



**BERKELEY LAB**

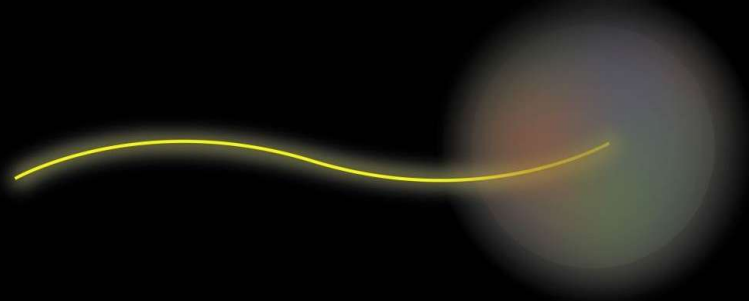
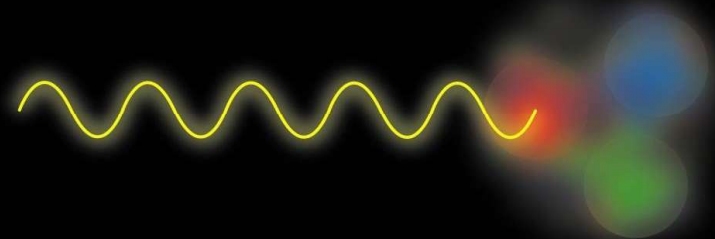
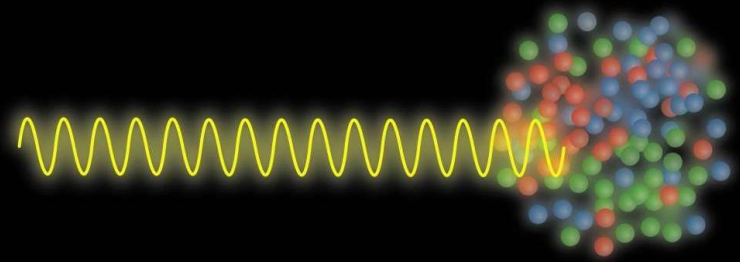
Bringing Science Solutions to the World



## Past and Future Super-Rosenbluth Experiments

*John Arrington - Lawrence  
Berkeley National Laboratory*

*E01-001, E05-017, E12+23-012*



# Proton form factors: Rosenbluth (50s-90s)

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

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

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

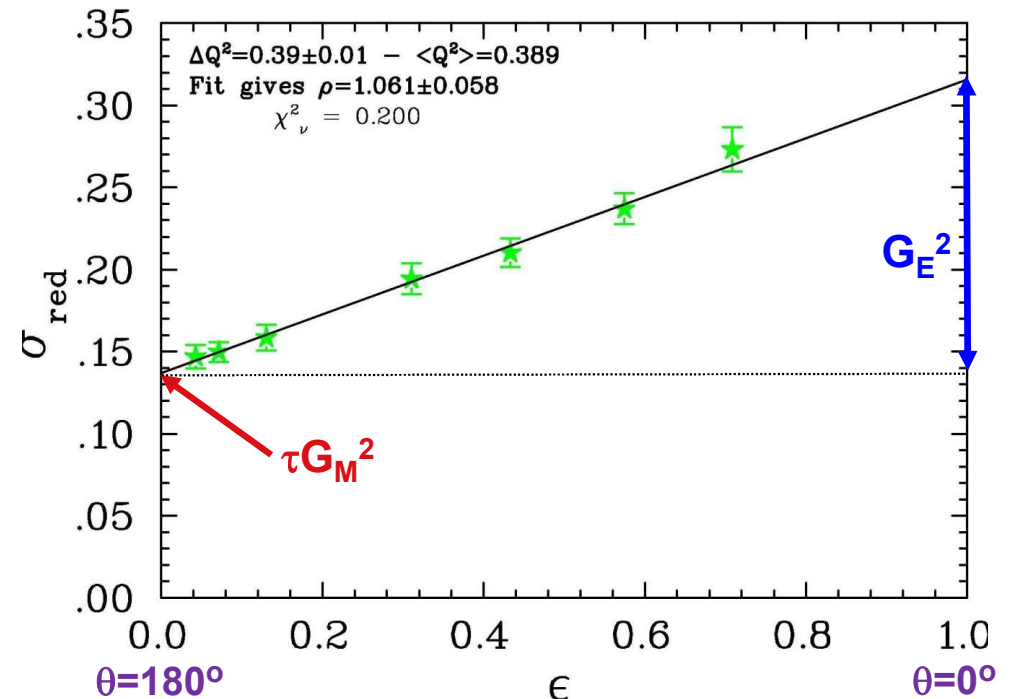
$$\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$$

Reduced sensitivity when one term dominates:

- $G_M$  if  $\tau \ll 1$
- $G_E$  if  $\tau \gg 1$
- $G_E$  if  $G_E^2 \ll G_M^2$  (e.g. neutron)

Worlds data give  $G_M$  and  $G_E$  proportional to dipole form:  $(1+Q^2/[0.71 \text{ GeV}^2])^{-2}$

$$\rightarrow \mu_p G_E(Q^2) / G_M(Q^2) \approx 1$$



# Form factors: 90s-now

Mid '90s brought measurements using polarization degrees of freedom

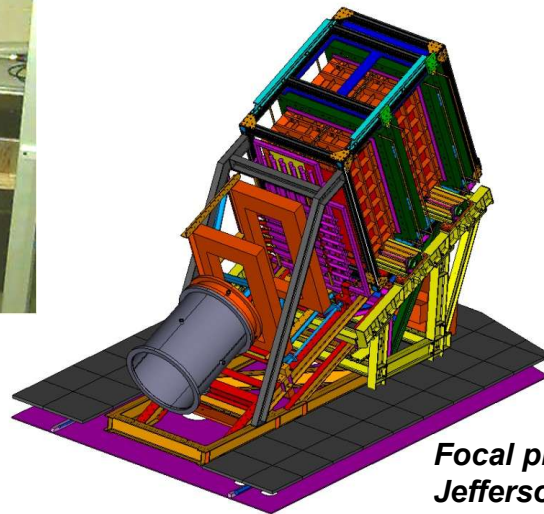
- High luminosity, highly polarized electron beams
- Large acceptance detectors
- Polarized targets ( $^1\text{H}$ ,  $^2\text{H}$ ,  $^3\text{He}$ ) or recoil polarimeters



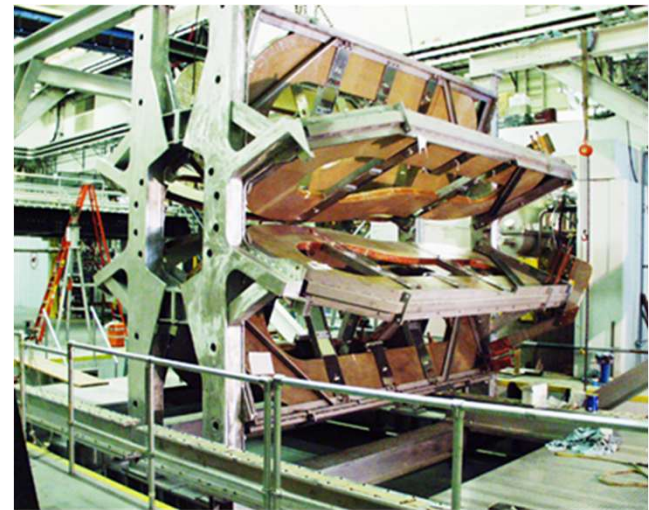
*Polarized  $^3\text{He}$  target*

$$\text{Unpol: } \tau G_M^2 + \varepsilon G_E^2$$

$$\text{Pol: } G_E / G_M$$



*Focal plane polarimeter – Jefferson Lab*



*BLAST at MIT-Bates*

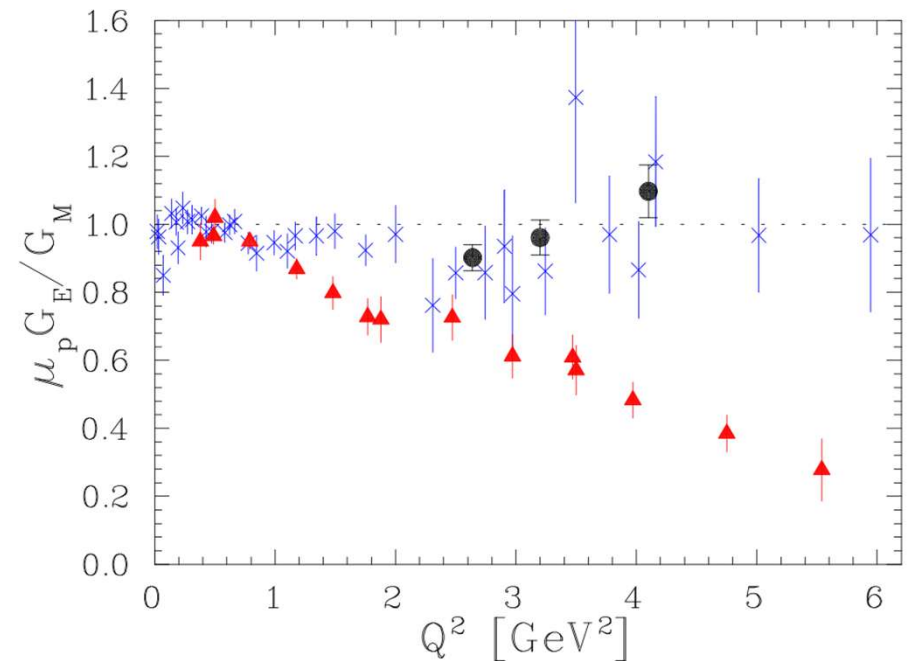
# Form factors (2000-2015) Rosenbluth vs Polarization

