LT-10: Rosenbluth separation of the elastic electron-proton scattering cross section at $Q^2 = 9.5\ (\mathrm{GeV}/c)^2$

PAC54 proposal PR12-26-007

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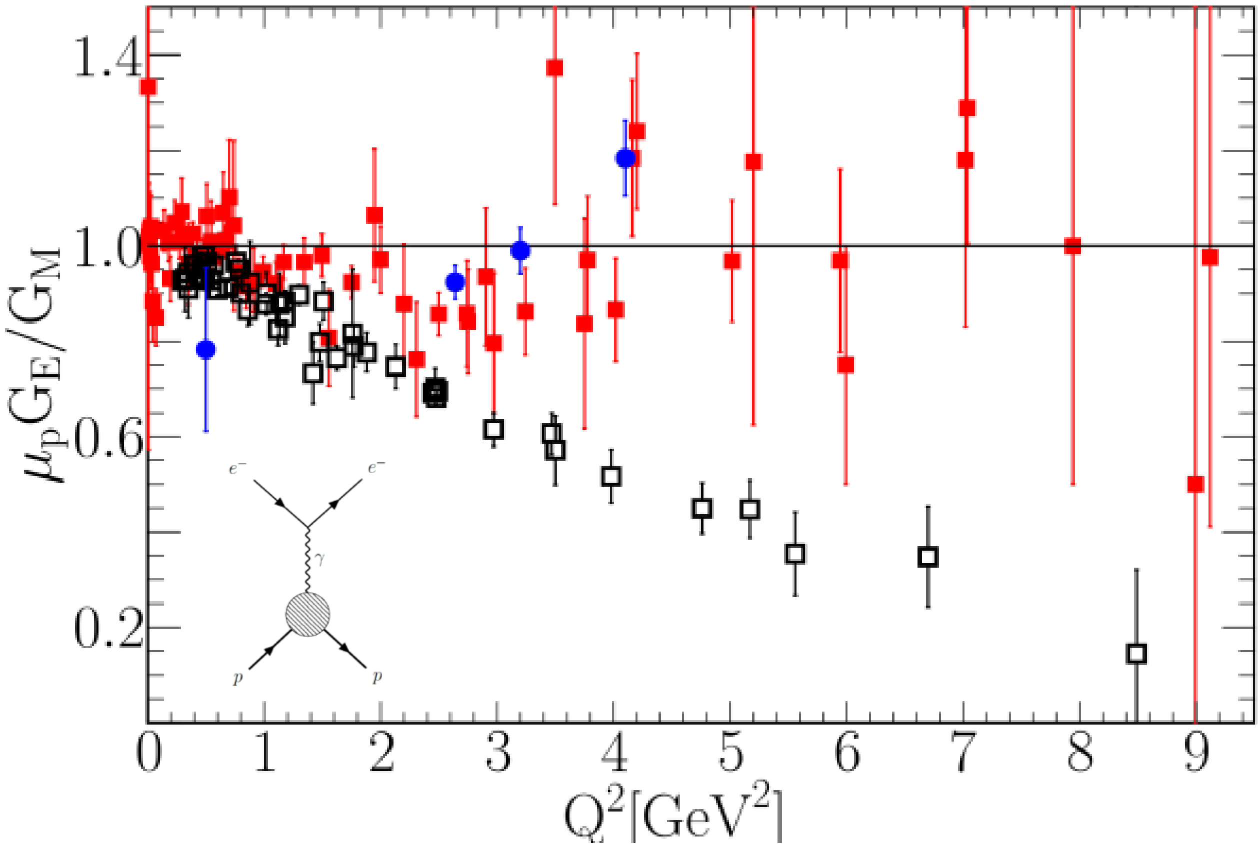
Elastic electron-proton scattering L/T separation at high Q^2

- The electromagnetic form factors of the proton are fundamental quantities that encode the spatial distribution of magnetization (G_M) and charge (G_E) in the proton.
- In the one photon-exchange approximation, the individual form factors are found by using cross-section measurements at fixed Q^2 but different values of epsilon (ε), corresponding to different electron beam energies and scattering angles.
- The observed form-factor ratio obtained through the above Longitudinal-Transverse (L/T) separation method **contradicts** the ratio obtained using the polarization transfer method.

