A Measurement of Two-photon Exchange in Unpolarized Elastic e^+ and e^- Scattering

Hall C Collaboration

01/19/2024

BERKELEY LAB

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Form Factors: ***Rosenbluth Separation***

Unpolarized elastic cross section depends on charge and magnetic form factors: $G_E(Q^2)$ & $G_M(Q^2)$

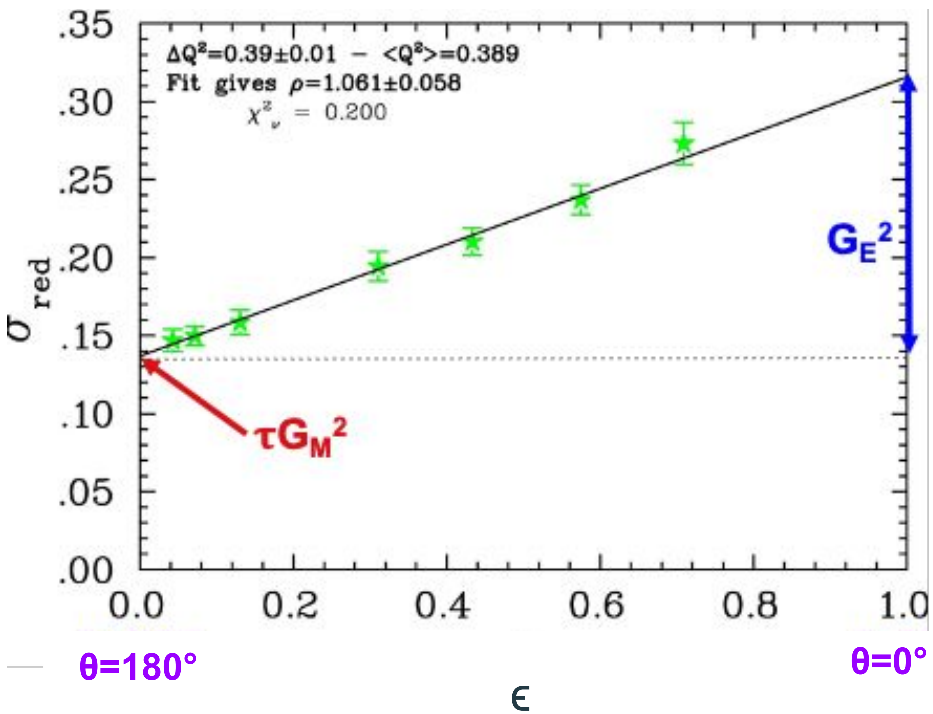
$$\sigma_R = d\sigma/d\Omega\ [\varepsilon(1+\tau)/\sigma_{Mott}] = \tau\ G_M^{\,2}(Q^2) + \varepsilon\ G_E^{\,2}(Q^2)$$

$$\tau = Q^2/4M^2$$

$$\varepsilon = [\ 1 + 2(1+\tau)\tan^2(\theta/2)\ ]^{-1}$$

Measure cross section as a function of ε

Requires:
Multiple beam energies and scattering angles



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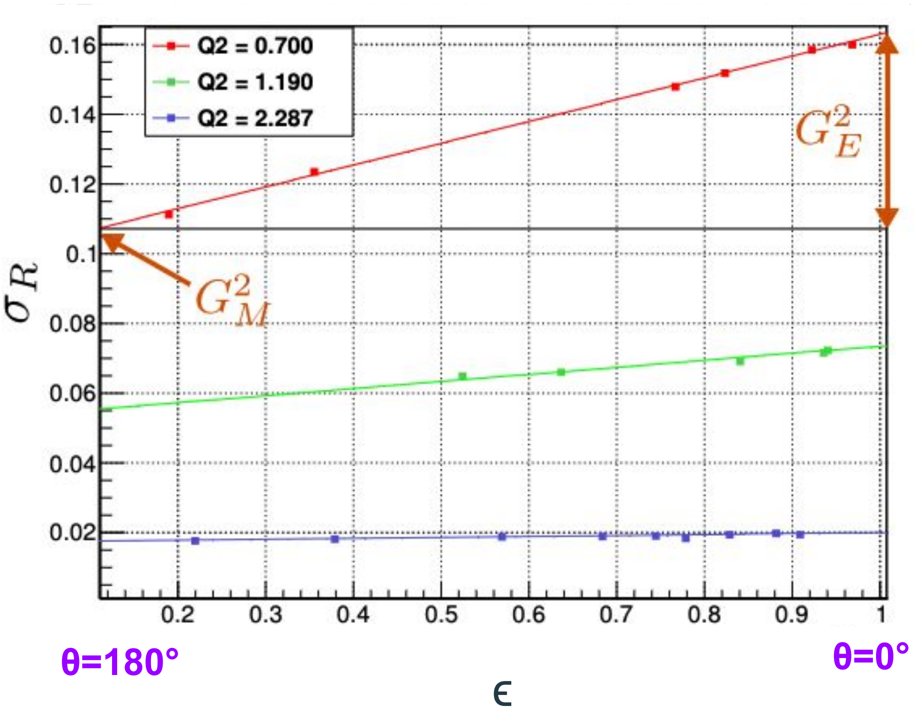
Measure cross section as a function of ε

Requires:
Multiple beam energies and scattering angles

Lower sensitivity when one term dominates:

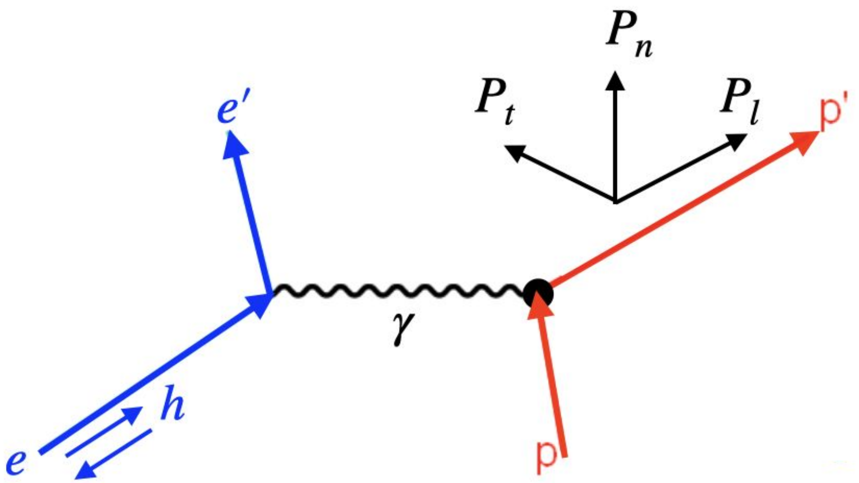
High Q^2: $\tau G_M^2(Q^2) >> \varepsilon G_E^2(Q^2)$

Large uncertainty on G_E at high Q^2



Form Factors: ***Polarization Measurements***

Polarization transfer



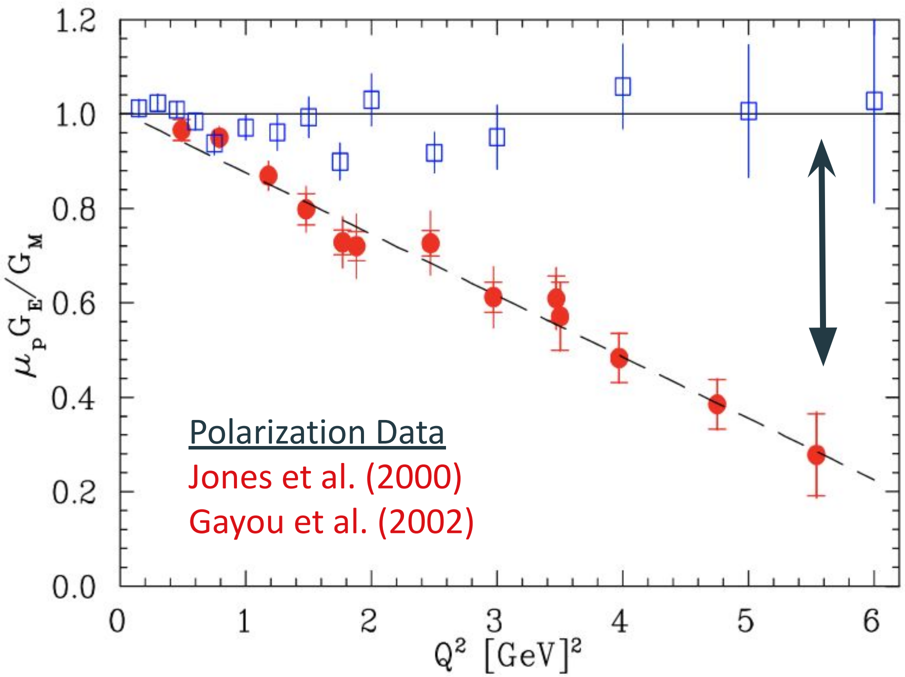
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E+E')}{2M}tan(\theta_e/2)$$

Scattering of longitudinally polarized electrons off an unpolarized target.