**Blue points are global Rosenbluth extractions**

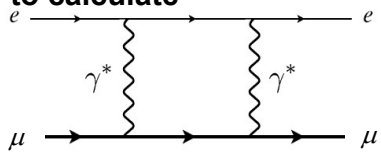
**Red points are polarization measurements**

- Significant difference at high  $Q^2$ , where Rosenbluth have large errors, typically limited by systematics

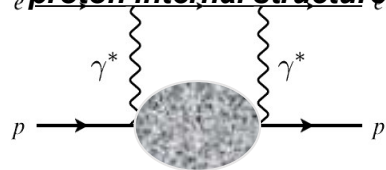
**Difference assumed to be caused by two-photon exchange (TPE) corrections**



**QED: straightforward to calculate**



**QED+QCD: depends on proton internal structure**



**Black points – “Super-Rosenbluth” measurement:**

Modified technique that gives significantly smaller uncertainty on the RATIO  $G_E/G_M$

*I. A. Qattan, et al, PRL 94, 142301 (2005)*

# Super-Rosenbluth technique

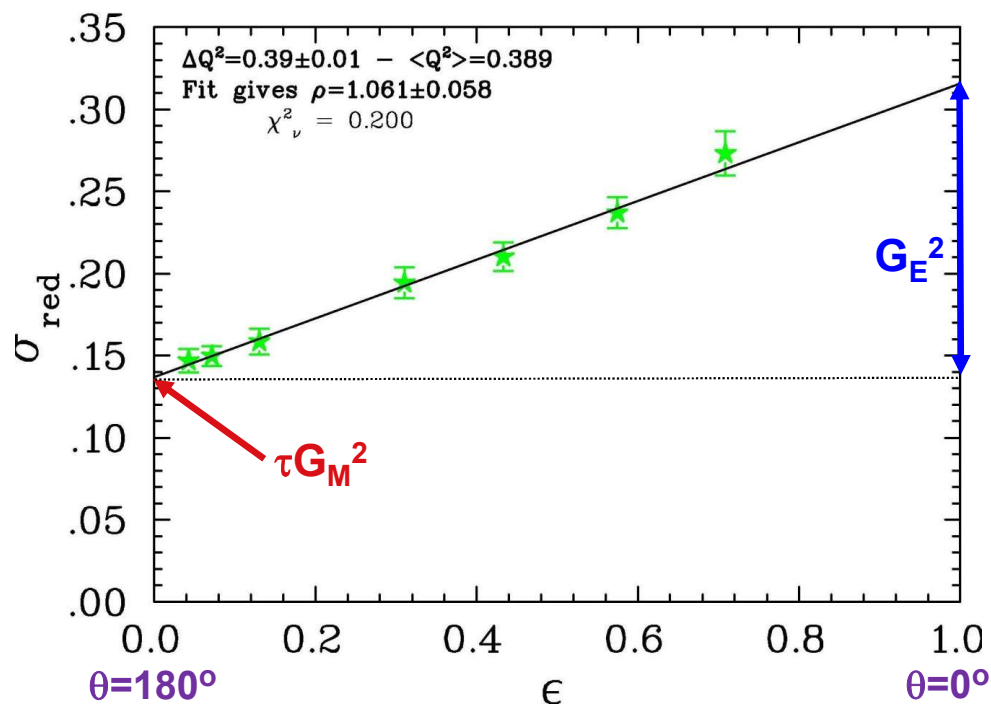
Rosenbluth (L/T) measurement: vary  $\varepsilon$  ( $\theta$ ) at fixed  $Q^2$

Conventional measurement: electron detection

- $\varepsilon \approx 1$ : large beam energy, small scattering angle, large electron momentum, high rates
- $\varepsilon \approx 0$ : small beam energy, large angle, small electron momentum, low rates
- Extraction of  $\varepsilon$  dependence sensitive to momentum- and rate-dependent corrections (including rad corr)
- Limited by low cross sections at large scattering angle

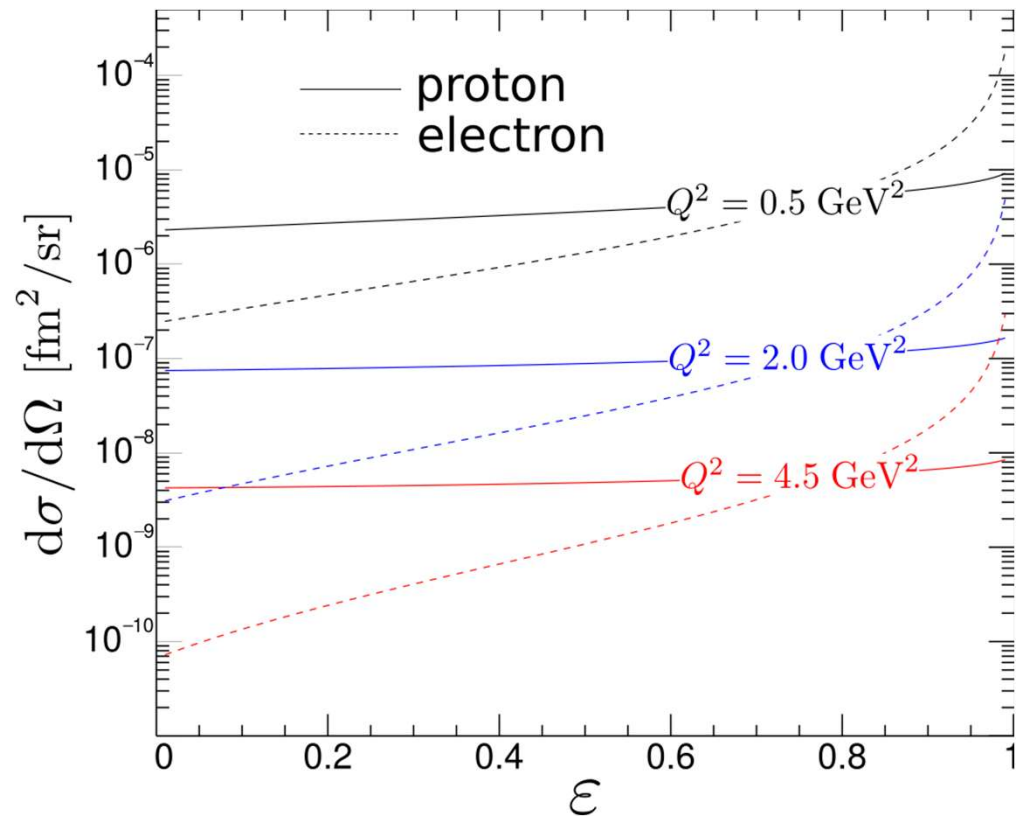
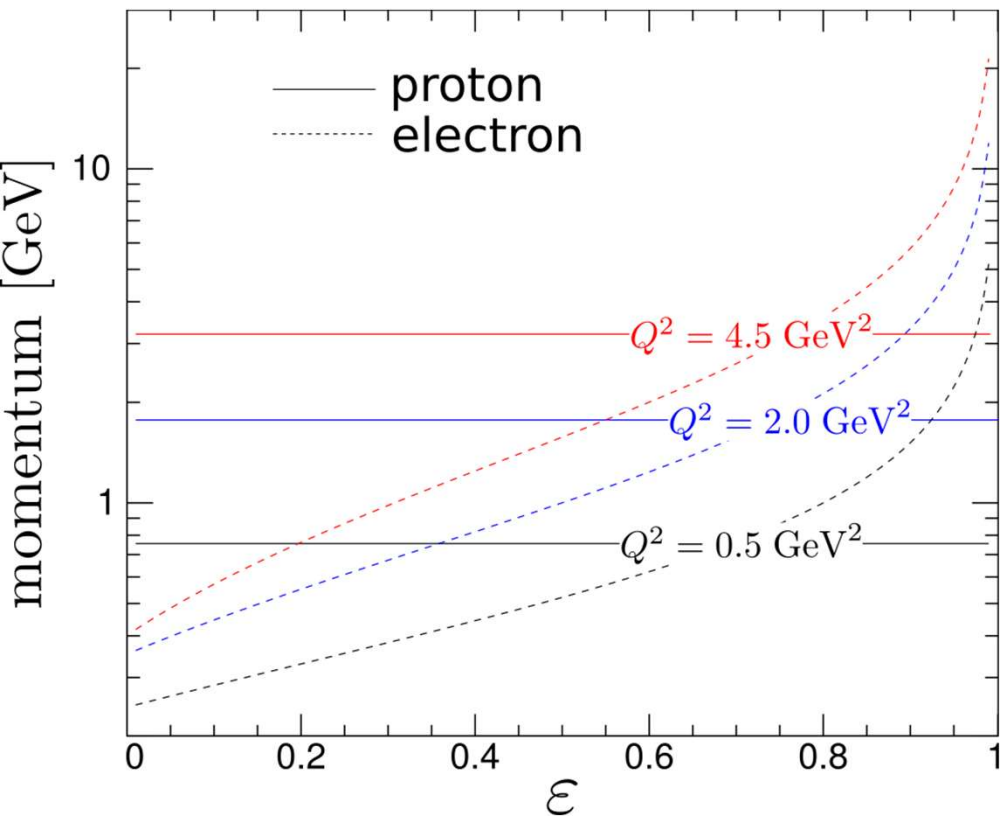
## Super-Rosenbluth: Proton detection

