Towards a resolution of the proton form factor problem:
New electron and positron scattering data

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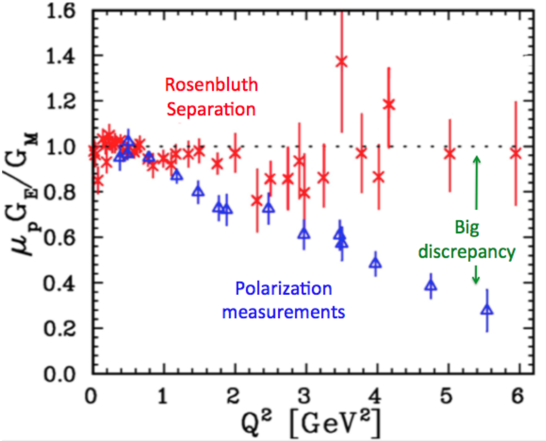
Outline

- Proton form factor measurements
- Two Photon Exchange (TPE) Correction
  - TPE calculations
  - TPE measurements
- CLAS TPE Experiment
  - Data analysis
  - Systematic uncertainties
  - Results
  - World data and theoretical calculation
  - Implications of the results
- Summary

Proton form factor puzzle

- Proton form factors, $G_E(Q^2)$ and $G_M(Q^2)$ describe its charge and magnetization distributions.



- The possible explanation is the two photon exchange (TPE) correction to the Rosenbluth separation measurements.

Possible TPE effect on Rosenbluth measurements

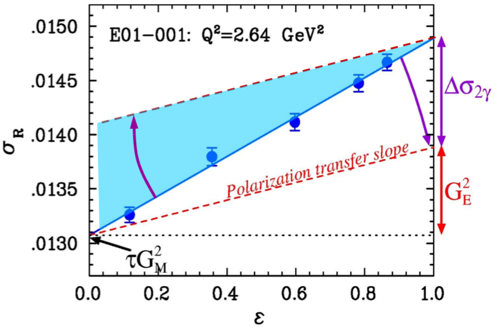
- The general 1-γ and 2-γ exchange cross-sections

$$1: \frac{d\sigma}{d\Omega} \propto \left[\varepsilon G_E^2 + \tau G_M^2\right]$$
$$2: \frac{d\sigma}{d\Omega} \propto \left[\varepsilon \tilde{G}_E^2 + \tau \tilde{G}_M^2\right] + \left[2\varepsilon\left(\tau|\tilde{G}_M| + |\tilde{G}_E \tilde{G}_M|\right) Y_{2\gamma}\right]$$

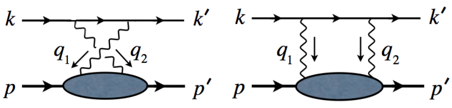
[Guichon and Vanderhaegen, PRL 91 (2003) 142303)]

- Another ϵ dependent term
- Modified G_E and G_M
- A few percent change in the cross section has a large impact on the Rosenbluth G_E extraction.

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$

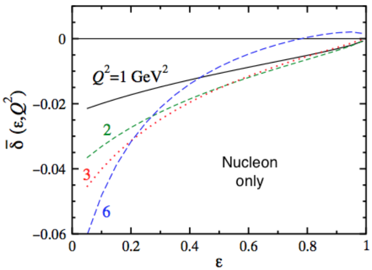


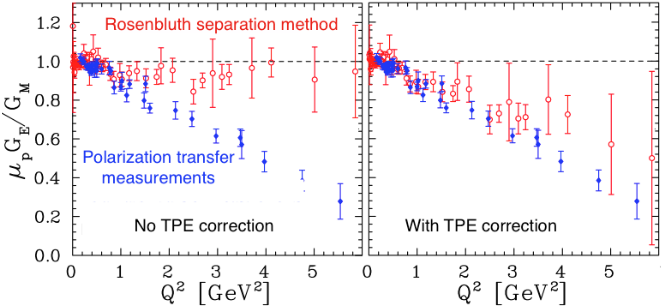
Hadronic calculation of TPE



- Integrating over all intermediate proton states (resonances) is difficult.
- Higher Q^2 requires including more resonances.

