Reanalysis of Proton Form Factor Ratio Data at $Q^2 = 4.0$, 4.8, and 5.6 GeV^2

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Recently published measurements of the proton electromagnetic form factor ratio $R = \mu_p G_{Ep}/G_{Mp}$ at momentum transfers Q^2 up to 8.5 GeV^2 in Jefferson Lab Hall C deviate from the linear trend of previous measurements in Jefferson Lab Hall A, favoring a slower rate of decrease of R with Q^2. While statistically compatible in the region of overlap with Hall A, the Hall C data hint at a systematic difference between the two experiments. This possibility was investigated in a reanalysis of the Hall A data. We find that the original analysis underestimated the background in the selection of elastic events. The application of an additional cut to further suppress the background increases the results for R, improving the consistency between Halls A and C.

The elastic electromagnetic form factors of the nucleon have been revived as a subject of high interest in hadronic physics since a series of precise recoil polarization measurements of the ratio of the proton's electric and magnetic form factors [1, 2] in Jefferson Lab's Hall A established the rapid decrease with momentum transfer Q^2 of $R = \mu_p G_{Ep}/G_{Mp}$, where μ_p is the proton's magnetic moment, for 0.5 GeV$^2 \leq Q^2 \leq$ 5.6 GeV^2. Recent mea-

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surements from Jefferson Lab's Hall C [3] extended the Q^2 reach of this method to 8.5 GeV^2. The published Hall A data are well described by a linear Q^2 dependence [4],

$$R = 1.0587 - 0.14265Q^2, \quad (1)$$

with Q^2 in GeV^2, valid for $Q^2 \geq 0.4$ GeV^2. All three of the recent Hall C data points are at least 1.5 standard deviations above this line, including the measurement at overlapping $Q^2 = 5.17$ GeV^2, which lies 1.8σ above (1). Due to the strong, incompletely understood discrepancy between the Rosenbluth and polarization transfer methods of extracting G_{Ep}/G_{Mp} and the fact that the new Hall C measurements are the first to check the reproducibility of the Hall A data using a completely different apparatus in the Q^2 region where the discrepancy is strongest, it is important to understand any systematic differences between the experiments, if they exist.

The recoil polarization method exploits the relation between the transferred polarization in elastic $\vec{e}p$ scattering and the ratio G_{Ep}/G_{Mp}. The polarization transferred to recoiling protons in the elastic scattering of longitudinally polarized electrons by unpolarized protons has longitudinal (P_ℓ) and transverse (P_t) components in the reaction plane given by [5–7]

$$\begin{aligned} P_t &= -hP_e\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{r}{1+\frac{\epsilon}{\tau}r^2} \\ P_\ell &= hP_e\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2} \\ r \equiv \frac{G_{Ep}}{G_{Mp}} &= -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}} = \frac{R}{\mu_p}, \end{aligned} \quad (2)$$

where $h = \pm 1$ is the electron beam helicity, P_e is the beam polarization, $\tau \equiv Q^2/4M_p^2$, M_p is the proton mass, $\epsilon \equiv \left[1 + 2(1+\tau)\tan^2(\theta_e/2)\right]^{-1}$ corresponds to the longitudinal polarization of the virtual photon in the one-photon-exchange (Born) approximation, and θ_e is the lab electron scattering angle.

Table I shows the central kinematics of the three highest-Q^2 measurements from Hall A [2]. These measurements share several important features with the Hall C measurements [3]. Both used magnetic spectrometers instrumented with Focal Plane Polarimeters(FPPs) to detect protons and measure their polarization, and large solid angle electromagnetic calorimeters to detect electrons in coincidence. The use of calorimeters in both experiments was driven by the requirement of acceptance matching; at large Q^2 and θ_e, the Jacobian of the reaction magnifies the electron solid angle compared to the proton solid angle fixed by the spectrometer acceptance. The drawbacks of this choice compared to electron detection using a magnetic spectrometer are twofold. First, the energy resolution of lead-glass calorimeters is relatively poor, so that elastic and inelastic reactions are not well separated in reconstructed energy. Second, the signals in lead-glass from electrons and photons of similar energies are indistinguishable, leaving one vulnerable to photon backgrounds from the decay of π^0, which played an important role in the analysis of both experiments.

