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

PAC 51

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Form Factors: ***Rosenbluth Separation***

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

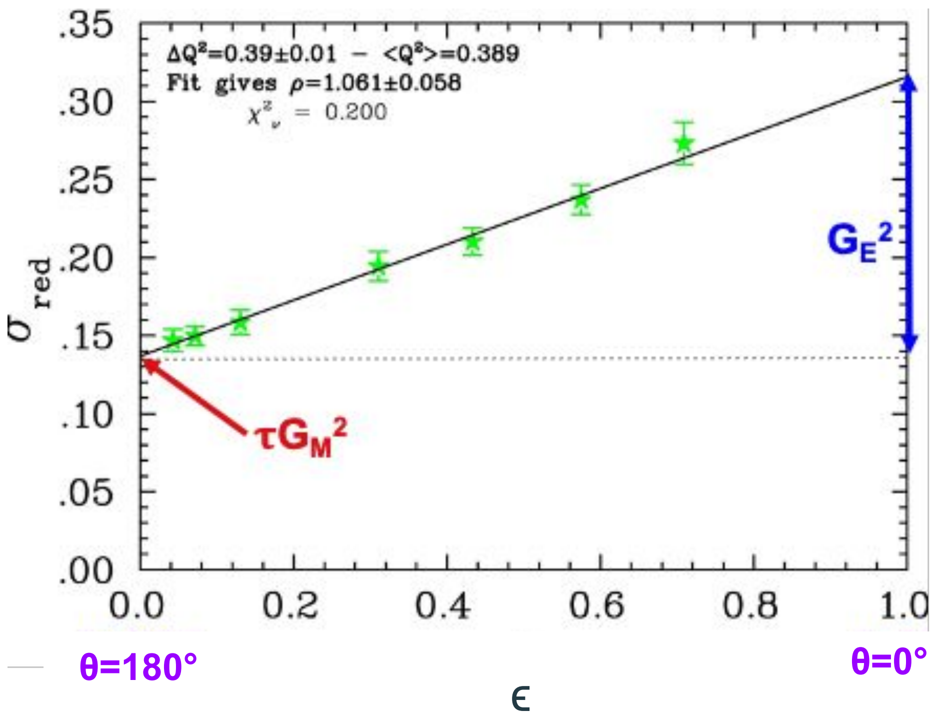
$$\sigma_R = d\sigma/d\Omega\,[\varepsilon(1+\tau)/\sigma_{Mott}] = \tau\, G_M^{\,2}(Q^2) + \varepsilon\, G_E^{\,2}(Q^2)$$

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

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

Measure cross section as a function of ε

Requires:
Multiple beam energies and scattering angles



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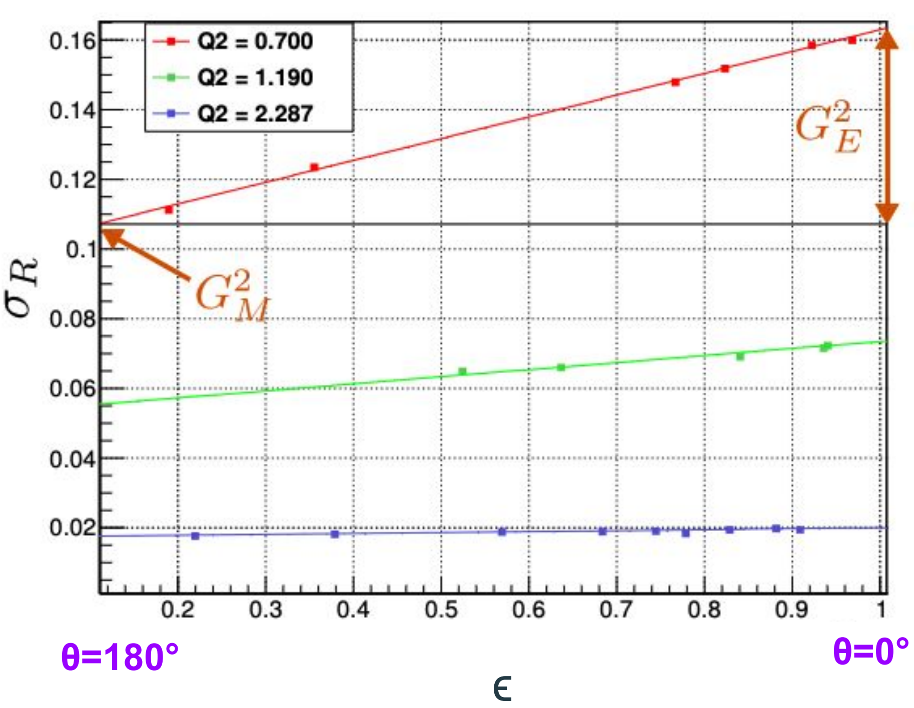
Measure cross section as a function of ε

Requires:
Multiple beam energies and scattering angles

Lower sensitivity when one term dominates:

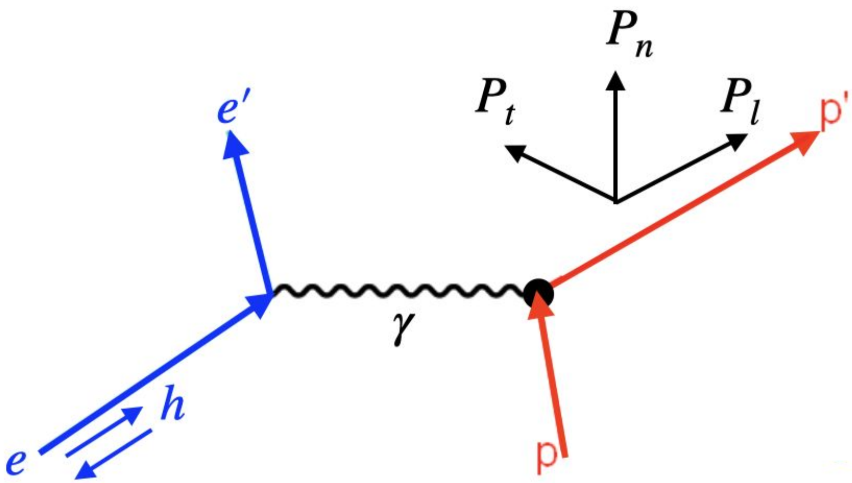
High Q^2: $\tau G_M^2(Q^2) >> \varepsilon G_E^2(Q^2)$

Large uncertainty on G_E at high Q^2



Form Factors: ***Polarization Measurements***

Polarization transfer



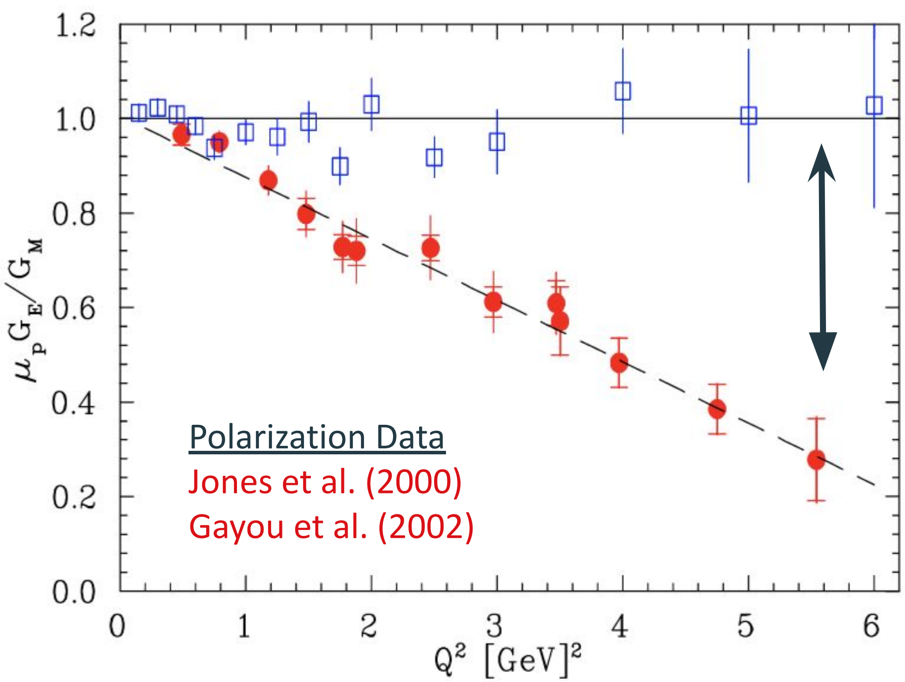
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E+E')}{2M}tan(\theta_e/2)$$

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

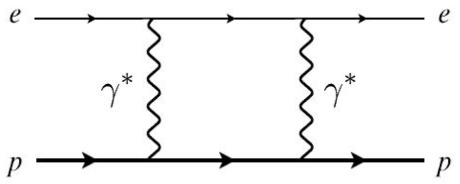
J. Arrington Phys. Rev. C 68, 034325

Questions remain over 20 years

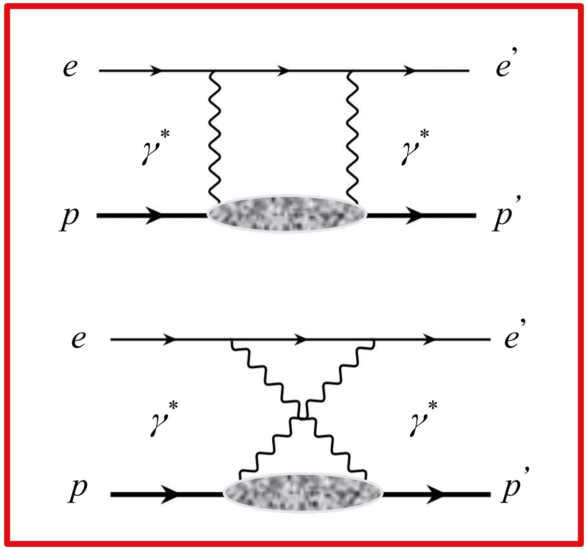
Two-Photon Exchange: ***Corrections***

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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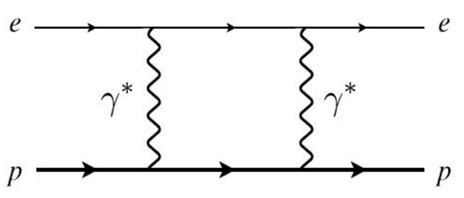