Form Factors: ***Rosenbluth vs Polarization***

VOLUME 84, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 2000

G_{E_p}/G_{M_p} Ratio by Polarization Transfer in $\vec{e}p \rightarrow e\vec{p}$



Large discrepancy!

Global reanalysis and additional experimental evidence confirmed discrepancy

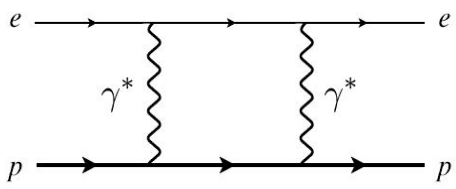
J. Arrington Phys. Rev. C 68, 034325

Questions remain over 20 years

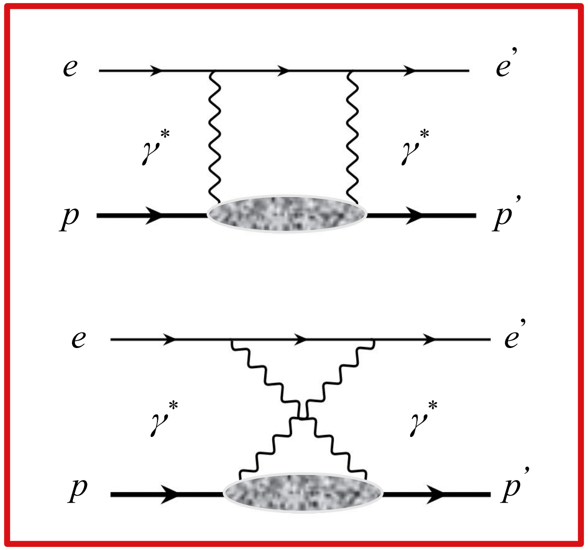
Two-Photon Exchange: ***Corrections***

Difference believed to be caused by two-photon exchange (TPE) corrections

QED: straightforward to calculate



QED+QCD:
depends on *proton internal structure*



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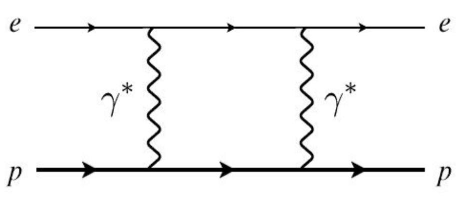
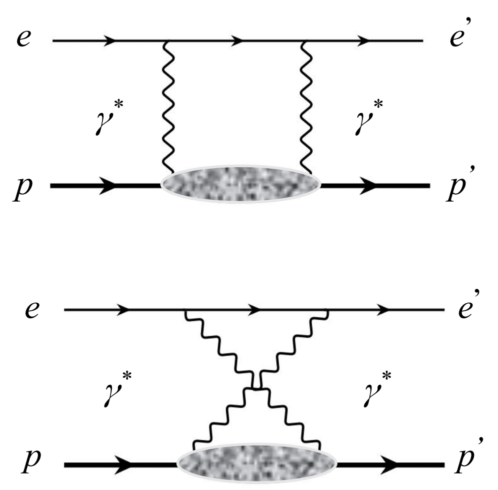
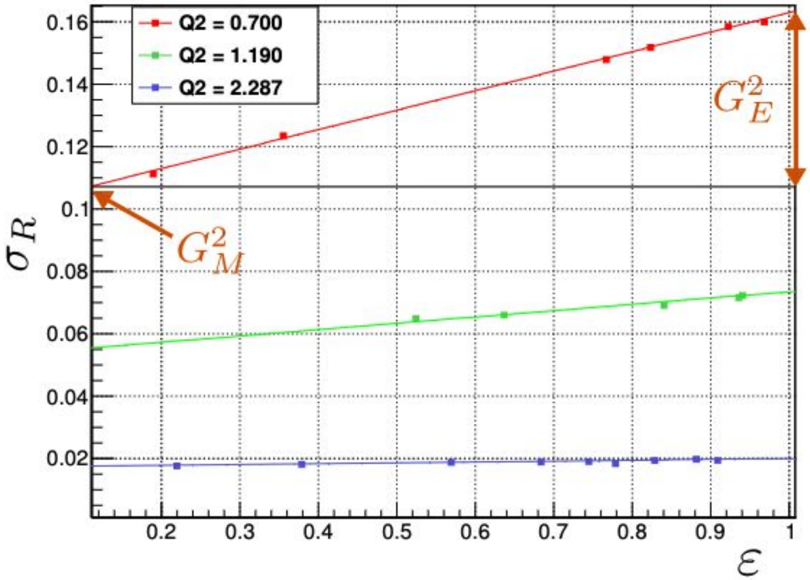


QED+QCD:
depends on proton internal structure





<u>Implication for Rosenbluth Measurements</u>
At large Q^2, the contribution of G_E to σ_R is small

A few-percent TPE correction, with the **correct *ε* dependence**, could have a major impact

Two-Photon Exchange: ***Recent Measurements***

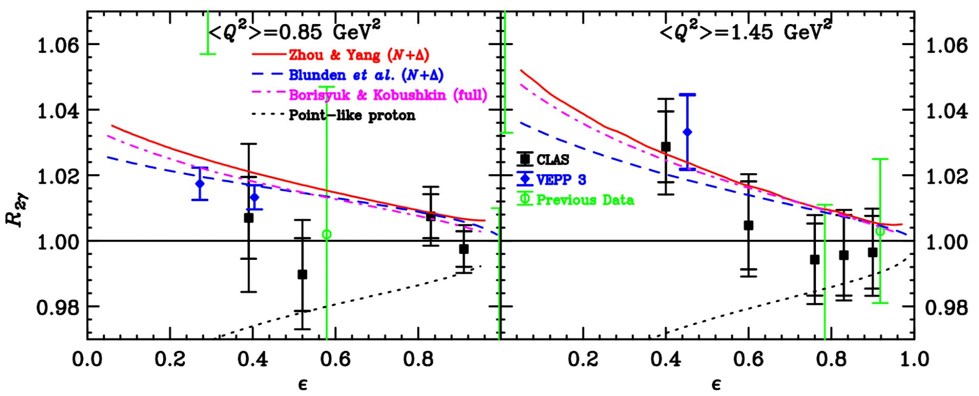
$$R \equiv \frac{\sigma^+ p}{\sigma^- p} = \frac{|M_{1\gamma} + M_{2\gamma}|^2}{|M_{1\gamma} - M_{2\gamma}|^2} \rightarrow R_{2\gamma} = 1 - 2\delta_{2\gamma}$$

Ratio of e^+ to e^- is very sensitive to effect from TPE

Recent e^+/e^- experiments

VEPP-3 (2009), CLAS (2010-2011)

Moderate increase in $R_{2\gamma}$ at $Q^2 = 1.45$ at low ε



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Recent e^+/e^- experiments

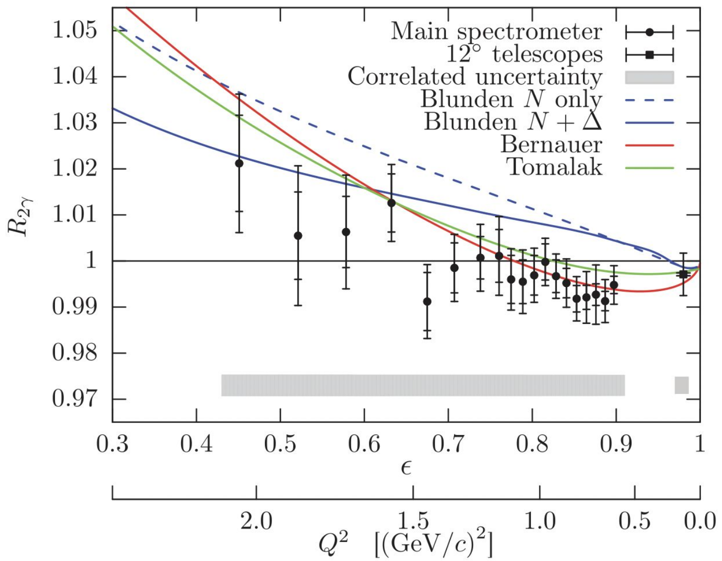
VEPP-3 (2009), CLAS (2010-2011)

