Polarization Transfer in Positron-Proton Elastic Scattering (A Letter of Intent to JLab PAC51)

A. J. R. Puckett (co-spokesperson and contact person) and K. Joo
University of Connecticut, Storrs, CT, 06269, USA *

J. Bernauer (co-spokesperson)
Stony Brook University, Stony Brook, NY 11794, USA and
RIKEN-BNL Research Center, Brookhaven National Lab, Upton, NY 11973, USA

A. Schmidt (co-spokesperson) and W. J. Briscoe
George Washington University, Washington, DC 20052, USA

S. Covrig Dusa, M. McCaughan, and B. Wojtsekhowski
Thomas Jefferson National Accelerator Facility, Newport News, VA, 23606, USA

D. Androic
University of Zagreb, Faculty of Science, Croatia

R. Singh
Center for Nuclear Theory, Department of Physics and Astronomy,
Stony Brook University, Stony Brook, New York, 11794-3800, USA

S. Širca
Faculty of Mathematics and Physics, U of Ljubljana, Slovenia

P. Markowitz
Florida International University, Miami FL 33199

J. Arrington
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

T. Kolar, J. Lichtenstadt, and E. Piasetzky
Tel Aviv University, Tel Aviv, Israel

M. Nycz
University of Virginia, Charlottesville, VA, 22904, USA

(Dated: May 21, 2023)

We propose a first set of exploratory measurements of polarization transfer in elastic positron-proton scattering $\vec{e}^+ p \to e^+ \vec{p}$, at a series of momentum transfers Q^2 and virtual photon polarizations ϵ where a large discrepancy exists between extractions of the proton form factor ratio $\mu_p G_E^p / G_M^p$ based on cross section and polarization measurements. These measurements probe the hard two-photon-exchange (TPE) contributions to elastic $e^\pm p \to e^\pm p$ scattering, with different and complementary sensitivities to the generalized form factors of the proton as compared to planned measurements of the unpolarized e^+p/e^-p cross section ratios and Rosenbluth separations. The proposed measurements have small systematic uncertainties and would be statistics-limited. The experiment would take advantage of the planned high-intensity polarized positron source at CEBAF and the Super BigBite Spectrometer apparatus for recoil proton polarimetry. In this letter-of-intent, we discuss an optimal choice of kinematics and precision goals for an initial exploration, and positron beam parameter requirements to achieve those goals in a reasonable amount of beam time. We request the PAC's evaluation of the physics case for these measurements and the endorsement to proceed to the development of a full experiment proposal.

* puckett@jlab.org

I. INTRODUCTION

The long-standing discrepancy at large values of four-momentum transfer Q^2 between extractions of the proton form factor ratio G_E^p/G_M^p based on cross section and polarization observables is one of the main scientific motivations for efforts to accelerate high-intensity polarized and unpolarized positron beams in CEBAF [1]. Since the discovery of the rapid decrease of the proton form factor ratio $\mu_p G_E^p/G_M^p$ for $Q^2 \gtrsim 1$ GeV^2 using polarization observables [2–8], enormous efforts in theory and experiment have been ongoing to understand and resolve this discrepancy. On the theoretical side, most investigations have focused on the contribution of hard two-photon-exchange (TPE), which is $\mathcal{O}(\alpha)$ relative to the leading One-Photon-Exchange (OPE) or "Born" term, cannot presently be calculated model-independently, and is neglected in the standard radiative correction procedures to elastic $ep \to ep$ cross section measurements (see Ref. [9] for a recent review of the subject). On the experimental side, three major collaborations (OLYMPUS [10, 11], VEPP-3 [12], and CLAS [13, 14]) have performed precision measurements of e^+p/e^-p elastic scattering cross section ratios in the last decade, in an attempt to directly constrain the size of TPE contributions to unpolarized cross section measurements. Each of these experiments used complementary approaches with different systematics; however, none reached high enough Q^2 and/or low-enough ϵ with sufficient precision and accuracy to conclusively resolve the discrepancy.

The overarching goals of experimental investigations of hard TPE using positron scattering are to:

1. Determine whether the Rosenbluth/polarization discrepancy in the extraction of $\mu_p G_E^p/G_M^p$ can be fully and self-consistently explained by "hard" TPE (and higher-order QED corrections), as must be the case within a Standard Model paradigm.