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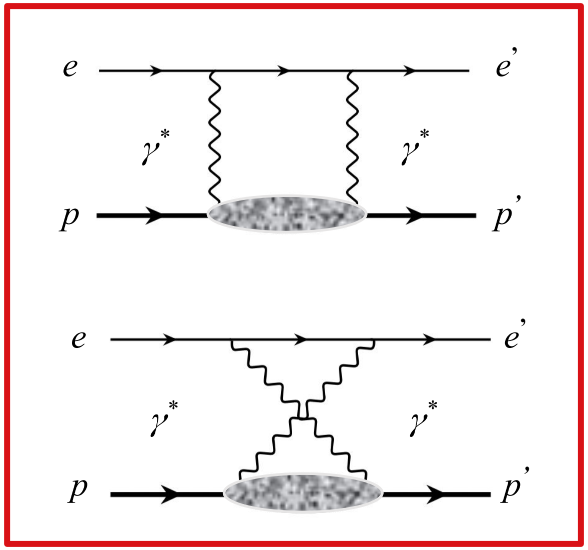
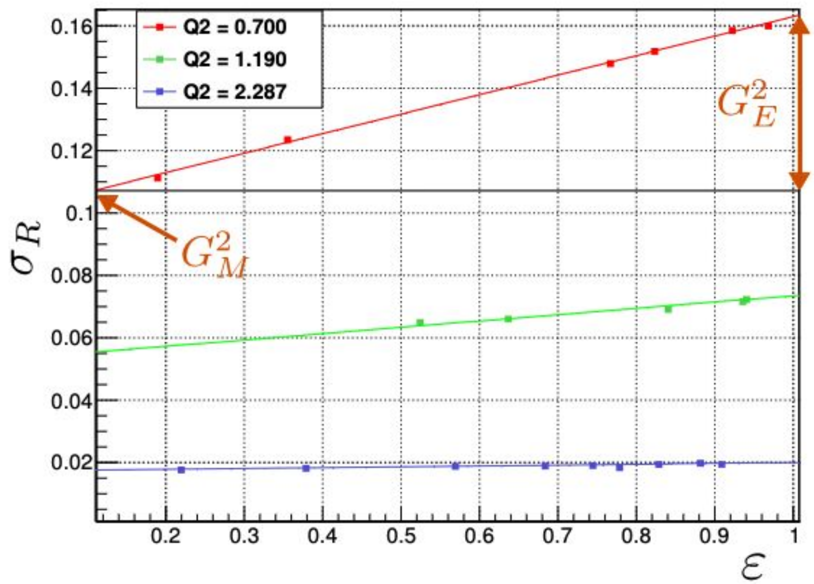




<u>Implication for Rosenbluth Measurements</u>
At large Q^2, the contribution of G_E to σ_R is small

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

Two-Photon Exchange:
Recent Measurements

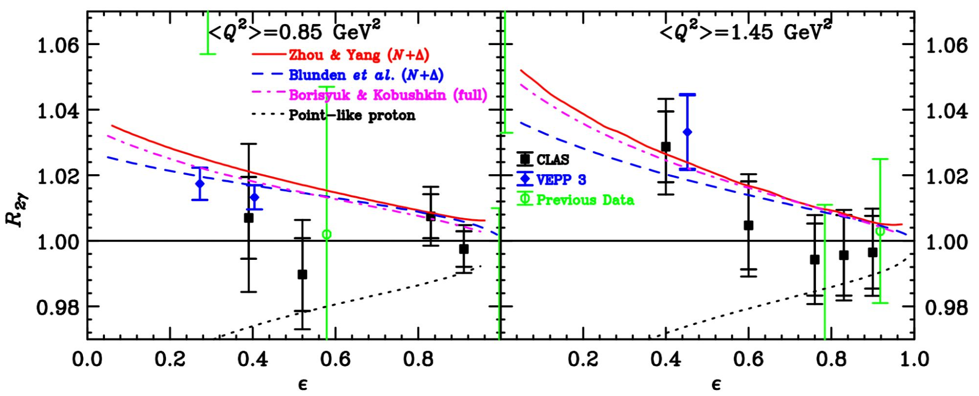
$$R \equiv \frac{\sigma^+ p}{\sigma^- p} = \frac{|M_{1\gamma} + M_{2\gamma}|^2}{|M_{1\gamma} - M_{2\gamma}|^2} \rightarrow R_{2\gamma} = 1 - 2\delta_{2\gamma}$$

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

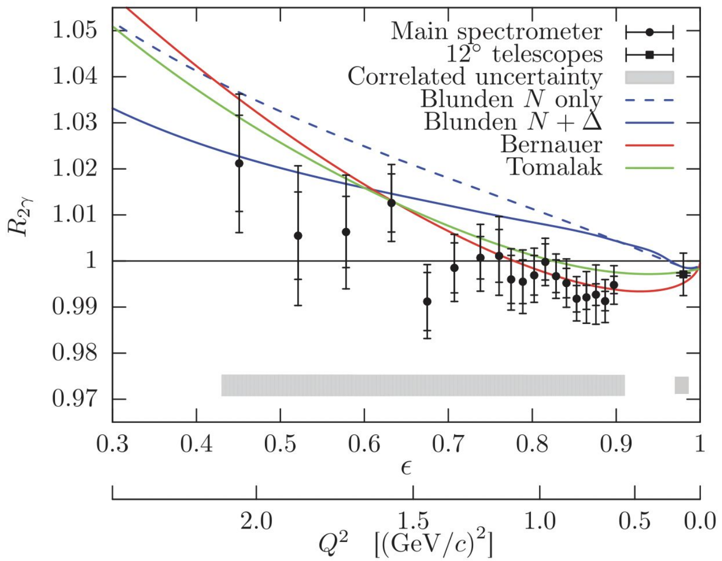
VEPP-3 (2009), CLAS (2010-2011)

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*

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

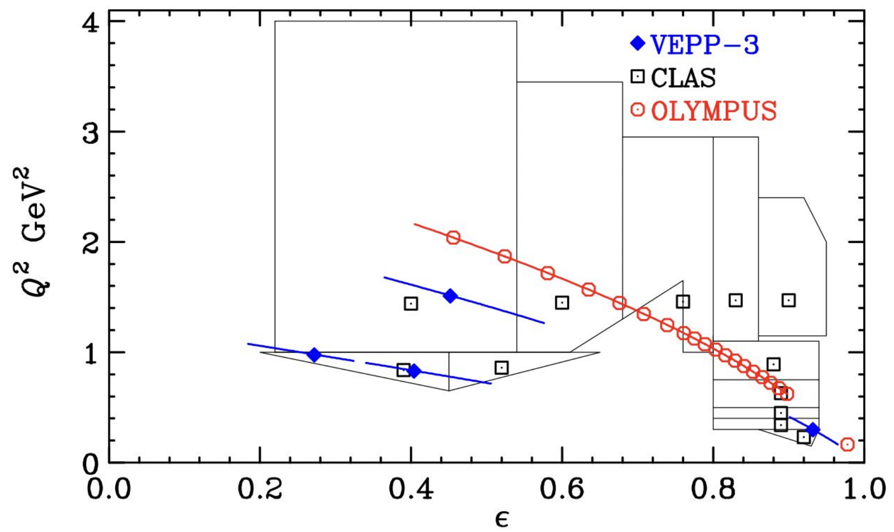
Ratio of e^+ to e^- is very sensitive to effect from TPE

Recent e^+/e^- experiments

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



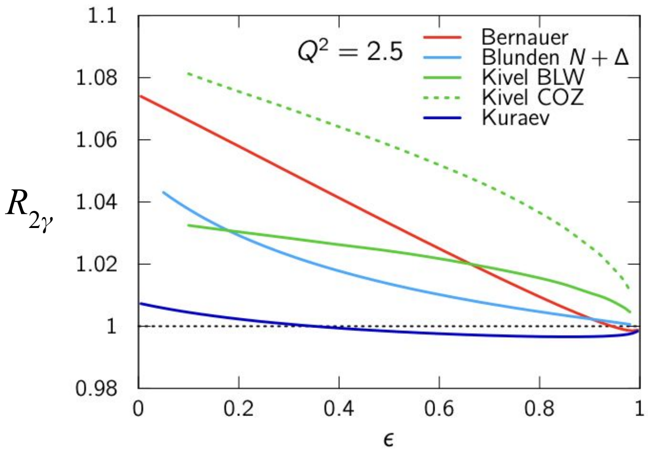
Two-Photon Exchange: ***Theory Predictions***

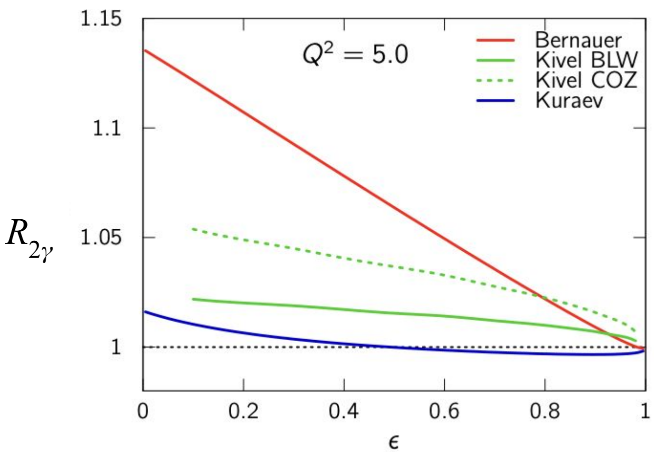
- Hadronic (Blunden et al.)
  - Modest ε dependence at moderate Q^2
  - Weak Q^2 dependence
- Partonic/pQCD (Chen et al.,Kivel et. al)
  - Valid at high Q^2
  - Significant ε dependence at large Q^2
  - Weak Q^2 dependence
  - Match Rosenbluth slope for Q^2 >5 GeV^2
- Dispersion relations
  - Borisyuk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

<u>Variations among different models</u>

Size of TPE effect

ε and Q^2 dependence





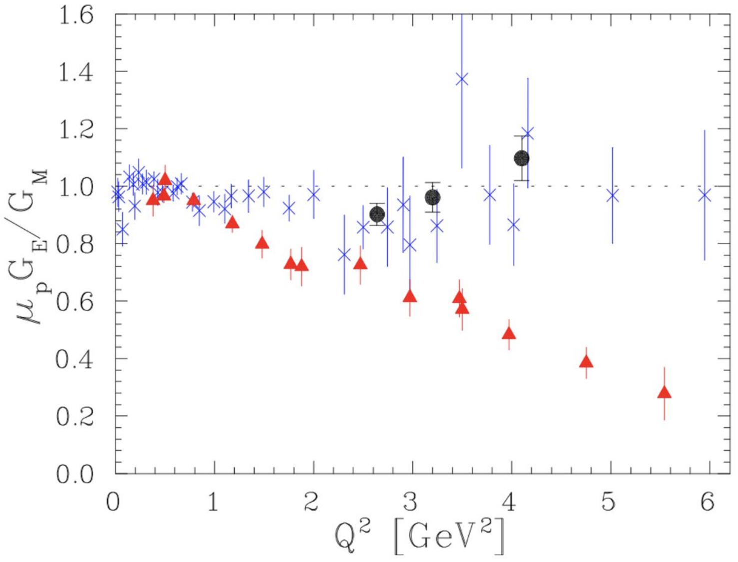
PR12+23-012

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

PR12+23-012

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

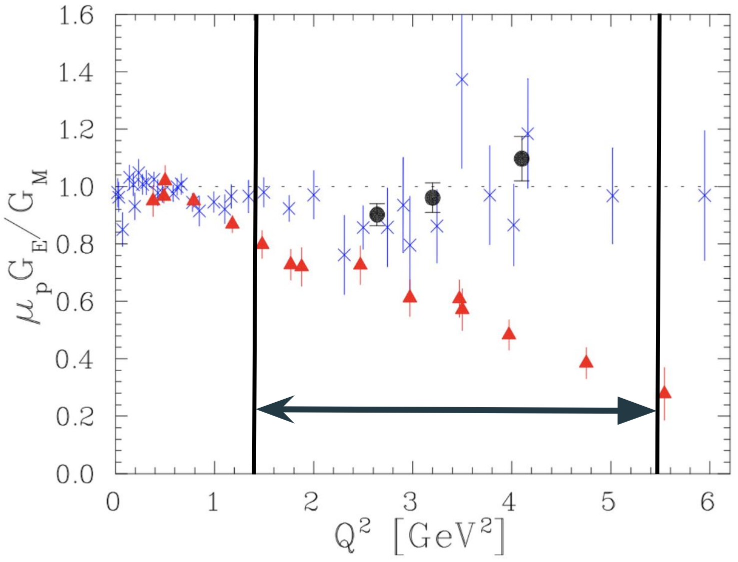
1.) Modified version of Rosenbluth separation using e^+ & e^-
   a.) Proton detection
2.) Proton detection allows for precision in extracting the ε dependence of the cross section
   a.) Cleaner extraction of G_E/G_M



