Polarization Transfer in Positron-Proton Elastic Scattering (LOI to PAC51)

Andrew Puckett, University of Connecticut

(spokespersons A. Puckett, J. Bernauer, A. Schmidt)

Positron Working Group Meeting, Jan. 31, 2024

UCONN

Motivation—Positrons @JLab

- https://inspirehep.net/literature/1809448

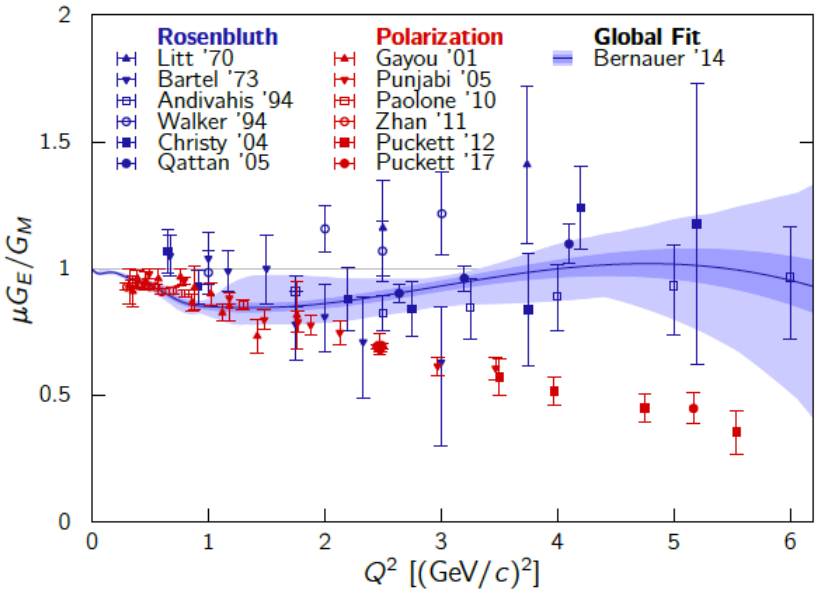


Fig. 1 A representative sample of the world data on the proton's form factor ratio, $\mu_p G_E/G_M$ shown as a function of squared four-momentum transfer, Q^2. Rosenbluth separations of unpolarized cross sections are shown in blue [48,49, 50,51,52,53]. Polarized measurements are shown in red [35, 36,37,38,39,40]. A global fit to unpolarized cross sections [59] is shown, along with statistical and systematic uncertainties, by a blue curve with light blue bands.

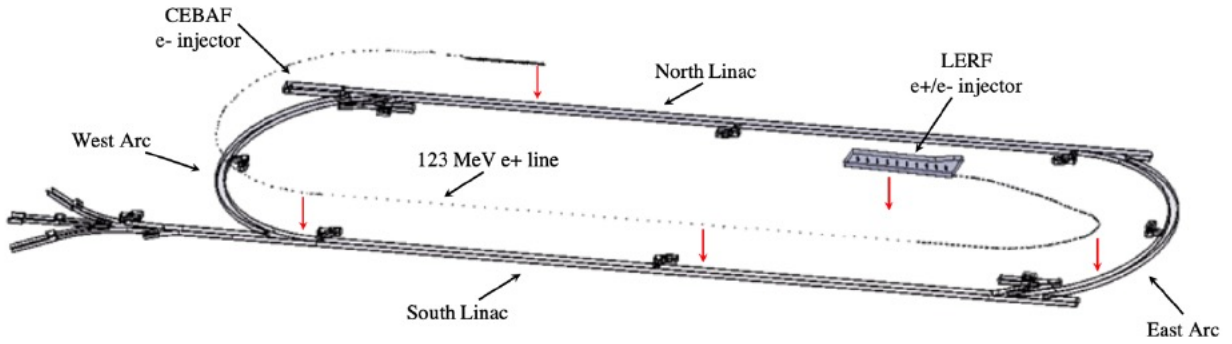


Figure 44: A new tunnel and beam line (shown raised) connects the LERF to CEBAF and transports the 123 MeV e^+ beam for injection and acceleration into CEBAF 12 GeV.

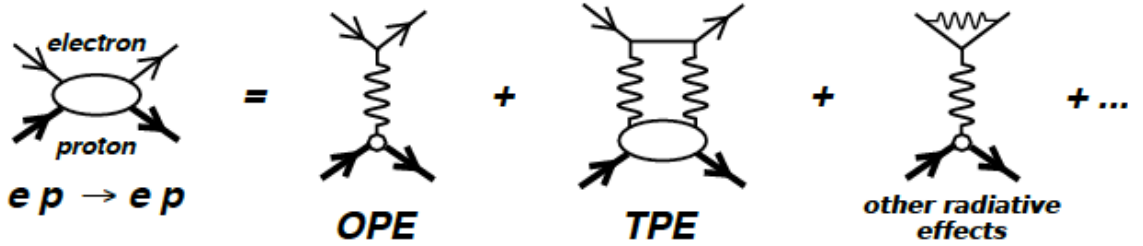


Fig. 2 Feynman diagram series for elastic electron-proton scattering. The two-photon exchange amplitude contributes at the same order as several other radiative processes.

- Differences between e^+p and e^-p scattering are considered "direct" signatures of hard TPE, as the $1\gamma - 2\gamma$ interference changes sign with the lepton charge

Experimental Status of TPE

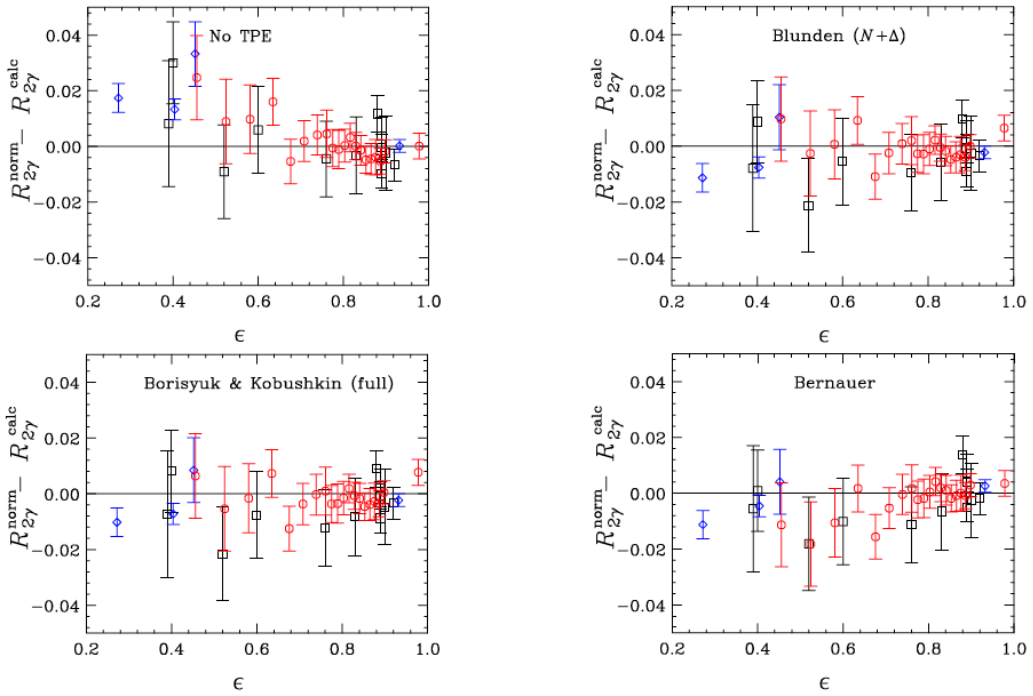


Figure 3.17: Difference between *normalized* $R_{2\gamma}$ and model predictions as a function of ε. Data symbols are the same as in Fig. 3.15.