Moderate increase in $R_{2\gamma}$ at $Q^2 = 1.45$ at low ε

OLYMPUS (2013)

Observe an epsilon-dependent effect

"Data favor smaller $R_{2\gamma}$"



B. S. Henderson et al. (OLYMPUS Collaboration)

Two-Photon Exchange: ***Recent Measurements***

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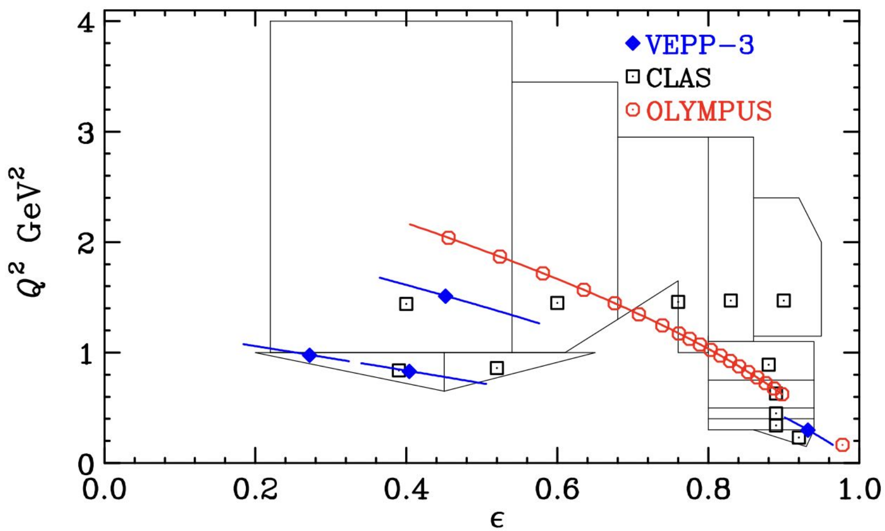
Ratio of e^+ to e^- is very sensitive to effect from TPE

Recent e^+/e^- experiments

TPE effects predicted to be largest at low ε and large Q^2 (most calculations)

Largest G_E/G_M discrepancy observed for Q^2 above 2-3 GeV^2

Experiments had limited ε and Q^2 coverage



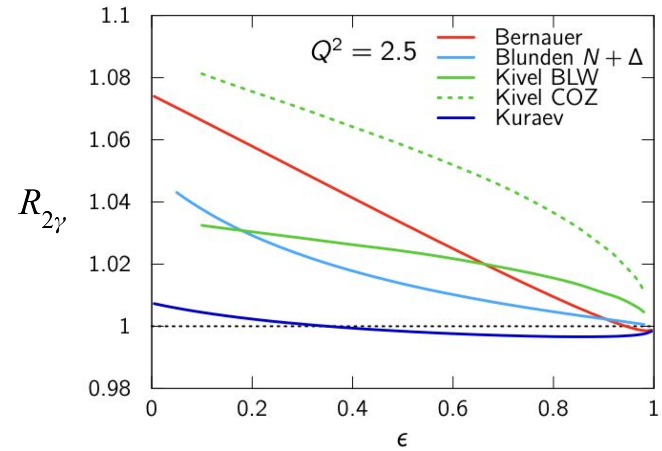
Two-Photon Exchange: ***Theory Predictions***

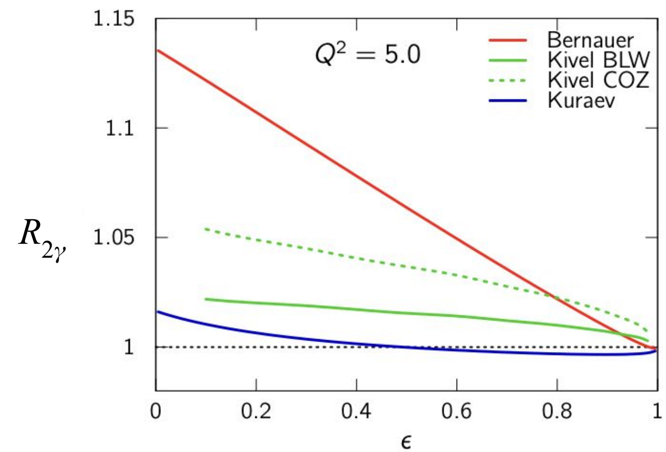
- Hadronic (Blunden et al.)
  - Modest ε dependence at moderate Q^2
  - Weak Q^2 dependence
- Partonic/pQCD (Chen et al.,Kivel et. al)
  - Valid at high Q^2
  - Significant ε dependence at large Q^2
  - Weak Q^2 dependence
  - Match Rosenbluth slope for Q^2 >5 GeV^2
- Dispersion relations
  - Borisyuk and Kobushkin
- Phenomenological
  - Bernauer

<u>Variations among different models</u>

Size of TPE effect

ε and Q^2 dependence

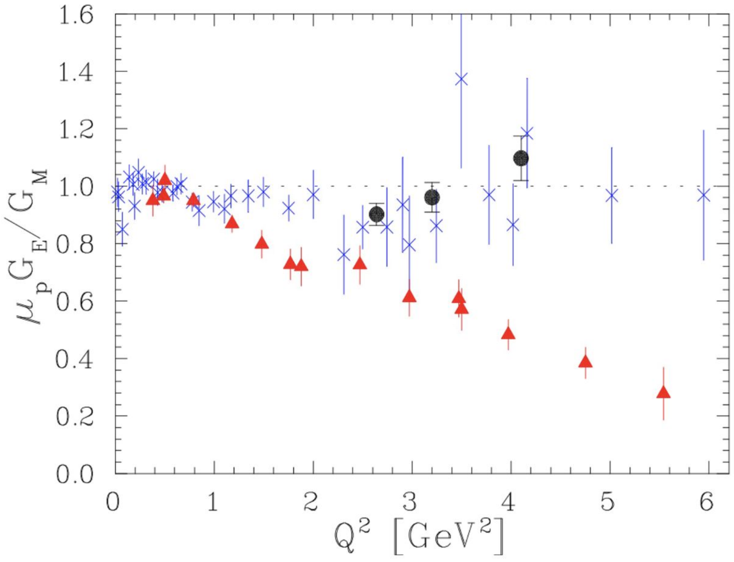




PR12+23-012

A Measurement of the Two-photon Exchange in Unpolarized Elastic Positron-proton and Electron-proton Scattering

1.) Modified version of Rosenbluth separation using e^+ & e^-
   a.) Proton detection
2.) Proton detection allows for precision in extracting the ε dependence of the cross section
   a.) Cleaner extraction of G_E/G_M



PR12+23-012

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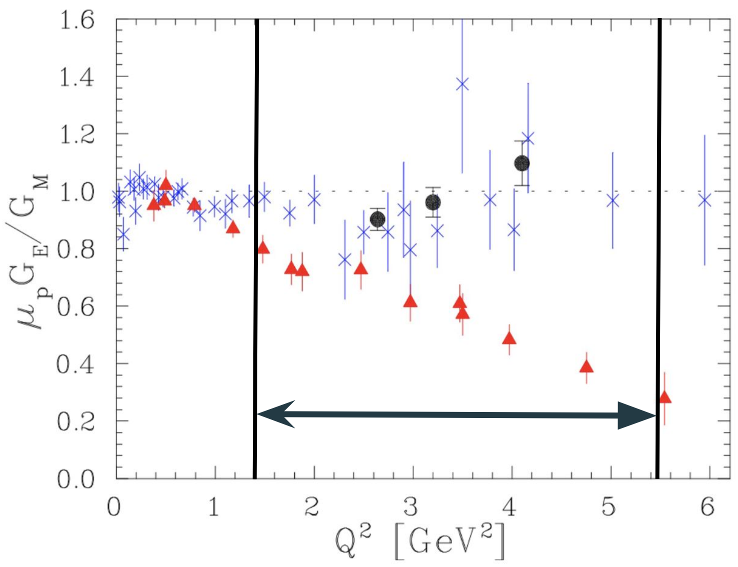
1.) Modified version of Rosenbluth separation using e^+ & e^-
   a.) Proton detection
2.) Proton detection allows for precision in extracting the ε dependence of the cross section
   a.) Cleaner extraction of G_E/G_M
3.) Direct comparison of e^+ & e^- S-R data will test the assumption that the discrepancy at high Q^2 is due to TPE effects
4.) Wide kinematic range: $1.4 < Q^2 < 5.5$ GeV^2
5.) Does not require rapid beam changes or identical beam characteristics