PR12+23-012

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
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



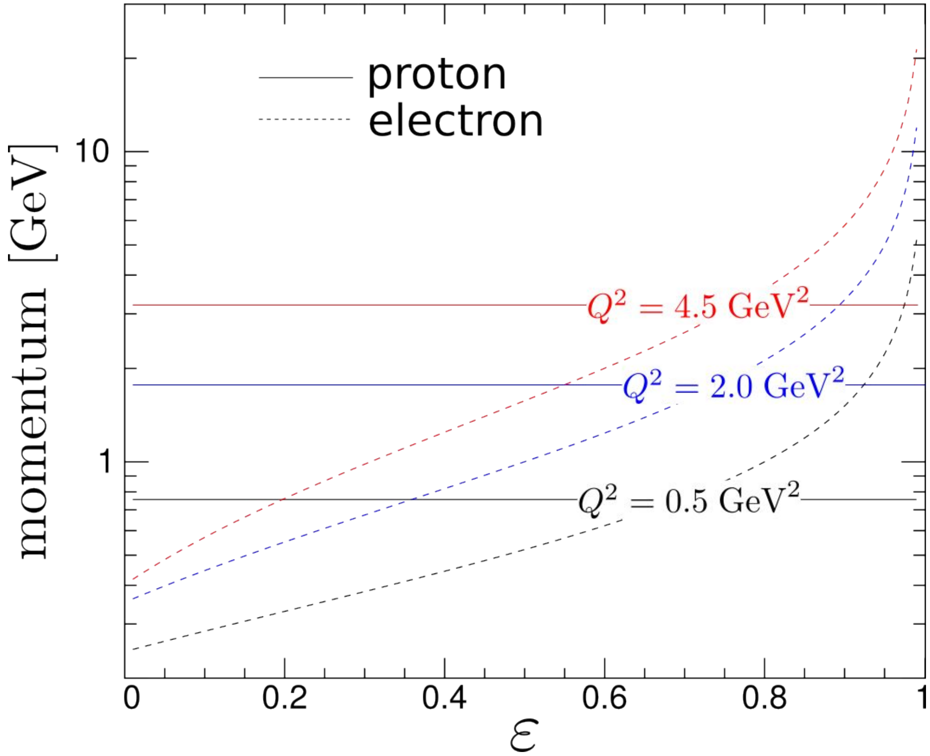
Advantages of Super-Rosenbluth: ***Momentum***

ε dependence of momentum:

Proton momentum fixed at fixed Q^2

Momentum dependent corrections

No ε dependence



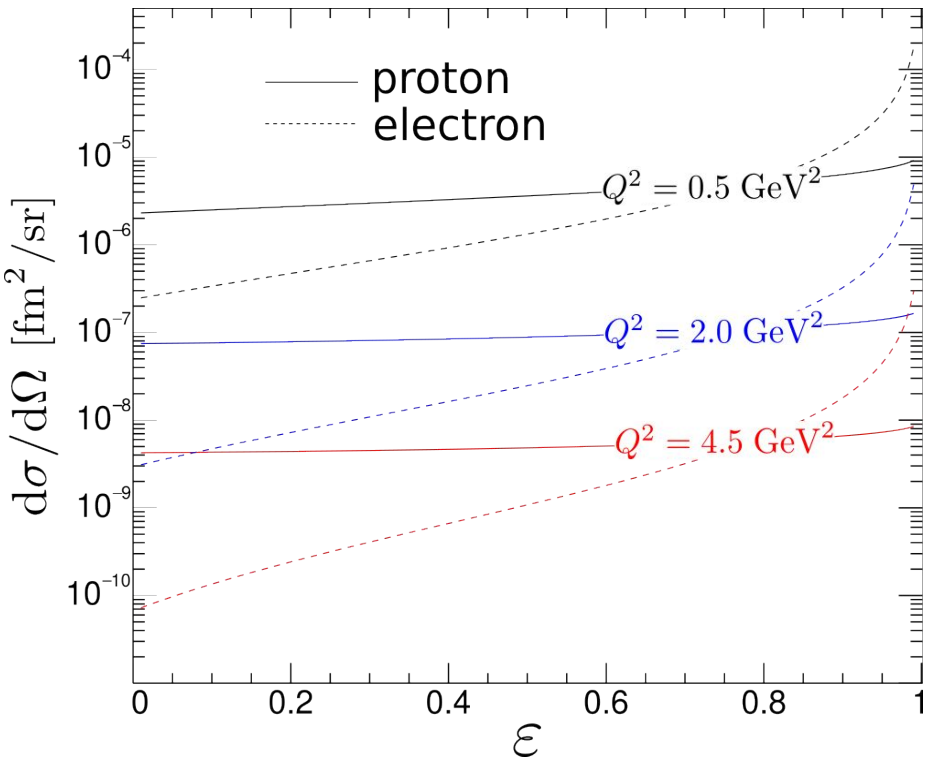
Advantages of Super-Rosenbluth: ***Cross Section***

ε dependence of momentum:

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

ε dependence of cross section:

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



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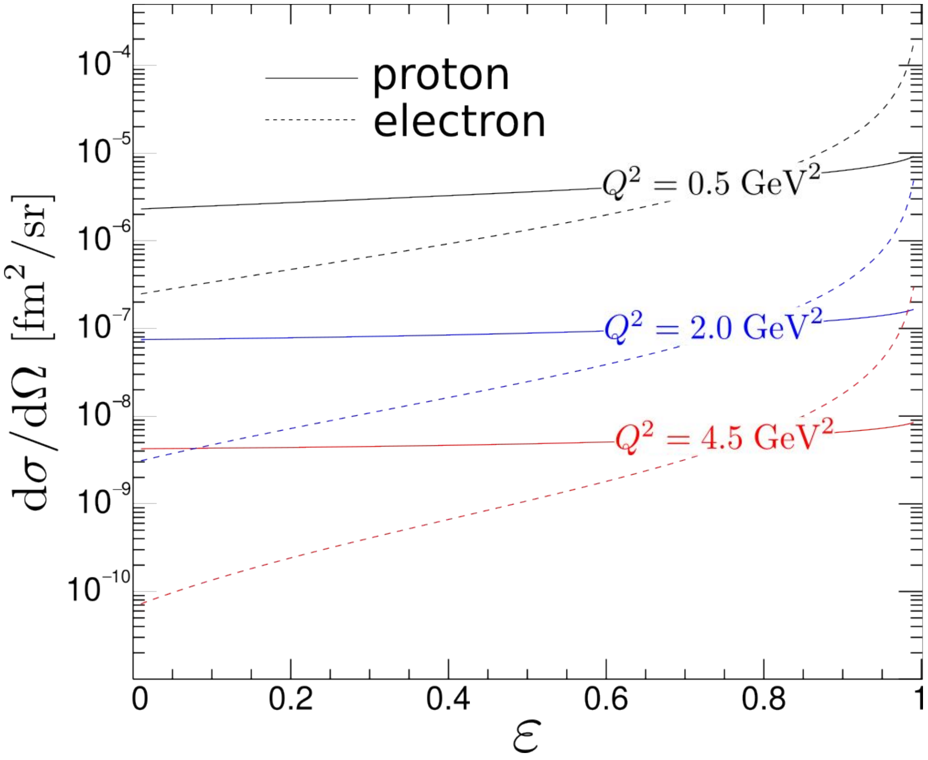
Less sensitive to kinematic uncertainties
- Beam energy
- Scattering angle



Advantages of Super-Rosenbluth: *Kinematic Uncertainties*

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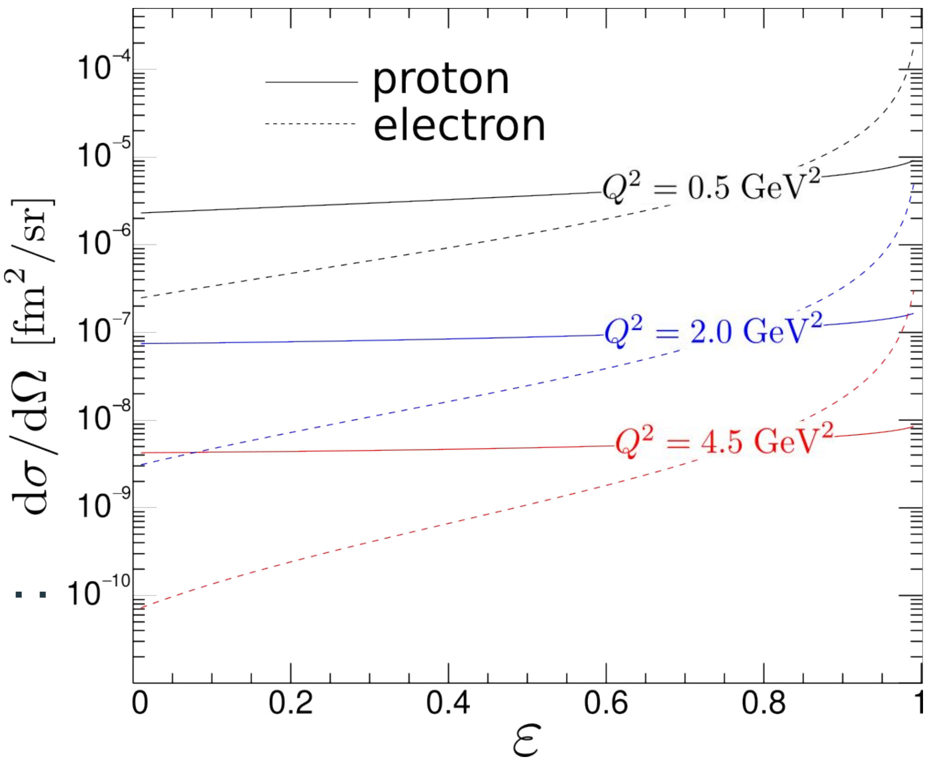


Some uncertainties (e.g. acceptance, proton absorption) have larger absolute uncertainties

