Measuring of TPE with Electron/Positron Elastic Scattering off the Proton

Brian Raue *

~~Florida International University~~

somewhere in Florida…

1. A brief history
2. Recent experiments
3. Current status
4. Future possibilities

* narrated by

Wally Melnitchouk

Jefferson Lab

Elastic Scattering Cross Section

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\left(F_1^2 + \kappa Q^2 4m_p^2 F_2^2\right) - \frac{Q^2}{2m_p^2}\left(F_1 + \kappa F_2\right)^2 \tan^2\frac{\theta}{2}\right]$$

$\left(\frac{d\sigma}{d\Omega}\right)_{Mott}$ Mott cross section for scattering of point-like particles

F_1: transverse structure fn

F_2: longitudinal structure fn

Can be related to Sachs electric and magnetic form factors

Rosenbluth Separation

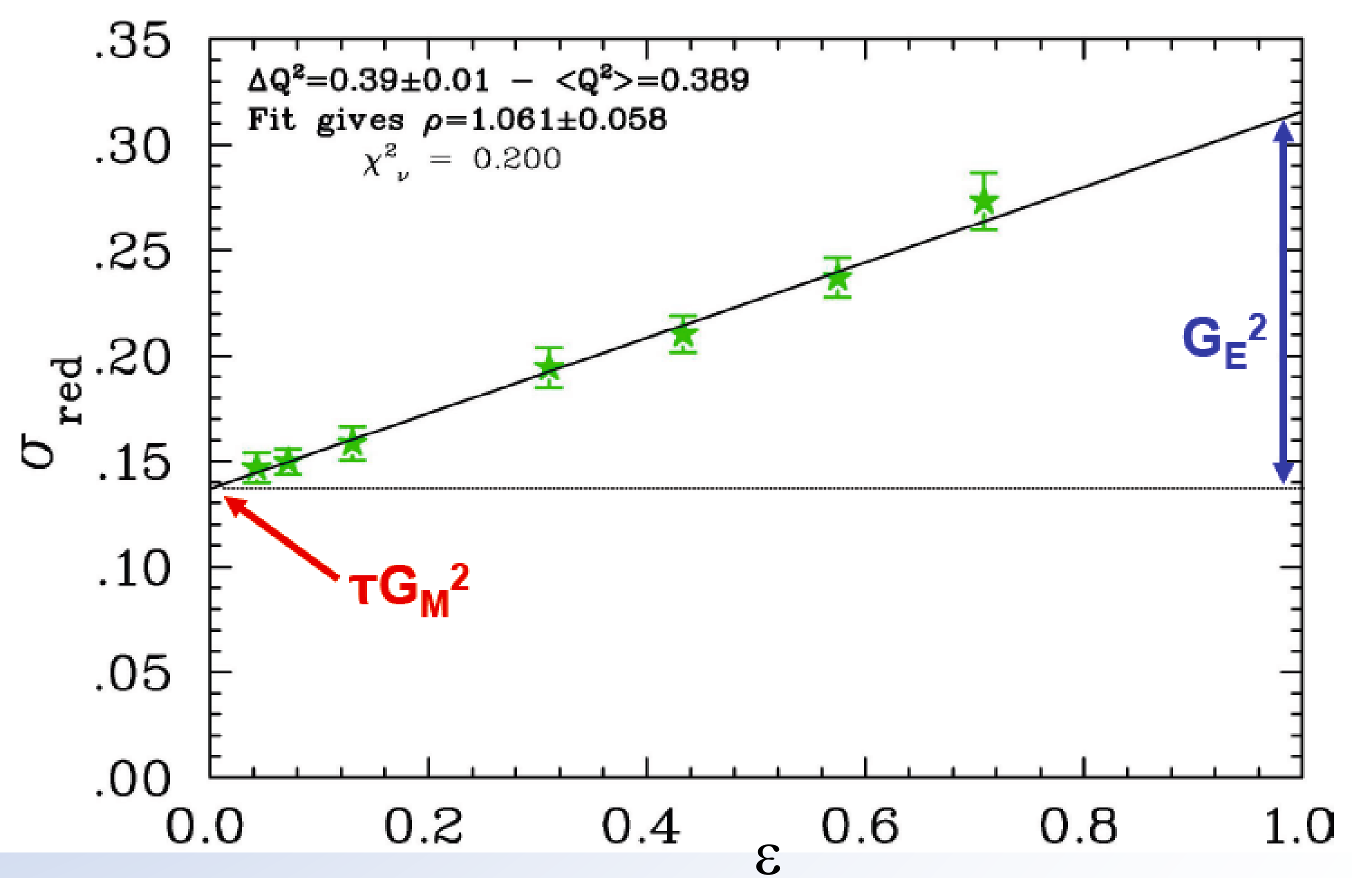
$$\sigma_R = \frac{\varepsilon}{\tau} G_E^2\left(Q^2\right) + G_M^2\left(Q^2\right)$$