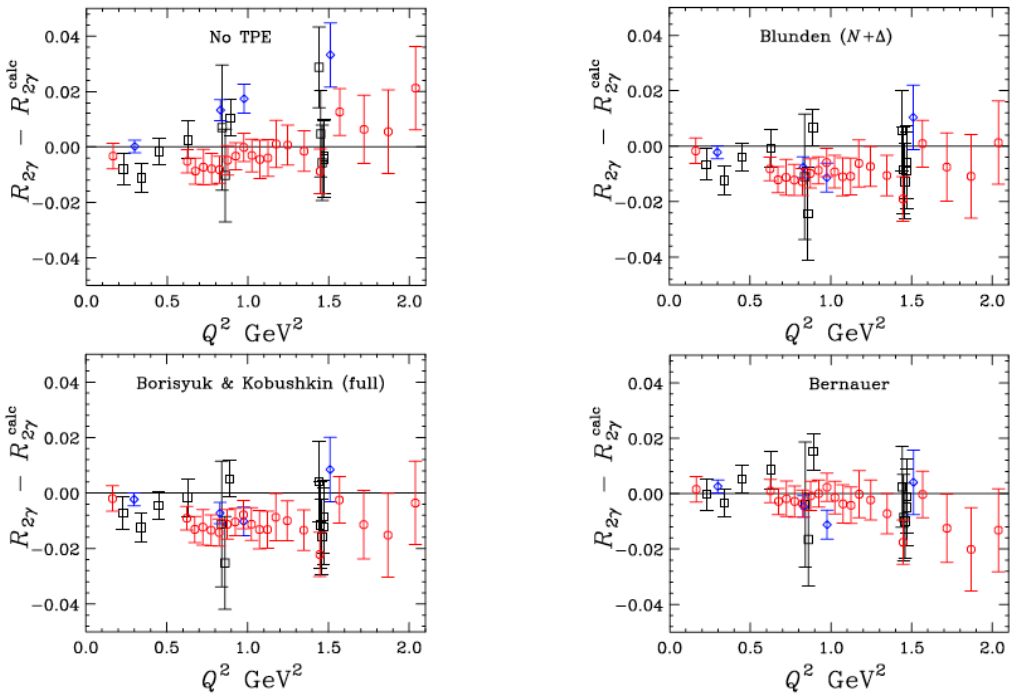
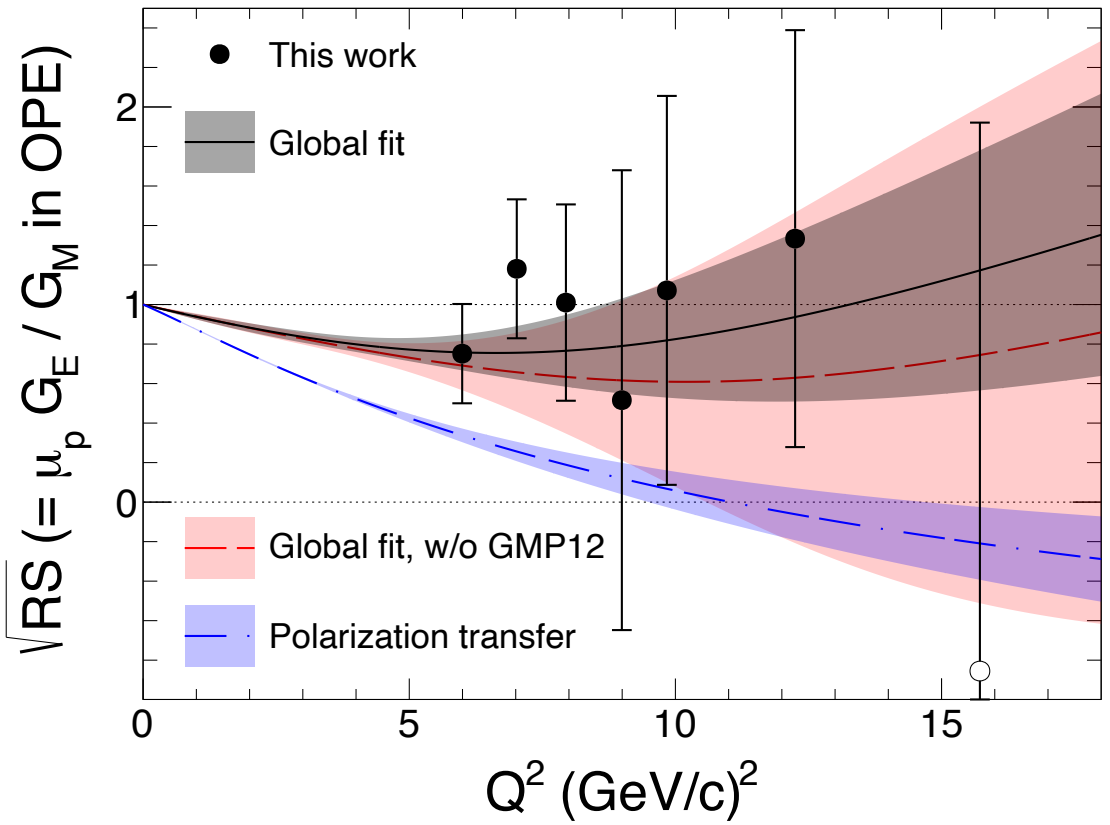
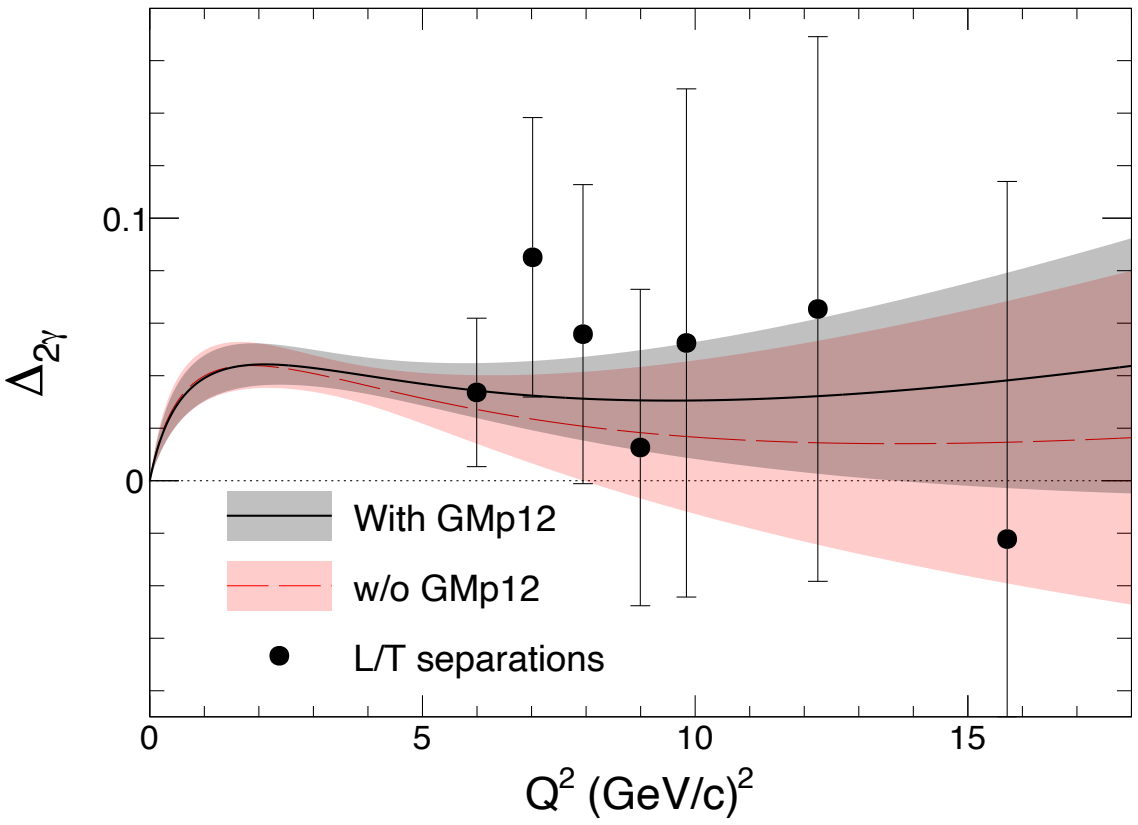