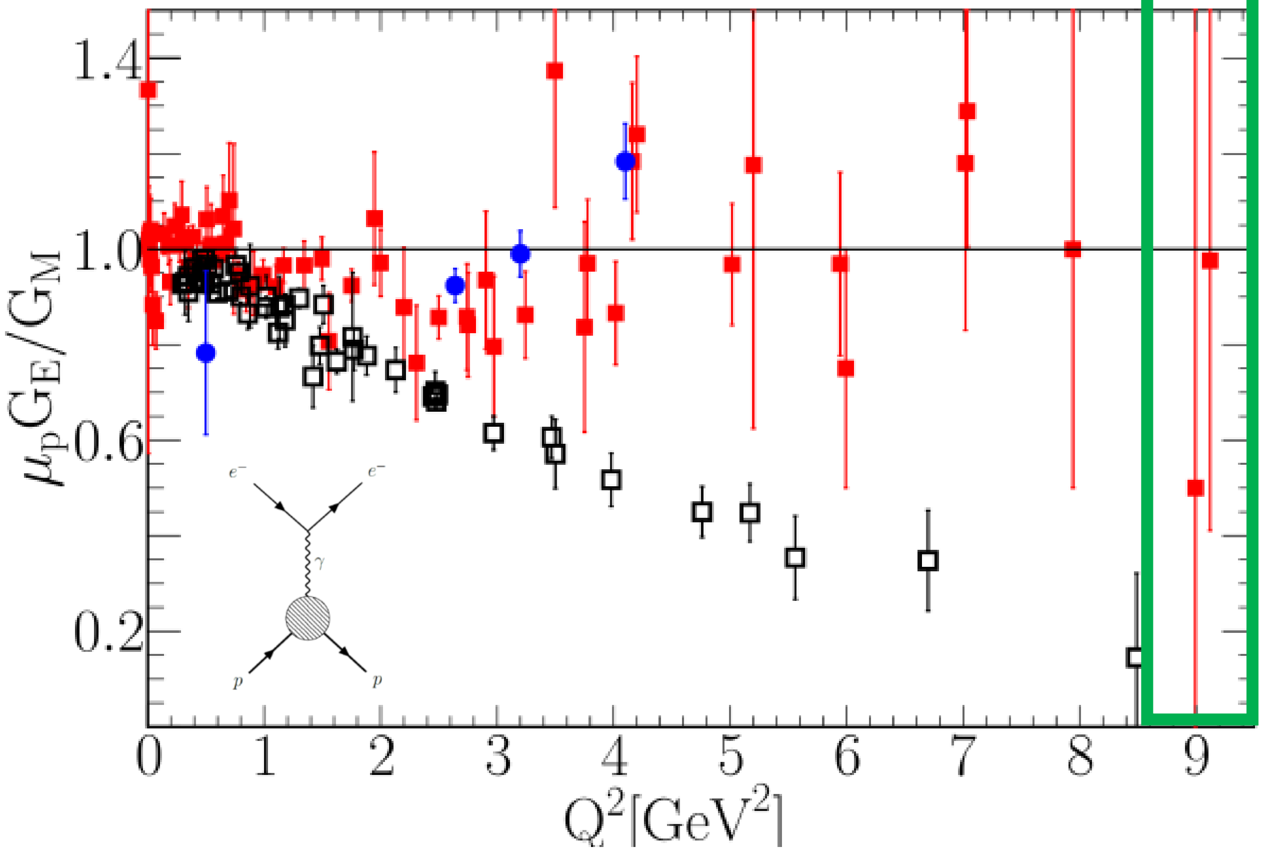


L/T separation: **Red** and **Blue** points
Polarization transfer: **Black** points

Elastic electron-proton scattering L/T separation at high Q^2

- Why is L/T important to measure at high Q^2?
  - G_M in the one-photon approximation has been determined experimentally to the 2-3% level.
  - For a complete understanding of the structure of the proton, we need to take into consideration the effects of two-photon exchange, which may contribute to the reduced cross section up to 5% at Q^2~10GeV^2 when ε=0.
  - The development of two-photon exchange theory will advance with the availability of experimental data.
- This presentation will describe how we can we can perform an L/T separation at Q^2 = 9.5 GeV^2 using the HMS and SHMS spectrometers in Hall C with a **15.5 day run**.

Currently have 50-100% Rosenbluth separation uncertainty at Q^2~10 GeV^2



L/T separation: **Red** and **Blue** points
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What makes the L/T separation challenging at high Q^2

- At fixed Q^2, the elastic e-p reduced cross section exhibits a linear epsilon dependence. The fractional change in the reduced cross section from ε=0 to ε=1 is proportional to $1/(\tau\mu_p^2)$.

at Q^2 = 9.5 GeV^2 $\boxed{\tau\mu_p^2 \approx 21}$

- So, a reduced cross section epsilon-dependent variation of only a few percent expected at high Q^2.
- Observed linearity of reduced cross section is not sufficient to exclude two-photon exchange contributions.