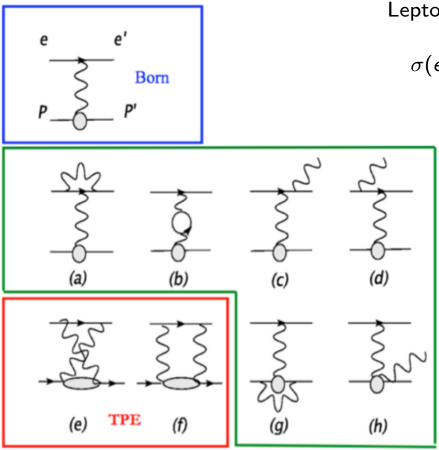
P.Blunden et al., Phys.Rev.C72: 034612 (2005).





Two Photon Exchange

Measure the positron-proton to electron-proton cross section ratio to determine the TPE correction.



Lepton-proton elastic scattering cross-section,

$$\sigma(e^{\pm}p) \propto |A_{ep\rightarrow ep}|^2 = |A_{\text{Born}} + \ldots + A_{2\gamma}|^2$$

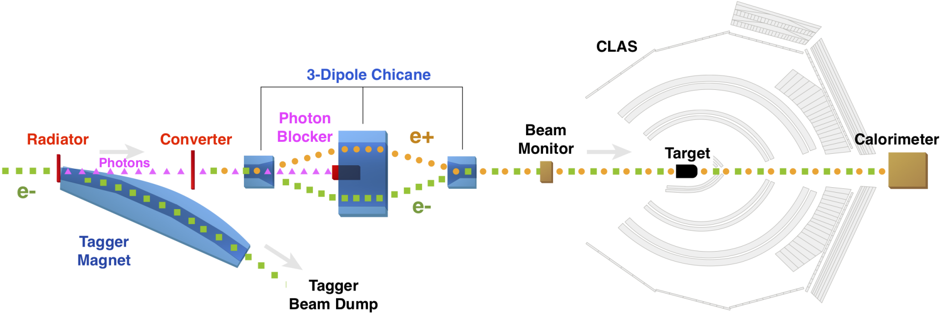
$$\sigma(e^{\pm}p) \propto |A_{\text{Born}}|^2 \pm 2A_{\text{Born}}\text{Re}(A_{2\gamma})$$

$$R = \frac{\sigma(e^{+}p)}{\sigma(e^{-}p)} = 1 + \frac{4\text{Re}(A_{2\gamma})}{A_{\text{Born}}}$$

- R provides a model-independent measurement of the TPE contribution.

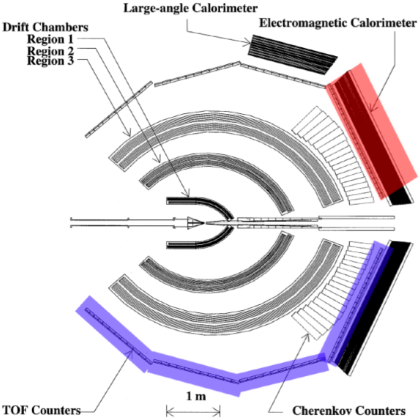
We measured $e^{+}p$ and $e^{-}p$ scattering simultaneously using a mixed electron-positron beam.