Figure 3.16: Difference between $R_{2\gamma}$ and model predictions as a function of Q^2. Data symbols are the same as in Fig. 3.15.

- Afanasev *et al.*, Prog. Part. Nucl. Phys. 95 (2017) 245-278
- CLAS-TPE, VEPP-3, and OLYMPUS exclude the "no-TPE" hypothesis at the ~98% confidence, and are largely consistent with existing calculations more or less sufficient to explain the discrepancy for $Q^2 < 2$ GeV².
- However, these experiments do not reach high-enough Q^2 and/or low-enough ϵ to conclusively resolve the discrepancy in favor of the TPE hypothesis in the region where it is large ($Q^2 \geq 2\ GeV^2$).

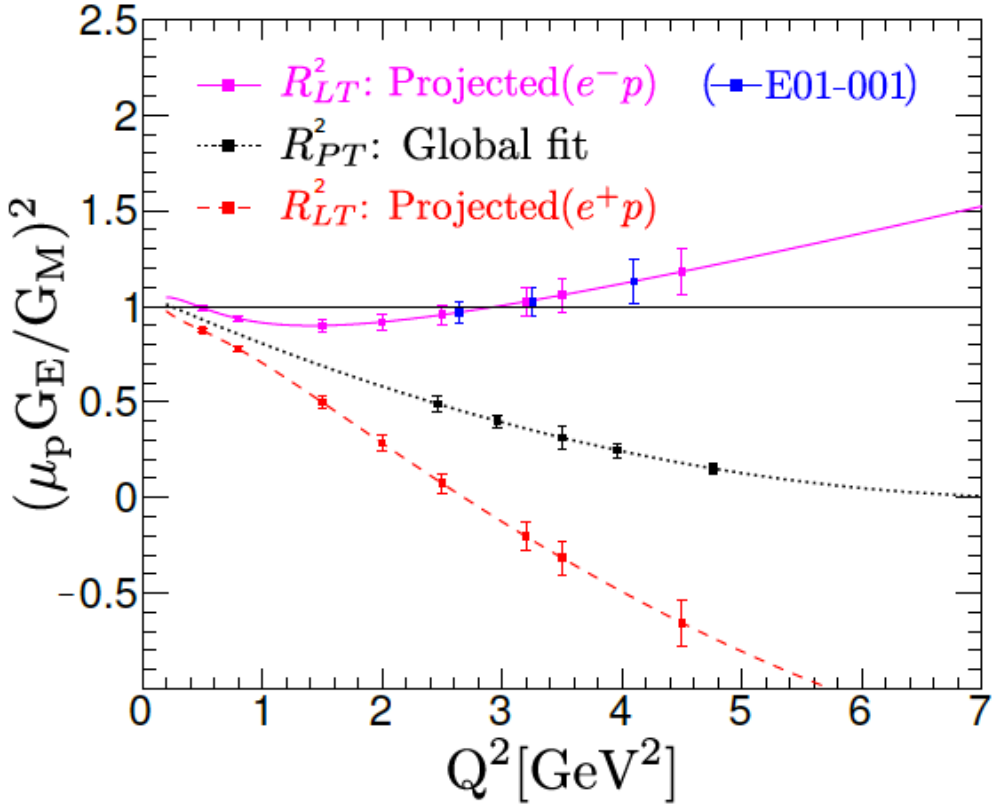
Size of the discrepancy at large Q^2

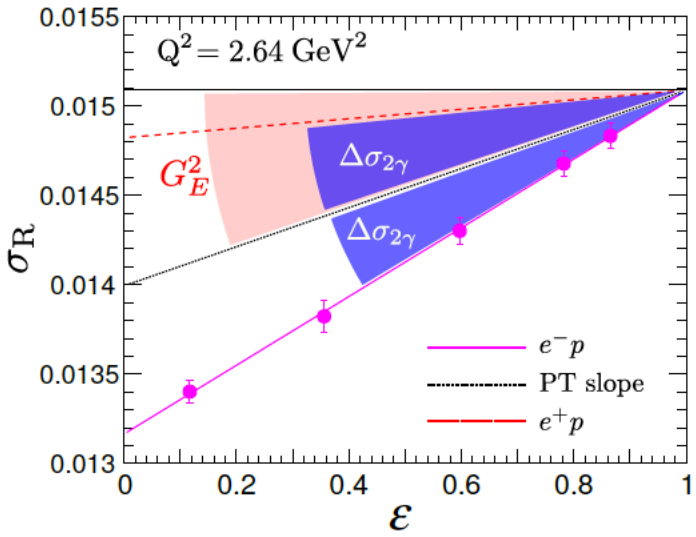


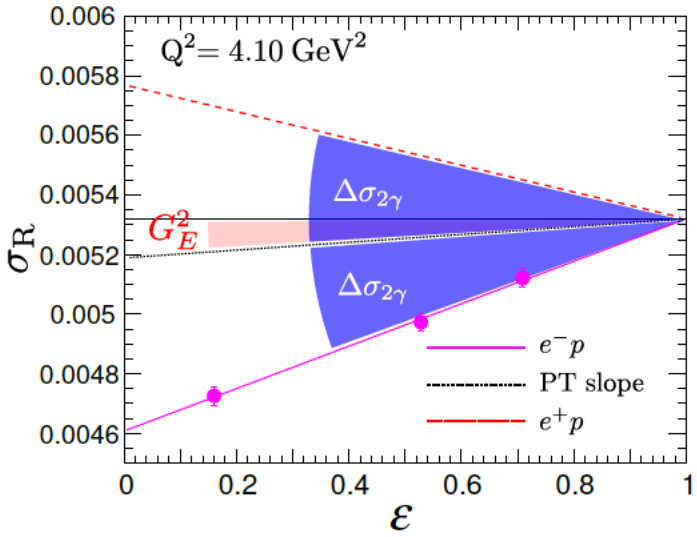


- From "Form Factors and Two-Photon Exchange in High-Energy Elastic Electron Proton Scattering": Christy *et al.*, Phys.Rev.Lett. 128 (2022) 10, 102002
- New model-independent L/T separations in the 6-16 GeV^2 region using the new Hall A GMP12 data indicate a TPE effect of $(4.2 \pm 2.1)\%$ (linear in ϵ) would account for the discrepancy in this region, AFTER updating RC to the state-of-the-art based on Maximon-Tjon (using original Mo-Tsai RC gives $\Delta_{2\gamma} = (6.6 \pm 2.1)\%$)