- Fixed proton momentum at fixed  $Q^2$
- Cross section, rad corr have much smaller  $\varepsilon$  dependence
- Higher cross section for small  $\varepsilon$
- Less sensitive to kinematic uncertainties

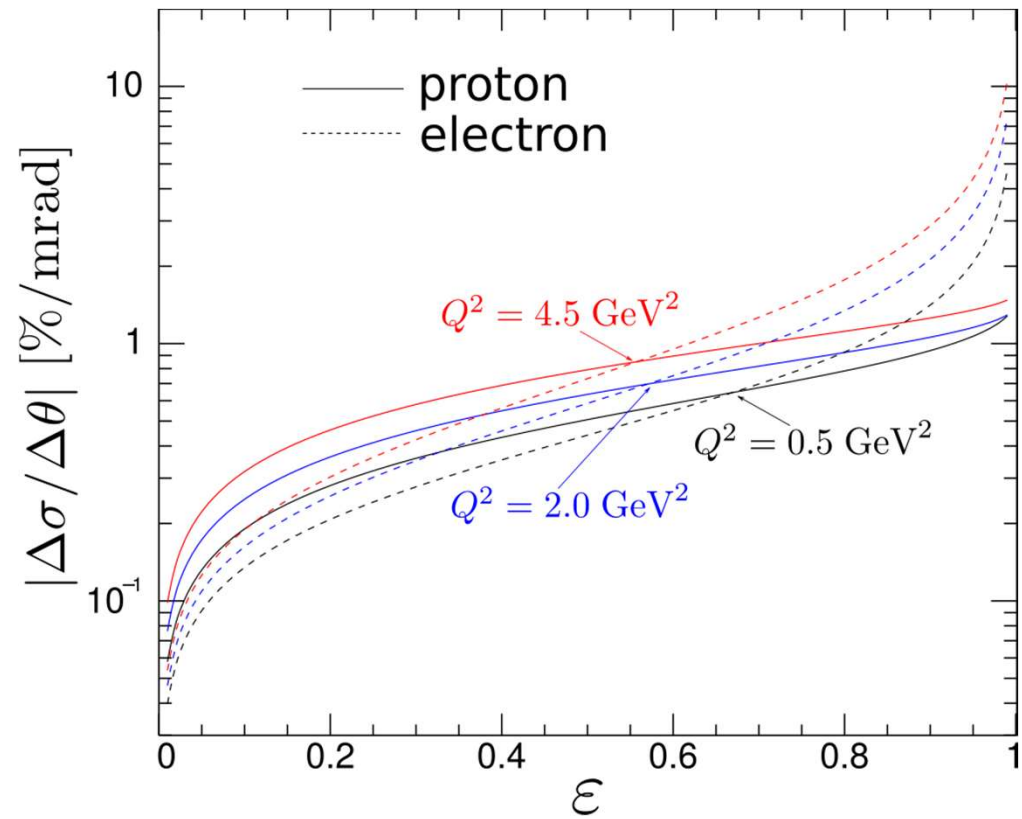
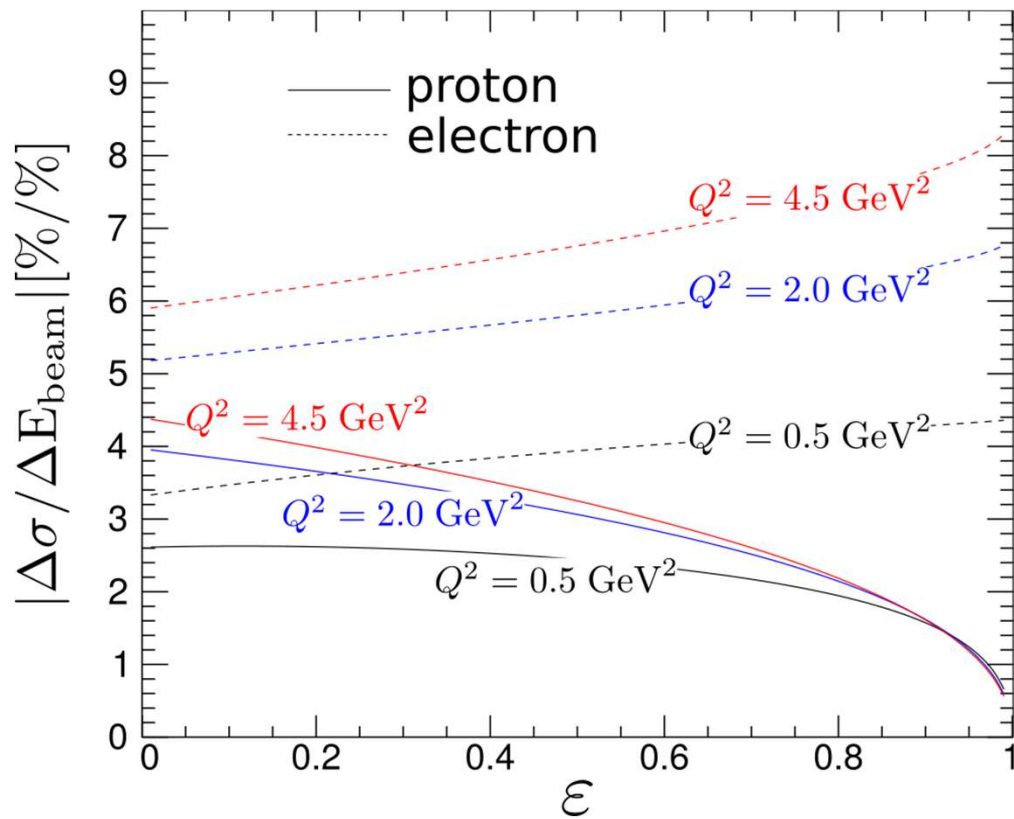


While some uncertainties (e.g. acceptance, proton absorption) have **larger absolute uncertainties**, they are independent of  $\varepsilon$  and **cancel completely in extraction of  $G_E/G_M$**

