for all data sets. The small error bar in the Jones *et al.* data is the statistical error and the large error bar is the statistical and systematic error added in quadrature. The small error bar in the BLAST data is the total error for the case where $\Delta p/p = 0.005$ and $\Delta\beta = 0.001$ rad; and the large error bar is the total error for $\Delta p/p = 0.023$ and $\Delta\beta = 0.003$ rad. Although the total error is quite sensitive to these systematic uncertainties at low Q^2, it is much less sensitive at high Q^2.

4. Results

The projections for the measurement of the proton form factor ratio at BLAST are shown in Figure 3. We have also plotted three theoretical

models and the Jones *et al.* data for comparison. We have plotted two error bars on the projections. The small error bar is the total error when $\Delta p/p = 0.005$ and $\Delta\beta = 0.001$ rad. The large error bar is the total error when $\Delta p/p = 0.023$ and $\Delta\beta = 0.003$ rad. For both error bars the projected uncertainties are very good in the region where the JLab data begin to differ noticeably from the earlier Rosenbluth separation data. BLAST will provide a high precision map of this extremely interesting region.

5. Conclusions

Despite being one of the most long-studied quantities in nuclear physics, the proton form factor ratio continues to prove challenging. The disparity in the data indicates a lack of real understanding on our part. As techniques and technologies have improved, the measurements have also improved. Now that high precision measurements are being made, we are in a position to improve our understanding of this important quantity. The Q^2 range accessible with BLAST covers the important transition region where the newer JLab data appear to diverge from the older Rosenbluth separation data. BLAST will make an important contribution to our knowledge of the proton form factor ratio by mapping out this region to high precision. Furthermore, since this experiment employs a completely different technique from earlier measurements, and is subject to different systematic errors, these measurements may shed some light on the puzzle discussed by Arrington[3].

Acknowledgments

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