Positron-proton "Super-Rosenbluth" proposal to PAC51

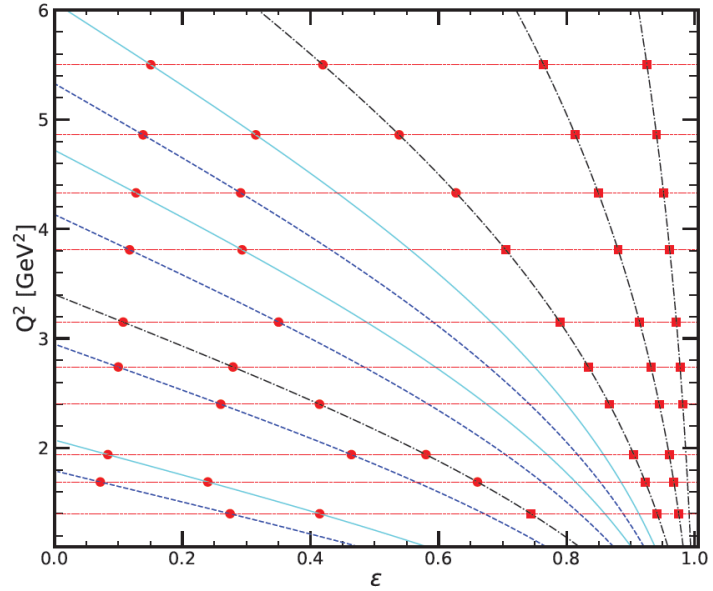




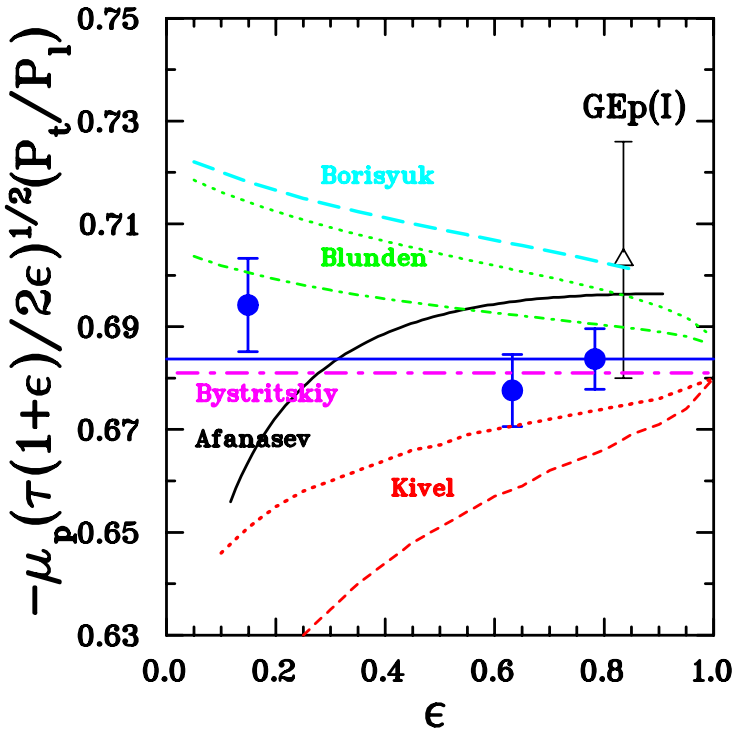


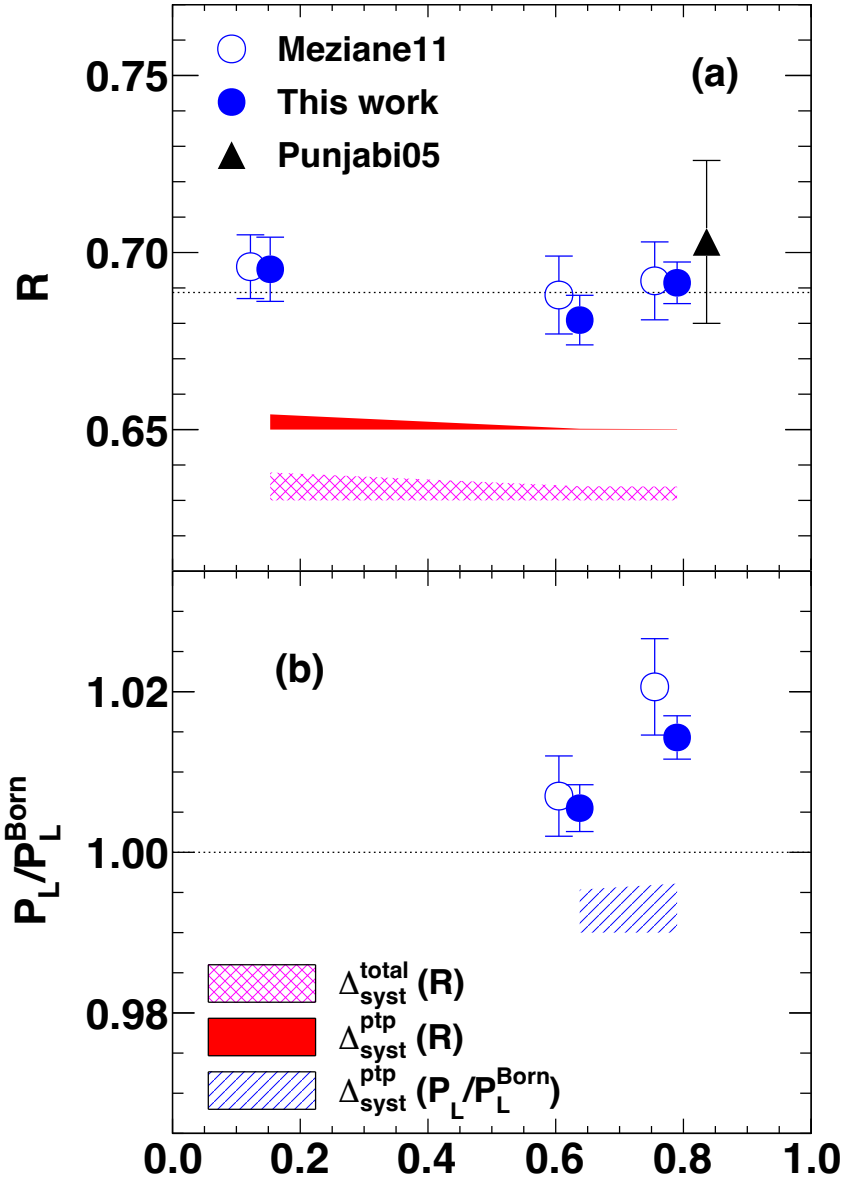
- Several proposals exist to measure $\frac{e^+p}{e^-p}$ cross section ratios, including a (conditionally approved) proposal for Hall B.
- "Super-Rosenbluth" method involving proton detection enables precision L/T separations in e^+p

- Spokespersons: M. Nycz, J. Arrington, S. N. Santiesteban, M. Yurov
- If TPE fully explains the discrepancy, the Rosenbluth Slope (RS) for positrons should fall well below the PT data and turn negative.
- **Status: Approved**



What about Polarization Transfer?