The high-Q^2 Hall C measurements [3] were carried out consecutively with precise measurements of R at $Q^2 = 2.5$ GeV^2 [7] designed to search for effects beyond the Born approximation, thought to explain the disagreement between Rosenbluth and polarization data [8]. Using the same apparatus and analysis procedure as the high-Q^2 measurements, the results of [7] are in excellent agreement with Hall A data [1] at nearly identical Q^2. The background correction to the Hall C measurements of R at $Q^2 = 2.5$ GeV^2 was negligible after the cuts described in [3]. In the Hall A experiment, electrons were detected in a high-resolution, small-acceptance magnetic spectrometer, so that the selection of elastic events was background-free [1]. In the absence of significant background corrections, the agreement between precise data from different halls, requiring the calculation of spin transport through different magnetic systems, suggests that such calculations, which dominate the systematic uncertainties of the recoil polarization method, are well understood in both systems. Therefore, a neglected systematic error due to spin transport in either the Hall A or Hall C data at high Q^2 is all but ruled out.

The liquid hydrogen targets used in Halls A and C had radiation lengths of ~2%, leading to a significant Bremsstrahlung flux across the target length, in addition to the virtual photon flux due to the presence of the electron beam. The kinematics of π^0 photoproduction ($\gamma + p \rightarrow \pi^0 + p$) near end point ($E_\gamma \rightarrow E_e$) are highly similar to elastic ep scattering at high energies ($E_\gamma \gg m_\pi$), such that protons from $\gamma + p \rightarrow \pi^0 + p$ overlap with elastically scattered protons within experimental resolution. In the lab frame, asymmetric π^0 decays with one photon emitted at a forward angle relative to the π^0 momentum, carrying most of the π^0 energy, are detected with a high probability. At high energies and momentum transfers, the π^0 photoproduction cross section is found to scale as s^{-7} for fixed Θ_{CM} [9], where s is the cms energy squared and Θ_{CM} is the cms π^0 production angle. In addition, the cms angular distribution is peaked at forward and backward angles. The goal of the Hall C experiment was to measure to the highest possible Q^2, given the maximum available beam energy of 5.71 GeV. At $Q^2 = 8.5$ GeV^2, the relatively high Q^2/s ratio, with $\Theta_{CM} \in$ 129-143°, led to a π^0p:ep ratio of ~40:1. The severity of the background conditions required maximal exploitation of elastic kinematics to suppress the π^0 background. Even after all cuts described in [3], the remaining background was estimated at ~6% of accepted events. Given the large difference between the signal and background polarizations, this level of contamination required a substantial *positive* correction to R.

In light of the improved understanding of the importance of the π^0 background in the Hall C experiment, an underestimation of its effect in the Hall A analysis seemed likely as a source of disagreement between the two experiments. Therefore, we reanalyzed the Hall A

TABLE I. Central kinematics and average Q^2 of Hall A experiment [2]. $\langle Q^2 \rangle$ is the acceptance averaged Q^2, while ΔQ^2 is the rms Q^2 acceptance. ϵ is the parameter appearing in equations (2), E_e is the beam energy, E'_e is the scattered electron energy, θ_e is the electron angle, p_p is the proton momentum, θ_p is the proton angle, P_e is the beam polarization, and R_{cal} is the distance from the target to the calorimeter surface.