# Proton vs electron detection: kinematics and rate



# Proton vs electron detection: kinematic sensitivity

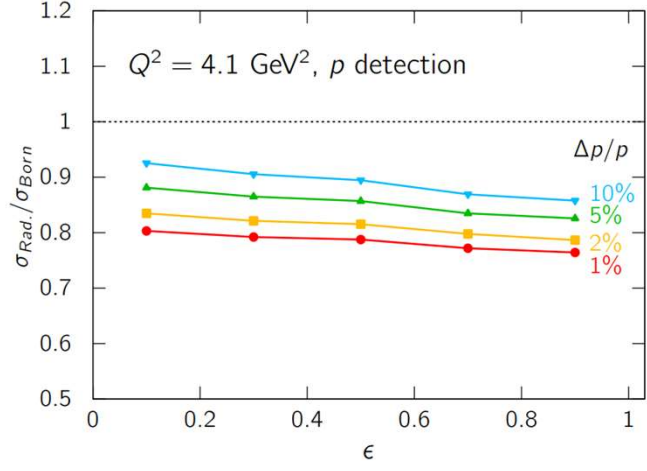
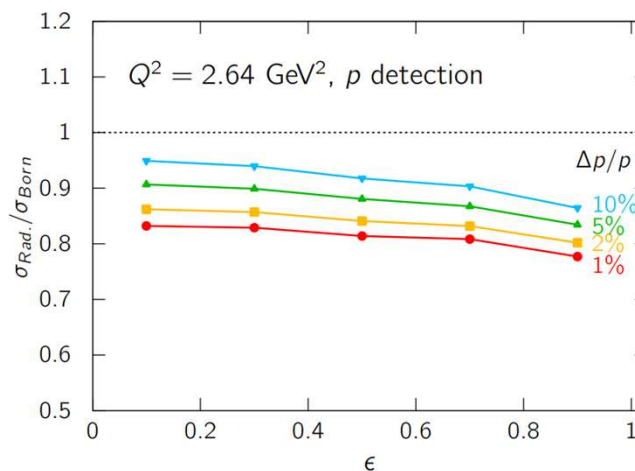
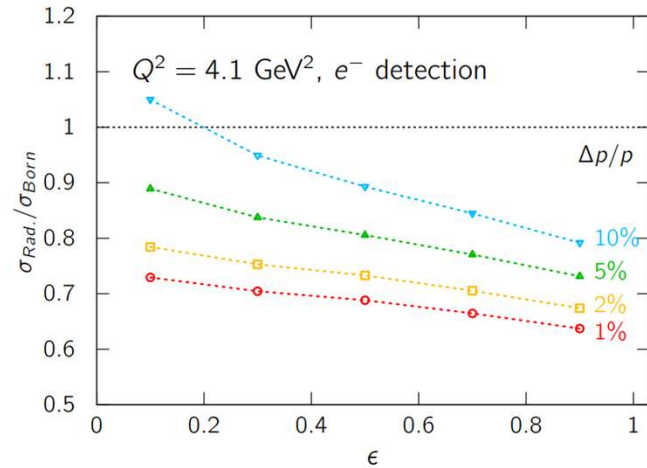
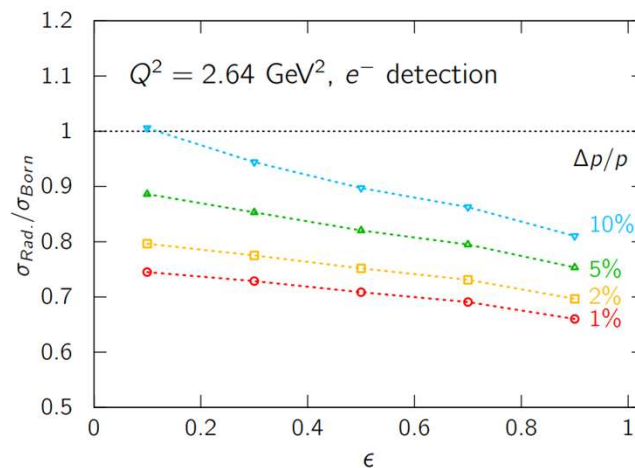
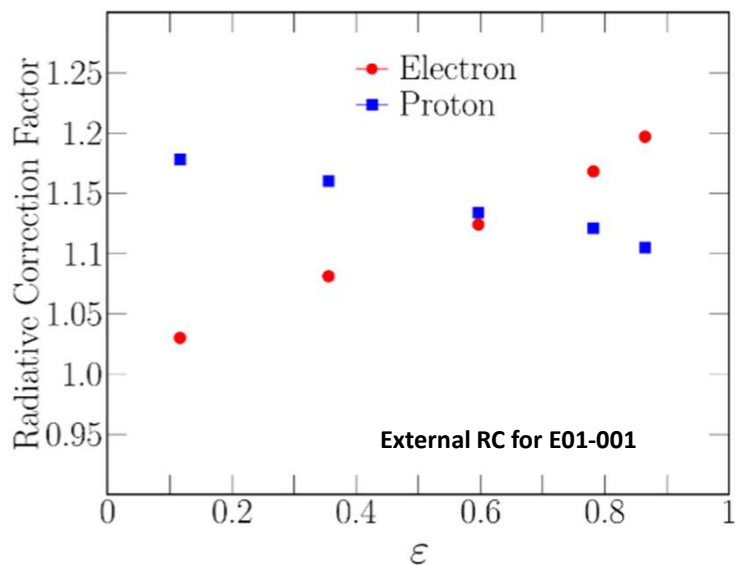


# Proton vs electron detection – radiative corrections

Radiative corrections for electron and proton detection are **similar in size**

**Proton detection has smaller  $\epsilon$  dependence, reduced sensitive to cutoff**

Q. Stefan, A. Schmidt *Eur. Phys. J. A* 60 (2024) 11, 229



# Super-Rosenbluth past: electrons

E01-001 – New Measurement of  $G_E/G_M$  for the proton [JA, R. Segel spokespeople] I.A.Qattan - PhD

- First Super-Rosenbluth extraction:  $Q^2=2.64, 3.2, \text{ and } 4.1 \text{ GeV}^2$
- Extraction of  $G_E/G_M$  with **precision comparable to polarization transfer**
- **Smaller and very different systematic uncertainties** from conventional Rosenbluth Separation
- Clear confirmation of discrepancy (PRL). Archival paper published last year (PRC)  
I. A. Qattan, et al., *Phys. Rev. Lett* **94** (2005) 142301  
I. A. Qattan, et al., *Phys.Rev. C* **112** (2025) 035205

E05-017 – Measurement of TPE in unpolarized e-p scattering [JA] M.Johnson, M.Yurov-PhDs

- 16 separation for  $Q^2$  from 0.4-5.8  $\text{GeV}^2$ , with 10+ epsilon points at  $Q^2=0.98, 2.28 \text{ GeV}^2$
- HMS resolution worse than normal – larger backgrounds for high  $Q^2$  settings
- Issues with TOF calibration and unexpected fluctuations at large epsilon delayed high- $Q^2$  results
- Updated QC checks complete, main issues have been identified – fixes in progress but no new results.

# Two Photon Exchange Corrections

Two-photon exchange effects can explain discrepancy in  $G_E$

Guichon and Vanderhaeghen, PRL 91, 142303 (2003)

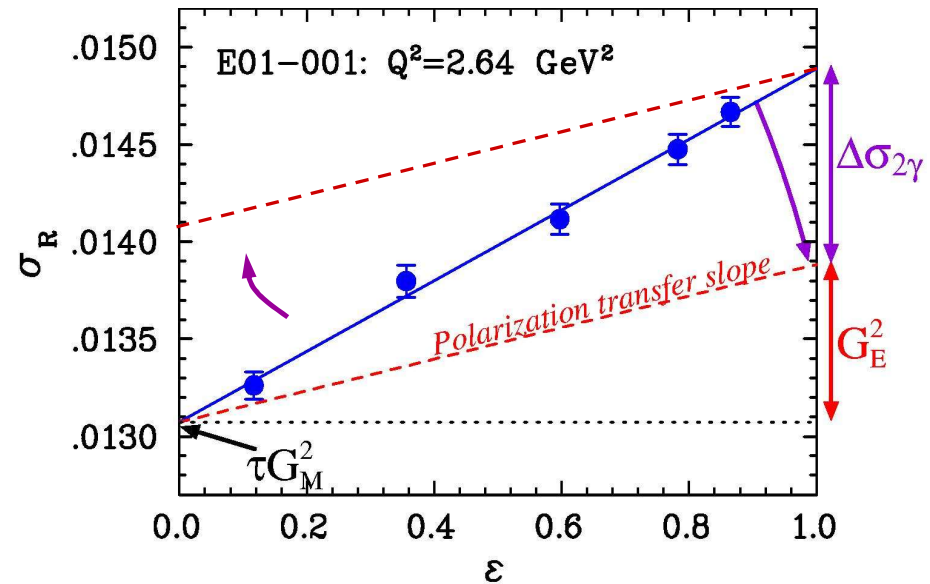
Requires  $\sim 6\%$   $\varepsilon$ -dependence, weakly dependent on  $Q^2$ ,  
roughly linear in  $\varepsilon$

JA, PRC 69, 022201 (2004)