2. *Assuming* this is shown to be the case in the Q^2 regime where the discrepancy is most significant, to validate and constrain theoretical calculations of these corrections, elevating hard TPE to the status of a "standard", trusted radiative correction to elastic ep scattering observables.

A large part of the CEBAF positron program will consist of precisely mapping the e^+p unpolarized elastic scattering cross sections with a wide coverage in ϵ in the Q^2 range of 1.5-6 GeV^2, where the existing discrepancy is most significant. Despite the Herculean efforts of the previous *positron*-proton scattering experiments to search for and precisely measure *direct* experimental signatures of TPE, the discrepancy seen in *electron*-proton scattering remains by far the most statistically significant direct or indirect evidence for the importance of these effects in charged lepton-proton elastic scattering.

Since the discrepancy first appeared in the polarization observables, an essential ingredient in its eventual conclusive resolution is to investigate whether any discrepancy *also* exists in *either* the comparison of polarization transfer between e^+p and e^-p scattering *and/or* the comparison between Rosenbluth separations and polarization observables in e^+p scattering, independently of the well-established discrepancy for e^-p scattering. No such data currently exist, and such a measurement would provide valuable independent constraints on the "generalized" form factors and their theoretical modeling. In this letter-of-intent, we present the concept for a first exploratory measurement of e^+p polarization transfer with a Q^2 reach and precision competitive with the best existing measurements of these observables for e^-p scattering. The main arguments and statistical uncertainty projections were already laid out in a peer-reviewed contribution [15] to the recent topical issue of the European Physical Journal A on the CEBAF positron program [1]. As such, this letter-of-intent is brief, as it is heavily based on that already published work.

II. THEORETICAL FORMALISM

In the OPE approximation, the polarization transferred to the scattered proton in the elastic scattering of longitudinally polarized electrons/positrons by unpolarized protons has longitudinal (P_ℓ) and transverse (P_t) components with respect to the momentum transfer parallel to the lepton scattering plane, given by:

$$P_t = -\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{r}{1+\frac{\epsilon}{\tau}r^2} \tag{1}$$

$$P_\ell = \frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2}, \tag{2}$$

where $r \equiv G_E^p/G_M^p$ is the ratio of the Sachs electric and magnetic form factors, $\tau \equiv \frac{Q^2}{4M^2}$ with M the proton mass, and $\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$, with θ_e the lab-frame scattering angle of the electron, is the longitudinal polarization of the virtual photon (in OPE). The ratio of the two polarization transfer components is directly proportional to the form factor ratio by a precisely measurable kinematic factor:

$$\mu_p \frac{G_E^p}{G_M^p} = -\mu_p \frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}} = -\mu_p \frac{P_t}{P_\ell}\frac{E_e+E_e'}{2M}\tan\left(\frac{\theta_e}{2}\right), \tag{3}$$

where the last expression in Eq. (3) holds in the proton rest (lab) frame, with E_e (E_e') the incident (scattered) electron energy, and μ_p the proton's magnetic moment in nuclear magnetons.

The simultaneous measurement of both recoil polarization components and the rapid beam helicity reversal lead to cancellation of most major sources of experimental systematic uncertainty. While polarization transfer is less sensitive to the effects of radiative corrections and hard TPE, it is not immune. Following the formalism of Ref. [16], one finds that

$$\begin{aligned}\frac{P_t}{P_\ell} = -\sqrt{\frac{2\epsilon}{\tau(1+\epsilon)}}\frac{G_E}{G_M} \times \Bigg[1 &\pm \mathrm{Re}\left(\frac{\delta\widetilde{G}_M}{G_M}\right) \\ &\pm \frac{1}{G_E}\mathrm{Re}\left(\delta\widetilde{G}_E + \frac{\nu}{M^2}\widetilde{F}_3\right) \\ &\mp \frac{2}{G_M}\mathrm{Re}\left(\delta\widetilde{G}_M + \frac{\epsilon\nu}{(1+\epsilon)M^2}\widetilde{F}_3\right) + \mathcal{O}(\alpha^2)\Bigg],\end{aligned} \tag{4}$$