- No significant ϵ dependence seen in P_T/P_L ratio
- Hint of an effect in $\frac{P_L}{P_L^{Born}}$, but only ~2σ significance
- Positron PT observables never measured before!
- Polarization observables less sensitive to TPE, but not immune!
- Not just ϵ dependence, but also difference between e^+p/e^-p

Prospects for polarization transfer using positrons

Regular Article - Experimental Physics | Published: 09 June 2021

Polarization transfer in $e^+p \rightarrow e^+p$ scattering using the Super BigBite Spectrometer

A. J. R. Puckett, J. C. Bernauer & A. Schmidt

The European Physical Journal A **57**, Article number: 188 (2021) | Cite this article

142 Accesses | **3** Citations | **1** Altmetric | Metrics

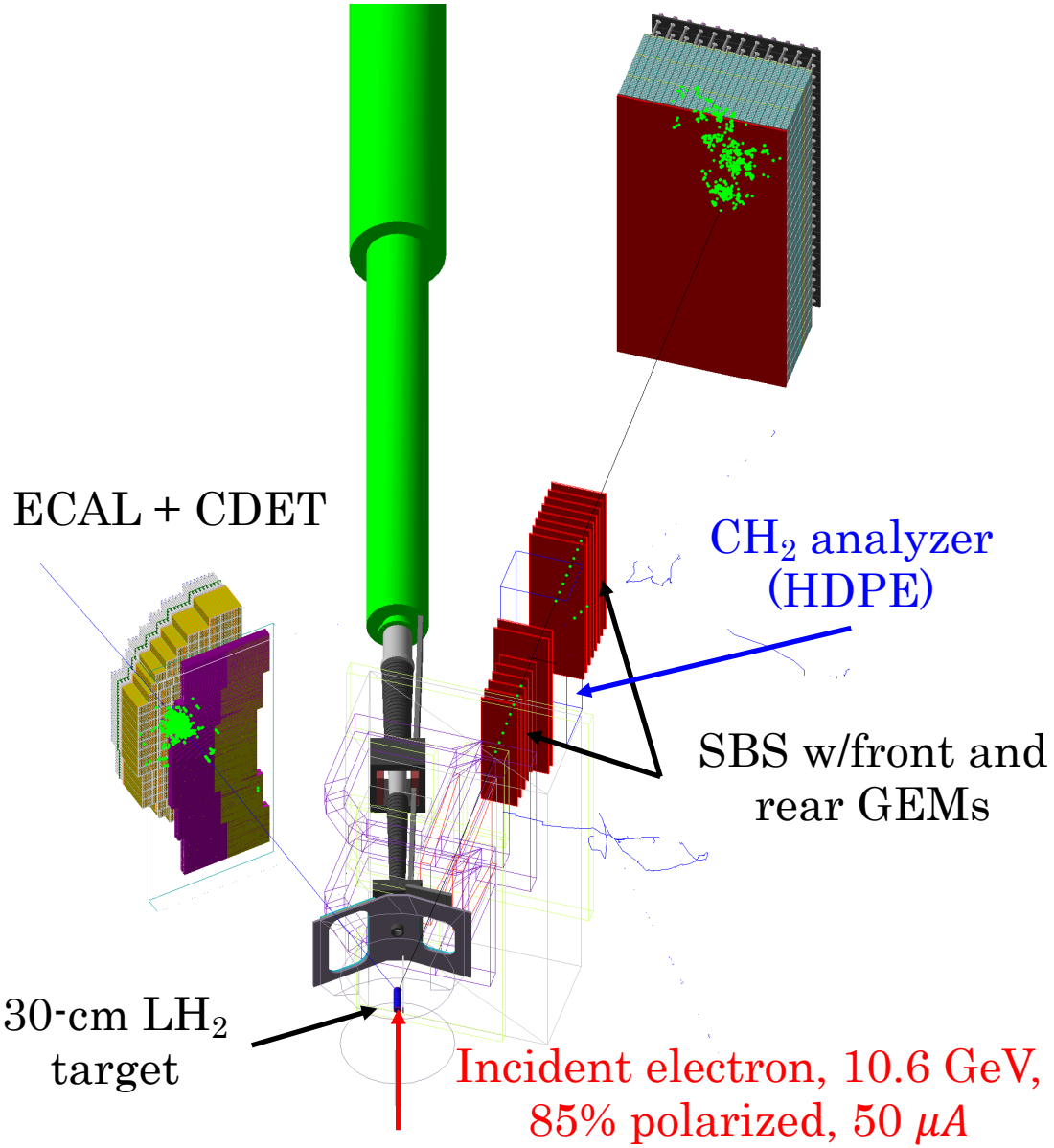
Abstract

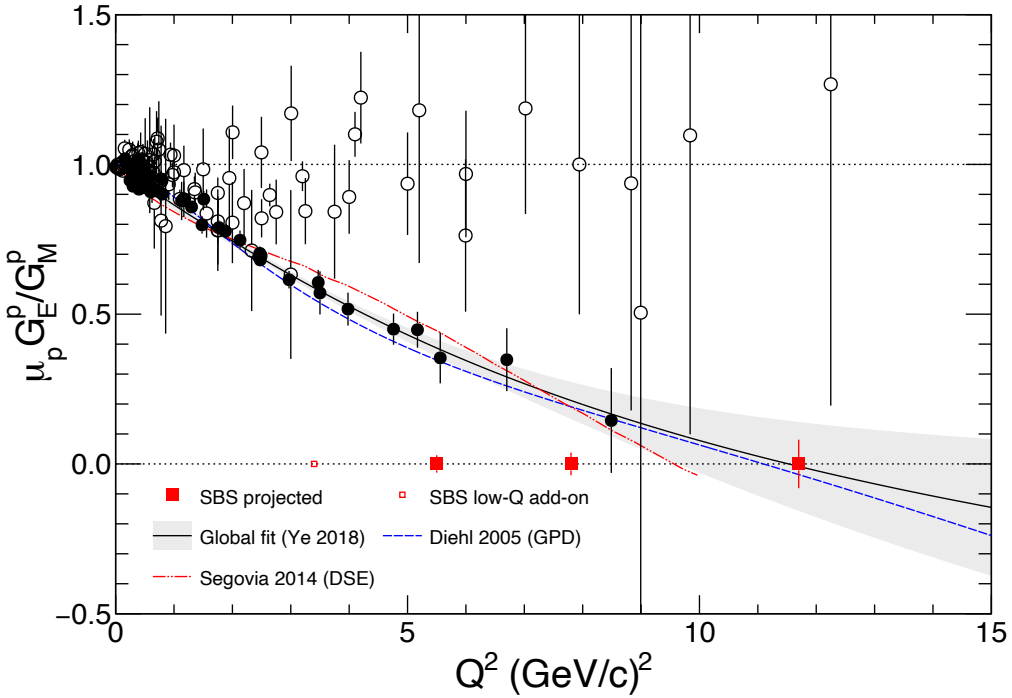
The effects of multi-photon-exchange and other higher-order QED corrections on elastic electron-proton scattering have been a subject of high experimental and theoretical interest since the polarization transfer measurements of the proton electromagnetic form factor ratio G_E^p/G_M^p at large momentum transfer Q^2 conclusively established the strong decrease of this ratio with Q^2 for $Q^2 > 1$ GeV^2. This result is incompatible with previous extractions of this