If this were the whole story, LT would give  $G_M$ , PT gives  
 $G_E/G_M$

There are other issues to be addressed

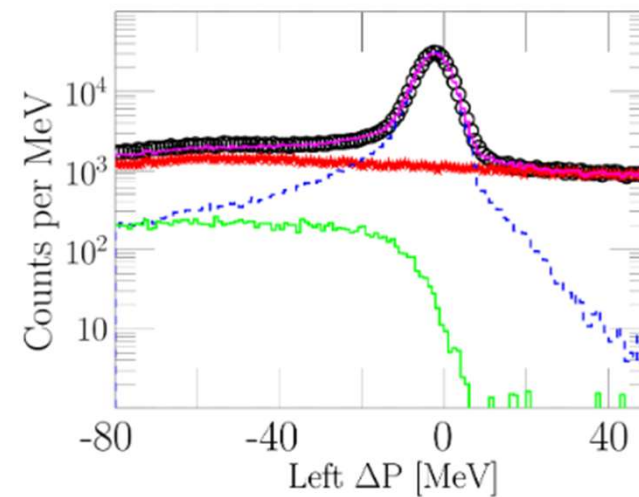
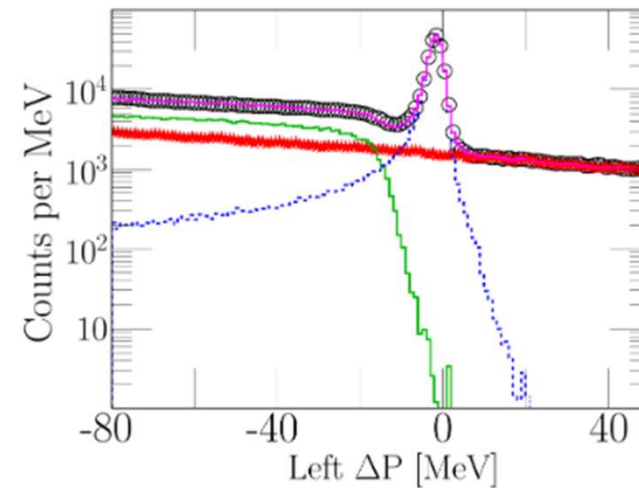
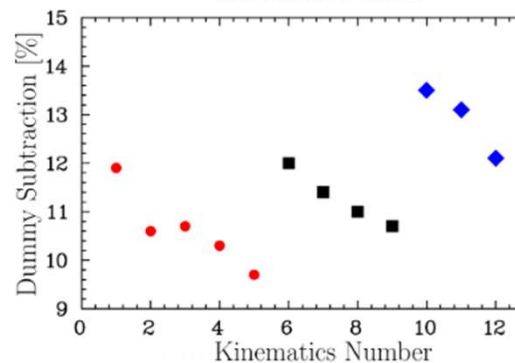
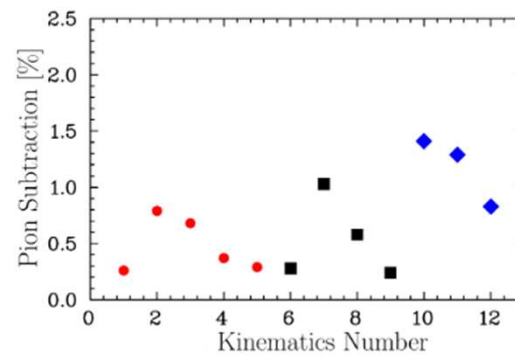
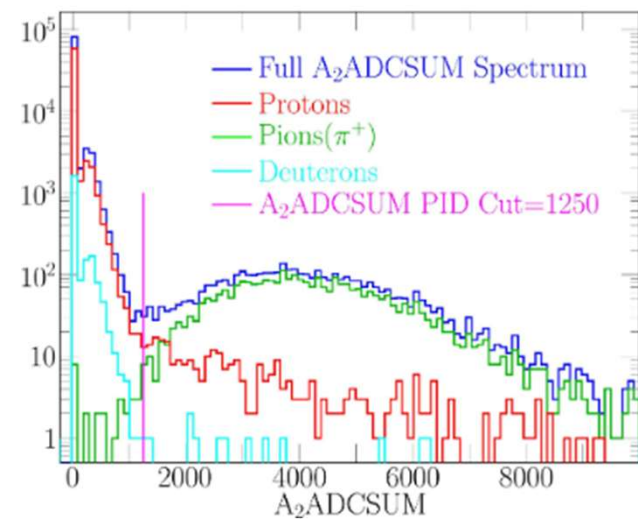
Constraints ( $\sim 1\%$ ) from positron-electron comparisons  
TPE effects on *polarization transfer*?



# E01-001 Archival Paper

I. A. Qattan, et al., Phys.Rev. C 112 (2025) 035205

- Detailed discussion of analysis, PID, background sub
- Cross sections, form factors, and Ge/Gm ratio
- Updated constraints on TPE corrections/models



# E01-001 Archival Paper

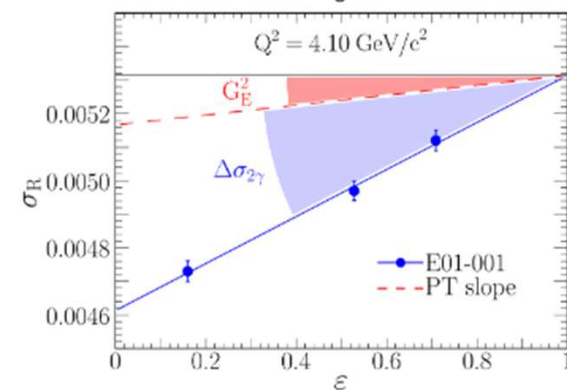
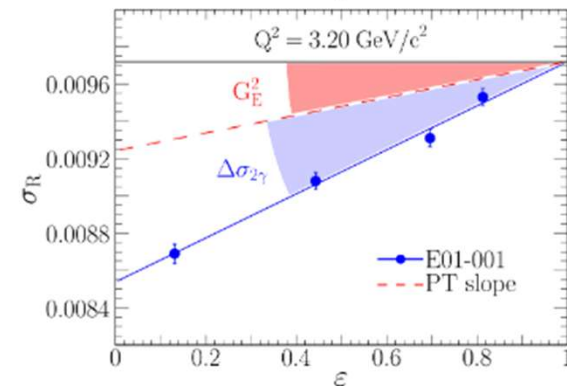
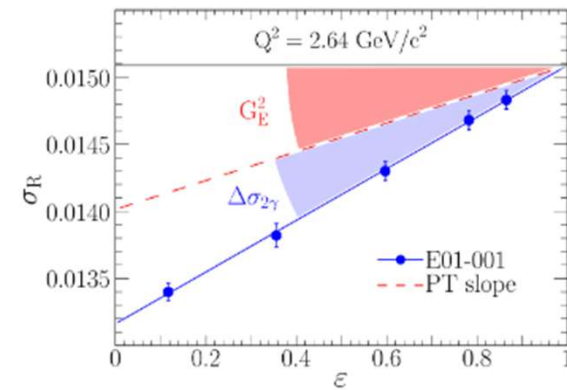
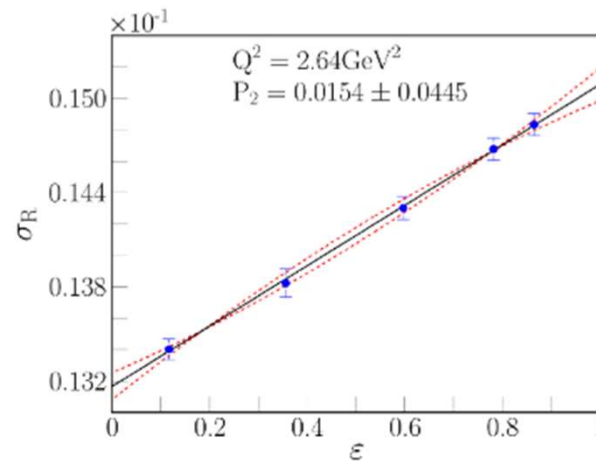
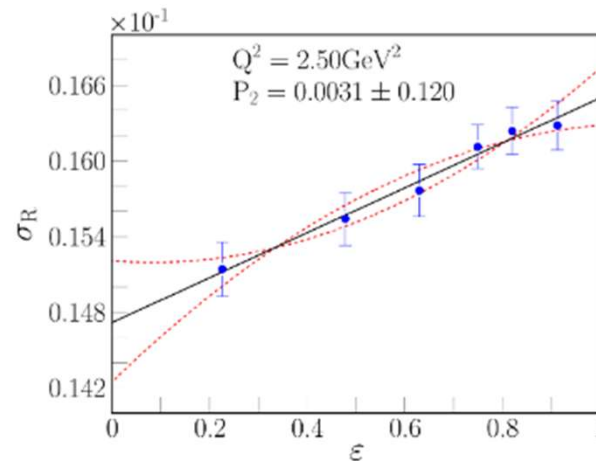
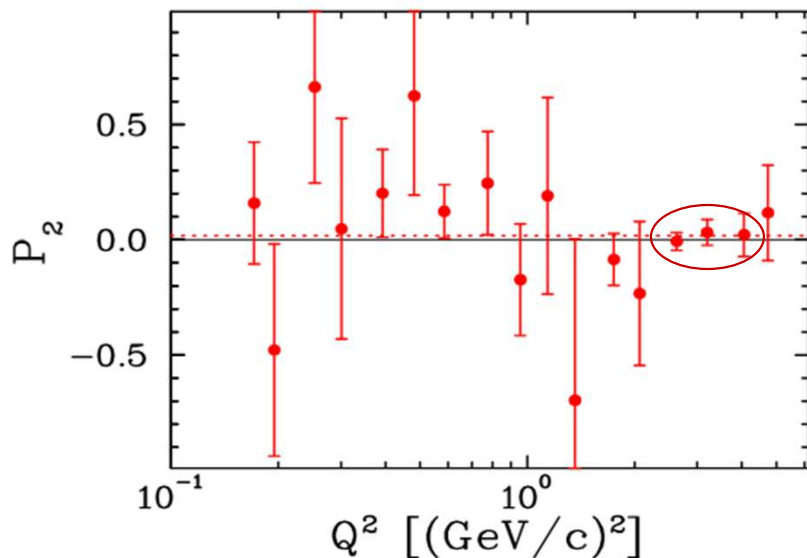
I. A. Qattan, et al., Phys.Rev. C 112 (2025) 035205