with $\nu \equiv (p_e + p_{e'})_\mu (p_p + p_{p'})^\mu$, and where $\delta\widetilde{G}_E$, $\delta\widetilde{G}_M$, and $\widetilde{F}_3$ are additional form factors that become non-zero when moving beyond the one-photon exchange approximation and, crucially, depend on both Q^2 and ϵ, whereas the one-photon-exchange form factors depend only on Q^2. The correction terms $\delta\widetilde{G}_E$, $\delta\widetilde{G}_M$, and $\widetilde{F}_3$ are $\mathcal{O}(\alpha)$ relative to the one-photon-exchange form factors G_E, G_M. The $\pm/\mp$ symbols in Eq. (4) indicate the sign with which the two-photon-exchange amplitudes enter the observable P_t/P_ℓ depending on the lepton charge, with the upper (lower) symbol indicating the appropriate sign for $e^-(e^+)$ beams. This particular dependence on new form factors is slightly different than what one finds when taking a positron to electron cross section ratio:

$$\begin{aligned}\frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 &+ 4G_M\mathrm{Re}\left(\delta\widetilde{G}_M + \frac{\epsilon\nu}{M^2}\widetilde{F}_3\right) \\ &- \frac{4\epsilon}{\tau}G_E\mathrm{Re}\left(\delta\widetilde{G}_E + \frac{\nu}{M^2}\widetilde{F}_3\right) + \mathcal{O}(\alpha^2).\end{aligned} \tag{5}$$

A measurement of the difference in polarization transfer between electron and positron scattering therefore adds information about TPE in addition to what can be learned from cross section ratios alone. Moreover, as described in a separate proposal to PAC51, precise Rosenbluth separations of e^+p scattering will be pursued using the precision spectrometers in Hall C, in the same Q^2 range as the proposed polarization transfer measurements using SBS. These Rosenbluth separations of e^+p scattering can then be directly compared to the e^+p polarization transfer measurements described in this letter-of-intent. Such comparisons will be extremely interesting in addition to the comparison with existing and planned e^-p polarization transfer data, given that the existing discrepancy between cross sections and polarization observables in e^-p scattering is *much* greater than the combined uncertainty of the two observables. If a discrepancy of similar magnitude exists for e^+p scattering, as might reasonably be expected if hard TPE is the physical mechanism for the discrepancy seen in e^-p scattering, it will easily be seen, even in an experiment only half as precise as our stated goal.

III. CONCEPT OF THE PROPOSED EXPERIMENT

Figure 1 and Table I summarize the proposed measurement kinematics and precision goals. The considerations driving the choice of kinematics for the proposed measurements were already discussed at length in Ref. [15], so we will only briefly summarize them here. The most natural choice of Q^2 for a first, exploratory measurement of e^+p polarization transfer is 2.5 GeV^2, as this is the Q^2 of the most precise existing measurements [6, 8] of e^-p polarization transfer in the Q^2 regime where the Rosenbluth/polarization discrepancy is significant. In our paper, we showed that in two months' beam time, with one month each at first and second pass CEBAF energies, the ratio R_p for positron-proton scattering can be measured at 2.5 GeV^2 with less than 2% absolute statistical uncertainty at each of two epsilon values ($\epsilon = 0.39$ and 0.84). The precision of the combined result at 2.5 GeV^2 would be 1.2% (absolute), which is competitive with the GEp-2γ data and sufficient to discriminate among various theoretical calculations for the TPE effects in this observable, in terms of both ϵ dependence and the difference between e^+p and e^-p. With two