Producing a mixed electron positron beam in Hall-B



- Primary electron beam: 5.5 GeV and 100-120 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: sweep the primary electrons to the tagger dump
- Converter: 9% of photons convert to electron/positron pairs
- Chicane: separate the lepton beams, stop photons and recombine the e^+ and e^- beams
- Target: 30 cm liquid hydrogen
- Detector: CEBAF Large Acceptance Spectrometer (CLAS)

The experiment



1. Continuous incident energy distribution
2. Detect scattered particles over a wide range
3. Match acceptance
   - Select regions of detector with 100% acceptance for both e^+ and e^-
4. Systematic controls
   - Reversed torus and beam line magnetic fields periodically to cancel artificial charge asymmetries
5. Select elastic events using four kinematic cuts

Selecting elastic events

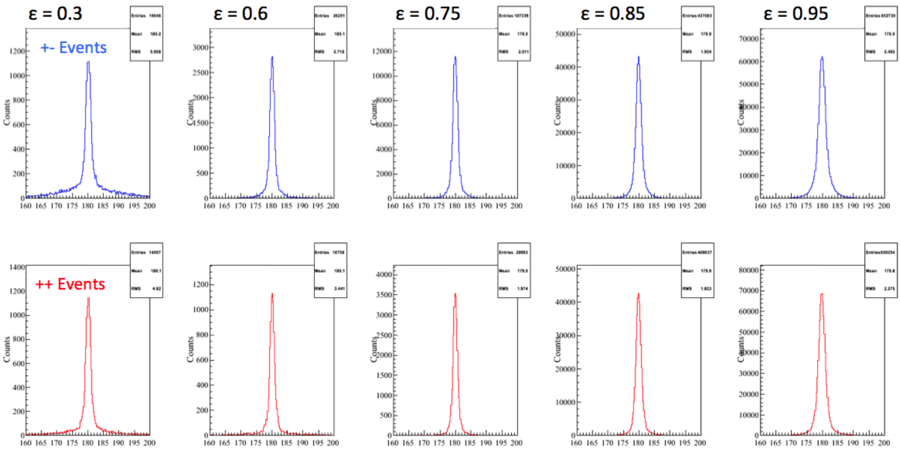
- Select two track events
- Measure $(p, \theta, \phi)_{\text{lepton}}$ and $(p, \theta, \phi)_{\text{proton}}$
- Select elastic events using energy and momentum conservation

1. Coplanarity cut $\Delta\phi = \phi_{\text{lepton}} - \phi_{\text{proton}}$
2. Calculate
   - incident lepton energy (E_{Beam})
   - scattered lepton energy (E'_e)
   - proton momentum (P_p)

   a) from θ_e and θ_p

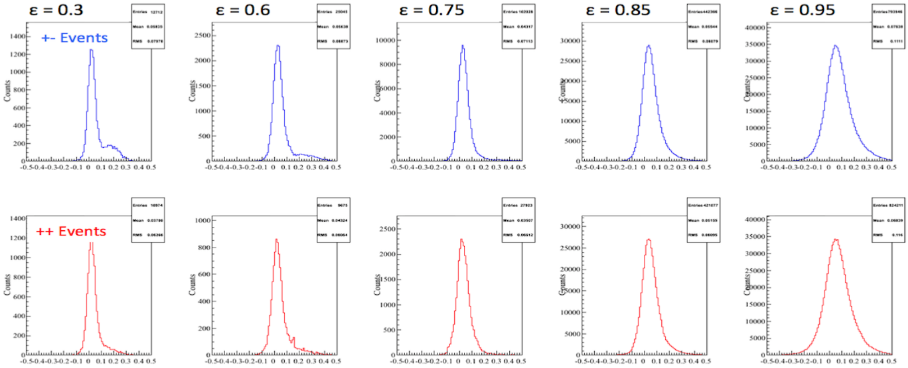
   b) from measured momenta
3. Cut on differences: ΔE_{Beam}, $\Delta E'_e$ and ΔP_p
4. There is a strong correlation between ΔE_{Beam} and $\Delta E'_e$
   - So, makes cut on $\Delta E^{\pm} = \Delta E_{\text{Beam}} \pm \Delta E'_e$

Δϕ: cut on other 3



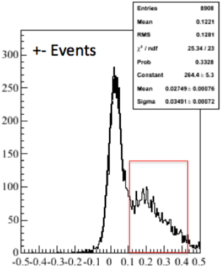
$\Delta\phi$(deg)