Nominal Q^2 (GeV^2)	$\langle Q^2 \rangle \pm \Delta Q^2$ (GeV^2)	ϵ	E_e (GeV)	E'_e (GeV)	θ_e (°)	p_p (GeV)	θ_p (°)	P_e (%)	R_{cal} (m)
4.0	3.98 ± 0.12	0.71	4.61	2.47	34.5	2.92	28.6	70	17.0
4.8	4.76 ± 0.14	0.59	4.59	2.04	42.1	3.36	23.8	73	12.5
5.6	5.56 ± 0.14	0.45	4.60	1.61	51.4	3.81	19.3	71	9.0

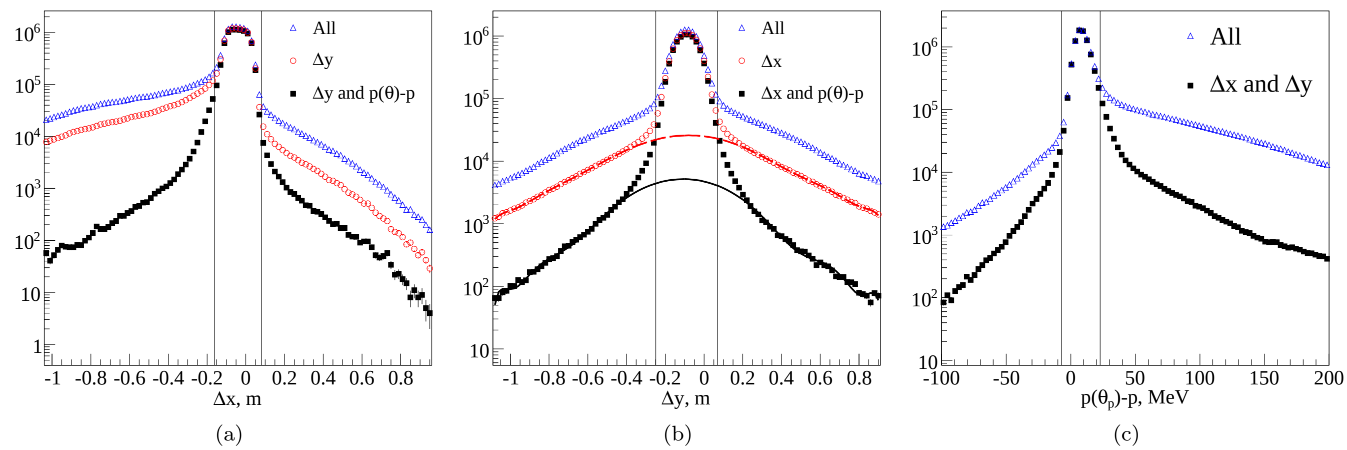

FIG. 1. (color) Elastic event selection at $Q^2 = 4.8$ GeV^2. The effects of cuts are shown for the horizontal calorimeter coordinate difference Δx (a), the vertical difference Δy (b), and the proton "missing momentum" $p_{miss} \equiv p_p(\theta_p) - p_p$ (c). Vertical lines indicate the cut applied. Open triangles show events with no cuts applied. Filled squares show events passing the cuts on *both* of the other two variables. Open-circles in (a) and (b) show the Δx (Δy) distribution of events passing the Δy (Δx) cut, regardless of p_{miss}. In (b), the dashed and solid curves show the estimated background before and after the p_{miss} cut.

data for $Q^2 = 4.0$, 4.8, and 5.6 GeV^2 to investigate the systematics of the π^0 background. The point from Ref. [2] at $Q^2 = 3.5$ GeV^2 was not reanalyzed, since electrons were detected in a magnetic spectrometer, and the result is consistent with that of Ref. [1] at the same Q^2. The systematics of this configuration were thus irrelevant to the comparison between Halls A and C at higher Q^2.

Figure 1 illustrates the procedure for isolating elastic events at $Q^2 = 4.8$ GeV^2. Figures 1(a) and 1(b) show the horizontal (Δx) and vertical (Δy) differences between the measured shower coordinates at the calorimeter and the coordinates calculated from the measured proton kinematics assuming elastic scattering[1]. Figure 1(c) shows the difference between the measured proton momentum p_p and the momentum $p_p(\theta_p)$ of an elastically scattered proton at the measured angle θ_p, given by

$$p_p(\theta_p) = \frac{2M_p E_e (M_p + E_e)\cos\theta_p}{M_p^2 + 2M_p E_e + E_e^2 \sin^2\theta_p}. \quad (3)$$

[1] Since the two-body reaction kinematics are overdetermined, the method used to calculate Δx and Δy is not unique; θ_e can be predicted from either p_p, θ_p, or a combination of both.