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}, \quad \varepsilon = \left[1 + 2\left(1 + \frac{E - E'}{Q^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}, \quad \tau = Q^2 / 4M_p^2$$

Rosenbluth Separation

$$\sigma_R = \left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right]$$

Measure reduced cross section as a function of ε for fixed values of Q^2.



Many experiments conducted at SLAC, MIT Bates, Mainz, and Jefferson Lab

Polarization Transfer Method

$$\vec{e} + p \rightarrow e + \vec{p}$$

Measure transverse (P_T) and longitudinal (P_L) polarization of outgoing proton.

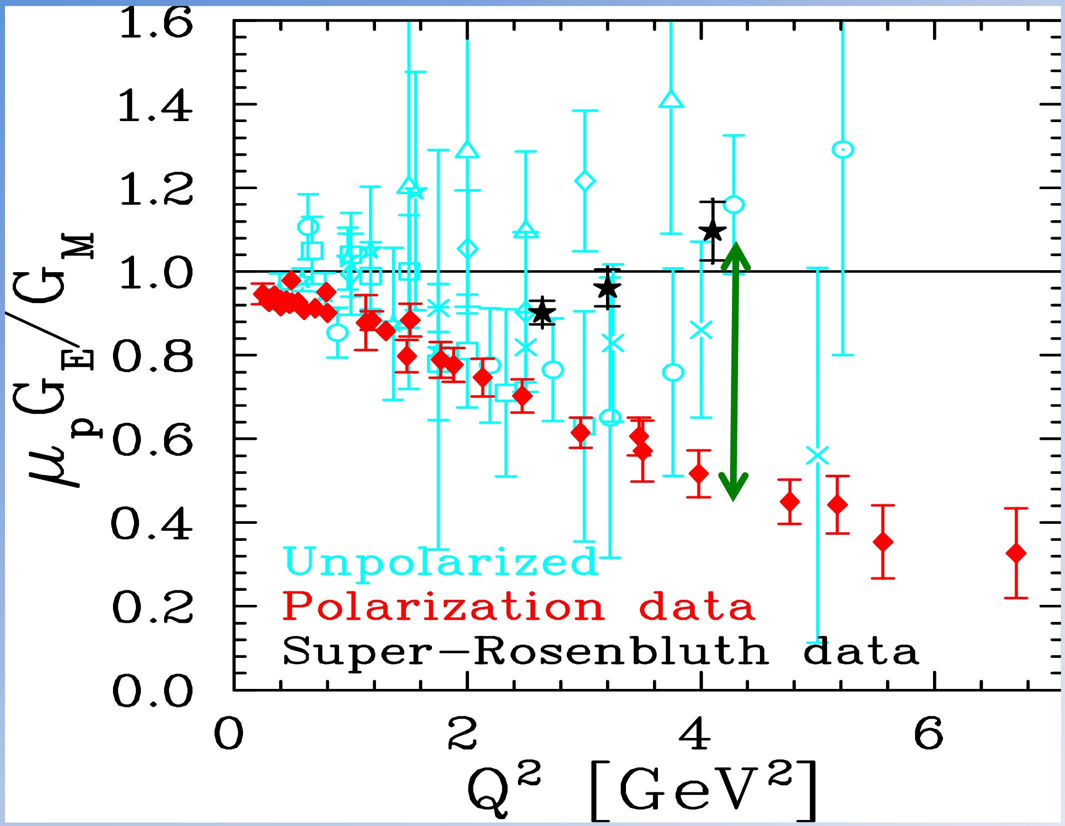
$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E+E')}{2m_p}\tan\frac{\theta}{2}$$

Experiments conducted in Halls A & C at Jefferson Lab:

M.K. Jones *et al.*, ***Phys. Rev. Lett. 84, 1398 (2000)***
O. Gayou *et al.*, ***Phys. Rev. C64, 038202 (2001)***
O. Gayou *et al.*, ***Phys. Rev. Lett. 88, 092301 (2002)***
V. Punjabi *et al.*, ***Phys. Rev. C71, 055202 (2005)***
M.K. Jones *et al.*, ***Phys. Rev. C74, 035201 (2006)***
G. MacLachian *et. al.*, ***Nucl. Phys. A764, 261 (2006)***
G. Ron *et al.*, ***Phys. Rev. C84, 0055204 (2011)***
A.J.R. Pucket *et al.*, ***Phys. Rev. C85, 0045203 (2012)***

Plus several at other labs. Clearly a high priority for the nuclear physics community.

G_E/G_M Comparison

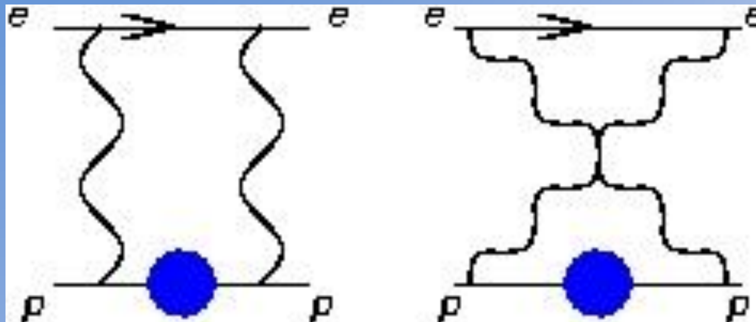


Huge discrepancy that grows with Q^2.

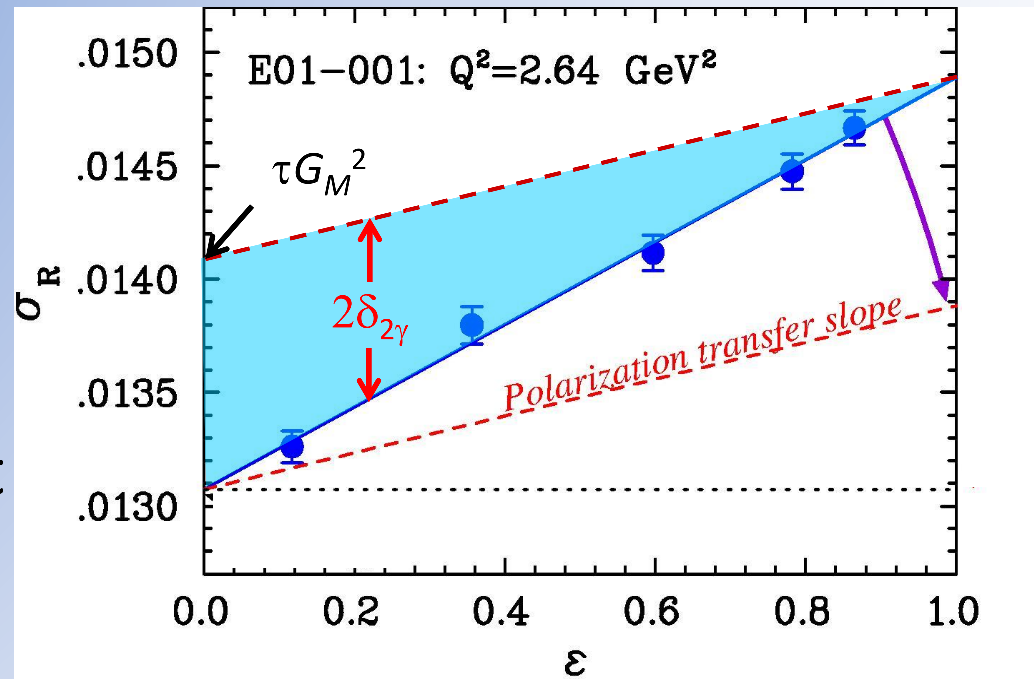
Why the discrepancy?