ΔE^-: cut on other 3

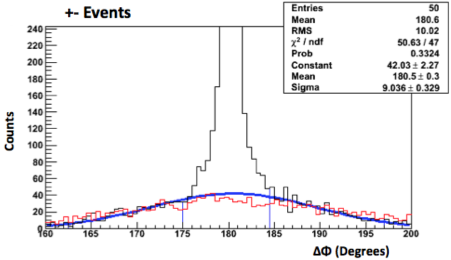


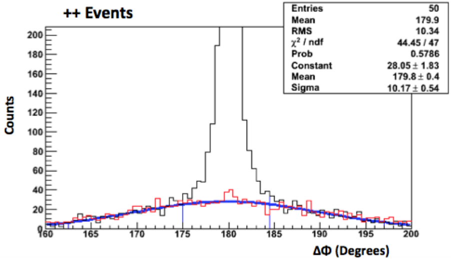
ΔE^- (GeV)

Background subtraction



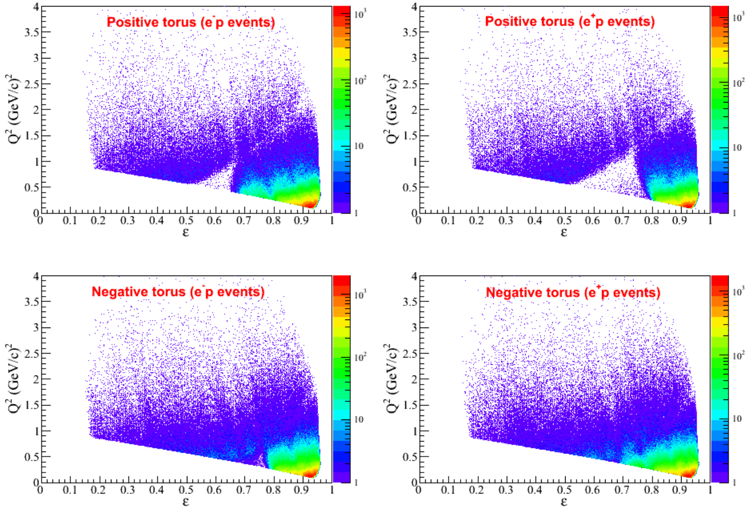
$\Delta E_{Beam} - \Delta E_e'$ after other 3 cuts





- Fit tails of the $\Delta\phi$ distribution with a Gaussian
- Validate Gaussian background shape by comparing to sampled background from $\Delta E_{Beam} - \Delta E_e$
  - Sampling fails at high ε due to increased width of $\Delta E_{Beam} - \Delta E_e$ peak
- Subtract fitted background from peak

Kinematic Coverage (Q^2 vs. ε)



Continuous wide Q^2-ε coverage

Ratios

- Single Ratio
  Measure elastic scattering ratio for given CLAS torus magnet polarity:
  Proton acceptance cancels

$$R_1^{\pm} = \frac{N^{e^+p}}{N^{e^-p}}$$

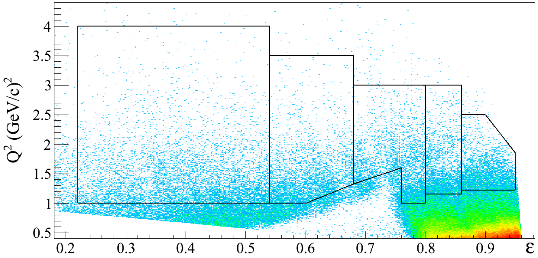
- Double Ratio
  Flip torus polarity and form a ratio for given chicane polarity:
  Lepton acceptance cancels