The Δx and Δy distributions of the background, widened by the angular distribution of π^0 decay photons, still overlap the elastic peak due to the similar reaction kinematics. Like the coordinate differences Δx and Δy, the "missing momentum" defined as $p_{miss} = p_p(\theta_p) - p_p$ exhibits a sharp elastic peak. A cut around this peak suppresses the background, estimated from a polynomial extrapolation of the tails of the Δy distribution into the peak region, by a factor of nearly six relative to the application of a Δx cut alone, as shown in Figure 1(b). The p_{miss} cut, found to be crucial in the Hall C analysis, was *not* applied in the analysis of Ref. [2]. Based on the procedure of Figure 1, we estimate that the background contamination in the original elastic event selection is 3.6%, 3.4% and 6.8% for $Q^2 = 4.0$, 4.8 and 5.6 GeV^2, respectively, which is higher than previously estimated by factors of 5.1, 8.5 and 4.9. After applying the p_{miss} cut, the background falls to 1.1%, 0.6%, and 1.1%.

The effect of underestimating the background on the form factor ratio extraction is illustrated in Figure 2, which shows P_t, P_ℓ and the background fraction f as a function of p_{miss}, for events identified as elastic in the original analysis. The data were divided into five p_{miss} bins, including three equal-width bins inside the cut region of Figure 1(c), where f is very small ($-7.3 \leq p_{miss} \leq$

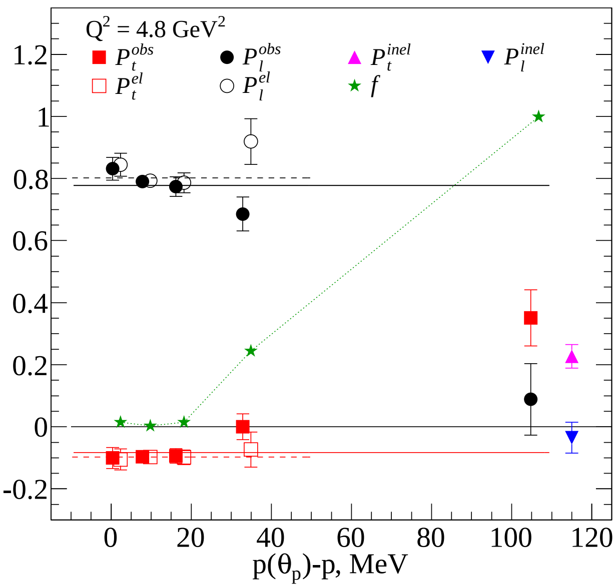

FIG. 2. (color) P_t, P_ℓ and f versus p_{miss}, at $Q^2 = 4.8$ GeV^2. Raw polarizations P_t^{obs} (filled squares) and P_ℓ^{obs} (filled circles) approach the background polarizations P_t^{inel} (triangle) and P_ℓ^{inel} (inverted triangle) at large p_{miss}, as the background fraction f (stars) approaches 1. Corrected values P_t^{el} (open squares) and P_ℓ^{el} (open circles) are offset in p_{miss} for clarity. Dashed and solid horizontal lines are weighted averages of the corrected and raw data, respectively. The dotted lines through the f points are only intended to guide the eye.