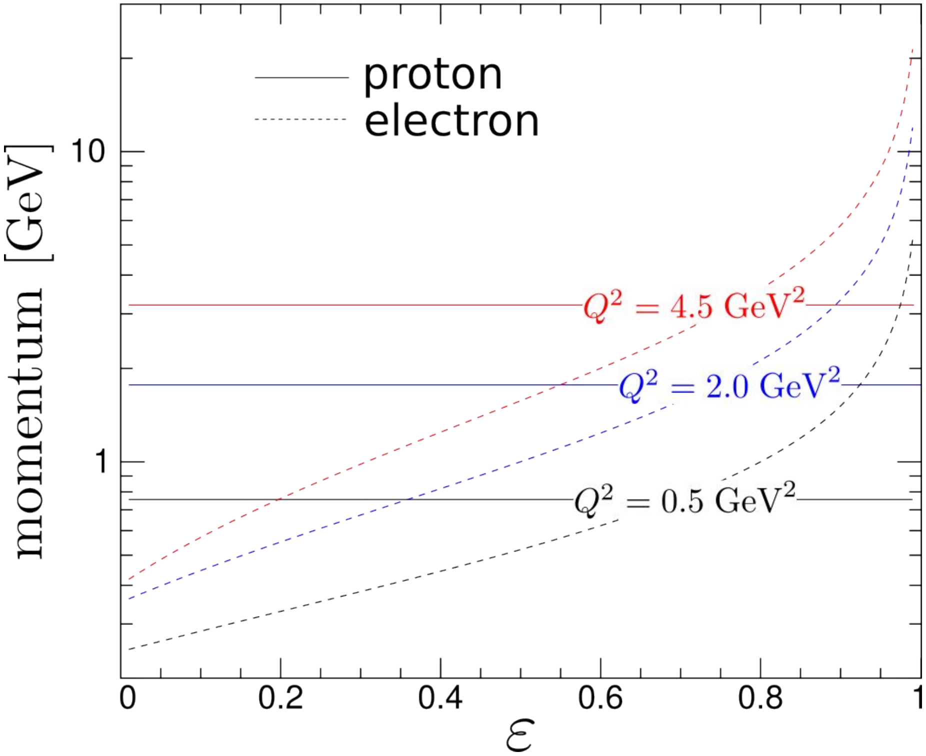
Advantages of Super-Rosenbluth: ***Momentum***

ε dependence of momentum:

Proton momentum fixed at fixed Q^2

Momentum dependent corrections cancel

No ε dependence



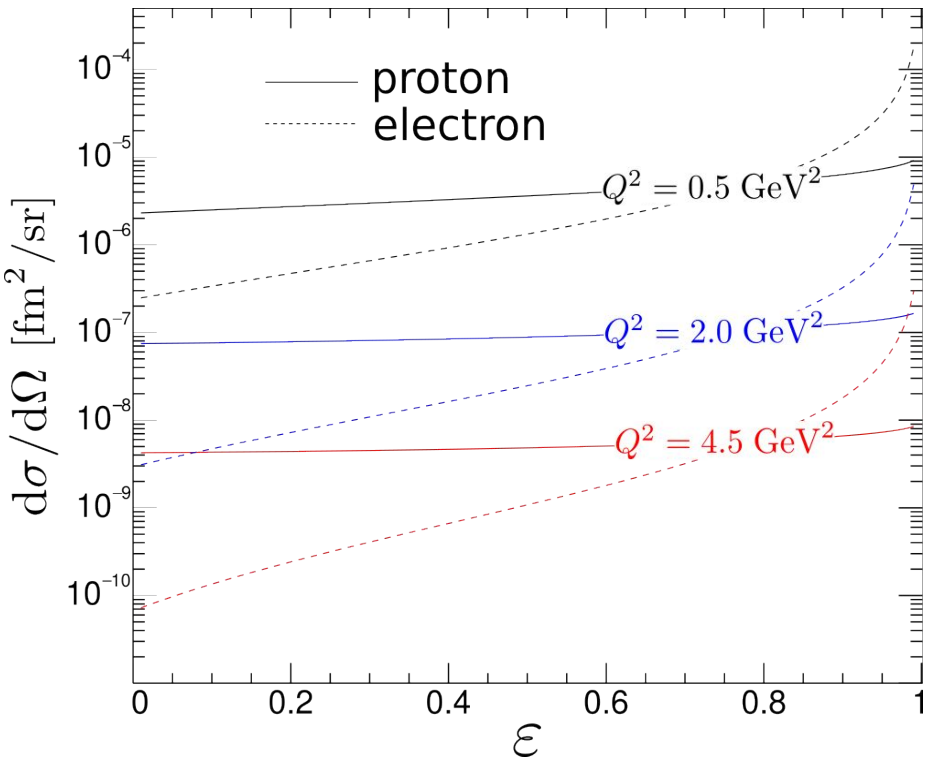
Advantages of Super-Rosenbluth: ***Cross Section***

ε dependence of momentum:

- Proton momentum fixed at fixed Q^2
- Momentum dependent corrections cancel
- No ε dependence

ε dependence of cross section:

- Higher statistical precision at low ε
- Minimal ε dependence
- Rate dependent corrections & uncertainties



Advantages of Super-Rosenbluth: *Kinematic Uncertainties*

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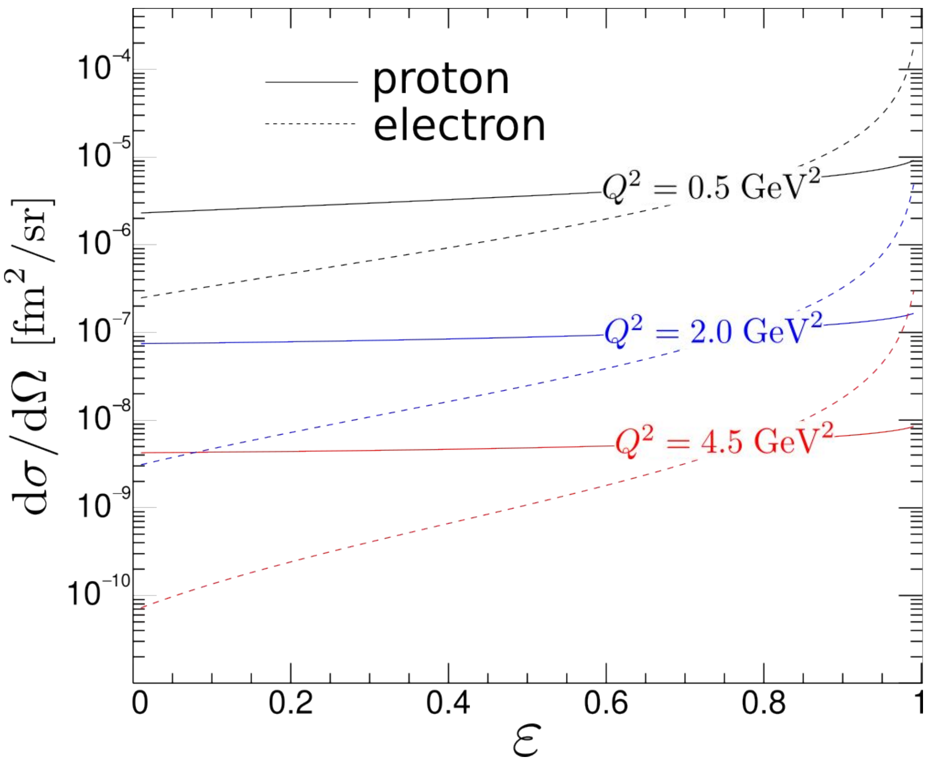
Less sensitive to kinematic uncertainties