$$R_2^{\pm} = \sqrt{(R_1^{+} R_1^{-})}$$

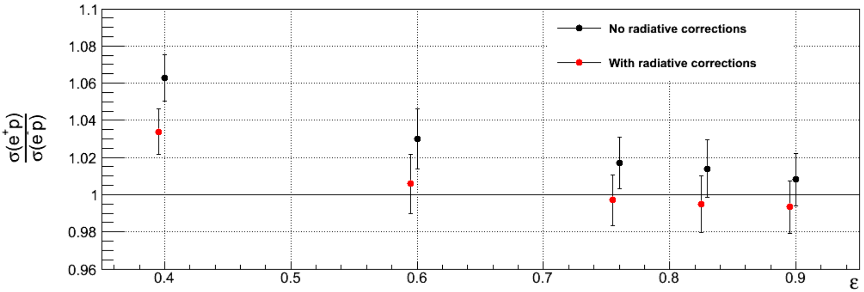
- Quadruple Ratio
  Flip beamline chicane magnet polarity and form a ratio:
  Beam asymmetry cancels

$$R = \sqrt{(R_2^{+} R_2^{-})}$$

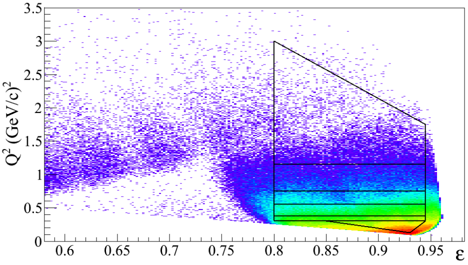
Results at $Q^2 = 1.45$ GeV^2



- $\langle Q^2 \rangle \approx 1.45$ GeV^2
- Background subtracted
- Dead detector cuts applied
- With radiative corrections



Results at $\varepsilon = 0.88$



- $\langle\varepsilon\rangle \approx 0.88$.
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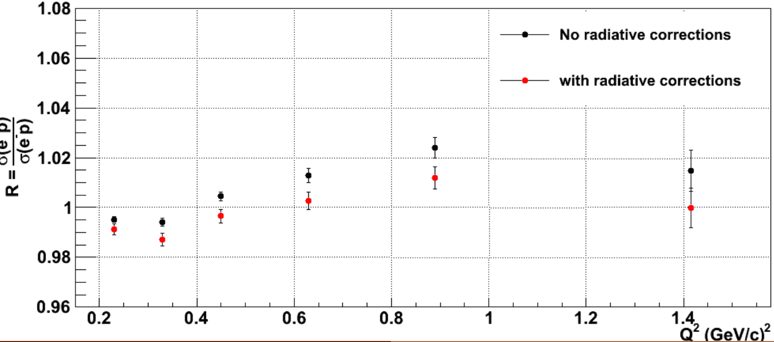
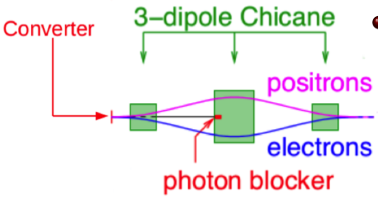


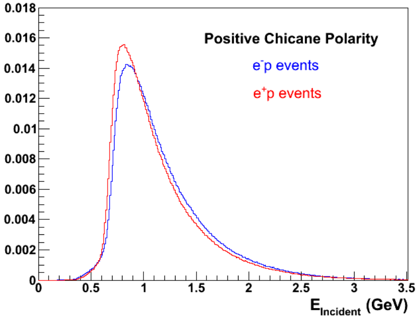
Sources of Systematic Uncertainty

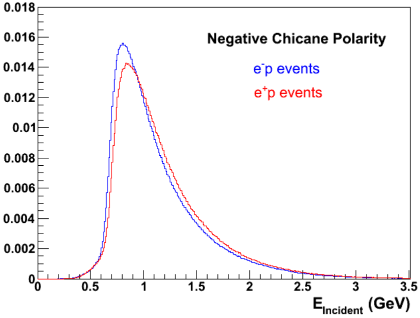
- e^+/e^- beam luminosity
  - beam chicane cycle variance
- CLAS detector imperfections
  - sector variance
- Background fitting
- Elastic event selection and background subtraction
- Fiducial cuts
- Target vertex cuts