Comparison to PT →

Constraints on non-linearity:

$$\text{Fit } \sigma_R = P_0 + P_1(x-0.5) + P_2(x-0.5)^2$$

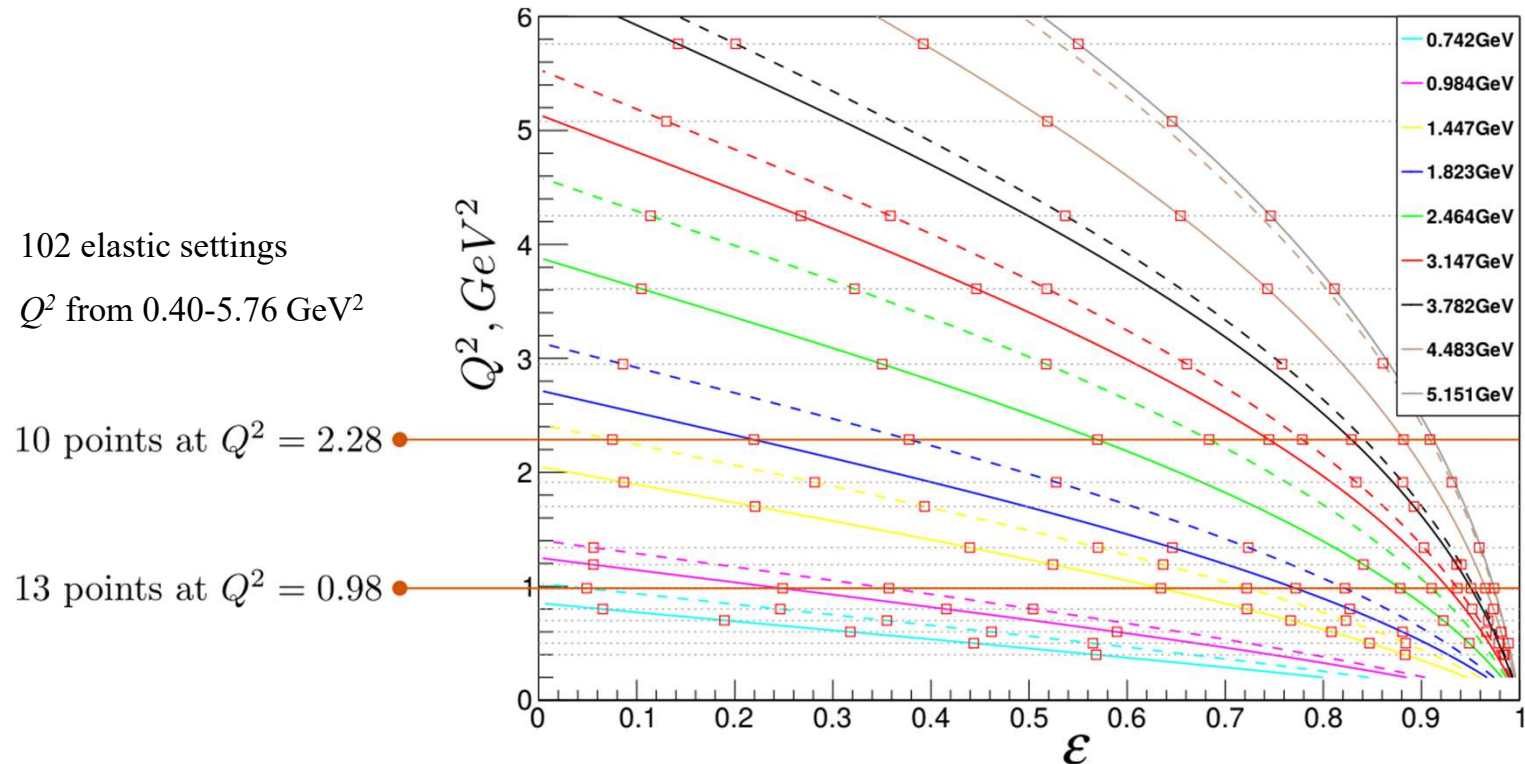
V. Tvaskis, et al, PRC 73 (2006) 025206



# E05-017: Extended $Q^2$ range, $\varepsilon$ coverage

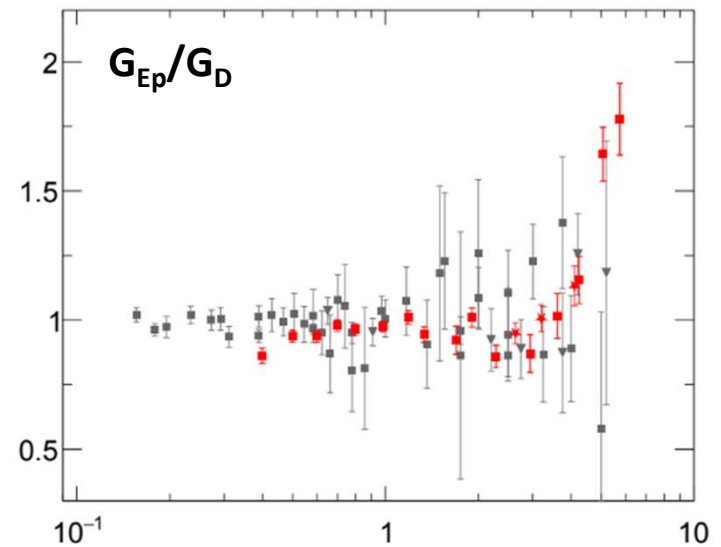
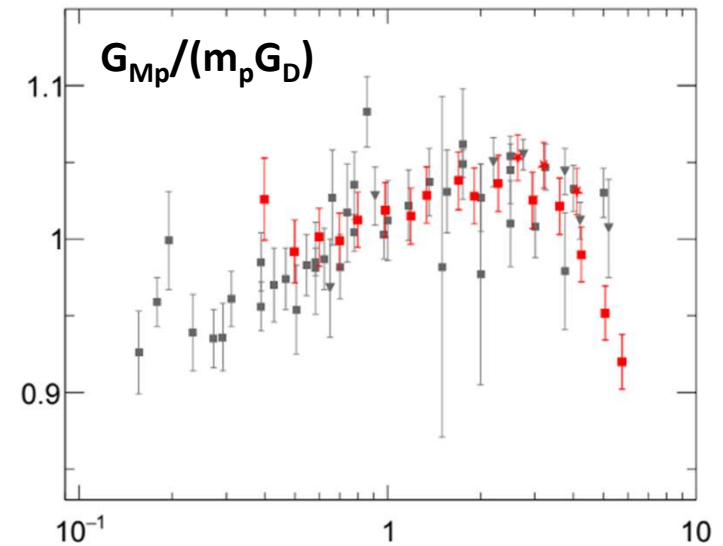
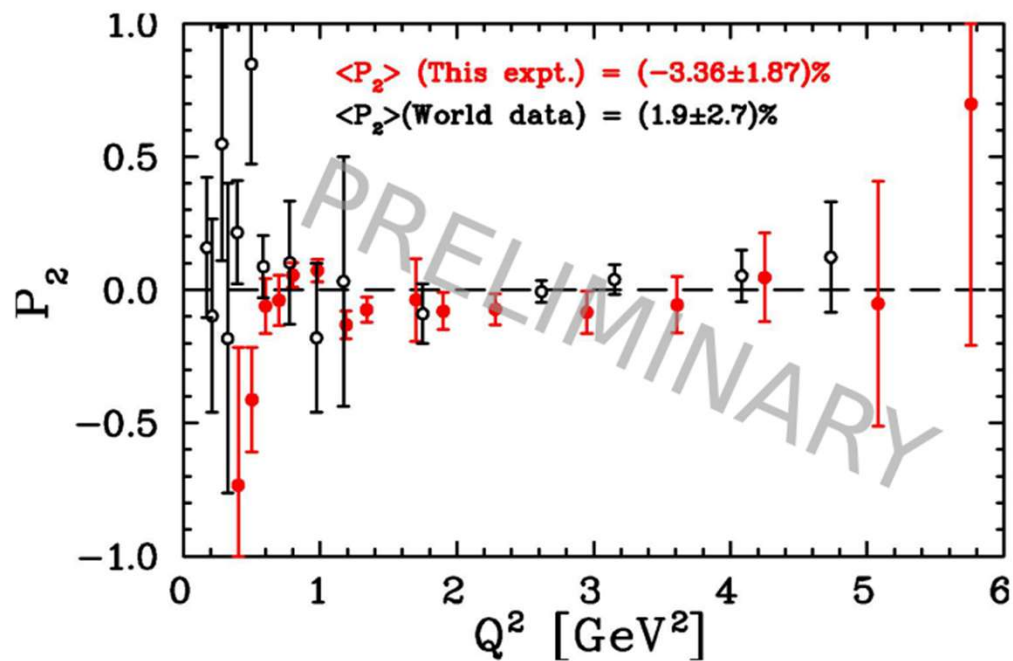
E05-017 – Measurement of TPE in unpolarized e-p scattering [JA] M.Johnson, M.Yurov-PhDs

- HMS resolution worse than normal – larger backgrounds for high  $Q^2$  settings
- Issues with TOF calibration and unexpected fluctuations at large epsilon delayed high- $Q^2$  results
- Updated QC checks complete, main issues have been identified – fixes in progress but no new results.