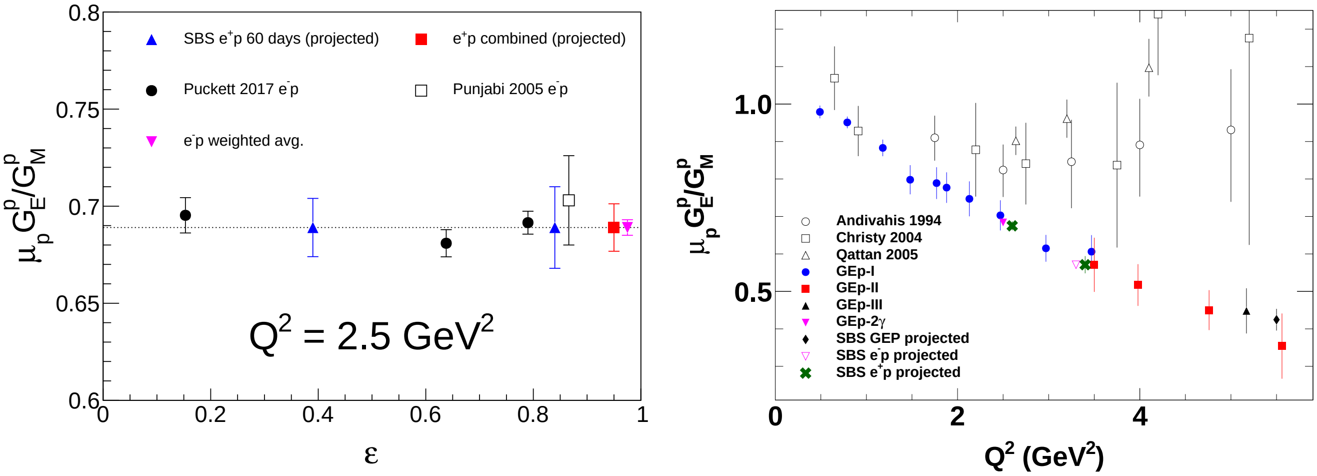

FIG. 1. Projected statistical precision of the proposed measurements of the ratio $R_p \equiv -\mu_p \frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}$, which equals $\mu_p \frac{G_E^p}{G_M^p}$ in the one-photon-exchange approximation. See Table I and Ref. [15] for more details. Left: ϵ-dependence of the ratio at $Q^2 = 2.5$ GeV^2, compared to existing data. Right: Q^2-dependence of the ratio compared to selected existing and planned data for e^-p polarization observables and Rosenbluth separations. Figures reproduced from Ref. [15].

TABLE I. Summary of proposed measurements (reproduced from Ref. [15]). E_e is the incident lepton energy, $\langle Q^2 \rangle$ is the acceptance averaged Q^2, θ_e is the central lepton scattering angle, $\langle \epsilon \rangle$ is the acceptance averaged ϵ value, θ_p is the central proton scattering angle, and p_p is the central proton momentum. The expected event rate is based on the assumption of a 200 nA (30 μA) positron (electron) beam, and ΔR is the projected absolute statistical uncertainty for the indicated number of beam days in the ratio $R \equiv -\mu_p \frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}$, which equals $\mu_p G_E^p/G_M^p$ in the one-photon approximation, assuming 60% (85%) positron (electron) polarization. On the bottom row, we depict an ancillary e^-p measurement at kinematics identical to the higher Q^2 e^+p measurement, that could achieve 1% statistical precision in 24 hours. The ideal time to accomplish such a measurement would be during the upcoming SBS GEP run [17, 18], eliminating the overhead of switching CEBAF between positron and electron mode in the context of this experiment.

Lepton	E_e GeV	$\langle Q^2 \rangle$ GeV^2	θ_e deg.	$\langle \epsilon \rangle$	θ_p deg.	p_p GeV	Event rate Hz	Days	ΔR (absolute)
e^+	2.2	2.5	69.8	0.39	23.2	2.04	11	30	0.015
e^+	4.4	2.6	27.0	0.84	36.2	2.15	16	30	0.021
e^+	4.4	3.4	32.5	0.76	31.1	2.56	7	60	0.023
e^-	4.4	3.4	32.5	0.76	31.1	2.56	1,050	1	0.01

additional months' beam time, we could also perform another measurement at 3.4 GeV^2 to probe the Q^2 dependence, with about 2% absolute statistical uncertainty, which would be significantly *better* than the precision of the existing e^-p data at this Q^2. To enhance the physics impact and interpretation of the result at the higher Q^2, we propose to add a short, $\approx$ 1-day run at 2nd pass to the upcoming SBS GEP run in Hall A, to achieve a $\approx 1\%$ measurement of $\mu_p G_E^p/G_M^p$ in electron scattering at the same Q^2 of 3.4 GeV^2, in anticipation of a comparison to a future positron measurement. Such an addition to the SBS GEP run would also greatly benefit the commissioning of that experiment, and aid in controlling the systematics of the planned high-Q^2 measurements.