In the one-photon exchange (OPE) approximation:

$$\sigma_R = \tau G_M^2 + \varepsilon G_E^2 \qquad \tau \equiv \frac{Q^2}{4M^2}$$

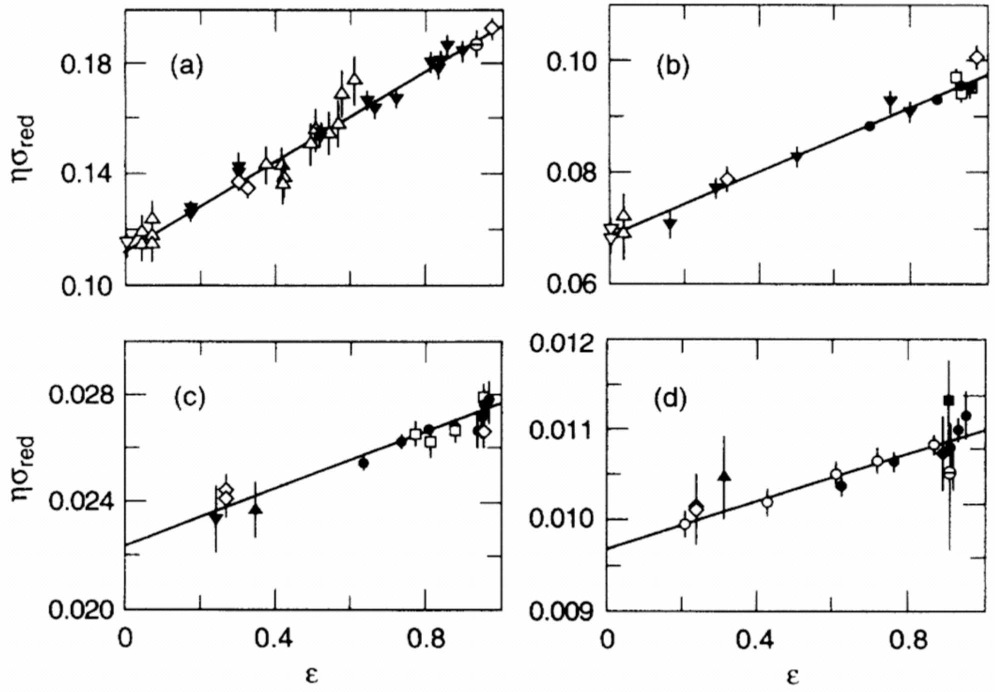

FIG. 9. Four typical Rosenbluth fits for the form factor extraction from the global data set at (a) $Q^2 = 0.6$, (b) $Q^2 = 1.0$, (c) $Q^2 = 2.0$, and (d) $Q^2 = 3.0$ (GeV/c)^2.

Requirements of L/T separation with electron detection

In an L/T experiment with detection of the scattered electron we need to measure the following very accurately:

- Beam charge
- Beam energy
- Target thickness
- Spectrometer momentum
- Spectrometer angle
- Spectrometer solid angle
- Detector efficiency

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta_e}{2}\right]$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2 \cos^2(\theta_e/2)}{4E^2 \sin^4(\theta_e/2)} \frac{E'}{E}$$

Example high-Q^2 configuration:

Quantity	Symbol	Value
Incident beam energy	E	11.00 GeV
Recoil proton momentum	$\lvert\vec{P}\,'\rvert$	5.927 GeV/c
Recoil proton energy	E_p'	6.001 GeV
Recoil proton angle	ϕ	22.030°
Scattered electron energy	E'	5.94 GeV
Scattered electron angle	θ	21.979°
Squared momentum transfer	Q^2	9.50 GeV^2/c^2
Polarization parameter	ε	0.781

$5\text{x}10^{-4}$ change in beam energy → 0.38% change of $\frac{d\sigma}{d\Omega}$

1 mrad change in θ_e → 2.1% change of $\frac{d\sigma}{d\Omega}$

Advantages of L/T separation with proton detection

In an L/T experiment with detection of the scattered proton we need to measure very accurately:

- Beam charge
- Beam energy
- Target thickness stability
- Spectrometer solid angle
- Spectrometer momentum stability
- Detector efficiency stability

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left(1 - \frac{Q^2}{2EM} - \frac{Q^2}{4E^2}\right)\frac{G_E^2 + \frac{\tau}{\epsilon}G_M^2}{1+\tau}$$

$$Q^2 = 2M_p(E_p - M_p)$$

Proton energy (momentum) is constant at fixed Q^2!

Example high-Q^2 configuration:

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5×10^{-4} change in beam energy → 0.017% change of $\frac{d\sigma}{dQ^2}$

1×10^{-4} change in E_p → 0.069% change of $\frac{d\sigma}{dQ^2}$

Experimental considerations

- **Largest possible Q^2** with an 11 GeV beam and accessible with the Hall C spectrometers' momentum and angular range
- **Three epsilon points** with standard beam energies and fixed spectrometer momentum and magnetic optics
- **20-cm long LH_2 target**, allowing for the removal of inelastic protons produced in the target windows by a cut on reaction vertex and to avoid luminosity variation with beam position
- Study of **spectrometer momentum resolution** (shape) using dedicated coincidence measurements
- Study of **proton spectrum related to pion production** with a dedicated run with a radiator
- **Rejection of pions and other background particles** in the spectrometer acceptance by the combined use of aerogel and gas Cherenkov counters