A. J. R. Puckett *et al.*, Eur.Phys.J.A 57 (2021) 6, 188

- PEPPO experiment demonstrated concept of polarized positron source driven by high-intensity polarized electron beams.
- ***PT has never been measured in positron scattering at any Q^2 (to my knowledge)***
- PT/LT discrepancy is still by far the most significant (albeit indirect) evidence for the importance of hard TPE effects in elastic *ep*.
- Positron/electron cross section ratios and L/T separations with positrons will be pursued in the Q^2 regime where the discrepancy is most significant
- Comparison of PT between e^+/e^- and comparison of LT/PT results for e^+p scattering (independent of electron scattering data) will be extremely interesting, and essential in the eventual conclusive resolution of the discrepancy
- **SBS GEP apparatus enables competitive precision in a "reasonable" amount of beam time!**

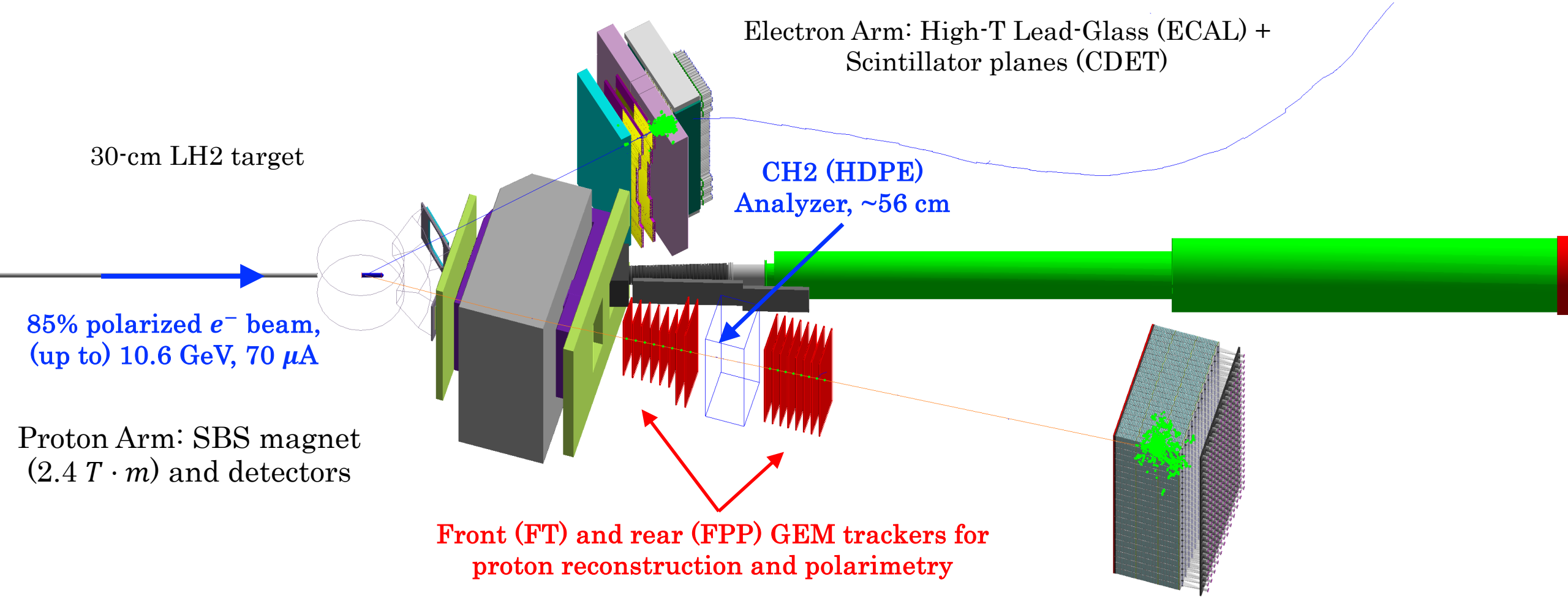
The SBS G_E^p Experiment (E12-07-109): Scheduled 2024-2025





- Proposed 2007, designated "High Impact Experiment" by JLab PAC41
- Jeopardy proposal reapproved by PAC47 in 2019
- Currently scheduled to run 2024-2025
- ERR April 2023
- Novel high-temperature lead-glass calorimeter detects scattered electron with scintillator-based coordinate detector—trigger, aid tracking in front GEMs, and reject inelastics
- GEM-based trackers with CH_2 analyzer for proton polarimetry
- HCAL for trigger and preferential selection of nuclear scattering events with high analyzing power

SBS GEP in *g4sbs* (GEANT4-based Monte Carlo framework for SBS program)



https://github.com/JeffersonLab/g4sbs

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

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https://sbs.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=398