The statistical precision of the measurement of the ratio R_p is dominated by the relative uncertainty of the transverse polarization transfer component P_t, which is proportional to $\sqrt{\epsilon(1-\epsilon)}$ at any given Q^2. The longitudinal component P_ℓ is proportional to $\sqrt{1-\epsilon^2}$ and is generally significantly larger than P_t, and therefore measured with better relative precision. As such, the figure-of-merit of a polarization transfer measurement of G_E^p/G_M^p, all else equal, reaches a maximum at $\epsilon \approx 0.5$ for any given Q^2. Indeed, looking at Table I, which is the product of a detailed Monte Carlo simulation, despite the slightly higher event rate at the forward-angle, high-ϵ kinematics at second pass, the large-angle, low-ϵ measurement at first pass has a significantly smaller statistical uncertainty for the same beam time, due to its being much closer to the optimal ϵ value of 0.5.

In any plausible scheme for polarized positron acceleration in CEBAF, the beam current (and therefore the luminosity) will be at best 2-3 orders of magnitude below the typical polarized electron beam currents available in Hall A or C. As such, large solid-angle acceptance for the detection of the scattered leptons and protons is mandatory to achieve the precision goals in a reasonable amount of beam time. As such, the most obvious and straightforward solution is to use the Super BigBite Spectrometer (SBS) apparatus in a configuration more or less identical to the upcoming high-Q^2 measurements of G_E^p/G_M^p using polarization transfer in electron-proton scattering [17, 18], hereafter referred to as the "SBS GEP" experiment (E12-07-109).

The SBS program started in Hall A in the fall of 2021. The SBS GEP experiment underwent its experimental readiness review in late April 2023, and is scheduled to run in Fall-Spring, 2024-2025. The high-Q^2 measurements planned using SBS are actually much more difficult than the proposed positron measurements would be, owing to the much higher luminosities, accompanied by high radiation in Hall A and high background rates in the detectors. At the luminosities of the proposed positron measurements, event reconstruction in the detectors and proton polarimetry will be extremely clean, as discussed in Ref. [15].

According to the Positron Working Group's (PWG's) letter to PAC51, the expected positron current available in a "first-generation" polarized source will be "$>$ 50 nA" at a polarization of "$>$ 60%". In our published paper [15] describing the proposed measurements (and as shown in Table I) we assumed, based on commonly discussed assumptions at the time, a 200-nA positron beam at 60% polarization on a 40-cm liquid hydrogen target, representing a figure-of-merit P^2I four times greater[1] than the conservative 50-nA baseline for a "first-generation" source quoted in the PWG's letter to PAC51. On the one hand, even at 200 nA current, the proposed measurements would be somewhat expensive in terms of beam time to achieve a 1-2% precision goal. On the other hand, the same beam time allocation even at 50-nA polarized positron current would lead to a roughly 2% (4%) measurement at 2.5 (3.5) GeV^2, which is still highly competitive with the existing e^-p data in this region, and more than precise enough to see the expected "discrepancy" between polarization transfer and Rosenbluth separation in e^+p scattering at high significance/confidence level.

Considering that the e^-p polarization transfer measurements from Hall A, originally approved with a "B+" rating by the JLab PAC, constitute one of the most signicant discoveries and most famous results in the history of JLab, we argue that the potential impact of a first-ever precision determination of these never-before-measured observables justifies a substantial beam time allocation within the overall CEBAF positron program. Even the 50-nA version of the proposed measurements for the same beam time allocation would greatly enhance the physics impact of the proposed e^+p Rosenbluth separation program in particular, even if it would probably not be precise enough to detect a small difference in polarization transfer observables between e^+p and e^-p.

Furthermore, it must be noted that the 50 nA polarized positron current assumed as a baseline for a "first-generation" source is not an inherent limitation of the PEPPO method [19] for polarized positron production. The limit is instead defined by the energy, intensity, and polarization of the primary polarized electron beam used to drive the positron source, and several straightforward approaches to achieve polarized positron currents up to and even exceeding the 200 nA assumed in our projections have already been proposed [20]. The measurements described in this LOI could serve as part of a compelling science case to develop higher-intensity polarized positron beams in CEBAF beyond the "first generation" approach.