- Rosenbluth results
- Super-Rosenbluth results
- Polarization transfer results

Possible Solution: Two-Photon Exchange



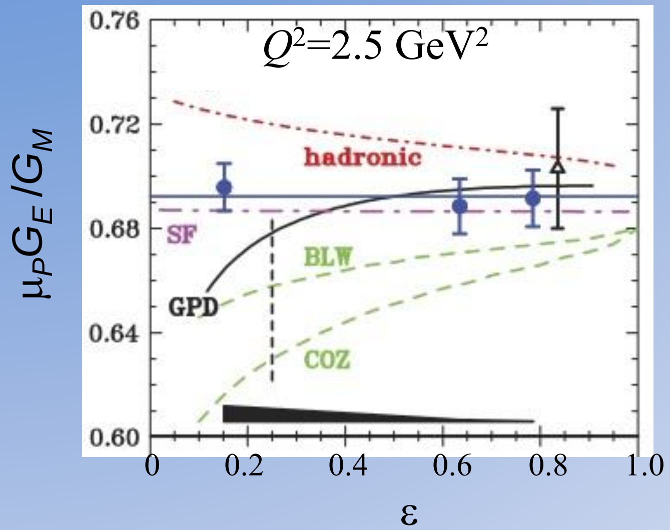
Leads to few %, ε-dependent correction to cross section.



TPE correction ($\delta_{2\gamma}$) expected to increase with decreasing ε.

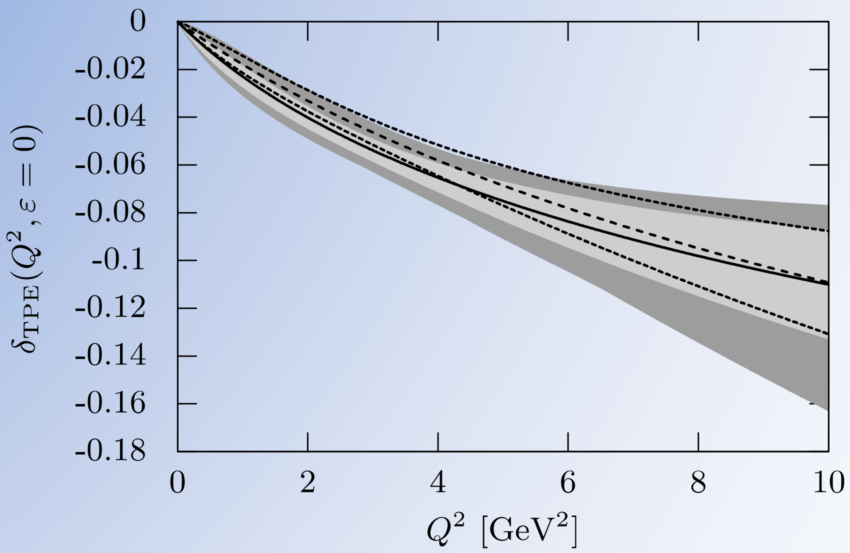
Phenomenological Extractions and Tests of TPE

This has become a cottage industry in nuclear physics. Some examples:



Looked for ε dependence

Meziane *et al.*, PRL 106, 132501 (2011)



Fits to cross section and polarization results to extract δ_{TPE} (TPE correction)

Bernauer *et al.*, PRC 90, 015206 (2014)

Direct Measurement of TPE via $e^{\pm}p$ Elastic Scattering

To first order in the sign of the lepton charge:

$$R = \frac{\sigma(e^+)}{\sigma(e^-)} \approx \frac{1+\delta_{even} - \delta_{2\gamma} - \delta_{e.p.brem}}{1+\delta_{even} + \delta_{2\gamma} + \delta_{e.p.brem}}$$

$$R \approx 1 - \frac{2(\delta_{2\gamma} + \delta_{e.p.brem})}{1+\delta_{even}}$$

δ_{even}	total charge-even radiative correction
$\delta_{e.p.brem}$	lepton-proton bremsstrahlung interference
$\delta_{2\gamma}$	TPE correction to elastic cross section. Arises from the interference of Born and TPE amplitudes.