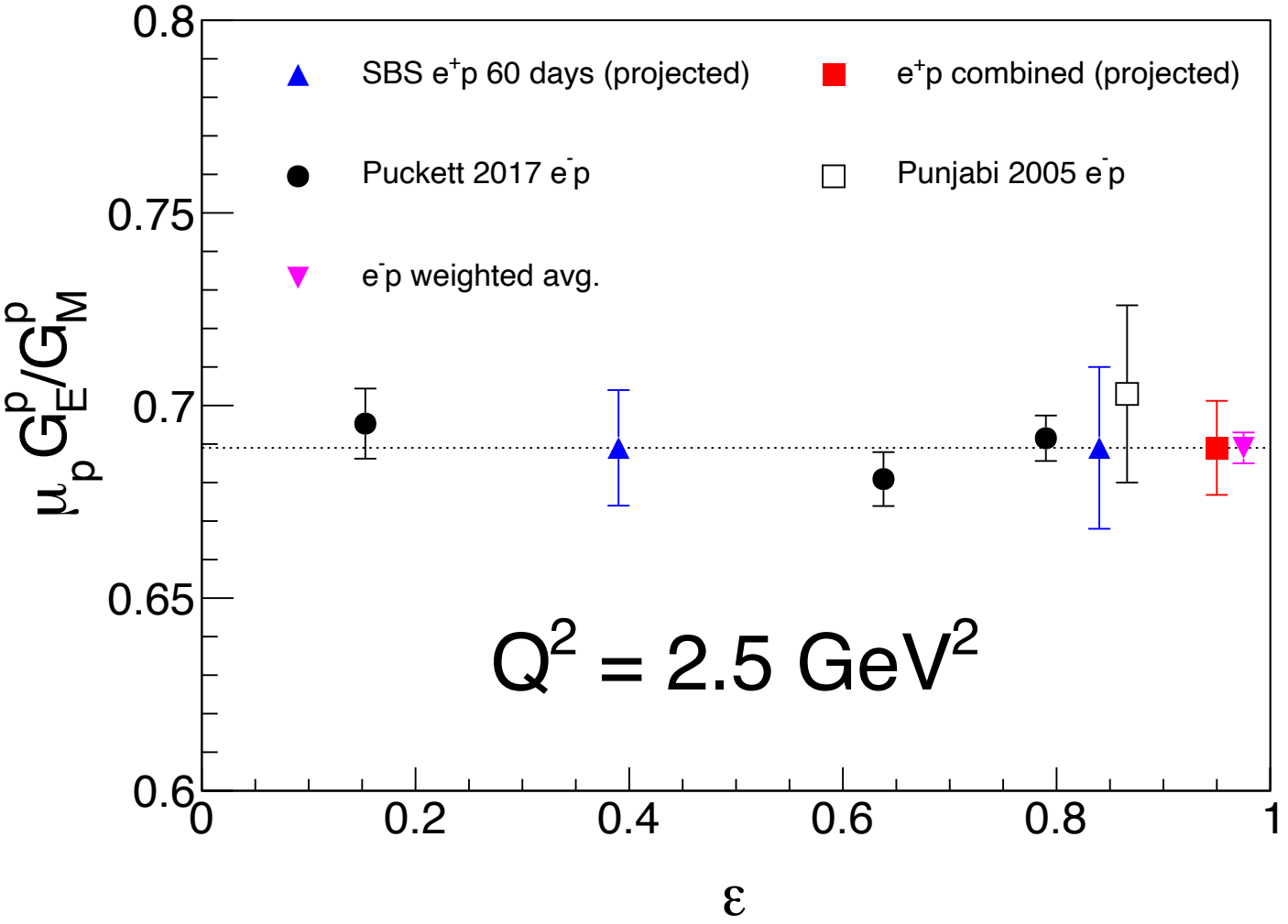
Kinematics and precision goals

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

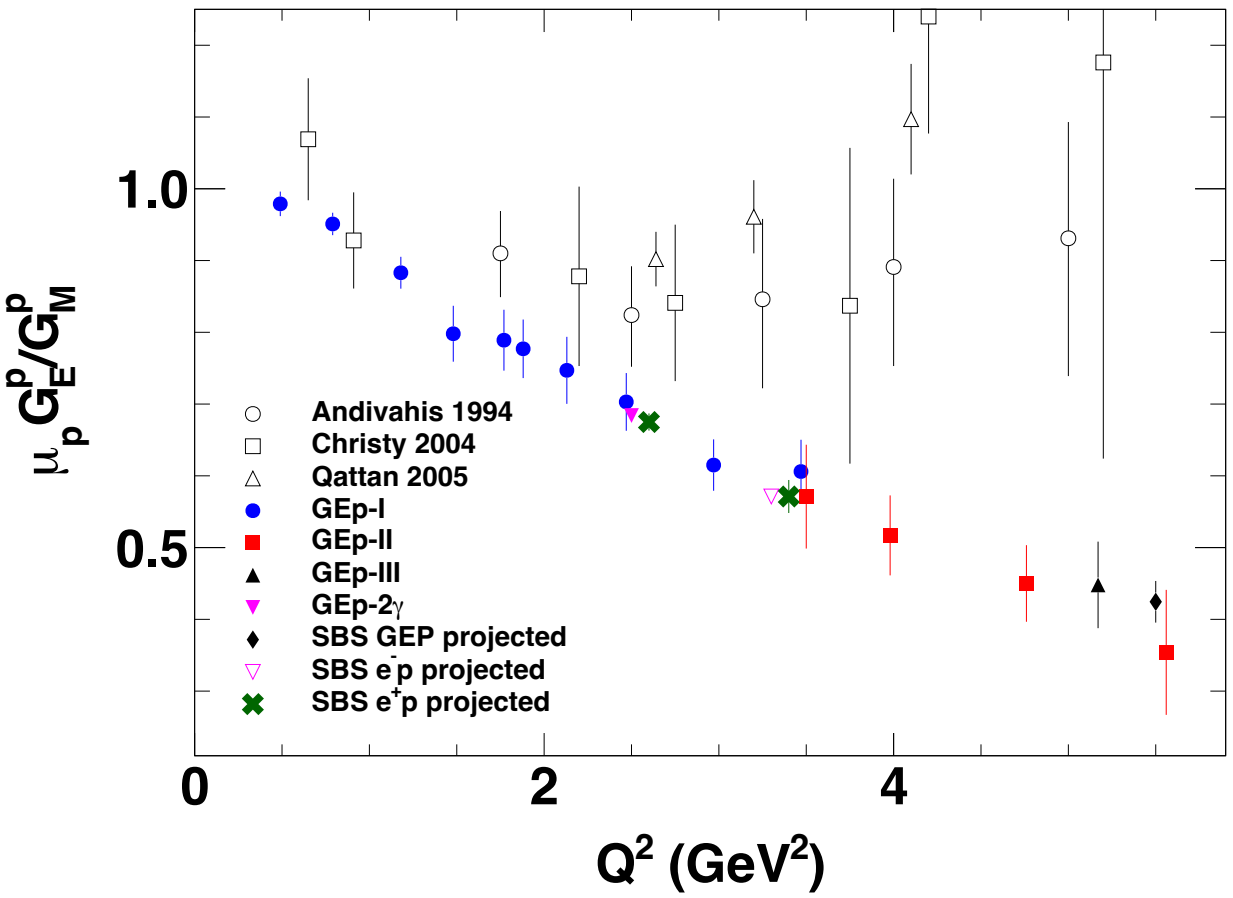
- Measure ϵ-dependence at 2.5 GeV^2 for precise comparison to existing electron data (GEp-2γ) (60 days)
- Measure another point at ~3.5 GeV^2 with ~2% statistical precision, BETTER than existing electron data. (60 days)
- Add one Q^2 point at 2nd-pass (3.5 GeV^2) to upcoming SBS GEP run; 1% statistical precision in 1-2 PAC days, anticipating comparison to future positron measurement (also will aid GEP commissioning and systematics control)
- "Special" requirements assumed in LOI: 40-cm LH2 target, 200 nA positron beam at 60% polarization, SBS+ECAL