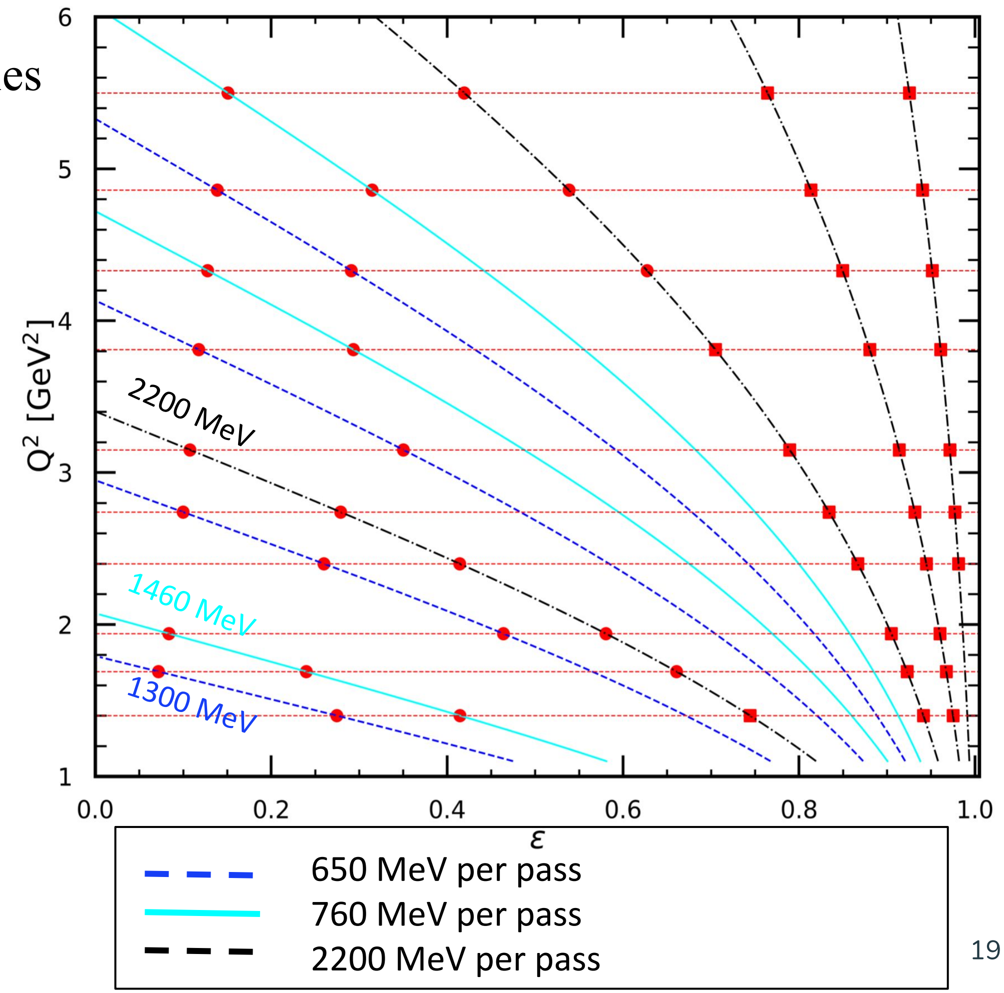
➡ They are independent of ε and cancel completely in extraction of G_E/G_M

PR12+23-012
Experimental Overview

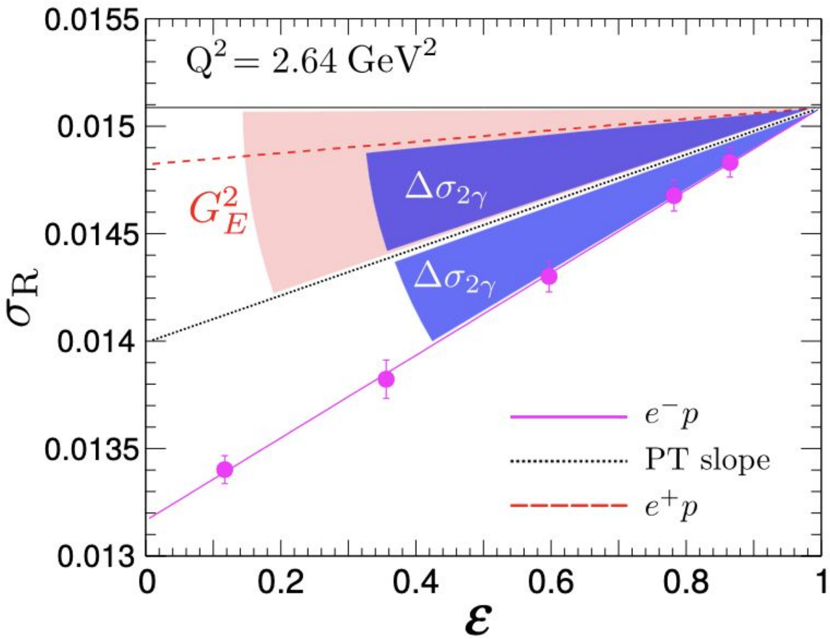
- Three linac settings; 11 beam energies
- Ten Q^2 points: 1.4 - 5.5 GeV^2
- Four or five ε points at each Q^2

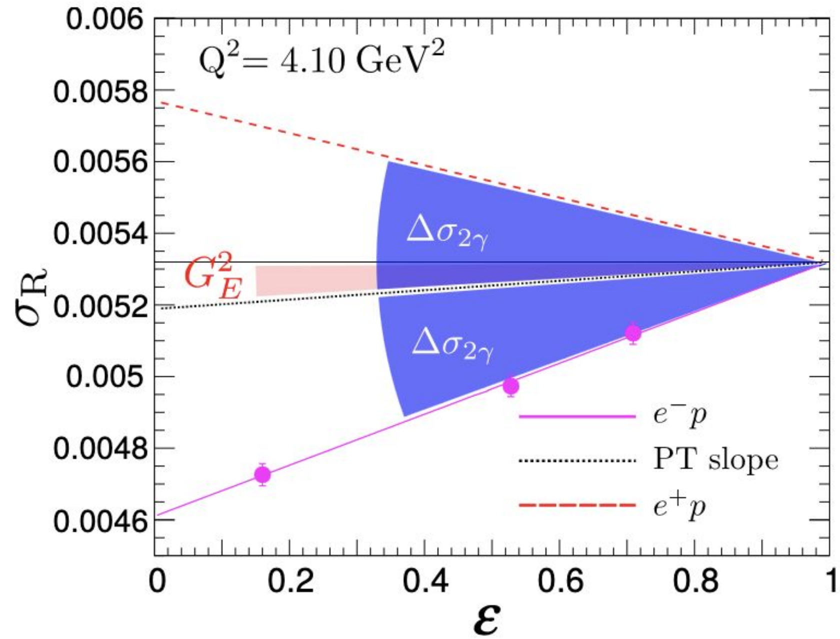
<u>Standard Hall C configuration</u>

- 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



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



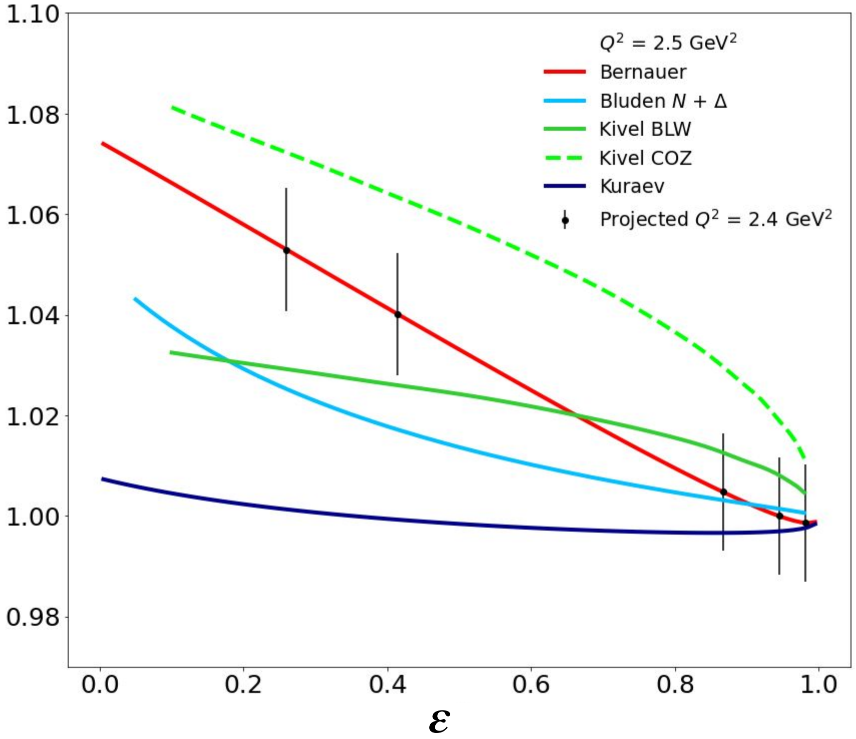


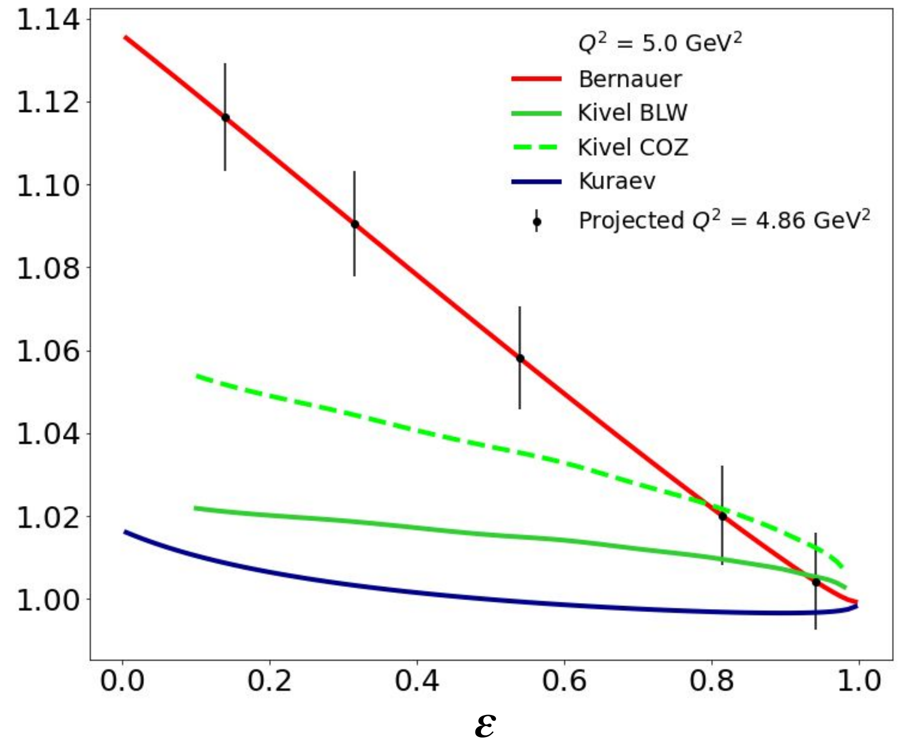
- Data from E01-001 (Super-Rosenbluth)
- Projected Super-Rosenbluth using positrons (Red dashed line)
- Slope from PT (Black dashed line)