- Beam energy
- Scattering angle



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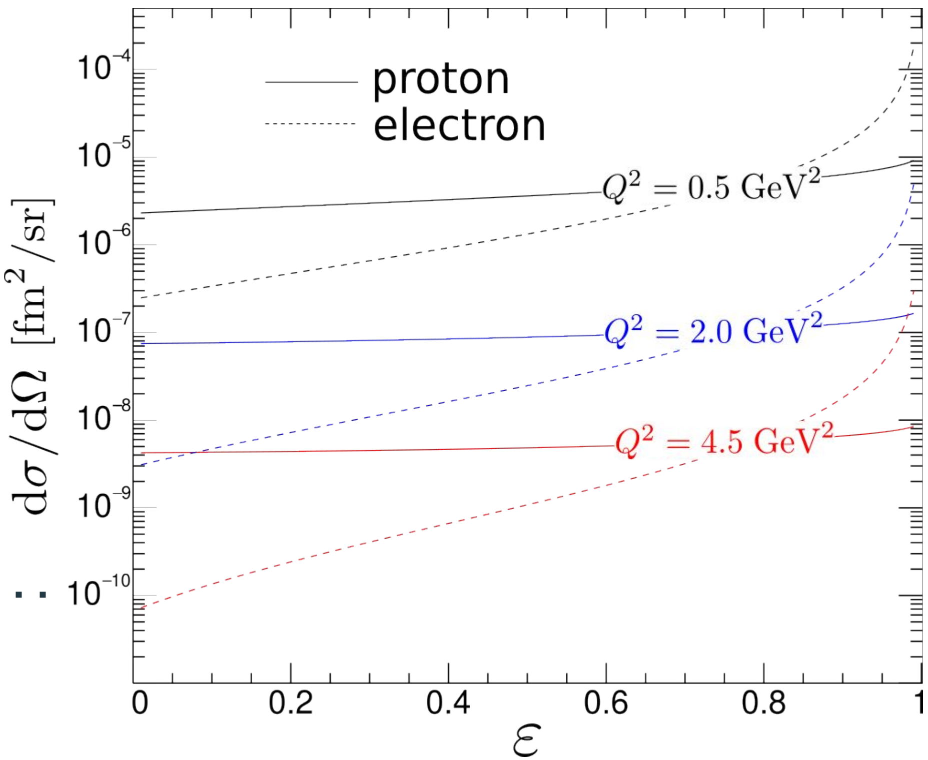

Some uncertainties (e.g. acceptance, proton absorption) have larger absolute uncertainties

➡ They are independent of ε and cancel completely in extraction of G_E/G_M

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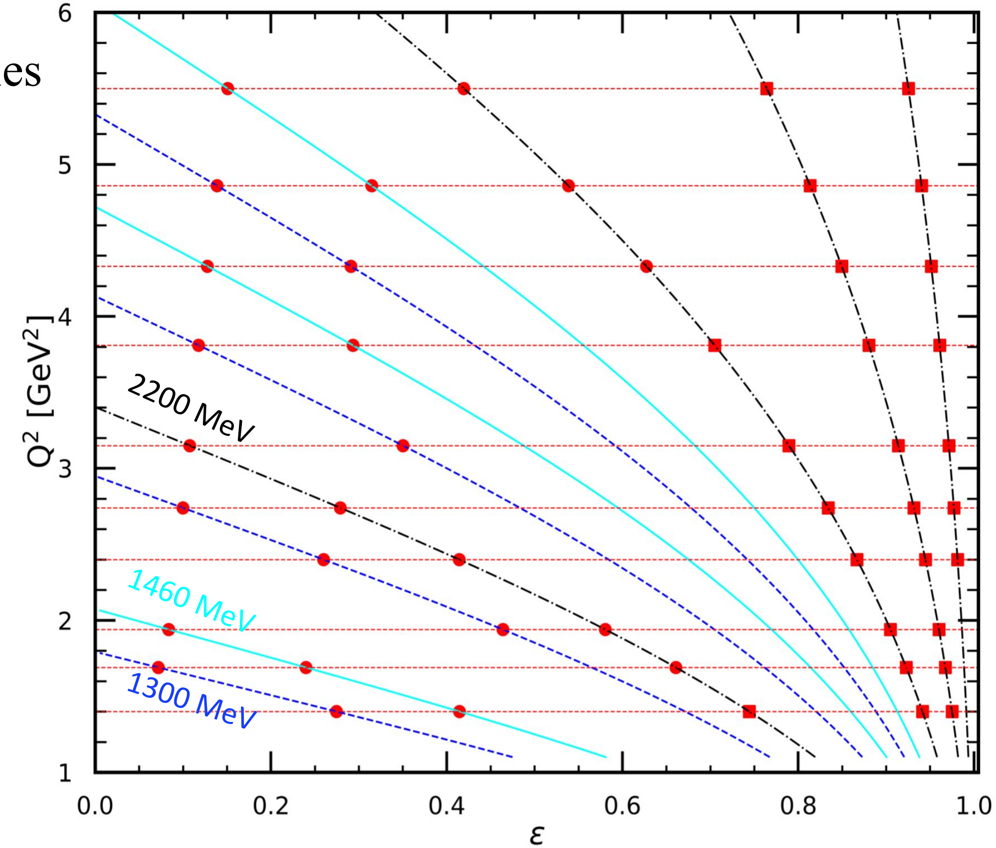
Experimental Overview

- Three linac settings; 11 beam energies
- Ten Q^2 points: 1.4 - 5.5 GeV^2
- Four or five ε points at each Q^2

<u>Standard Hall C configuration</u>

- 10 cm liquid hydrogen target
- HMS (proton arm): 11°-54°
- SHMS (lepton arm): 10°-39°
- Positron beam current: 1 μA
- Electron beam current: 20 μA



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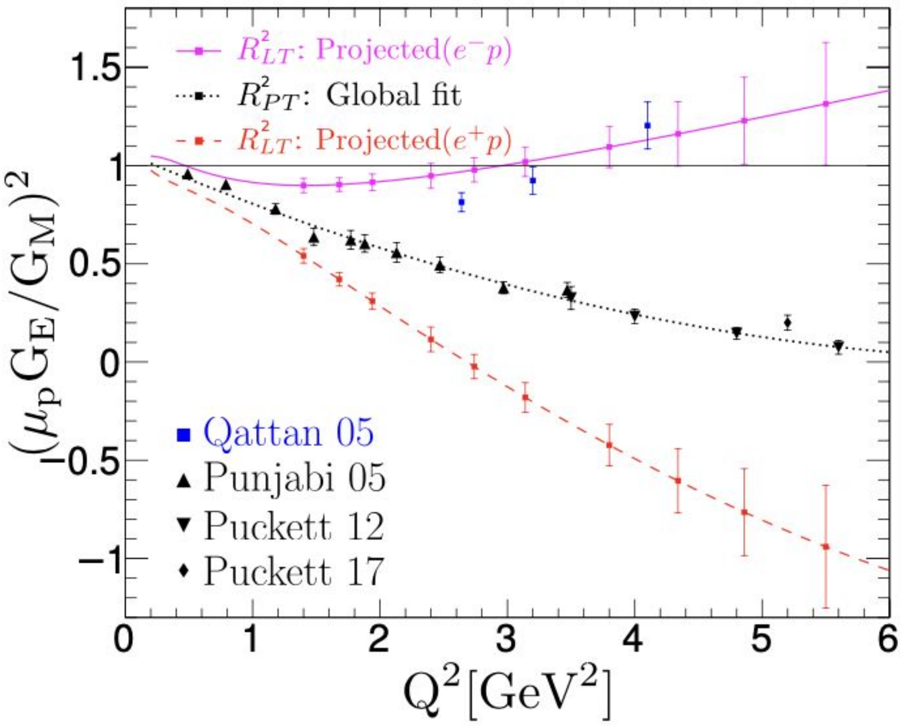
Sensitivity to Various Physics