IV. SUMMARY AND REQUEST TO PAC51

In this Letter-Of-Intent, we propose a first investigation of polarization transfer in positron-proton scattering, in the Q^2 regime where a large discrepancy between cross sections and polarization observables exists in electron-proton scattering, and where precise data already exist for polarization transfer and Rosenbluth separations. The possibility to achieve useful precision in a "reasonable" amount of beam time, demonstrated in our published paper [15], is enabled by the large-acceptance Super BigBite Spectrometer, which was designed around the requirements of high-Q^2 polarization measurements of G_E^p/G_M^p. While our chosen kinematics and precision goals would be somewhat expensive in terms of beam time ($\approx$ 4 PAC-months at 200 nA with a 1-2% statistical precision goal, or 2-4% at 50 nA for the same beam time), the proposed measurements would directly address one of the primary motivations driving the effort to accelerate positrons in CEBAF, and are unique and complementary to other proposals focused on cross section (and cross section ratio) measurements in $e^+p \to e^+p$ scattering. The opportunity to perform such measurements for the first time, at a precision competitive with the best existing electron scattering data in this Q^2 regime, justifies a substantial beam time allocation within the overall CEBAF positron program. Moreover, these measurements (and

[1] corresponding to a statistical error twice as large

the potential for a more comprehensive set of measurements) contribute to the science case for the development of higher-intensity polarized positron beams relative to the "first-generation" baseline, which would greatly benefit the positron science program as a whole.

a. ***"Ask" to PAC51*** We ask for the PAC's guidance addressing the science case for the proposed measurements, including the choice of kinematics and precision goals, and for the PAC's endorsement to develop a full proposal to be submitted to PAC52. Assuming the PAC's encouragement to proceed to the development of a full proposal, we will work with theorists to quantify the impact of these measurements on constraining TPE corrections in elastic lepton-proton scattering and on the interpretation of other elastic positron-proton measurements planned at CEBAF. In addition, we will develop a detailed and optimized experiment plan assuming the use of the SBS in Hall A (or perhaps Hall C). We will also evaluate the figure-of-merit for a polarized target measurement as an alternative to polarization transfer. While a polarization transfer measurement is *significantly* less difficult than a polarized target measurement in terms of both carrying out the experiment and control of systematic uncertainties, a polarized target measurement *may* be statistically competitive with polarization transfer given the expected limitations on polarized positron current, due to the efficiency and analyzing power of proton recoil polarimetry as compared to the dilutions associated with a polarized target measurement. Finally, as part of the intended full proposal, we will request a short (≈1-2 PAC-days) addition to the upcoming SBS GEP run at second pass, currently on the Hall A schedule starting fall 2024, to achieve a 1% measurement of $\mu_p G_E^p/G_M^p$ in electron scattering at 3.4 GeV^2, anticipating comparison to a future positron measurement at the same (or similar) Q^2.

---

[1] A. Accardi *et al.*, An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab, Eur. Phys. J. A **57**, 261 (2021), arXiv:2007.15081 [nucl-ex].

[2] M. K. Jones *et al.*, G_{E_p}/G_{M_p} Ratio by Polarization Transfer in $\vec{e}p \to e\vec{p}$, Phys. Rev. Lett. **84**, 1398 (2000).

[3] O. Gayou *et al.* (Jefferson Lab Hall A), Measurement of $G_{\mathrm{Ep}}/G_{\mathrm{Mp}}$ in $\vec{e}p \to e\vec{p}$ to $Q^2 = 5.6$-GeV^2, Phys. Rev. Lett. **88**, 092301 (2002), nucl-ex/0111010.

[4] V. Punjabi *et al.*, Proton elastic form-factor ratios to $Q^2 = 3.5$-GeV^2 by polarization transfer, Phys. Rev. **C71**, 055202 (2005), [Erratum: Phys. Rev.C71,069902(2005)], arXiv:0501018 [nucl-ex].

[5] A. J. R. Puckett *et al.*, Recoil Polarization Measurements of the Proton Electromagnetic Form Factor Ratio to $Q^2 = 8.5$ GeV^2, Phys. Rev. Lett. **104**, 242301 (2010).