*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**

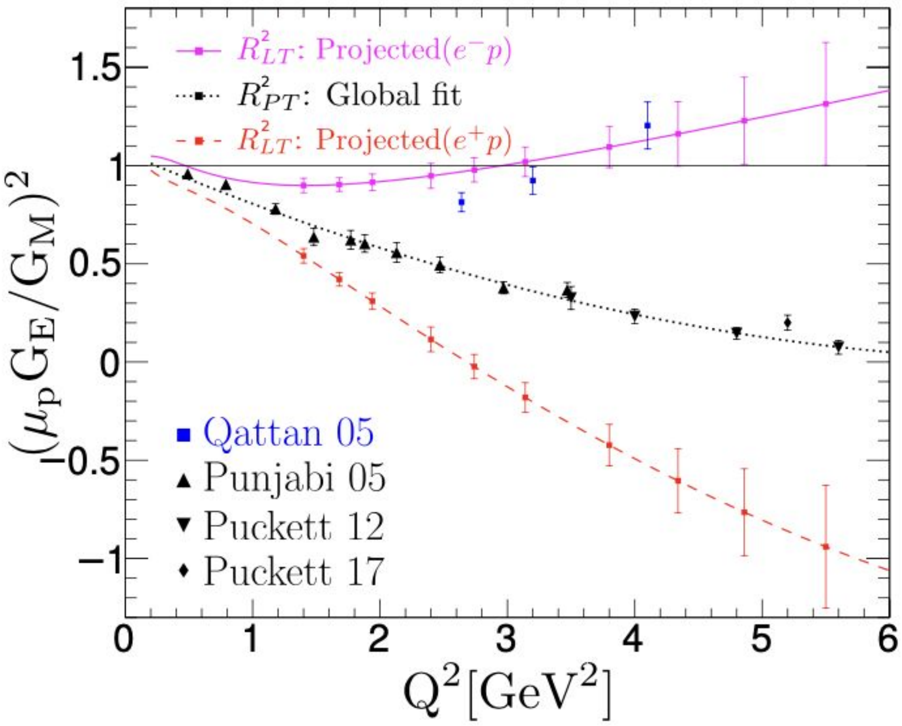




PR12+23-012

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



PR12+23-012

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)**

Beam Time Request: 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

Thank You

Questions

1.) It appears the main data taking will be on LH2. Carbon and Aluminum are for empty target, to check for target positions and beam offsets (Carbon) and target windows (Aluminum). Will the dummy targets be interspersed with LH2 running? There are potentially a large number of configuration changes and how the change-overs occur may drive certain systematics.

   a.) At each setting, LH2 followed immediately by Dummy data, to minimize the potential for any changes in the running conditions. For longer run periods, we will likely take LH2/dummy/LH2 or even do multiple cycles through LH2 and dummy (depending on the total run time) to minimize the time between LH2 and dummy data taking.

Questions

2.) Are the planned changes optimized to limit systematic uncertainties?

a.) To simplify running in multiple halls with pass and linac changes, the order will be driven mainly to simplify these changes and keep our time at each linac energy as close as possible to the scheduled times. At intermediate Q^2, there is flexibility and in order to stay on time and/or minimize time and non-standard energies. Hall A (E01-001) and Hall C (E05-017) experiments were ran in this way.

b.) At each Q^2, beam current, particle momentum, & rate in spectrometer should be identical, so efficiencies, deadtime, and other correction factors should be identical as well. The high statistics will allow for checks on possible time-dependent effects. E01-001 and E05-017 did not have any negative impact due to the timing of data collection of epsilon points at constant Q^2.

Questions

3.) **Are the down times between configuration changes adequately described?**
   - a.) **The configuration change times are based on the previous Super-Rosenbluth experiments, as well as other recent measurements with frequent kinematic changes.**

4.) **How often will the flip between electrons and positrons occur?**
   - a.) **We assume only one change between positrons and electrons as the positron and electron Super-Rosenbluth experiments are essentially run as separate.**

Questions

5.) **Because only the proton is measured, knowing the beam energy precisely is necessary. Have you considered variations of only detecting the proton that could reduce the systematic errors associated with proton-only detection?**

a.) **The cross section is always less sensitive to the beam energy uncertainty for proton rather than electron detection. For example, at 4.5 GeV^2, a 1% change in the beam energy changes the electron cross section by 6-8%, but the proton cross section by only 1.5-4.5%.**

b.) **We will have 40 kinematic settings where we can use the proton elastic peak to constrain the beam energy and scattering angle, where roughly half of those will also have the SHMS detecting electrons in coincidence, providing an additional handle on the kinematics.**

Questions

6.) **Precise beam energy measurements (0.04% absolute and point-to-point) are required after each beam energy change.**

   a.) **We made very conservative estimates in obtaining the uncertainties associated with the beam energies. The assumed beam energy uncertainty of 0.04% has a very small contribution to the total uncertainties and was based on past experiences and the anticipation that the level of precision will improve in the 12 GeV era. By increasing uncertainty to 0.1%, it will only increase the uncertainties by 10%.**

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%

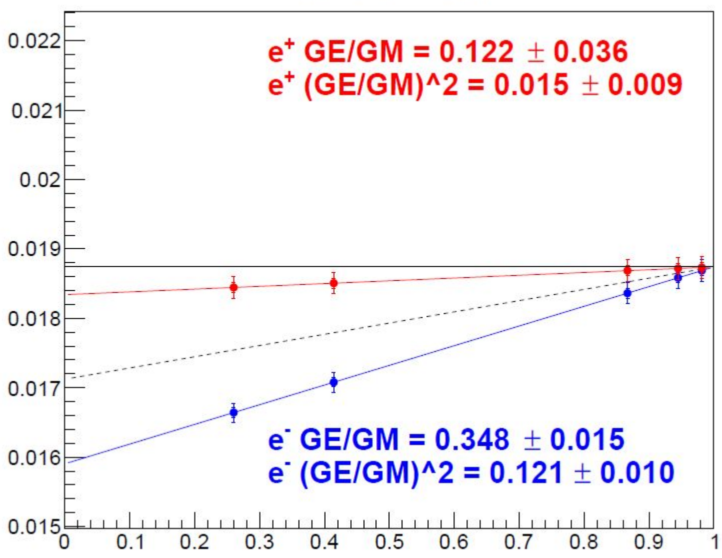
*Uncertainty given is on the slope rather than the individual cross sections

Break Down of Time

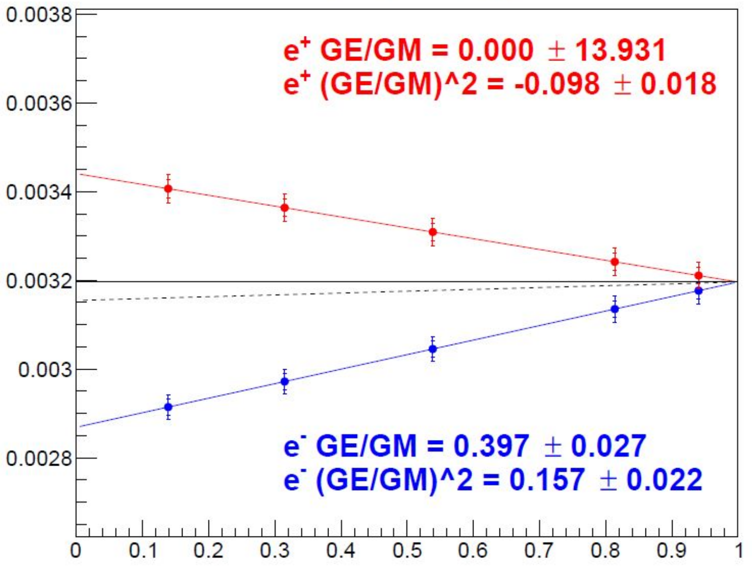
Setting	Beam Energy [GeV]	Percentage of Time	
1	1.3	0.55%	
1	1.95	2.56%	
1	2.6	6.75%	
1	3.25	9.45%	19.3%
2	1.46	0.95%	
2	2.92	8.78%	
2	3.65	10.8%	20.5%
3	2.2	5.41%	
3	4.4	21.6%	
3	6.6	18.2%	
3	11.0	14.9%	60.1%

Projected Uncertainties:
e^{+} **and** ***e***$^{-}$ ***Super-Rosenbluth Separation***

Q^2 = 2.40 GeV^2



Q^2 = 4.86 GeV^2



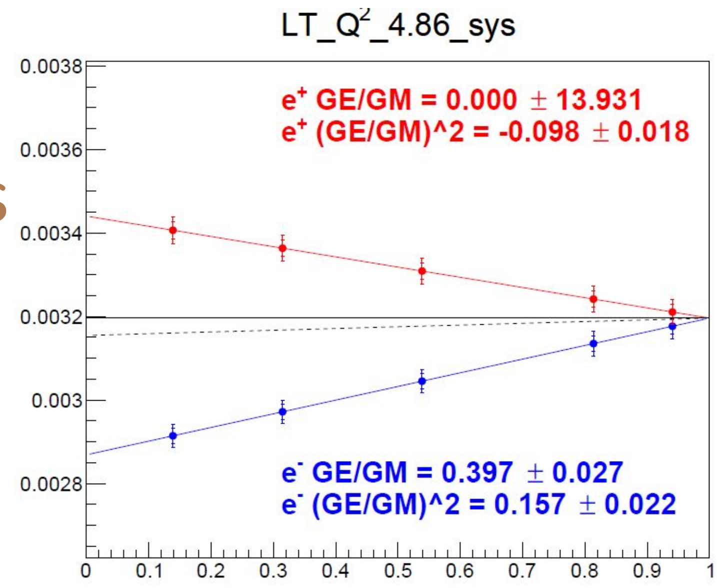
Advantages of Super-Rosenbluth

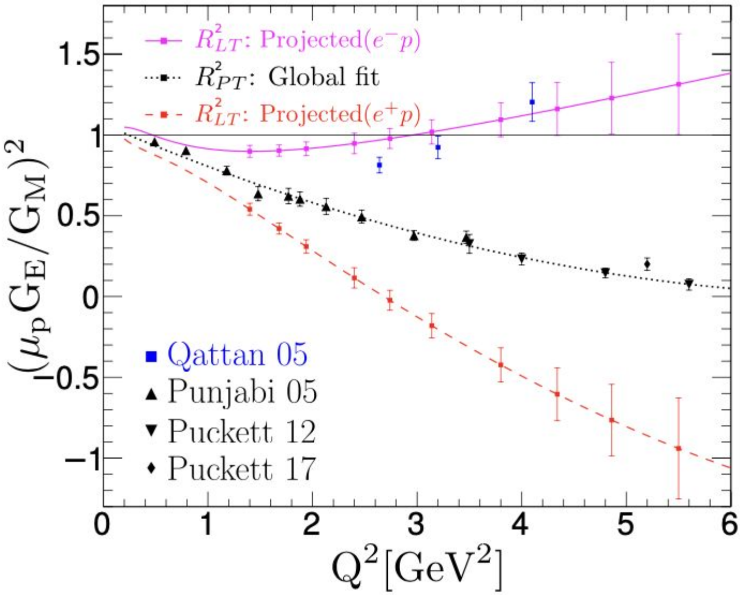
Q^2	ε	θ_e [degrees]	θ_p [degrees]	σ_e [nb/sr]	σ_p [nb/sr]	E'_e [GeV]	E'_p [GeV]
2.0	0.08	123	11.4	0.045	0.77	0.4	1.7
2.0	0.98	7.7	41.8	10	1.7	9.9	1.7