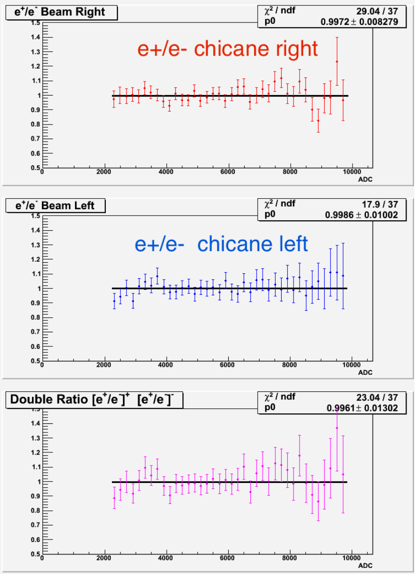
Systematics - e^+/e^- Luminosity



- The reconstructed electron and positron incident energy distributions are slightly different due to asymmetric beam transportation through beamline magnets (chicane).





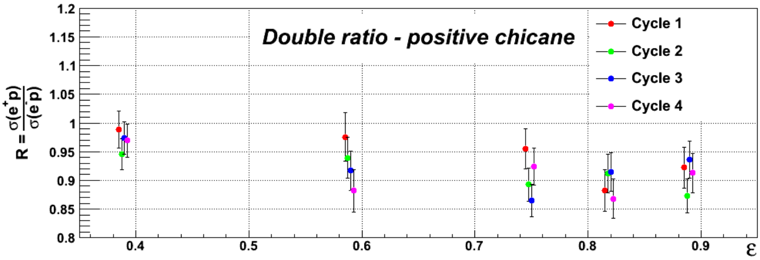


Energy (arb. scale)

Energy distribution measured by TPE calorimeter.

- The e^+/e^- pair-production is inherently charge-symmetric.
- Chicane is not perfectly symmetric but e^+-left is the same as e^--left.
- Periodically flipping the chicane leads to symmetric luminosities.
- Uncertainty due to luminosity is measured by the comparison of magnet cycles.

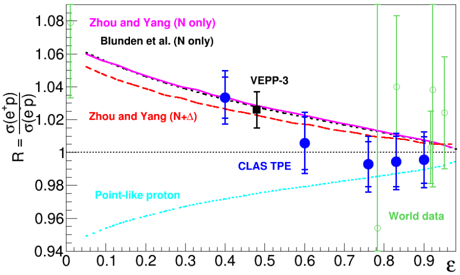
Systematic Uncertainty Due to Lepton Beam Variation



- Periodically reversed beamline and torus magnet polarities results four magnet cycles.
- Measure the e+/e- ratio for each chicane polarity and each magnet cycle.
- The measured variance of ratios (σ^2_{total}) includes both statistical and systematic uncertainties.
- Systematic uncertainty: ${\sigma_{\text{syst}}}^2 = \sigma^2_{\text{total}} - \sigma^2_{\text{stat}}$
- Repeat this for the six CLAS sectors to determine the systematic uncertainties

Comparison to the world data

$Q^2 \sim 1.5$ GeV^2



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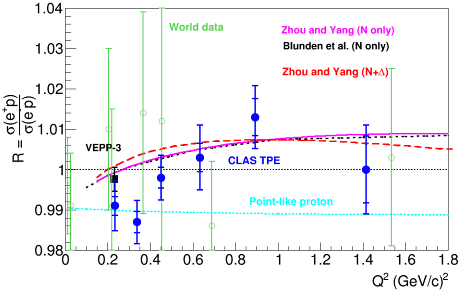