Experimental Configuration

The experiment will have **three kinematic settings**, all with $Q^2 = 9.5\ GeV^2$ and both the HMS and SHMS set at $P_{central} = 5.927\ (GeV/c)$

Setting	Beam Energy [GeV]	Epsilon (ε)	Proton Scattering Angle [deg]	HMS Elastic Rate [Hz]	Proposed Run Time [Hrs]
1	6.6	0.307	12.69	2.1	56
2	8.8	0.635	19.05	2.5	51
3	11.0	0.782	22.03	2.8	47

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Rates have been updated based upon more accurate cross-section modeling, spectrometer acceptance modeling (using SIMC), and application of a cut on proton momentum deviation from elastic peak.

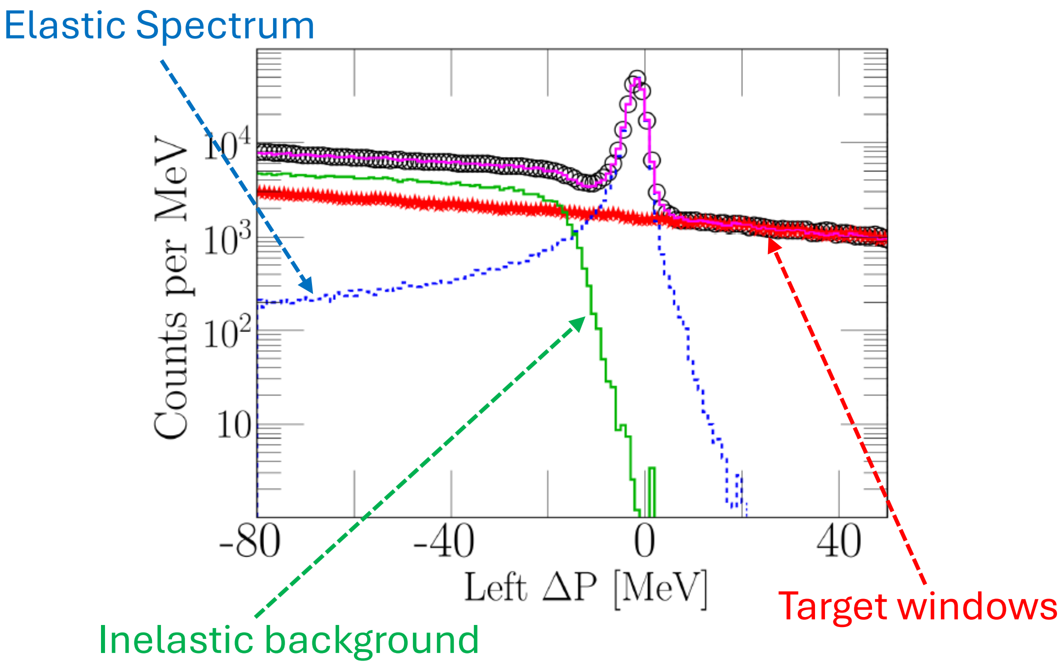
Approach to inelastic proton sources

Phys. Rev. C **112**, 035205

High precision measurements of the proton elastic electromagnetic form factors and their ratio at $Q^2 = 0.50$, 2.64, 3.20, and 4.10 GeV^2

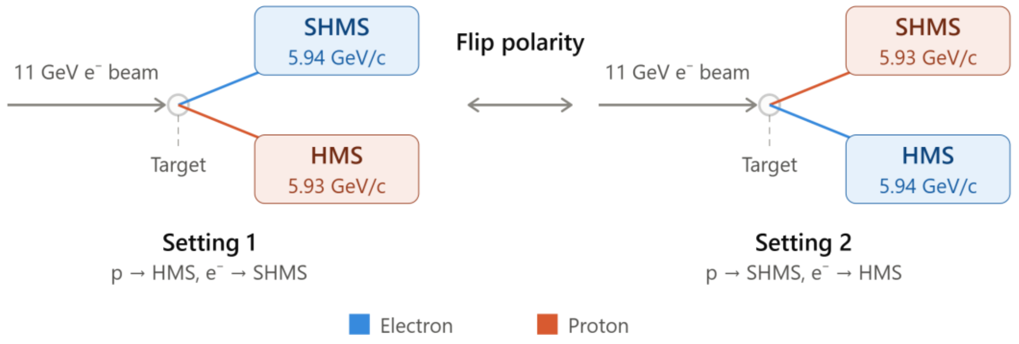
I. A. Qattan,[1,2] J. Arrington,[3,4] K. Aniol,[5] O. K. Baker,[6] R. Beams,[4] E. J. Brash,[7] A. Camsonne,[8] J.-P. Chen,[9] M. E. Christy,[6] D. Dutta,[10] R. Ent,[9] D. Gaskell,[11] O. Gayou,[12] R. Gilman,[13,9] J.-O. Hansen,[9] D. W. Higinbotham,[9] R. J. Holt,[4,*] G. M. Huber,[7] H. Ibrahim,[14] L. Jisonna,[2] M. K. Jones,[9] C. E. Keppel,[6] E. Kinney,[11] G. J. Kumbartzki,[13] A. Lung,[9] K. McCormick,[13] D. Meekins,[9] R. Michaels,[9] P. Monaghan,[10] L. Pentchev,[12] R. Ransome,[13] J. Reinhold,[15] B. Reitz,[9] A. Sarty,[16] E. C. Schulte,[4] K. Slifer,[17] R. E. Segel,[2] V. Sulkosky,[12] M. Yurov,[18,19] and X. Zheng[4,†]