22.7 MeV), a fourth bin with a significant fraction of both signal and background ($22.7 \leq p_{miss} \leq 60$ MeV), and a fifth bin dominated by background ($p_{miss} > 60$ MeV). Because the Δx and Δy distributions in the last p_{miss} bin showed no obvious signature of an elastic peak, $f = 1$ was assumed. A meaningful background estimation and subtraction was not possible for this bin. As p_{miss} increases, the raw transferred polarization components P_t^{obs} and P_ℓ^{obs} evolve from their values in the signal-dominated region to values that are consistent with the background components P_t^{inel} and P_ℓ^{inel}. The p_{miss}-integrated results for the background, extracted from events rejected by the cuts of Figure 1, are plotted at arbitrary $p_{miss} = 115$ MeV for comparison. The signal polarization $P_i^{el} (i = t, \ell)$ was obtained from P_i^{obs} in each bin using the subtraction

$$P_i^{el} = \frac{P_i^{obs} - f P_i^{inel}}{1 - f}. \tag{4}$$

At this Q^2, even a small contamination (3.4%) from events erroneously included as elastic induced a strong bias in P_t^{obs} and P_ℓ^{obs}, owing to the large difference between signal and background polarizations.

The final results of our reanalysis are reported in Table II and presented in Figure 3. The P_t and P_ℓ values in Table II and Figure 2 are obtained by correcting the raw FPP asymmetries for spin transport, P_e and the

TABLE II. Results. Raw (P_i^{obs}), background (P_i^{inel}) and corrected (P_i^{el}) transferred polarization components and resulting $R = \mu_p G_{Ep}/G_{Mp}$ values are shown with statistical uncertainties. The uncertainty in the background fraction f is systematic. ΔR_{syst}^{bkgr} is due to uncertainties in f and P_i^{inel}. ΔR_{syst}^{cuts} is due to variations in the cut width and the elastic event selection method. ΔR_{syst}^{total} is the total systematic uncertainty in R. See text for details.

Q^2 (GeV^2)	4.0	4.8	5.6
$P_t^{obs} \pm \Delta P_t^{obs}$	-.107 ± .011	-.096 ± .011	-.060 ± .017
$P_\ell^{obs} \pm \Delta P_\ell^{obs}$	.685 ± .012	.793 ± .013	.887 ± .030
$R \pm \Delta R$ (raw)	.509 ± .054	.456 ± .053	.299 ± .086
$f \pm \Delta f$	(1.08 ± .16)%	(.62 ± .14)%	(1.05 ± .21)%
$P_t^{inel} \pm \Delta P_t^{inel}$	.184 ± .060	.227 ± .038	.122 ± .033
$P_\ell^{inel} \pm \Delta P_\ell^{inel}$	.154 ± .063	-.035 ± .050	.308 ± .071
$P_t^{el} \pm \Delta P_t^{el}$	-.110 ± .011	-.098 ± .011	-.062 ± .018
$P_\ell^{el} \pm \Delta P_\ell^{el}$	.691 ± .012	.798 ± .014	.893 ± .031
$R \pm \Delta R$ (final)	.519 ± .055	.463 ± .054	.306 ± .087
ΔR_{syst}^{bkgr}	3.5×10^{-3}	1.9×10^{-3}	2.3×10^{-3}
ΔR_{syst}^{cuts}	3.7×10^{-3}	5.8×10^{-3}	7.5×10^{-3}
ΔR_{syst}^{total}	0.009	0.012	0.028

$\vec{p} + CH_2$ analyzing power. Due to the self-calibrating nature of $\vec{e}p$ elastic scattering [1], the total uncertainties of roughly 3% in the Möller and Compton measurements of P_e do not affect the extracted values of P_t and P_ℓ, which correspond to equations (2) with $P_e = 1$, but with relative statistical uncertainties equal to those of the raw asymmetries. For all three Q^2 values, a cut of ±15 MeV was applied to p_{miss}, centered at the midpoint between half-maxima on either side of the elastic peak. With the exception of this additional cut, all aspects of our analysis are identical to the original analysis [2], including event reconstruction, spin transport calculations, and all other cuts. Therefore, we have not reevaluated the other systematic uncertainties, primarily associated with spin transport, detailed in [1, 2], and [10]. Uncertainties associated with the elastic event selection procedure are divided into two parts. ΔR_{syst}^{bkgr} results from the uncertainties Δf and ΔP_i^{inel} in the background contamination and its polarization. ΔR_{syst}^{cuts} describes variations in R among different cut widths and methods of calculating Δx and Δy. ΔR_{syst}^{total} is the total systematic uncertainty in R, obtained by quadratically removing the background contribution from the original analysis, and replacing it with our estimates. Consistent with the previous analysis, no radiative corrections have been applied to the results presented here. Previous calculations [11] have shown that the correction to R is negligible compared to the uncertainties in the present data.