# E05-017: *Pre-preliminary*

- Mikhail Yurov – PhD results
- Conservative systematic uncertainties
- Some points excluded – systematic issues for  $\varepsilon > 0.95$



# E05-017 Issues

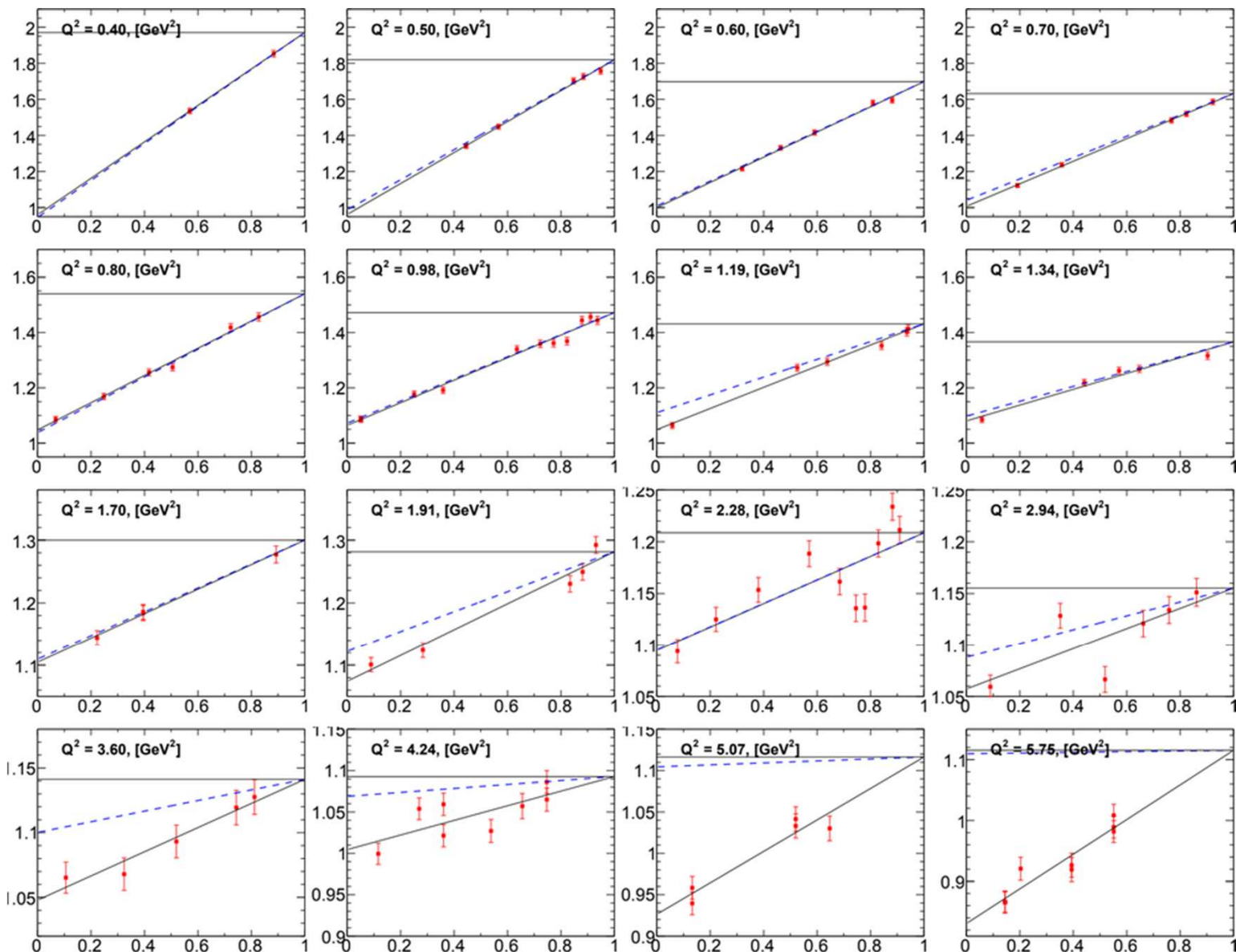
Reduced cross section vs  $\varepsilon$

- Pre-prelim (PhD) results
- Black = fit to data
- Blue = fit to PT slope

Non-statistical scatter even for  $\varepsilon < 0.95$

Some cases of nearly-identical kinematics during 2 run periods giving different results

Recently identified issues that were causing the fluctuations

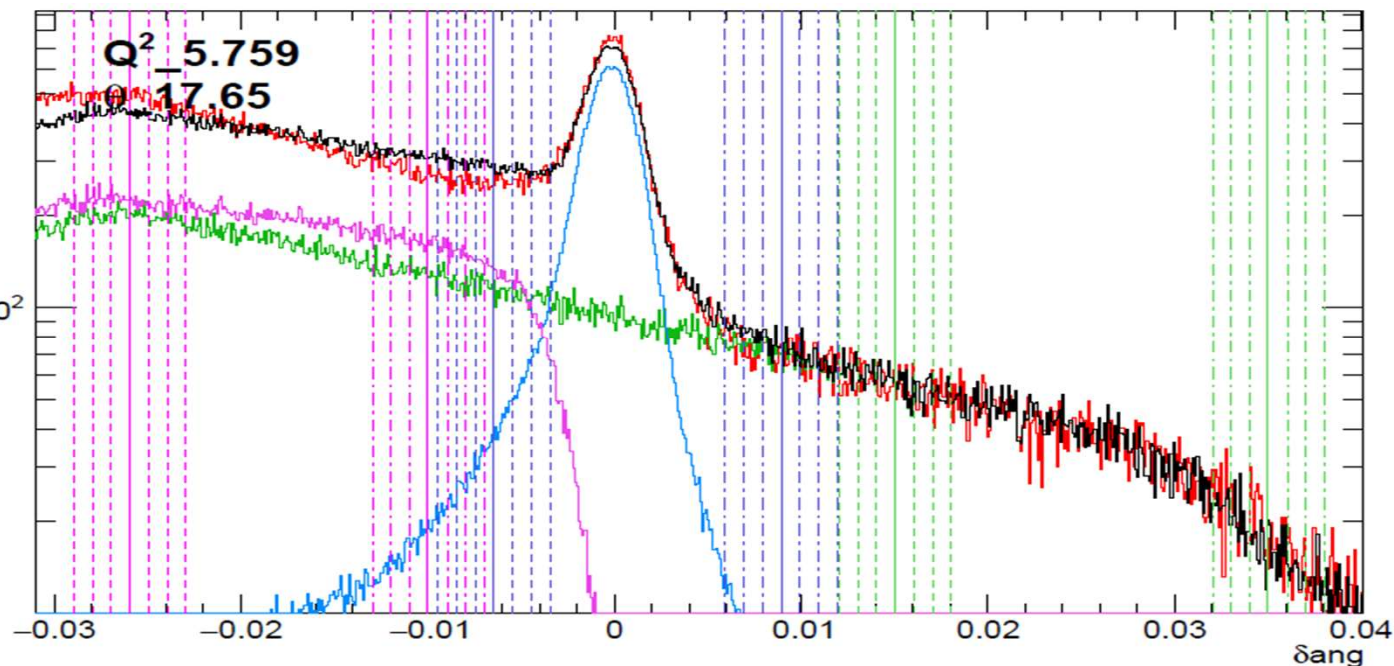


# Ongoing E05-007 Analysis [JA, M. Yurov]

- Updated run-by-run consistency/QC – **excluded runs with identified issues**
- Some kinematics were using **incorrect or non-optimal cuts on elastic peak** or backgrounds
- Error in the evaluation of the cut dependence led to underestimated systematics
  - Window was supposed to be varied +/-10% in total width
  - Code was varying position of left and right edges by 10%, based on ABSOLUTE VALUE of the cut position
  - Essentially **no cut dependence was calculated** for the left edge of the elastic window when close to  $\Delta\theta=0$
- Issue with pion offset fit

Spectra shown has bad offset in background (magenta) – poor match to data

In the process of addressing the newly-discovered issues



# Future: Super-Rosenbluth with positrons

E12+23-012: JA, M. Nycz, S. N. Santiesteban, M. Yurov

Conventional positron-electron comparisons **limited by positron luminosity** and **requirement of significant cancellation between e- and e+ systematics**

- Cross section limits low- $\epsilon$  kinematics where TPE are largest
- Require frequent changes between e+ and e- beams; similar beam properties