- The proton spectra from the E01-001 experiment performed in Hall A during the 6-GeV CEBAF era is shown to the right.
- We will suppress the contributions from the target windows by using a 20-cm long target and applying a cut on the reaction vertex.
- We will reduced uncertainty of the pion-related production by taking dedicated some data with a radiator in front of our target.



Dedicated run to study elastic peak shape

- We will exploit the availability of two spectrometers in Hall C to study the shape of the elastic peak in the absence of background processes.
- The symmetry between the scattered electron and proton kinematics at 11 GeV will allow us to perform this coincidence run without moving either spectrometer.



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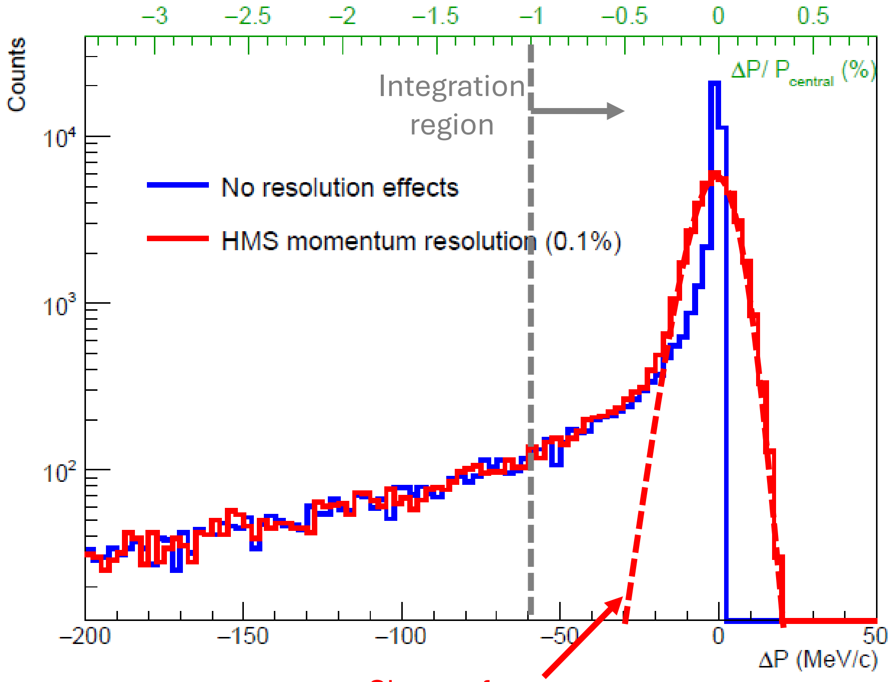


Dedicated run with external radiator

The rate of production of neutral pions (or charged pions) is the given by the sum of quasi-real photon interactions and real photon interactions:

$$\sigma^{\text{total}} = \int \frac{N_{\text{EPA}}(\omega)}{\omega} \cdot \sigma_{\gamma p}(\omega)\, d\omega + \int \frac{dN_{\text{brems}}}{d\omega} \cdot \sigma_{\gamma p}(\omega)\, d\omega$$

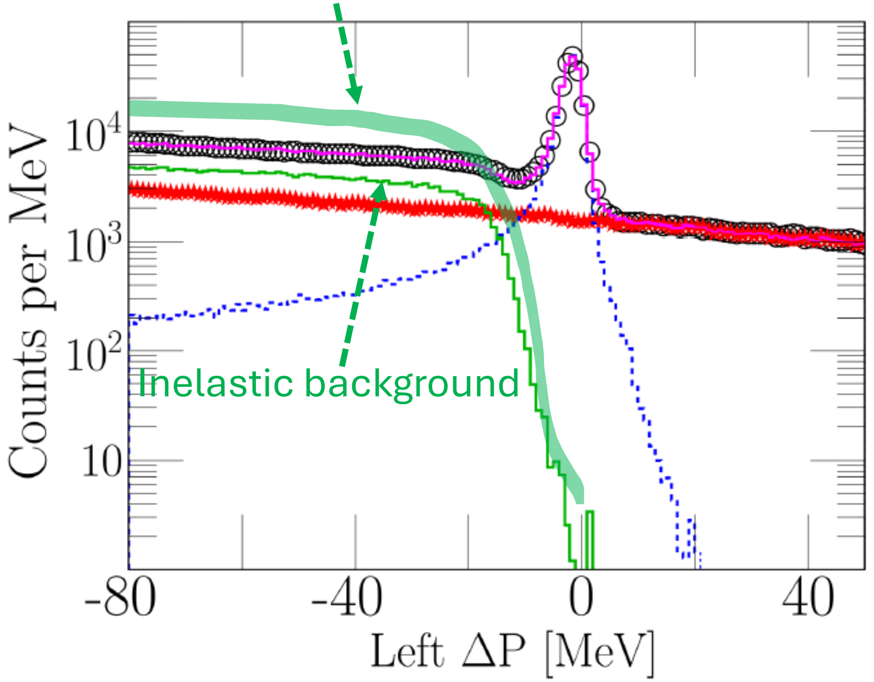
Quasi-real photon intensity per electron:

$$N_{\text{EPA}}(\omega) = \frac{\alpha}{\pi}\left[\left(1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2}\right)\ln\frac{q^2_{\text{max}}}{q^2_{\text{min}}} - \left(1 - \frac{\omega}{2E}\right)^2 \ln\frac{\omega^2 + q^2_{\text{max}}}{\omega^2 + q^2_{\text{min}}} - \frac{m_e^2\omega^2}{E^2 q^2_{\text{min}}}\left(1 - \frac{q^2_{\text{min}}}{q^2_{\text{max}}}\right)\right]$$

Real photon intensity (abbreviated formula, Phys. Rev. **93**, 768):

$$\frac{dN_{\text{brems}}}{d\omega} = \frac{d}{X_0} \cdot \frac{1}{\omega}\left[\frac{4}{3} - \frac{4\omega}{3E} + \frac{\omega^2}{E^2}\right]$$

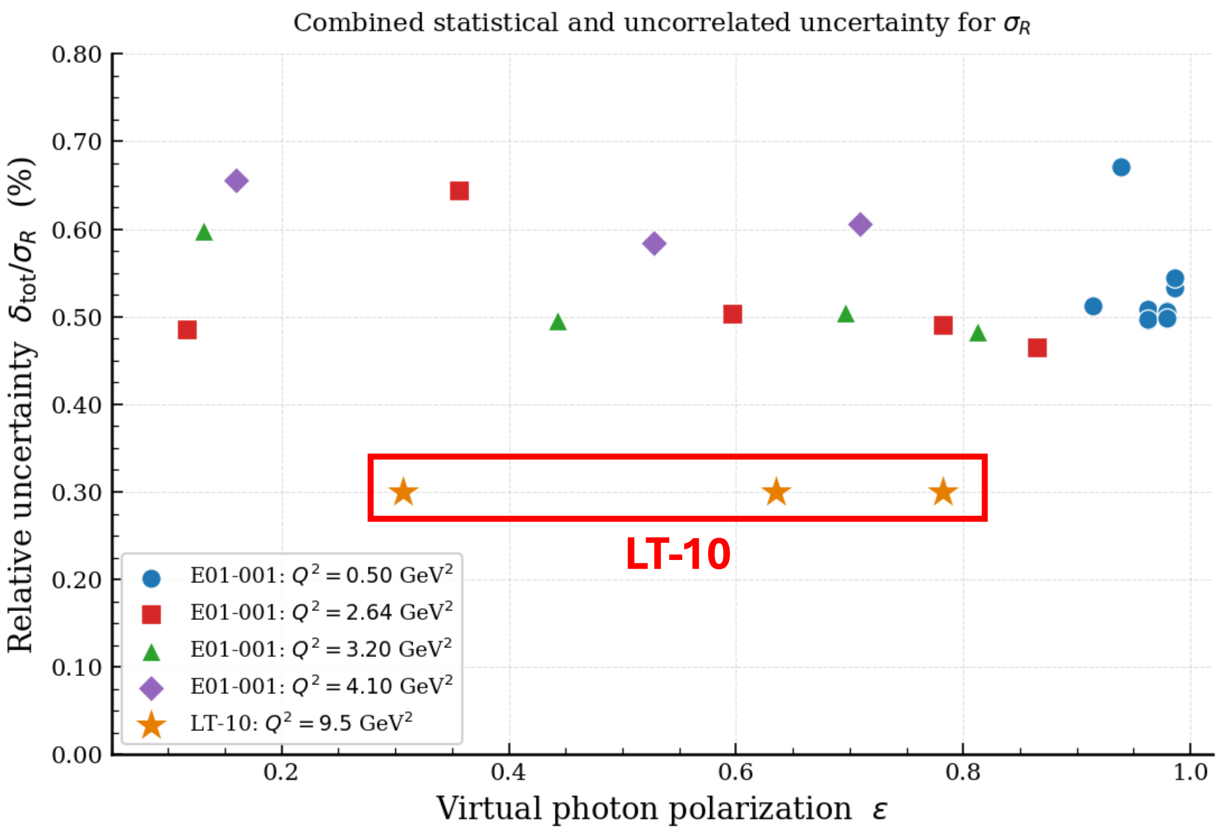
Determination of background shape by using data with external radiator