Hall C HMS Scattering Angle
10.5° - 90.0°

Sensitivity to various physics

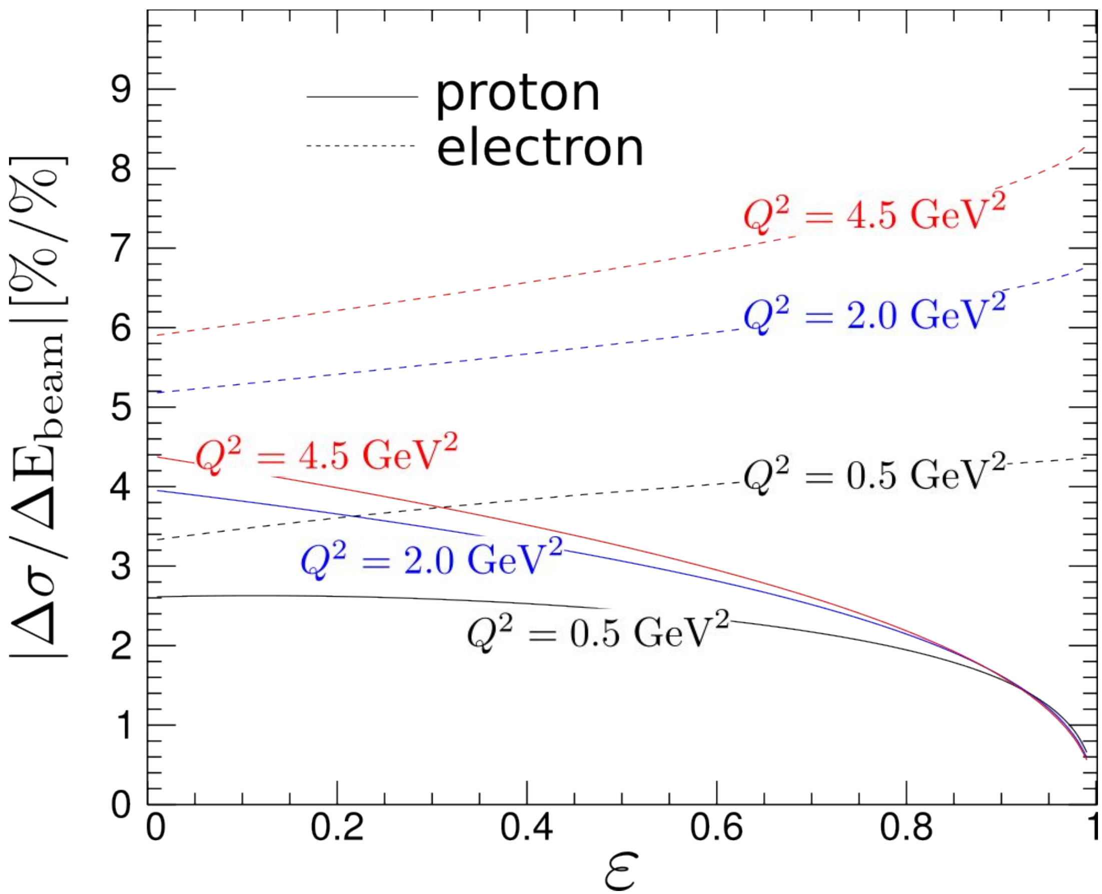
1. Positron (or electron) S-R
   a. Sensitive to non-linear contributions
2. Positron S-R vs polarization (e-)
   a. Sensitive to TPE in unpolarized cross section
   b. Sensitive to errors in conventional RC (much smaller)
   c. Sensitive to TPE in PT (much smaller)
3. Positron S-R vs electron S-R
   a. Doubles the sensitivity to TPE (size, non-linearity)
   b. Independent of conventional RC
   c. Independent of TPE in polarization
4. Positron-electron average S-R vs Polarization Transfer
   a. Sensitive to conventional radiative corrections
   b. Sensitive to TPE in polarization transfer



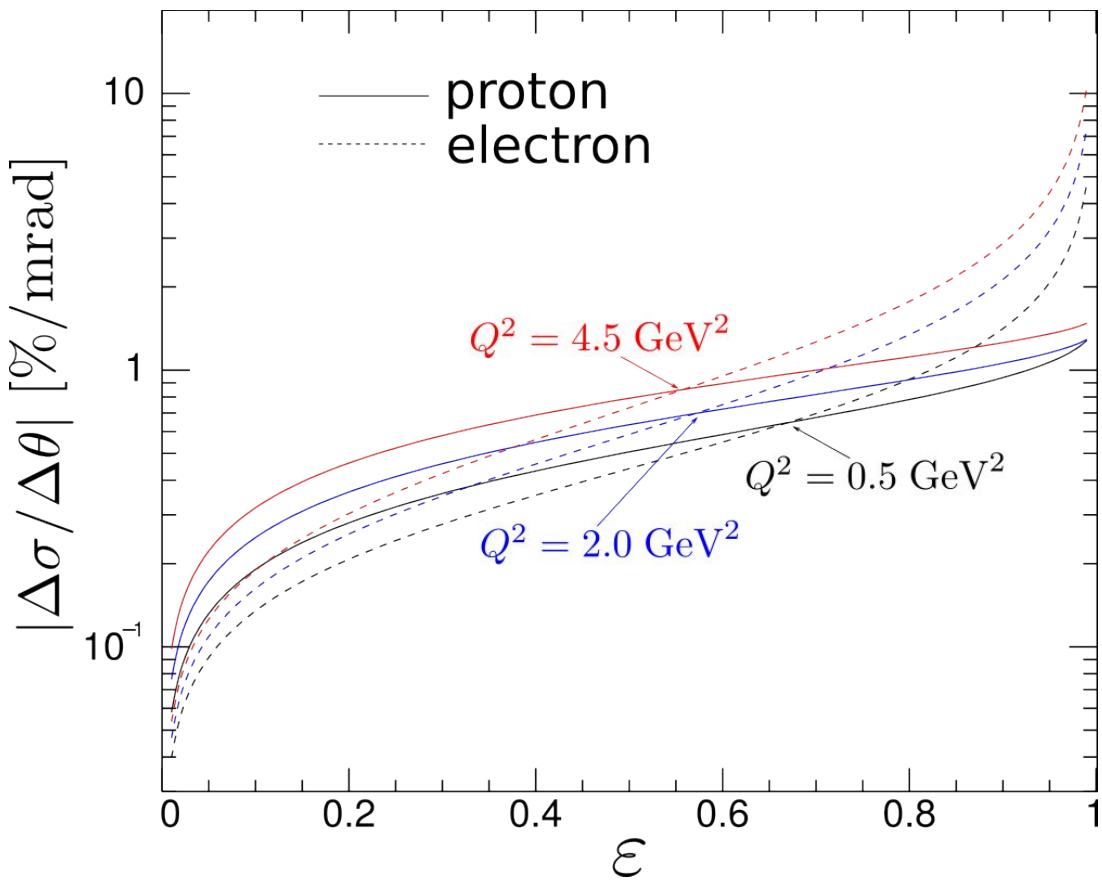


Advantages of Super-Rosenbluth:

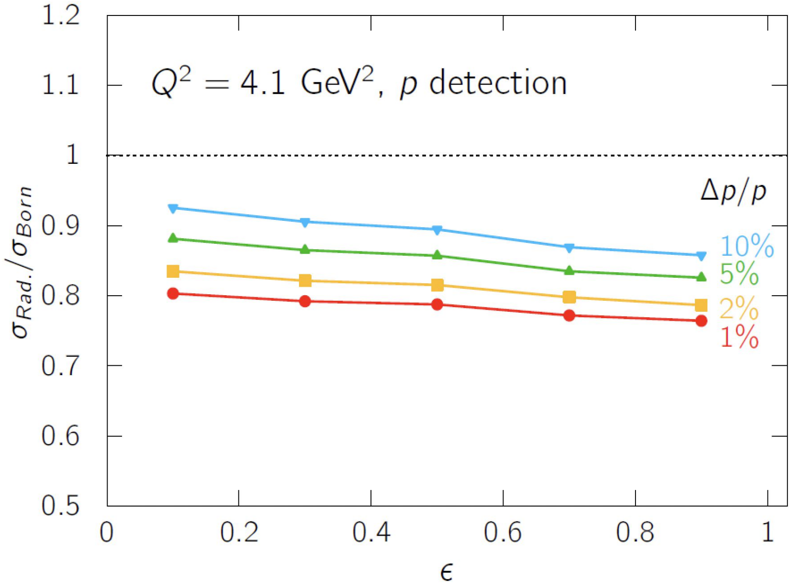
Kinematic Uncertainties

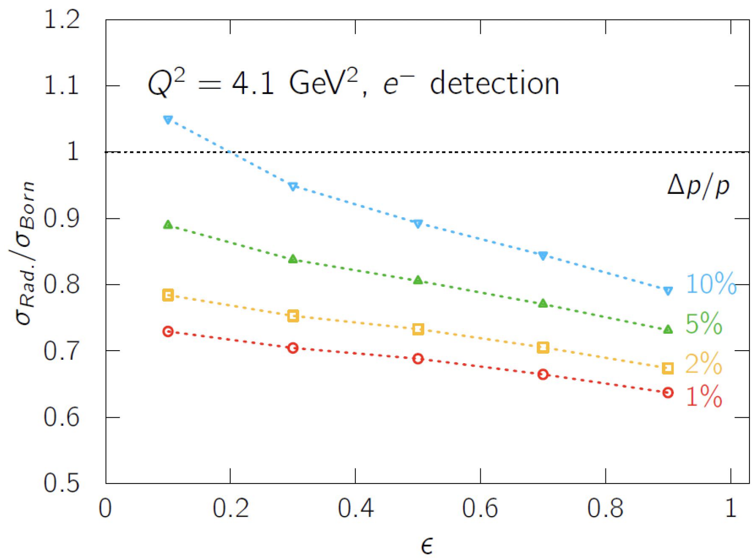


Advantages of Super-Rosenbluth: *Kinematic Uncertainties*



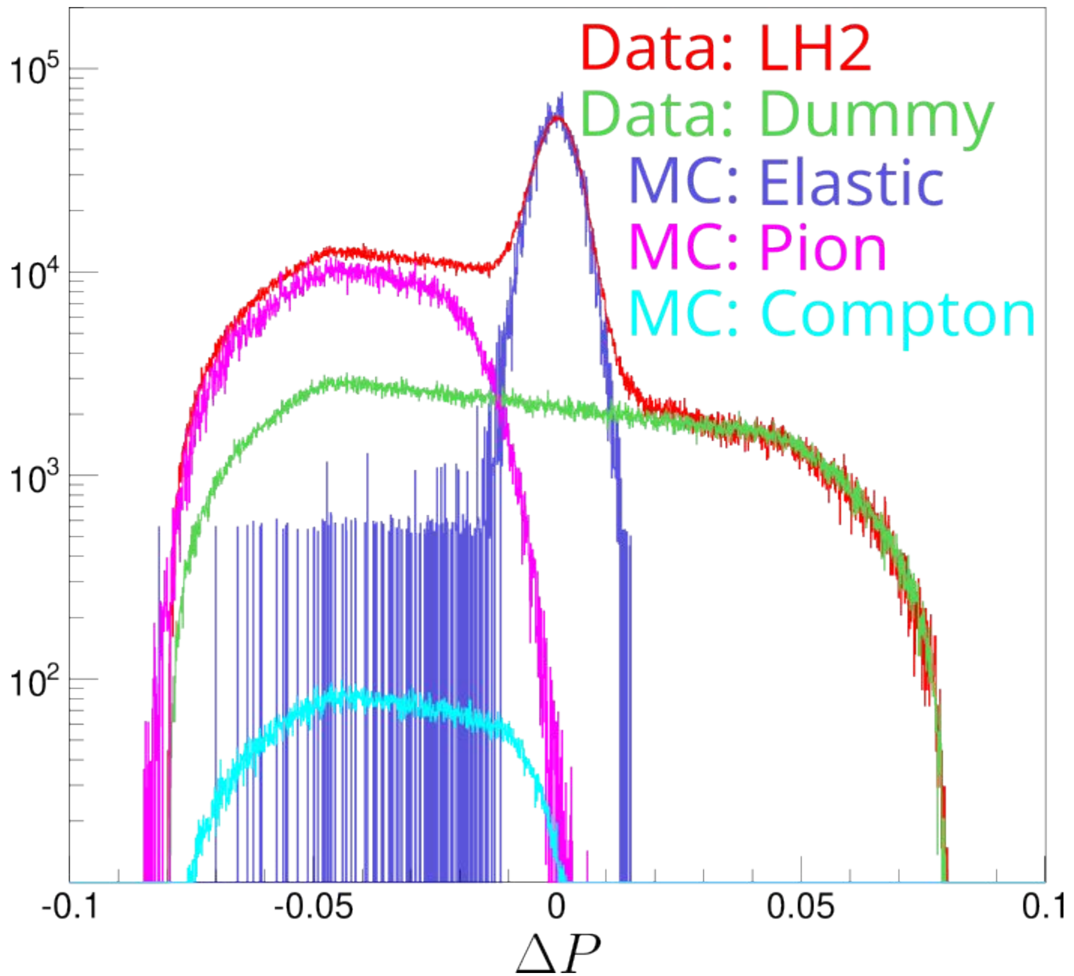
Advantages of Super-Rosenbluth:
Radiative Corrections



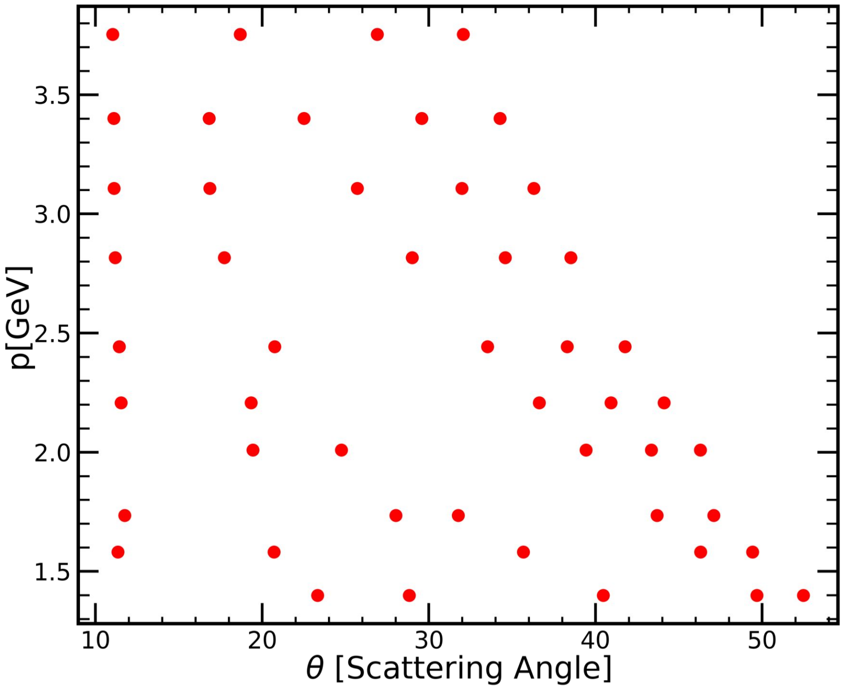


PR12+23-012

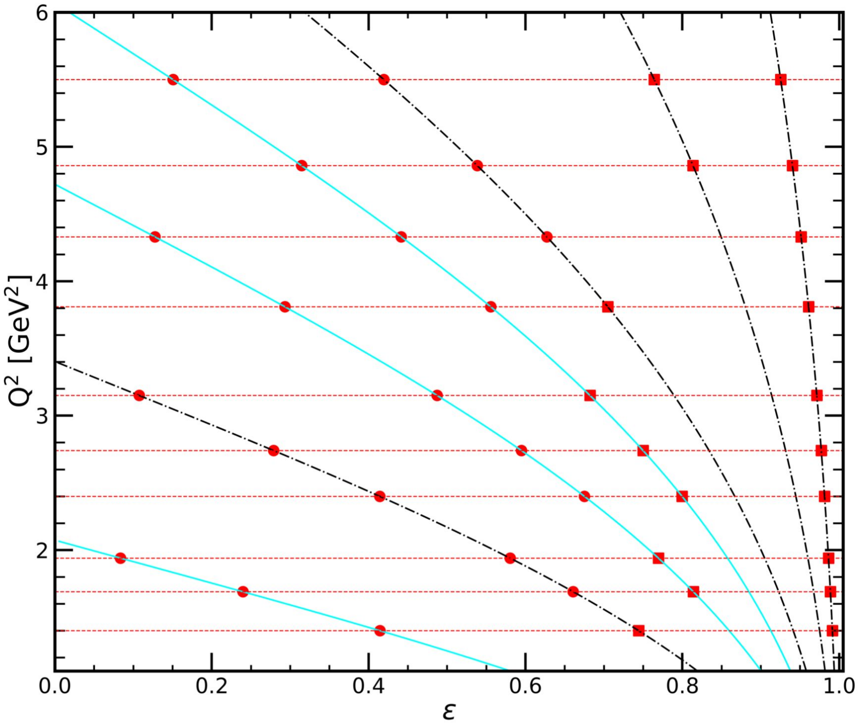
Background Subtraction



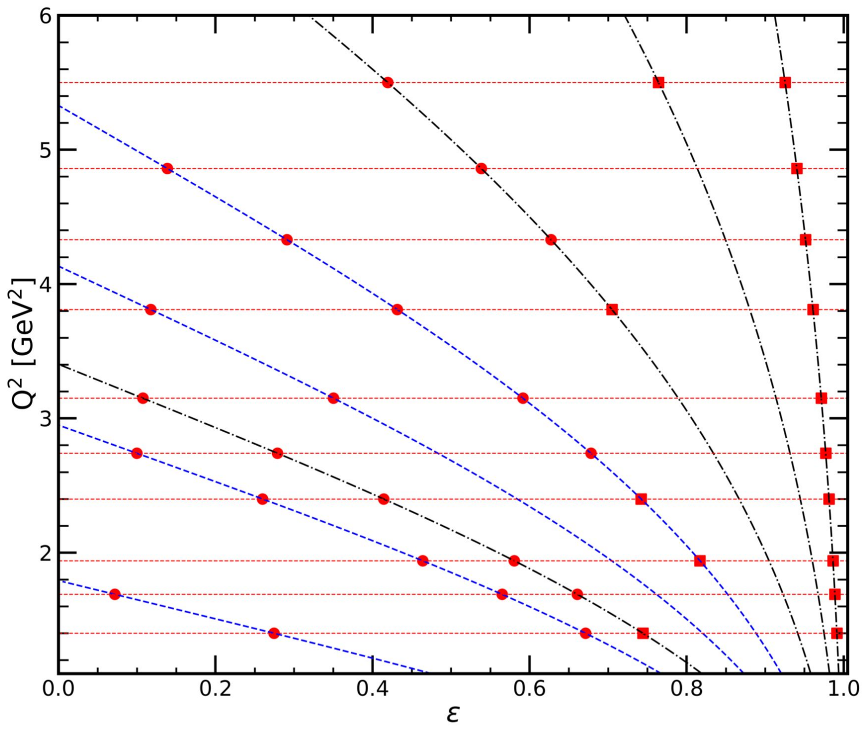
Momentum vs Scattering Angle



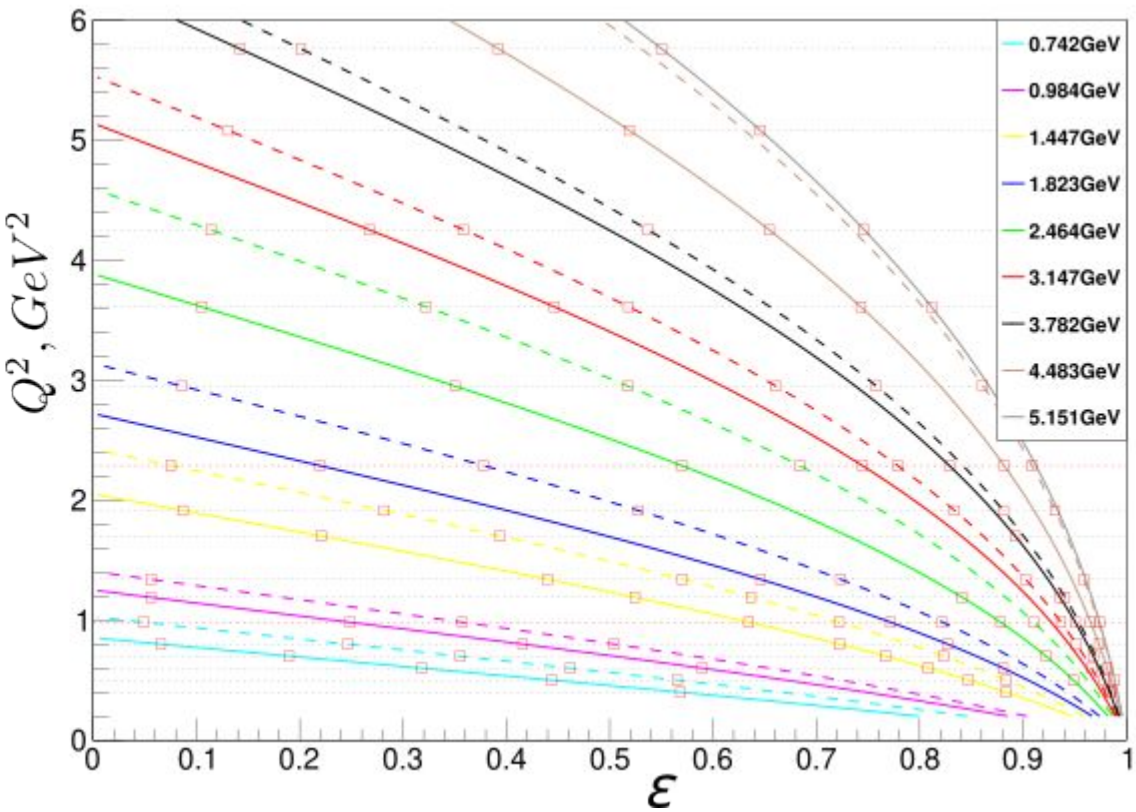
Modified Kinematics
(Linac Setting: 0.73)