1.) Positron S-R vs polarization (e-)
   a. Sensitive to TPE in unpolarized cross section
   b. Sensitive to errors in conventional RC (small)
   c. Sensitive to TPE in PT (small)
2. Positron S-R vs electron S-R
   a. Maximum TPE sensitivity (size, non-linearity)
3. Positron-electron average S-R vs Polarization Transfer
   a. Sensitive to conventional radiative corrections
   b. Sensitive to TPE in polarization transfer



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Beam Time Request

	positron time[hrs]		electron time[hrs]
Q^2=1.40	5 × 1.2 hrs	6	5
Q^2=1.69	5 × 1.8 hrs	9	5
Q^2=1.94	5 × 2.4 hrs	12	5
Q^2=2.4	5 × 4.0 hrs	20	5
Q^2=2.74	5 × 6.4 hrs	32	5
Q^2=3.15	5 × 11 hrs	55	6
Q^2=3.81	5 × 22 hrs	110	11
Q^2=4.33 (0.5% statistics)	5 × 24 hrs	120	19
Q^2=4.86 (0.6% statistics)	5 × 26 hrs	130	22
Q^2=5.5 (0.7% statistics)	4 × 38 hrs	112	25
High stat. coincidence runs	8 × 8 hrs	64	32
Dummy target data	(20% of LH2 data)	136	32
Carbon pointing runs		12	12
Total production		**818**	**184**
Target boiling studies		4	4
BCM calibrations		8	8
Checkout/calibration		12	12
Beam energy measurements	12 × 1 hr	12	12
linac changes	3 × 12 hrs	36	36
pass changes	9 × 8 hrs	72	72
kinematics changes	40 × 0.5 hrs	20	20
Total overhead/calibration		**164**	**164**
Total		**982 (41 days)**	**348 (15 days)**

PR12+23-012

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Summary: The PAC recognizes the strong science case of this important measurement, which may provide a definitive answer to the long-standing question of the role of TPE in form-factor extractions. To fully achieve the scientific goals of the experiment, it is essential to include measurements taken with non-standard positron beam energies. The experiment is complementary to the Hall B proposal (PR12+23-008), also reviewed by this PAC.
The PAC recommends conditional approval (C1) for the requested beam time of 56 days. A C1 review by the Lab should be conducted at an appropriate time and verify that positron beams will be available with the parameters required for the experiment.

Approved for: 56 PAC days

41 days (e^+)

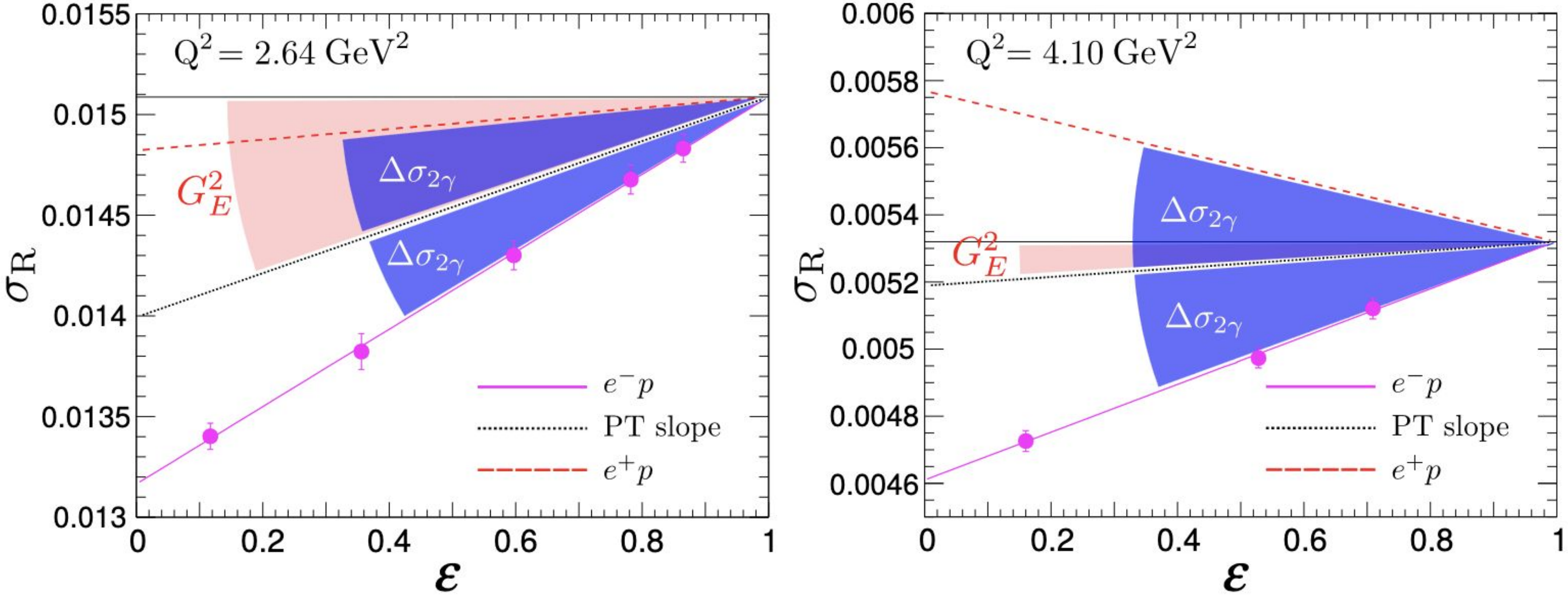
15 days (e^-)

PR12+23-012:
Summary

- **No direct experimental evidence of the G_E/G_M discrepancy**
  - Discrepancy is believed to be due to TPE
- Previous TPE measurements outside of Q^2 region where discrepancy is large
- Precise Super-Rosenbluth separations measurements, using both positrons and electrons over wide Q^2 range, will allow for first direct verification of the idea that TPE explain the form factor discrepancy
- Direct comparison of e^+ and e^- Super-Rosenbluth separations
  - Signal for TPE that is twice as large
  - Isolates TPE contribution
  - Does not require assumptions for PT results
- Approved by PAC 51 with A- rating