Phys. Rev. C **112**, 035205

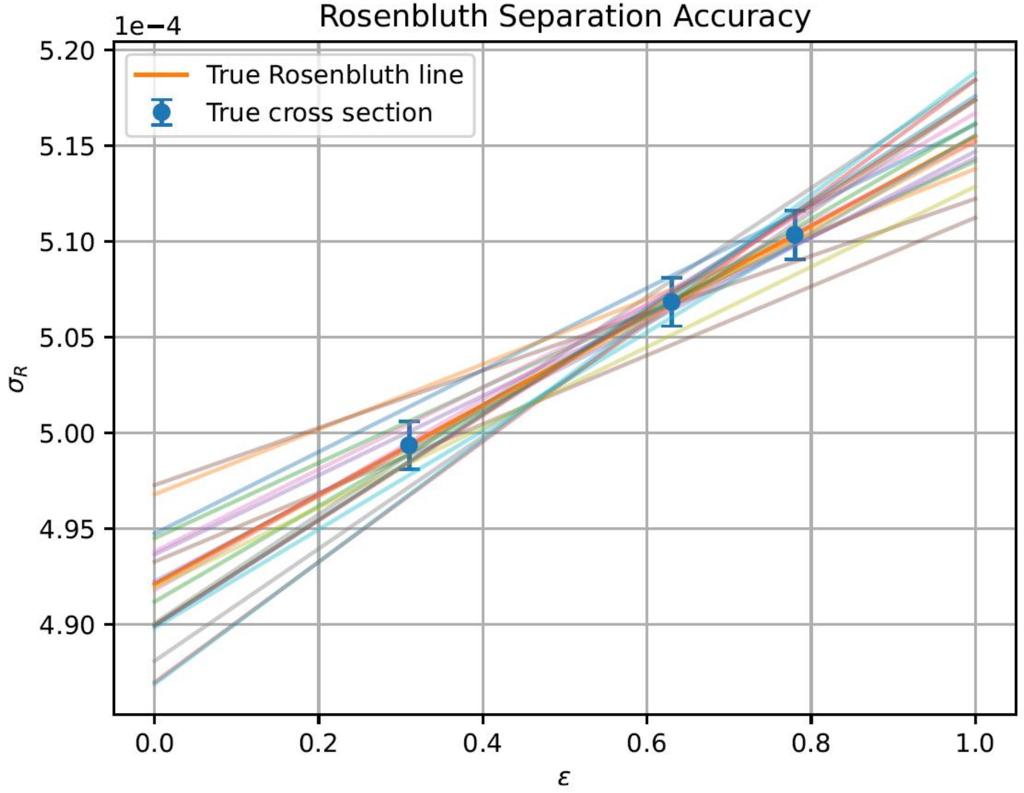
Accuracy on cross section

- Our goal is to measure the reduced cross section at each epsilon point with a combined statistical and uncorrelated systematic uncertainty of <0.30%.
- In the E01-001 experiment, which also used proton detection for L/T separation, the uncertainties ranged from about 0.45% to 0.67%.
- The improvements presented above in the determination of the elastic peak shape, the approach to inelastic proton sources, and the stability of the target thickness will allow us to reach the presented accuracy.
- At the same, even an accuracy of 0.6% would provide a dramatic improvement of our knowledge of two-photon exchange at Q^2~10 GeV^2.