Figure 3 shows the results of our reanalysis with the original Hall A data [1, 2], and the new Hall C data [3, 7]. Curves illustrate the effect of the revised data on a global fit using the Kelly parametrization [12] of G_E^p and G_M^p to elastic ep cross section and polarization data, including Ref. [3]. The data selection and fit method are detailed

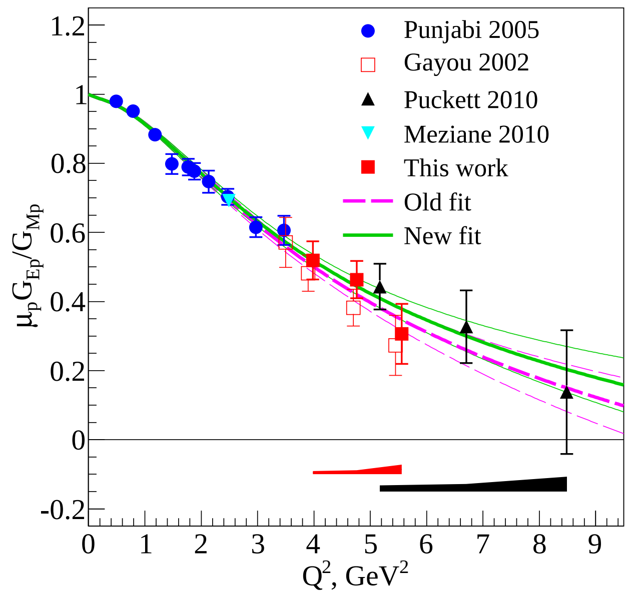

FIG. 3. (color) Recoil polarization data for G_{Ep}/G_{Mp}. Error bars are statistical. Data are [1] (Punjabi 2005), [2] (Gayou 2002), [3] (Puckett 2010), [7] (Meziane 2010) and the present work. The data of [2] are offset slightly in Q^2 for clarity. Systematic uncertainties for the present work and Ref. [3] are shown as bands below the data. Curves are global form factor fits using the previous data [2] (Old fit) and the present work (New fit), with standard 1σ uncertainty bands.

in Ref. [13]. The dashed "Old fit" curve uses the result of Ref. [2], while the solid "New fit" curve replaces the three highest-Q^2 points of Ref. [2] with the results of the present reanalysis. The combined contribution of the six data points with $Q^2 \geq 4$ GeV^2 to the χ^2 of the "Old" global fit is 2.68. In the "New" fit, the same χ^2 contribution drops to 1.55, indicating a significant improvement in the consistency of the data.

In summary, we have reanalyzed the Hall A recoil polarization data for the proton form factor ratio R at the three highest Q^2 values. We find a systematic increase in R that is directly attributable to an underestimation of the background in the original analysis. The proton polarization in the $\vec{\gamma}+p \to \pi^0+\vec{p}$ reaction differs strongly from that in $\vec{e}p \to e\vec{p}$, inducing a negative bias to R. The new p_{miss} cut of the present work removes most of this bias by suppressing the background to the 1% level or below. Corrections for the remaining background are small, with well-controlled systematic uncertainties whose contributions to the total are essentially negligible. With these new results, the data from Halls A and C [1–3, 7] are in excellent agreement over a wide Q^2 range, bringing added clarity to the experimental situation regarding G_{Ep}/G_{Mp}. The very large number of phenomenological nucleon models (see [4] for a recent review) whose parameters have been determined from fits to the data of [1, 2] may need reevaluation, in light of both the new Hall C data, which test the predictive power of the models when extrapolated to a previously unmeasured Q^2 region, and the improved accuracy of the Hall A data.

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