Thank You

Super-Rosenbluth: ***e*$^+$ *vs. e*$^-$ *Comparison***

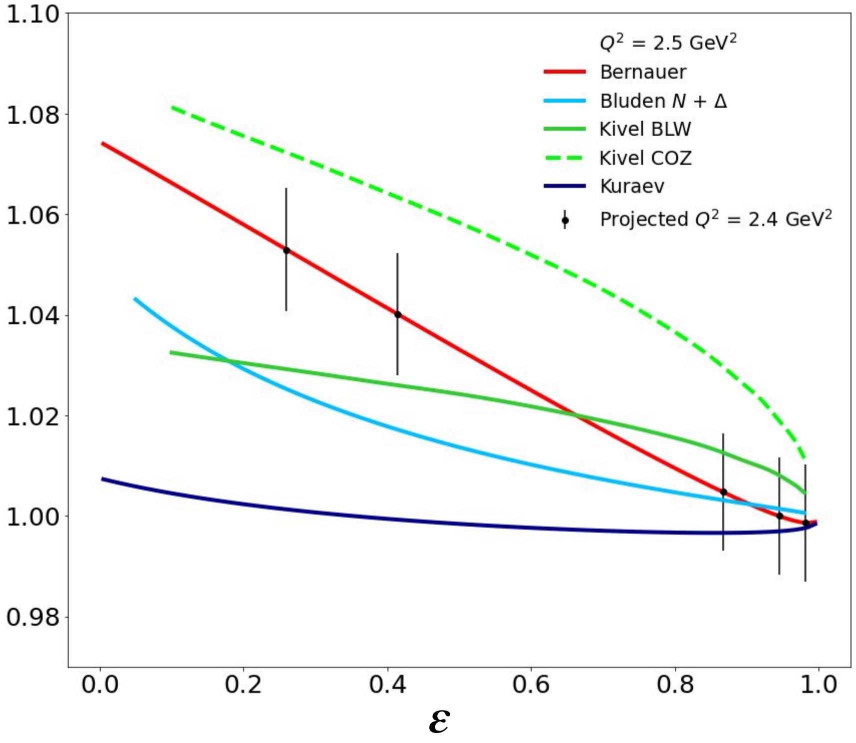


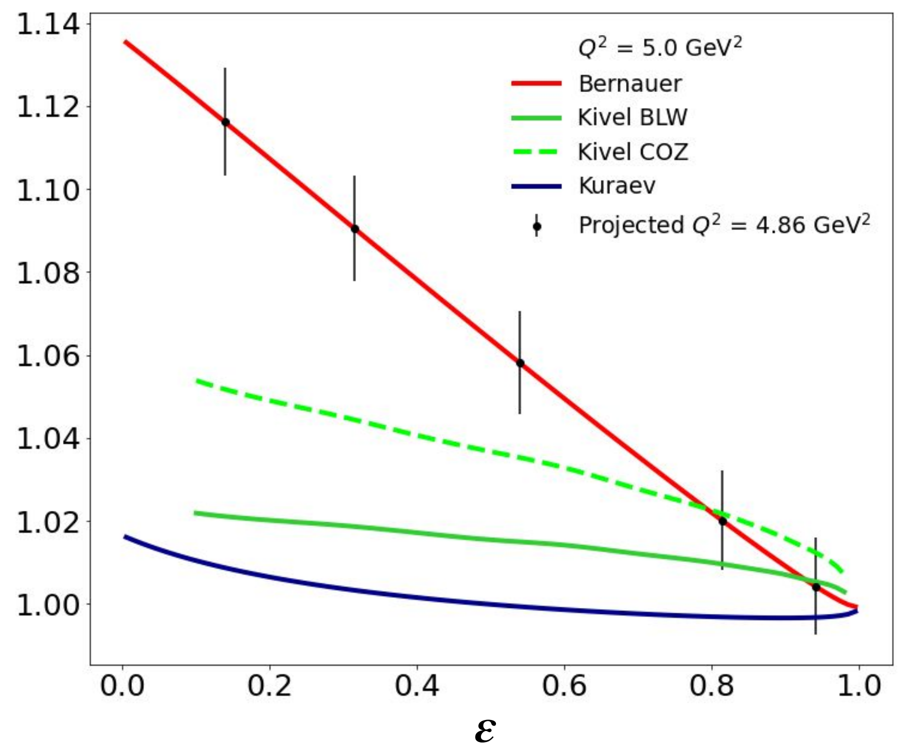
- Data from E01-001 (Super-Rosenbluth)
- Projected Super-Rosenbluth using positrons (Red dashed line)
- Slope from PT (Black dashed line)

*Recent study using Maximon & Tjon indicate the effect from TPE may smaller by ~⅓

TPE effects still dominant G_E contribution above 2.5 GeV^2!

Super-Rosenbluth: *e^+/e^- Ratio**





Error Budget

Source	size	$\delta\sigma/\sigma$ total	$\delta\sigma/\sigma$ G_E/G_M
Statistics	0.5%	0.5%	0.5%
Energy (fixed offset)	0.04%	0.2%	*0.1%
Energy (random)	0.04%	0.2%	0.2%
θ_p(fixed offset)	0.30 mr	0.2-0.5%	0.3%
θ_p(random)	0.20 mr	0.1-0.3%	0.1-0.3%
Dead Time		0.1%	<0.1%
Dummy Subtraction		0.2-0.5%	0.2%
Background Subtraction		0.1-1.0%	*0.3%
Radiative Corrections		1.2%	0.2%
			*0.2%
Luminosity		0.6%	0.2%
Proton Absorption		1.0%	≪0.1%
Acceptance		~2%	≪0.1%
Efficiency		0.5%	≪0.1%
Total		~2.9%	0.42-0.50% *0.52%

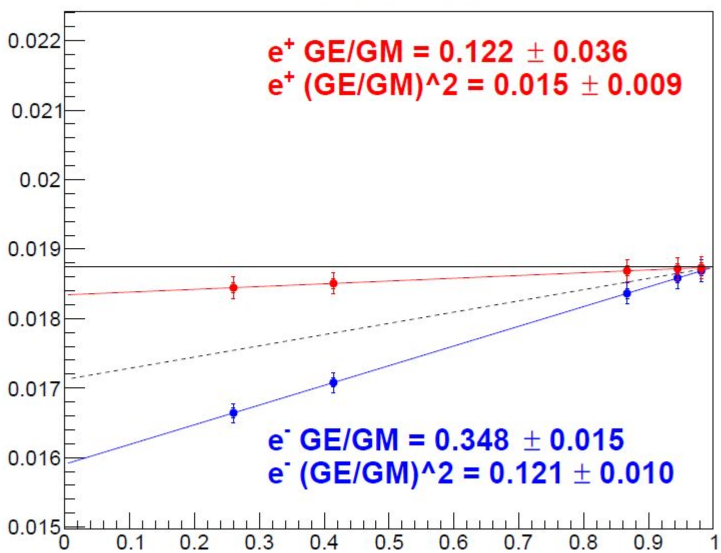
*Uncertainty given is on the slope rather than the individual cross sections

Break Down of Time

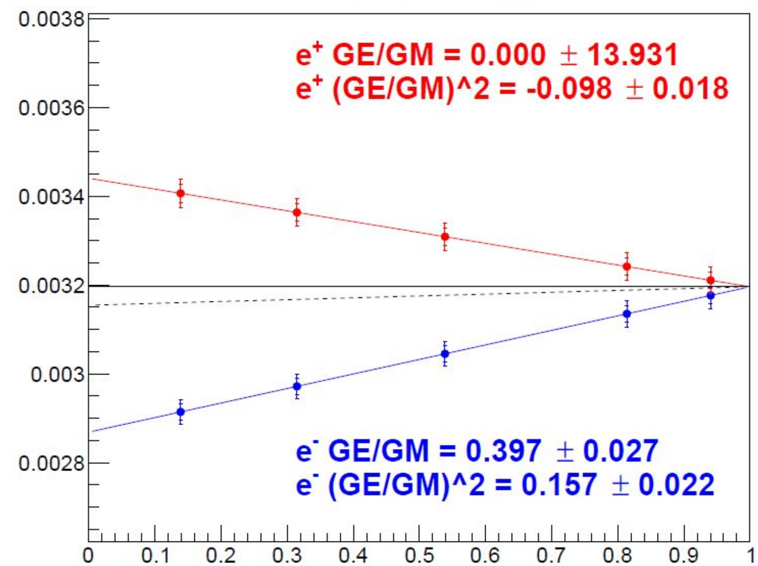
Setting	Beam Energy [GeV]	Percentage of Time	
1	1.3	0.55%	
1	1.95	2.56%	
1	2.6	6.75%	
1	3.25	9.45%	19.3%
2	1.46	0.95%	
2	2.92	8.78%	
2	3.65	10.8%	20.5%
3	2.2	5.41%	
3	4.4	21.6%	
3	6.6	18.2%	
3	11.0	14.9%	60.1%