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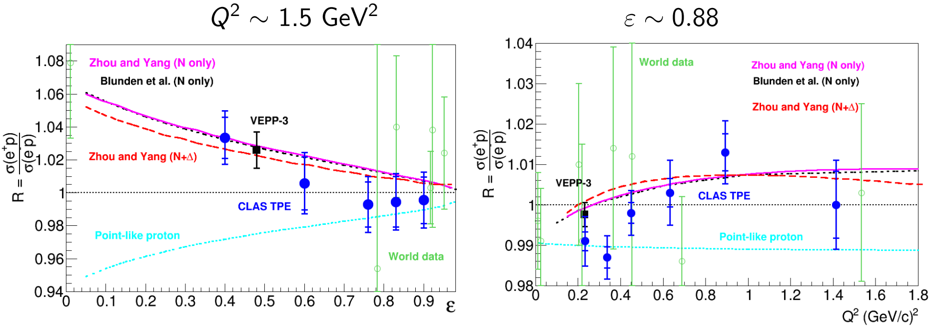
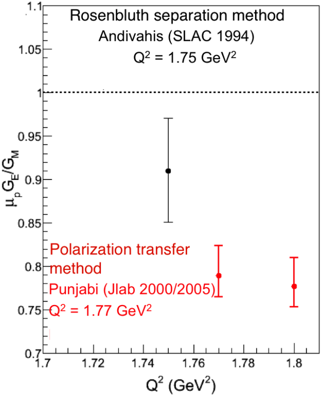


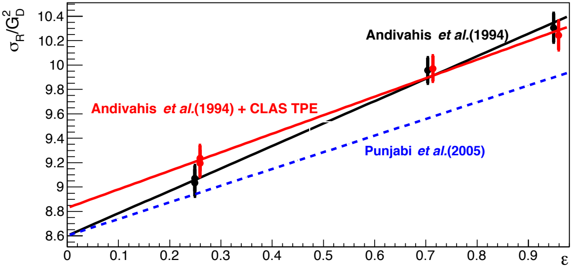
Preliminary combined analysis of CLAS + preliminary VEPP-3 data (from John Arrington)

- TPE for point like proton: $\chi^2_\nu = 11.1$, CL $\ll 10^{-10}$%
- δ_{TPE}=0: $\chi^2_\nu = 3.16$, CL $= 0.003$%
- BMT TPE: $\chi^2_\nu = 1.07$, CL $= 38$%

Implications of the CLAS TPE measurements on the existing Rosenbluth measurements

Proton form factor measurements at $Q^2 = 1 - 2$ GeV^2





Andivahis *et. al*(1994), $\mu_p G_E/G_M = 0.910 \pm 0.060$

Punjabi *et. al* (2005), $\mu_p G_E/G_M = 0.789 \pm 0.042$

Andivahis *et. al* (1994) $+$ CLAS TPE, $\mu_p G_E/G_M = 0.816 \pm 0.076$

Summary

- Proton form factors measured from Rosenbluth & polarization transfer methods disagree.
- Probable explanation: two photon exchange corrections to the Rosenbluth measurements.
- CLAS TPE experiment measured $\frac{e^+p}{e^-p}$ over wide range of Q^2 and ε.
  - The $\frac{e^+p}{e^-p}$ ratio is the only way to measure the TPE correction to the elastic cross section.
  - systematic uncertainties $\sim 1\%$.
- Results agree with the hadronic calculations which reconcile the form factor measurements up to $Q^2 \leq 2-3$ GeV^2.
- TPE corrected Rosenbluth G_E/G_M agrees with the polarization G_E/G_M at $Q^2 = 1.77$ GeV^2.
- Proton form factor discrepancy appears to solved up to $Q^2 = 2$ GeV^2. Need more measurements for $Q^2 > 2$ GeV^2.

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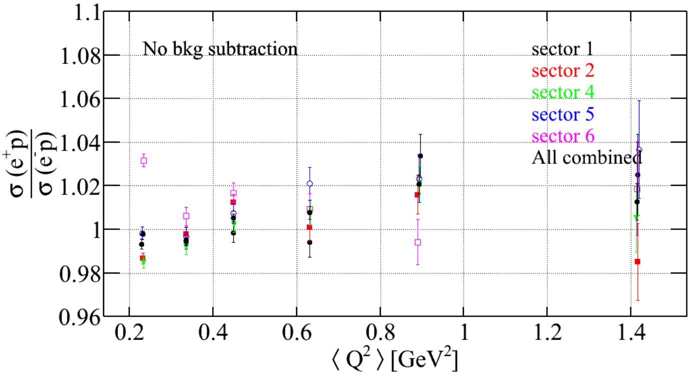
THANK YOU.