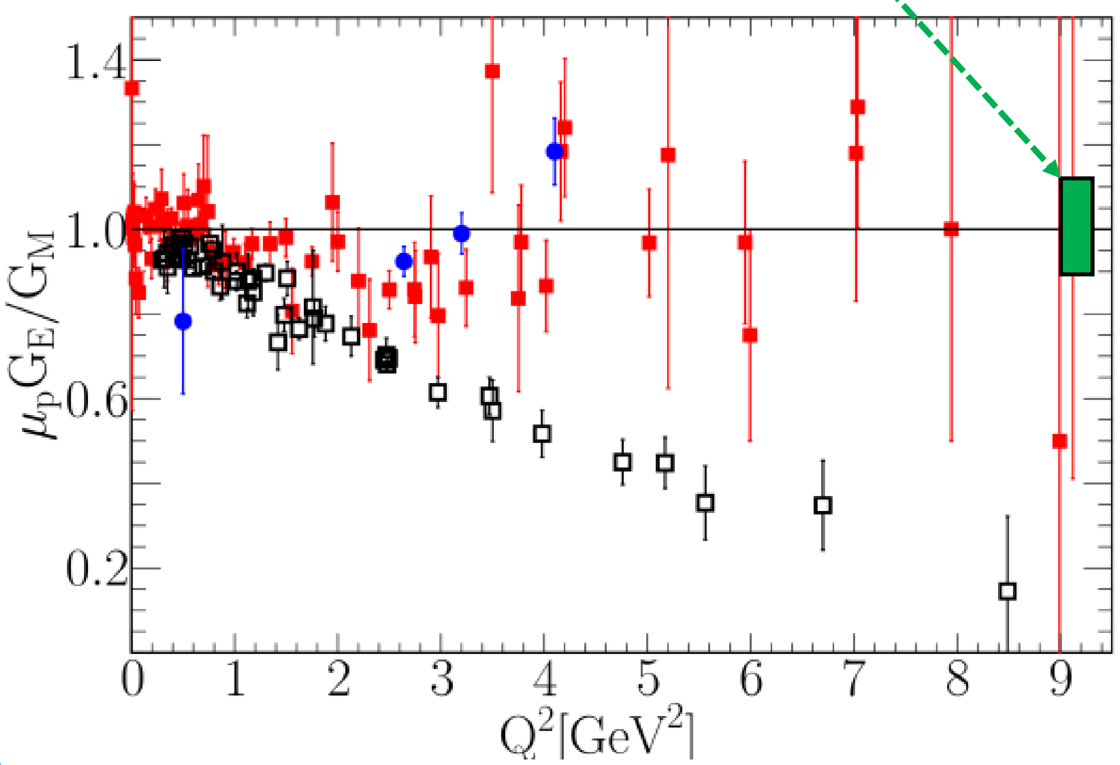


Projected 10% relative accuracy on G_E/G_M in OPE

Combined updated statistical (0.15%) and uncorrelated systematic (0.2%) uncertainties on each epsilon point



Projected result:
10% relative accuracy!



$$\frac{\delta R_{LT}}{R_{LT}} \simeq \frac{\tau\mu_p^2}{2\cdot\Delta\epsilon} \times \frac{\delta\sigma}{\sigma}$$

Detailed run plan for LT-10

Run Type	Summary	Time
Production running	Three kinematic settings, each with the HMS and SHMS placed at an identical angle and momentum to detect elastic protons	8.5 days
Commissioning	Commissioning of the beam parameters and beam instrumentation	1 day
Spectrometer elastic peak resolution (shape)	Calibration of the spectrometers with e-p elastic coincidence events at 11 GeV beam energy	1 day
Target boiling	Study boiling effect in the hydrogen target	1 day
Optics	Data taking on the optics and dummy targets	1 day
Radiator study	Measurement of the proton yield from meson production with radiator at 6.6 GeV beam energy	1 day
Acceptance and efficiency study	Study the stability of the elastic cross section as we adjust the position of the elastic peak within the spectrometer acceptance with small changes to the central momenta of both spectrometers	2 days
Total		**15.5 days**

Responses to selected TAC comments

- **Regarding impact of reaction vertex cut on cross-section accuracy**:
  - The vertex selection will be identical for all kinematics, and the stability of the cut will be defined by the vertex resolution, spectrometer angle, and event statistics. If the resolution on the vertex is 0.3 cm (in the y direction) and the full statistics is 2M proton events, the accuracy of the target length determination (at the smallest 12.7^{o} spectrometer angle) for a 15 cm software cut should be 35 microns – thus the relative accuracy of the used target length is 0.033%. The relative foil positions can be surveyed to similar high accuracy. This will ensure accurate control of the experiment luminosity.
- **Direct pion background**:
  - The HMS aerogel counter (refraction index of 0.015) will have a small signal from the proton, 6.2 times smaller than from a high-speed pion.
  - The SHMS aerogel counter has an aerogel tray with a refraction index of 0.0110 but the proton beta is approximately (1. - 0.0126). As a result, a proton does not produce a signal directly.
  - The SHMS Gas Cherenkov counter will also allow very good pion rejection. Similar options are available in HMS.
- **Boiling study:**
  - As our production running will use a 50 uA current, the boiling test can be performed up to beam current approximately 60 uA.

Summary and beam-time request

- The LT-10 experiment proposes to measure the elastic electron-proton cross section at three epsilon points at $Q^2 = 9.5\ \mathrm{GeV}^2$ using protons detected in both the HMS and SHMS in Hall C.
- For a complete understanding of the structure of the proton, we need to take into consideration the effects of two-photon exchange on the measured elastic cross section. The LT-10 experiment will allow us to do this at a Q^2 value where the measured epsilon dependence is dominated by two-photon exchange effects.
- We are requesting **15.5** days of beam time, which will allow for a determination of G_E/G_M in the OPE approximation with a relative accuracy of better than 10%.
- If approved, our plan prior to taking data is to study available Hall C optics and elastic data and perform more-detailed MC studies.