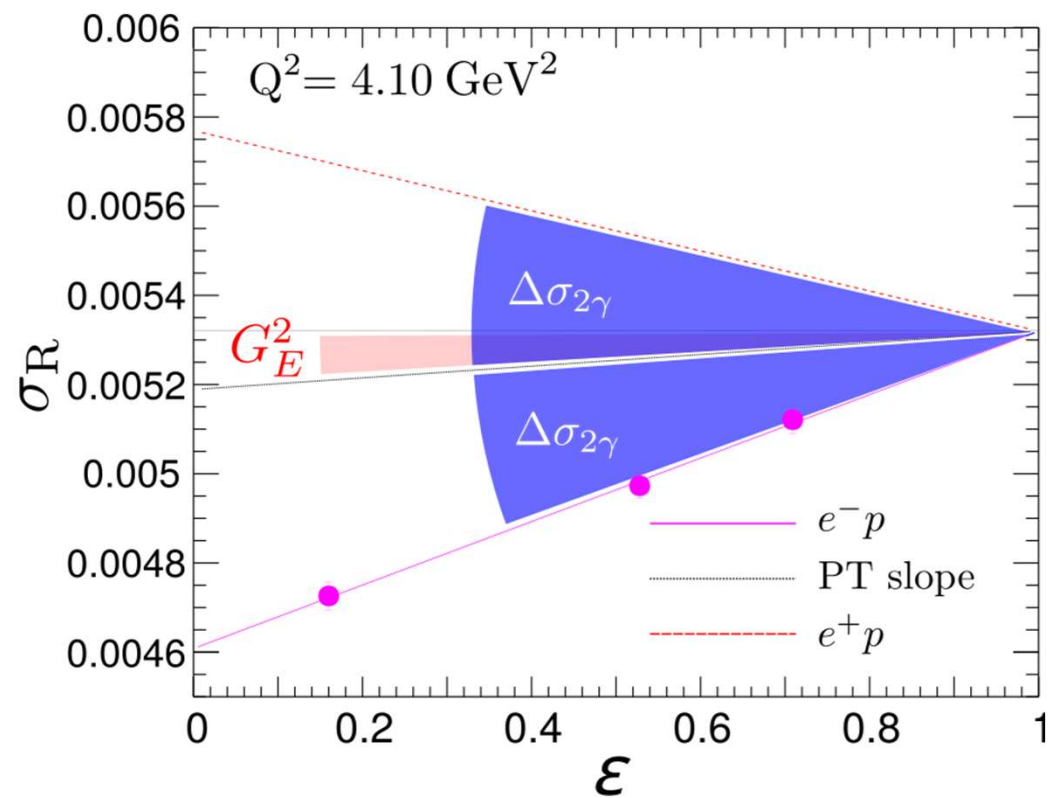
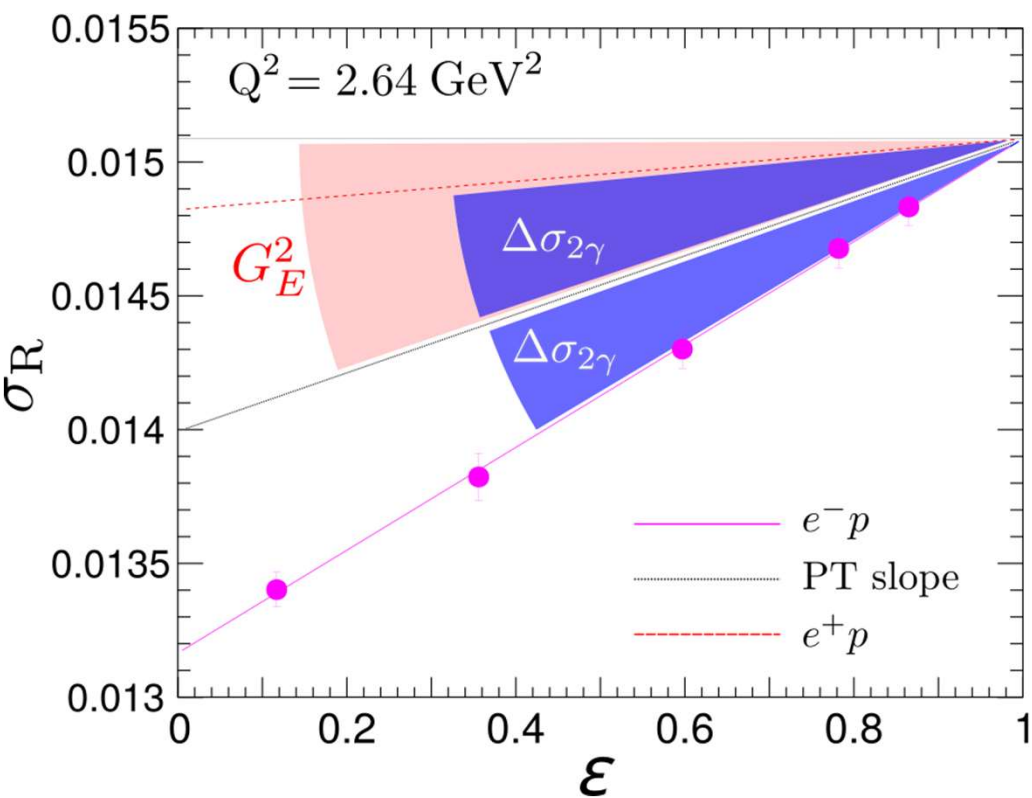
S-R technique **enhances cross section at low  $\epsilon$** , relies on **cancellation between points at different scattering angles (and fixed  $Q^2$ )**

- Allows precise e+ to e- comparison on the Rosenbluth slope, even for separate e+, e- experiments
- Does not allow direct e+/e- ratio at individual  $\epsilon$ ,  $Q^2$  points (without normalization at  $\epsilon=1$ )

Can perform precise S-R extraction with positrons and S-R with electrons independently.

Does not require rapid beam changes or identical beam characteristics.

# Rosenbluth separations: $e^+$ vs $e^-$



# Kinematics

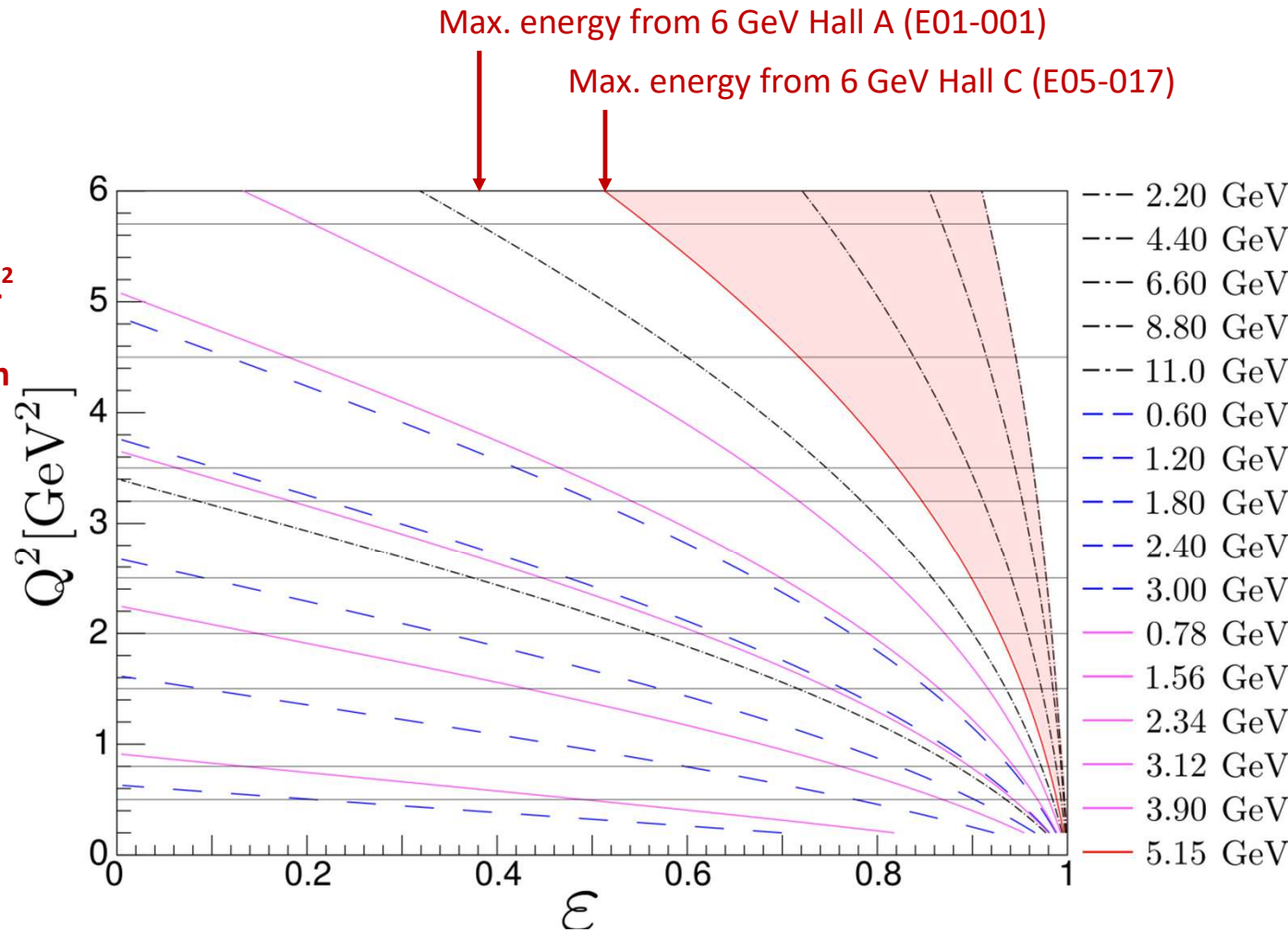
**Black: 2.2 GeV/pass**

- 2-3 high-epsilon points at each  $Q^2$
- Larger  $\epsilon$  range for higher  $Q^2$  points

**Blue or magenta: 0.6 or 0.78 GeV/pass**

- Each linac setting gives five different  $Q^2$  values with large lever arm in epsilon
- Intermediate  $Q^2$  with smaller lever arm

Can run with positrons only, compare to polarization  $\rightarrow$  should see opposite discrepancy than electrons



# Projected uncertainties

Uses all 3 linac settings from previous plot  
Assumes 2 uA for positrons, 10cm LH2 target  
Electron data in separate run: 20-50uA  
→ 41(e+) + 15(e-) days in Hall C

Comparison **doubles size of observed TPE** contributions and is **independent of TPE contributions in polarization measurements**

Can separate TPE from other missing RC contributions (which will not change sign)