Projected Uncertainties:
***e⁺* and *e⁻* Super-Rosenbluth Separation**

Q^2 = 2.40 GeV^2



Q^2 = 4.86 GeV^2

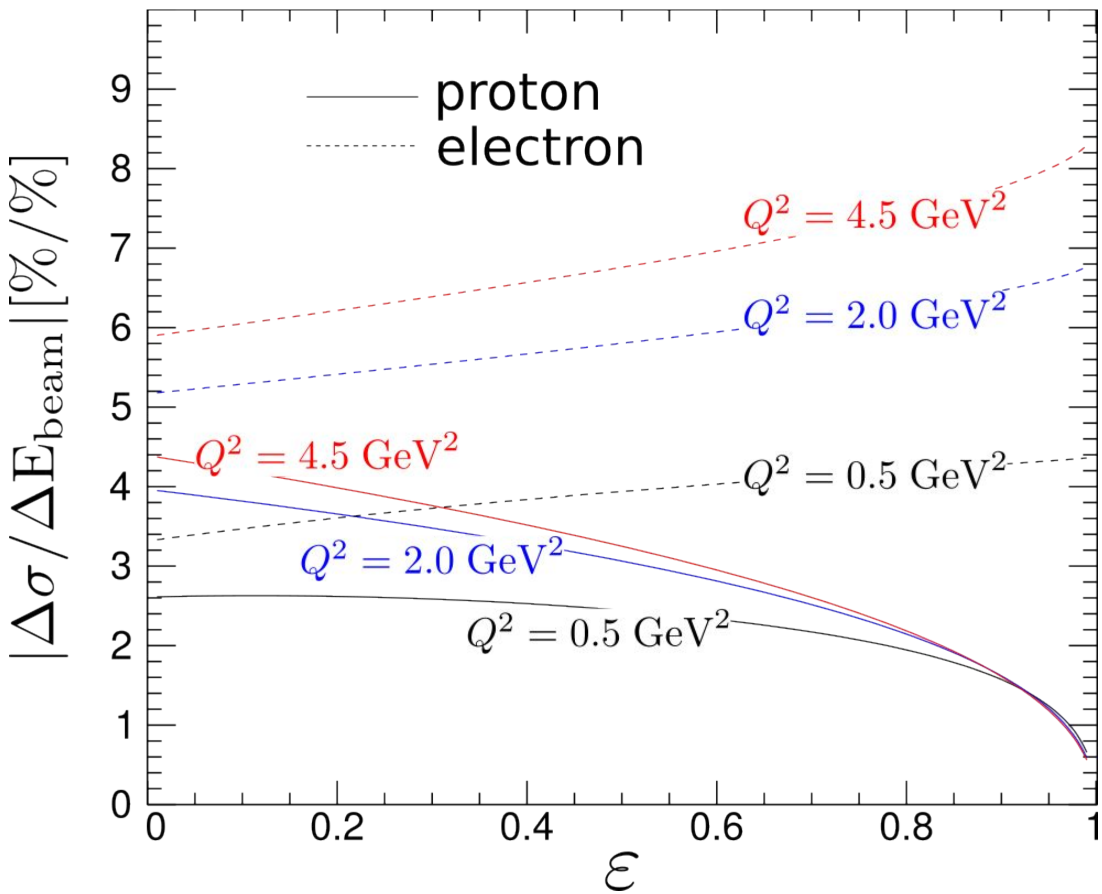


Advantages of Super-Rosenbluth

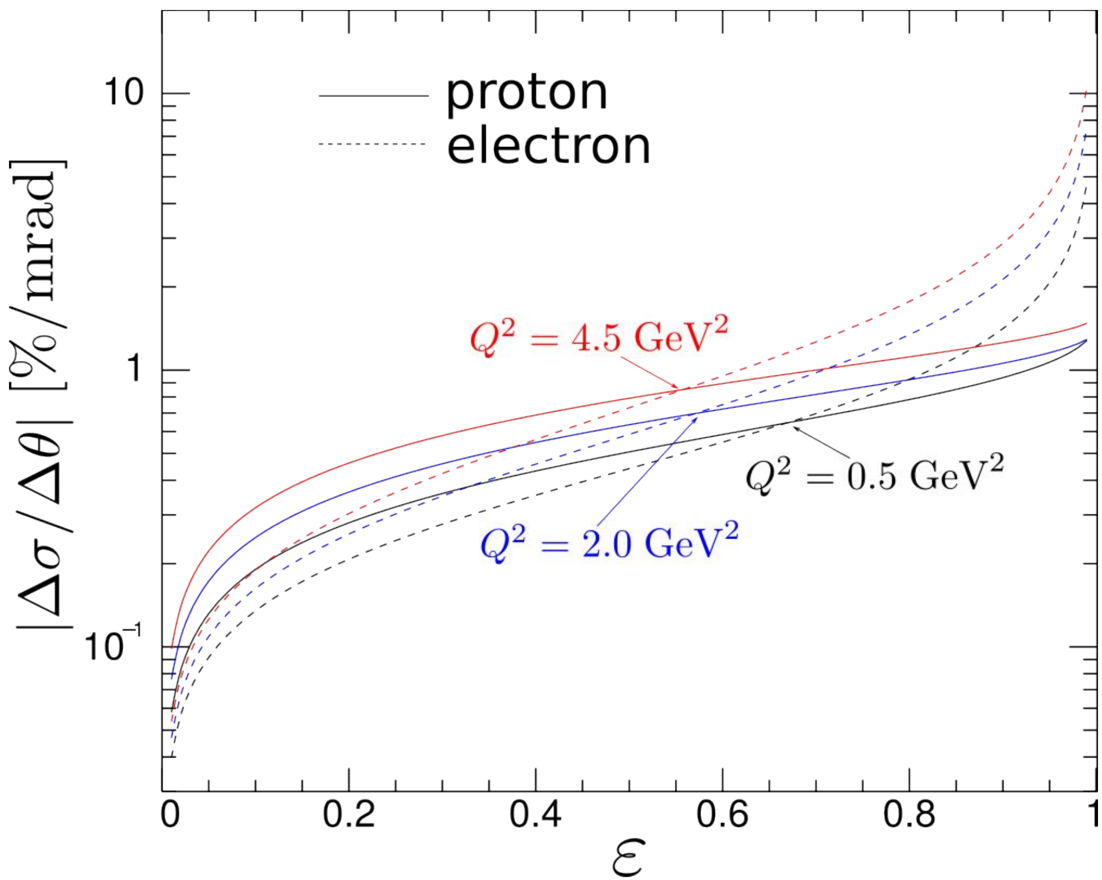
Q^2	ε	θ_e [degrees]	θ_p [degrees]	σ_e [nb/sr]	σ_p [nb/sr]	E'_e [GeV]	E'_p [GeV]
2.0	0.08	123	11.4	0.045	0.77	0.4	1.7
2.0	0.98	7.7	41.8	10	1.7	9.9	1.7

Hall C HMS Scattering Angle
10.5° - 90.0°

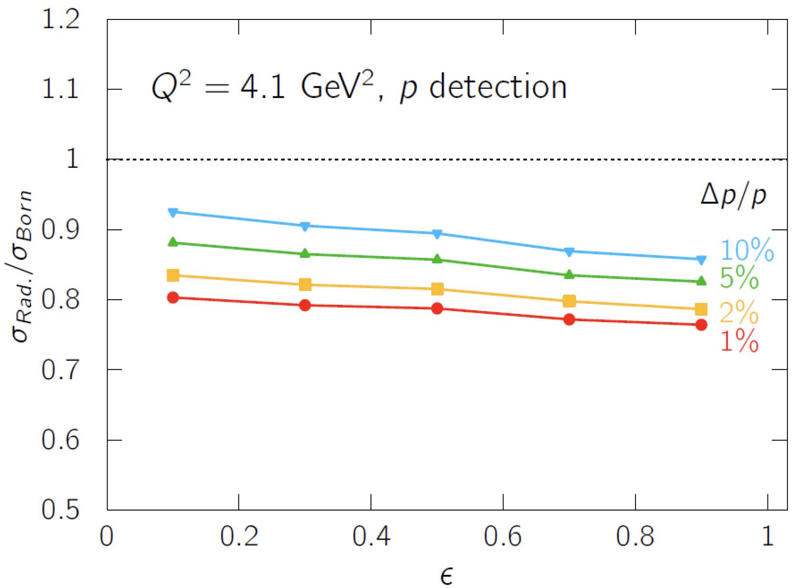
Advantages of Super-Rosenbluth:
Kinematic Uncertainties

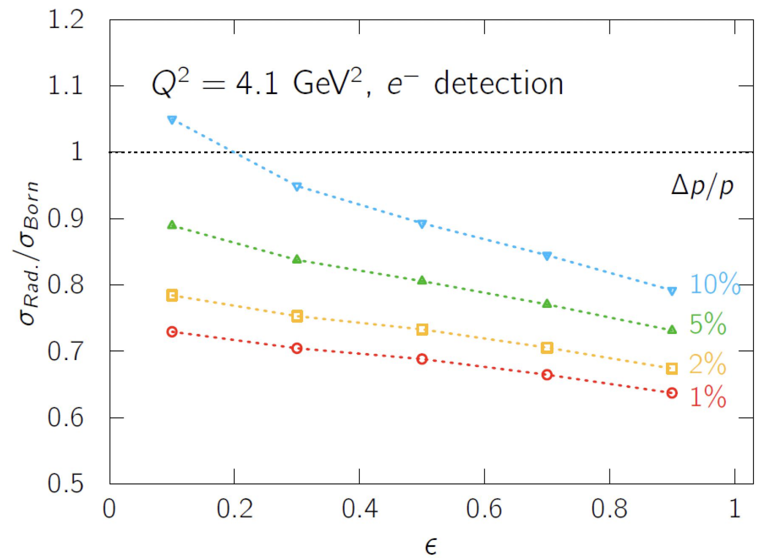


Advantages of Super-Rosenbluth: *Kinematic Uncertainties*



Advantages of Super-Rosenbluth:
Radiative Corrections





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Background Subtraction