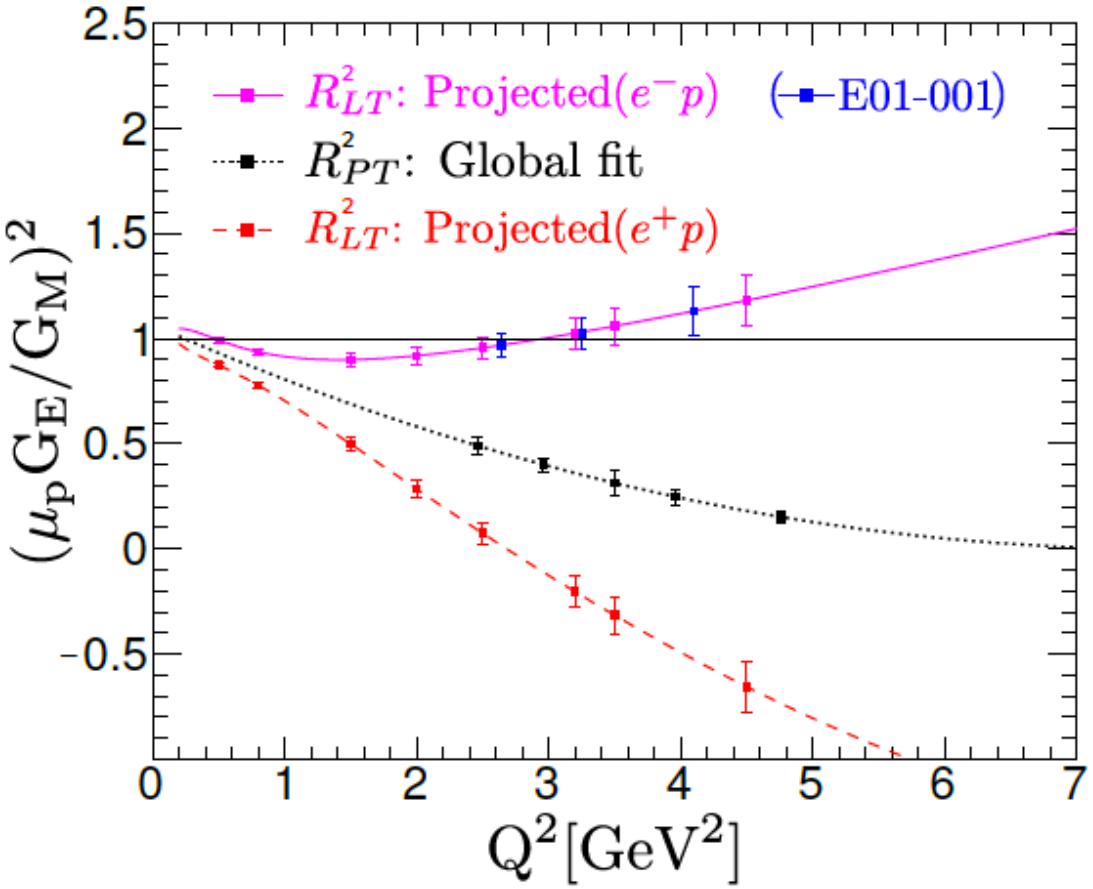
SBS Positron Polarization Transfer: ϵ dependence at 2.5 GeV^2



- First pass and second pass measurements would cover ϵ = 0.4 and 0.84
- Combined result would have 1.2% absolute statistical precision

SBS Positron Polarization Transfer: Q^2 dependence and comparison to L/T





- Experiment is *expensive* in beam time (4 PAC-months) and demanding in polarized positron current to reach ~1-2% precision goal at 2.5-3.5 GeV², but even a 2-4% measurement would be competitive with existing PT data and would EASILY see the expected "discrepancy" with positron Rosenbluth data that will be pursued in Hall C

PAC51 Report on LOI12-23-008:

LOI12+23-008

Title: Polarization Transfer in Positron-Proton Elastic Scattering

Spokespersons: A. Puckett (contact), J. Bernauer, A. Schmidt

Motivation: This LOI proposes to measure the polarization transfer from the initial lepton to the final proton in elastic positron-proton scattering e +p → e + p for a series of momentum transfers Q^2 and virtual photon polarizations ϵ where a large discrepancy exists between the proton form factor ratio G^pE/G^p_M extracted from cross section and polarization transfer measurements. Comparing the proposed positron measurements to existing data with electron beams will allow a determination of the two-photon exchange (TPE) contribution to the polarization transfer observable. An ancillary measurement with electrons at $Q^2 = 3.4$ GeV^2 is envisaged as well.

Measurement and Feasibility: The polarization transfer in electron-proton scattering has been extensively measured at JLab, and the present LOI extends such measurements to a positron beam. Experimental details are not given.

Issues: The bulk of material presented in the letter relies on a previous study that assumed a higher beam current for polarized positrons than is currently foreseen. The PAC recommends to use the beam parameters specified by the positron working group as a baseline for a proposal.

Summary: The proposed measurement would be a valuable addition to the quantitative study of TPE effects in elastic scattering. A full proposal should include a detailed study of anticipated systematic and statistical uncertainties, along with theory predictions for the expected difference between the polarization transfer observable for positron and electron beams. The latter will be needed in order to assess the physics impact of the measurement.

- The $\vec{e}^+p \rightarrow e^+\vec{p}$ LOI (as submitted to PAC51) can be found here: https://www.jlab.org/exp_prog/proposals/23/LOI12+23-008.pdf
- There would be no significant technical risk on any of the target or detector aspects of this proposal. All of this apparatus will be used in upcoming SBS GEP run.
- The uncertainties would be strictly statistics-limited, with small systematics.
- For me the PAC seems lukewarm on this LOI, so I am somewhat ambivalent to invest the time in a full proposal development.
- Nevertheless, we will probably proceed at PAC52, since our ancillary $\vec{e}^-p \rightarrow e^-\vec{p}$ measurement would ideally be added onto the upcoming SBS GEP run (Oct. 2024-May 2025)
- There are a few exploratory calculations to do before proceeding to a full proposal

Steps toward full proposal

- Investigate increasing the target thickness to increase luminosity—in principle, this is limited only by the useful acceptance of the SBS for an extended target. Target thickness and possible improvement of the polarimeter FOM could largely compensate for the lower polarized positron current than we assumed in our published study in EPJA
- Investigate a range of theoretical/phenomelogical calculations of the difference between e^+p and e^-p polarization transfer (and their interplay with cross section data)
- Optimize the kinematics and beam time and do detailed evaluation of uncertainties.
- Form (larger) collaboration, identify commitments

Summary and conclusions

- LOI was submitted to PAC51 based on our earlier published study in the EPJ A topical issue.
- We recognize that this proposal is expensive in beam time, and could be a hard sell to the PAC if the consensus of theoretical predictions is that the e^+p, e^-p difference in this observable is expected to be "small"
  - Even a 1-2% measurement over a range of Q^2, ϵ might not confirm a statistically significant difference
- However, I would argue that an exploratory measurement at a precision competitive with the best existing e^-p data in the high-Q^2 region has high value *regardless* of any e^+/e^- difference in this observable, owing to its uniqueness and complementarity:
  - Confirm (or refute) the "null" prediction of a small hard-TPE effect in this observable
  - Strongly support (or refute) the consensus that polarization transfer gives us the "true" Born FF ratio
  - Combine with (approved) Hall C positron "Super-Rosenbluth" measurements to establish (or refute) the very large expected difference between cross section and polarization transfer in e^+p scattering and measure its sign and magnitude with very high statistical significance
  - Provide precise independent constraints and consistency checks on the formalism for applying model-independent hard-TPE corrections to elastic scattering data
- Despite the somewhat lukewarm "endorsement" of our LOI by PAC51, we intend to proceed to a PAC52 submission assuming the exploratory studies and experiment optimizations look sufficiently promising.
- We are welcoming collaborators, as SBS is not a trivial thing to put on the floor and operate in any Hall, and this experiment would run long after the current SBS program leaves the floor of Hall A!
- Any significant surprises from an exploratory measurement here could motivate a larger, more comprehensive program and drive R&D for improvements in polarized positron P^2I that would also enable other, more ambitious physics goals