Variance of Ratios for Different Sectors

- Five independent measurements at five CLAS sectors.
- Systematic uncertainty due to dead detector and other CLAS issues takes into account.
- Same procedure as magnet cycle variance.

$\langle \varepsilon \rangle \approx 0.88$

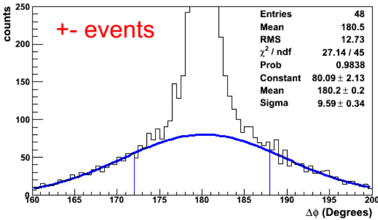
Bin	σ_{syst}(sector)
1	0.0079
2	0.0020
3	0.0028
4	0.0032
5	0.0046
6	0.0024

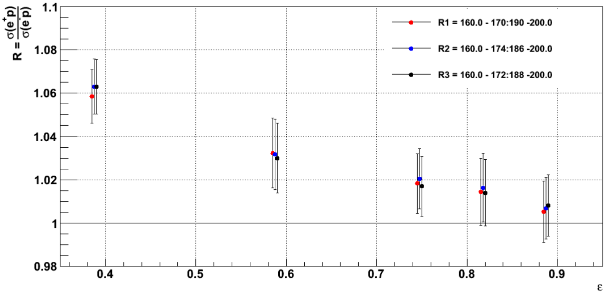


Systematic Uncertainty Due to Background Fitting

- The background is determined by a Gaussian fitted to the tails of the $\Delta\phi$ distributions.
- Nominal fitting range: 160-172°(left) and 188-200°(right).
- Uncertainties estimated by varying the fitting ranges.

$\Delta\phi$ at $\varepsilon = 0.4$





$\langle Q^2 \rangle \approx 1.45$ GeV^2

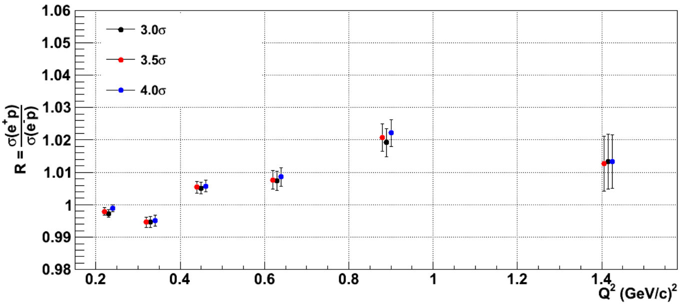
Bin	σ_{syst} (fitting range)
1	0.0023
2	0.0021
3	0.0024
4	0.0014
5	0.0021

Systematic Uncertainty Due to Elastic Event Selection

- Vary the widths of the elastic kinematic cuts: 3σ, 3.5σ(nominal) and 4σ.
- Varying the kinematic cuts changes the amount of background by a factor of 2.
- Therefore the effects due to the background subtraction is also taken into account.

$\langle\varepsilon\rangle \approx 0.88$

Bin	σ_{syst}(Kinematic cut)
1	0.0012
2	0.0005
3	0.0007
4	0.0011
5	0.0017
6	0.0016



Systematic Uncertainty Due to Fiducial Cuts

- Both inbending and out bending fiducial cuts were applied to all leptons to select regions of detector with 100% acceptance for both e^+ and e^-.
- Tightened fiducial cuts: change in ratio included as the systematic uncertainty.

$\langle \varepsilon \rangle \approx 0.88$

Bin	σ_{syst}(Fiducial cut)
1	0.0013
2	0.0006
3	0.0002
4	0.0005
5	0.0011
6	0.0041