[6] M. Meziane *et al.* (GEp2gamma), Search for effects beyond the Born approximation in polarization transfer observables in $\vec{e}p$ elastic scattering, Phys. Rev. Lett. **106**, 132501 (2011), arXiv:1012.0339 [nucl-ex].

[7] A. J. R. Puckett *et al.*, Final Analysis of Proton Form Factor Ratio Data at $\mathbf{Q^2 = 4.0}$, 4.8 and 5.6 GeV$^{\mathbf{2}}$, Phys. Rev. **C85**, 045203 (2012), arXiv:1102.5737 [nucl-ex].

[8] A. J. R. Puckett *et al.*, Polarization Transfer Observables in Elastic Electron Proton Scattering at Q^2 =2.5, 5.2, 6.8, and 8.5 GeV^2, Phys. Rev. **C96**, 055203 (2017), arXiv:1707.08587 [nucl-ex].

[9] A. Afanasev, P. G. Blunden, D. Hasell, and B. A. Raue, Two-photon exchange in elastic electron–proton scattering, Prog. Part. Nucl. Phys. **95**, 245 (2017), arXiv:1703.03874 [nucl-ex].

[10] B. S. Henderson *et al.* (OLYMPUS), Hard Two-Photon Contribution to Elastic Lepton-Proton Scattering: Determined by the OLYMPUS Experiment, Phys. Rev. Lett. **118**, 092501 (2017), arXiv:1611.04685 [nucl-ex].

[11] J. C. Bernauer *et al.* (OLYMPUS), Measurement of the Charge-Averaged Elastic Lepton-Proton Scattering Cross Sectionby the OLYMPUS Experiment, Phys. Rev. Lett. **126**, 162501 (2021), arXiv:2008.05349 [nucl-ex].

[12] I. A. Rachek *et al.*, Measurement of the two-photon exchange contribution to the elastic $e^{\pm}p$ scattering cross sections at the VEPP-3 storage ring, Phys. Rev. Lett. **114**, 062005 (2015), arXiv:1411.7372 [nucl-ex].

[13] D. Adikaram *et al.* (CLAS), Towards a resolution of the proton form factor problem: new electron and positron scattering data, Phys. Rev. Lett. **114**, 062003 (2015), arXiv:1411.6908 [nucl-ex].

[14] D. Rimal *et al.* (CLAS), Measurement of two-photon exchange effect by comparing elastic $e^{\pm}p$ cross sections, Phys. Rev. **C95**, 065201 (2017).

[15] A. J. R. Puckett, J. C. Bernauer, and A. Schmidt, Polarization transfer in $\vec{e}^{\,+}p \to e^{+}\vec{p}$ scattering using the Super BigBite Spectrometer, Eur. Phys. J. A **57**, 188 (2021), arXiv:2104.11879 [nucl-ex].

[16] C. E. Carlson and M. Vanderhaeghen, Two-Photon Physics in Hadronic Processes, Ann. Rev. Nucl. Part. Sci. **57**, 171 (2007), arXiv:0701272 [hep-ph].

[17] E. Brash, E. Cisbani, M. Jones, M. Khandaker, L. Pentchev, C. F. Perdrisat, V. Punjabi, B. Wojtsekhowski, *et al.*, Large Acceptance Proton Form Factor Ratio Measurements at 13 and 15 GeV^2 Using Recoil Polarization Method (2007), `http://www.jlab.org/exp_prog/proposals/07/PR12-07-109.pdf`.

[18] E. Cisbani, M. K. Jones, N. Liyanage, L. P. Pentchev, A. J. R. Puckett, and B. Wojtsekhowski, Update on E12-07-109 to PAC 47: Large Acceptance Proton Form Factor Ratio Measurements at 13 and 15 GeV^2 Using Recoil Polarization Method (2019), `https://puckett.physics.uconn.edu/wp-content/uploads/sites/1958/2019/08/gep_update.pdf`.

[19] (PEPPo Collaboration) D. Abbott *et al.*, Phys. Rev. Lett. **116**, 214801 (2016).

[20] L. S. Cardman, The PEPPo method for polarized positrons and PEPPo II, AIP Conf. Proc. **1970**, 050001 (2018).