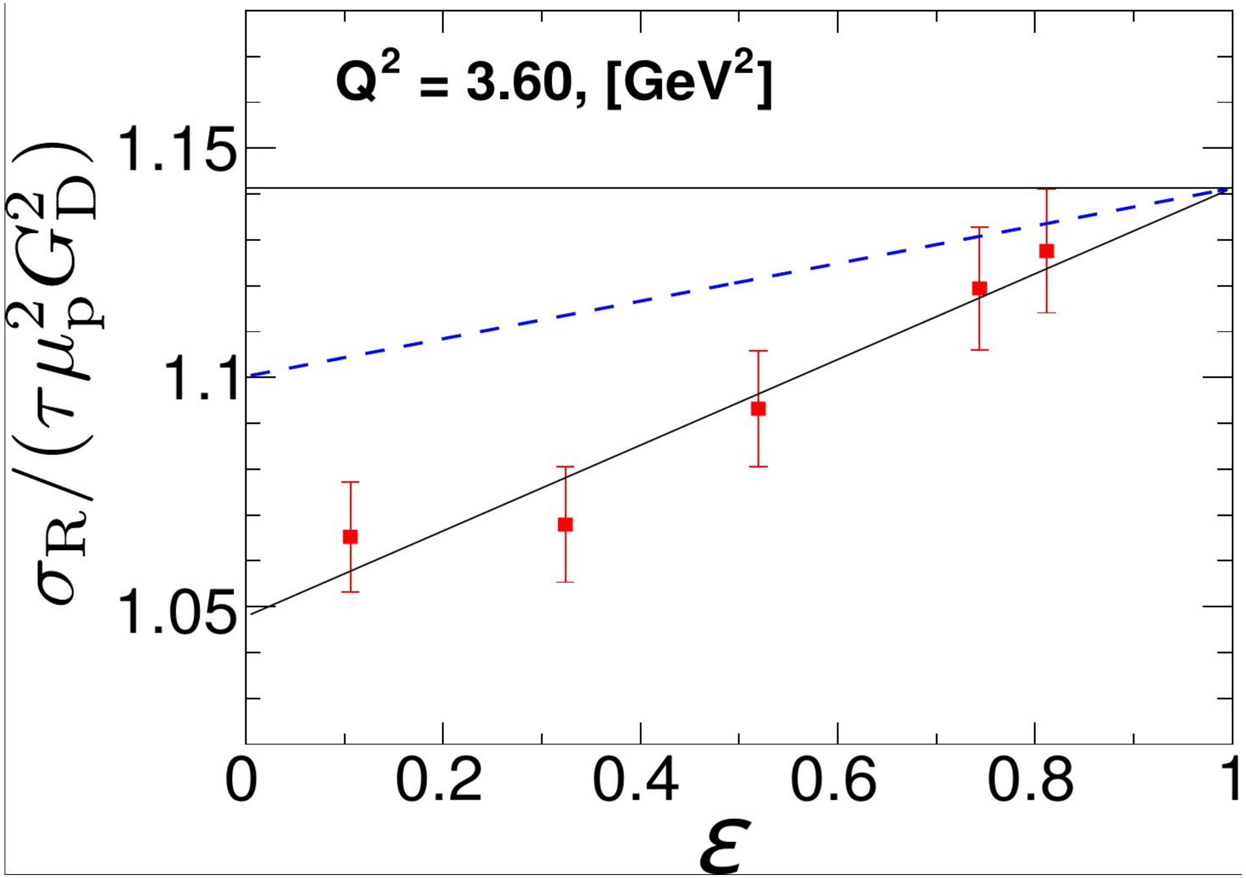
Modified Kinematics (Linac Setting: 0.65)



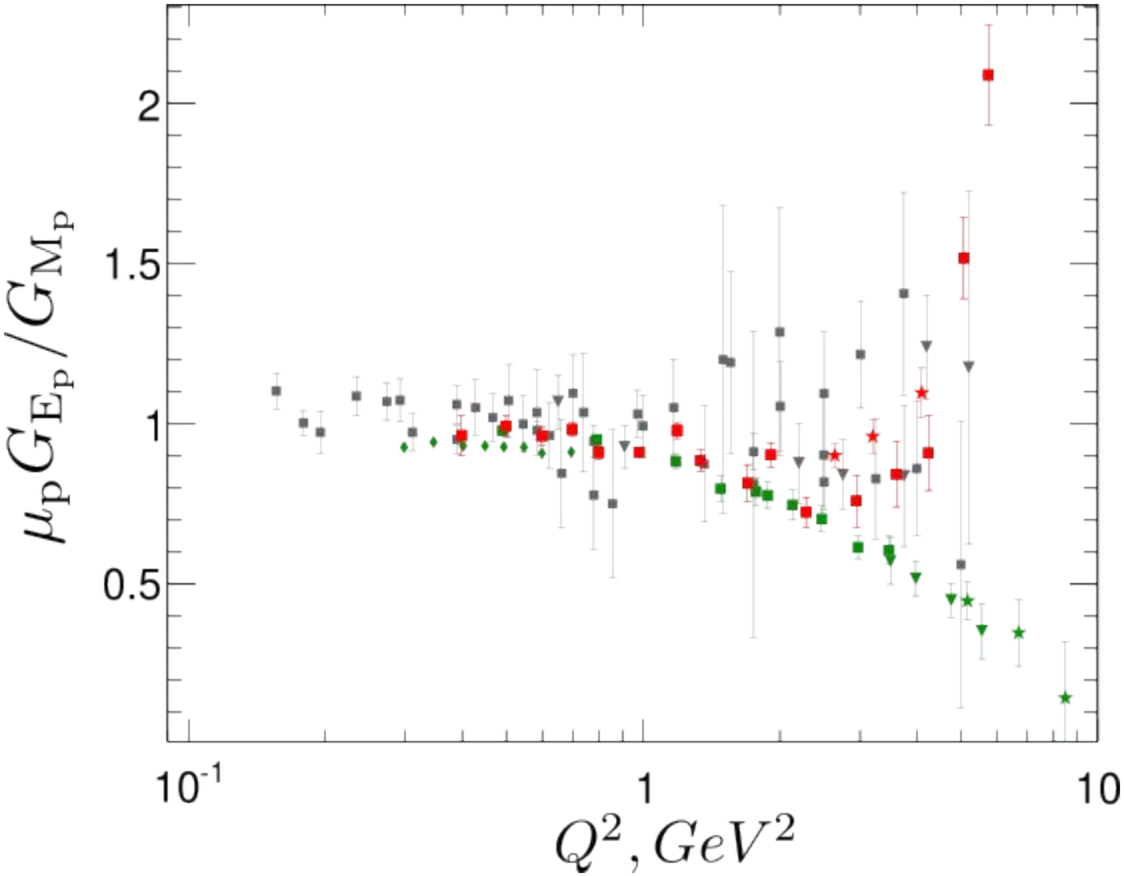
Backup - E05-017 plots (kine, Ge/Gm, linearity, p2 vs Q2,...)



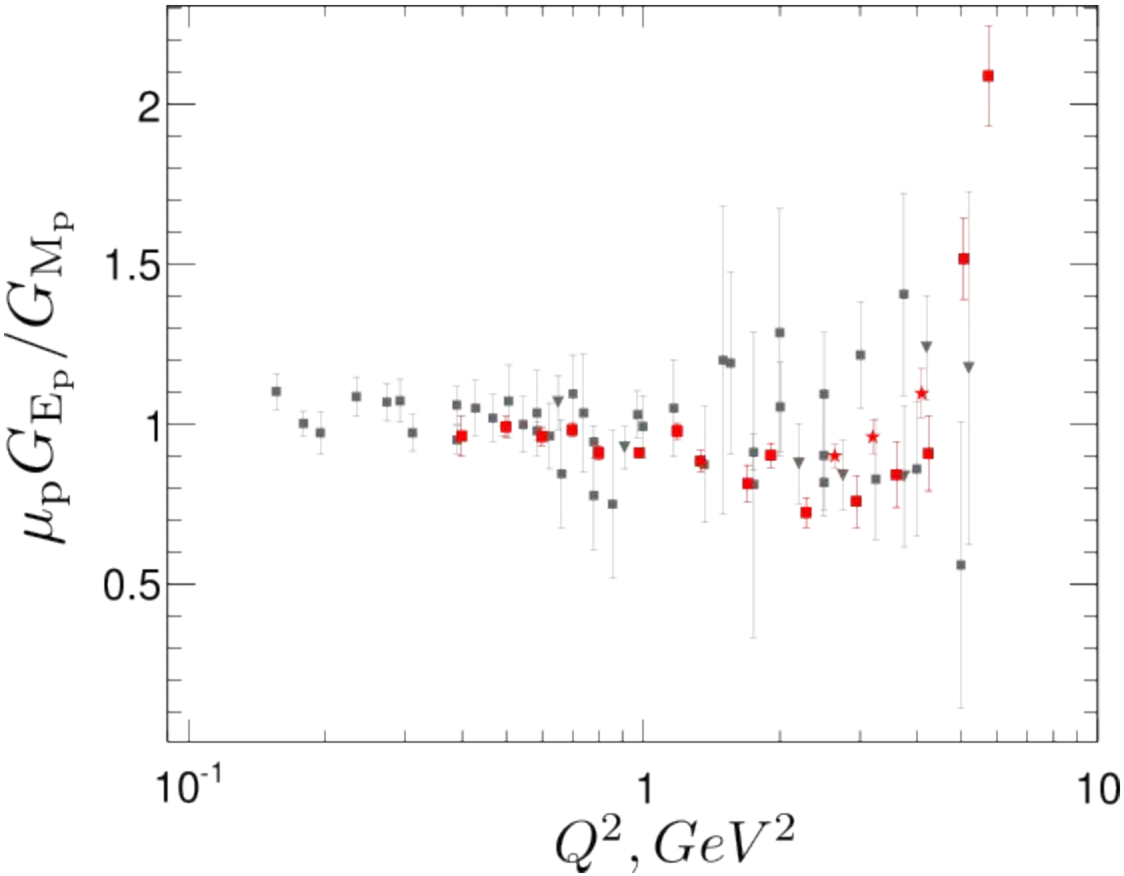
Backup - E05-017 plots (kine, Ge/Gm, linearity, p2 vs Q2,...)



Backup - E05-017 plots (kine, Ge/Gm, linearity, p2 vs Q2,...)



Backup - E05-017 plots (kine, Ge/Gm, linearity, p2 vs Q2,...)



Backup - E05-017 plots (kine, Ge/Gm, linearity, p2 vs Q2,...)