$$R \rightarrow R_{2\gamma} \approx 1 - 2\delta_{2\gamma}$$

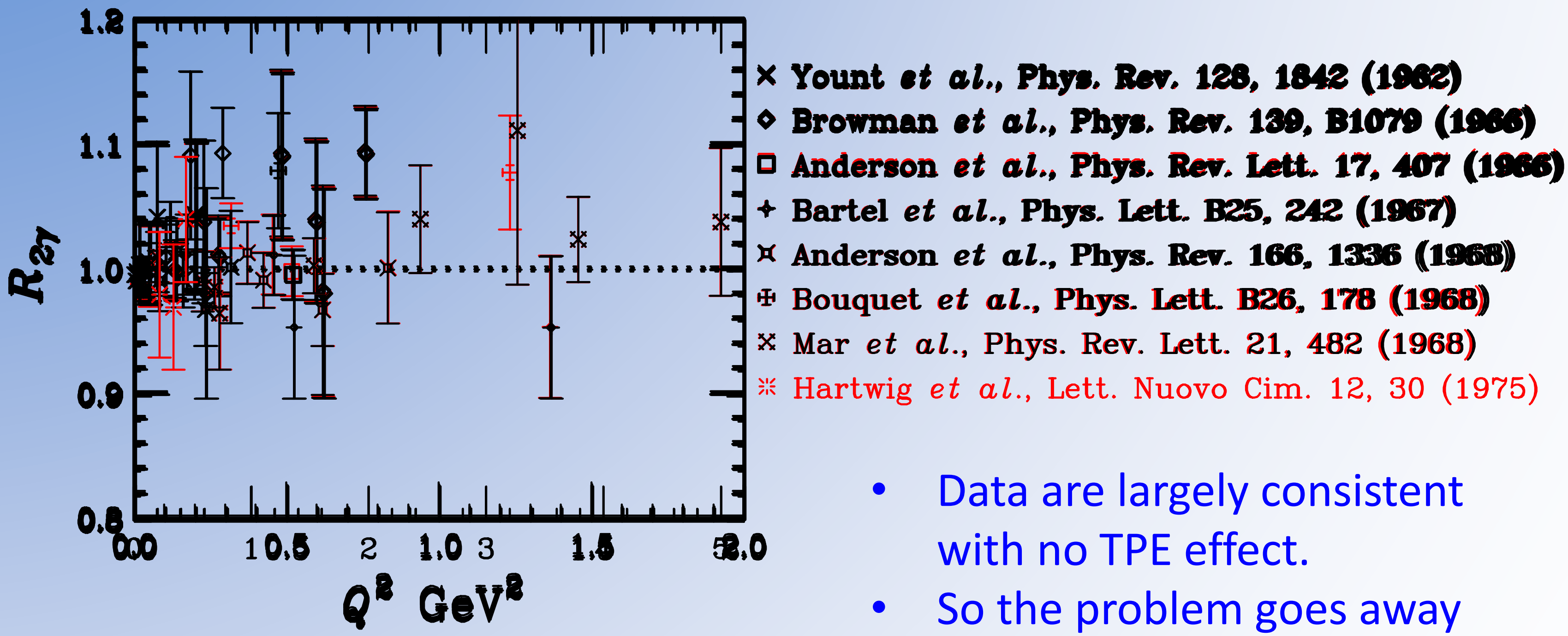
$$\sigma_R^{corr} = \sigma_R(1-\delta_{2\gamma})$$

where σ_R is the *measured* reduced electron-proton elastic scattering cross section:

$$\sigma_R^{corr} = \frac{d\sigma}{d\Omega}\frac{(1+\tau)\varepsilon}{\sigma_{Mott}\tau} = \frac{\varepsilon}{\tau}G_E^2(Q^2) + G_M^2(Q^2)$$

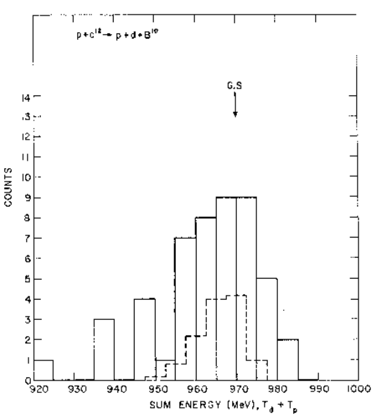
Early Measurements of $R_{2\gamma}$

Used electron beams to make photon beams that then made separate e^- and e^+ beams (pair production). Search for TPE effects started in 1962.



- Data are largely consistent with no TPE effect.
- So the problem goes away until Rosenbluth/Polarization discrepancy in 2000’s

Brief Aside on Early Measurements of $R_{2\gamma}$



and the large average kinetic energy of these clusters—about half that of the individual nucleons—we conclude that n-p pairs can move rather freely through the nucleus.

*Work supported by the U. S. Atomic Energy Commission.

†Work partially supported by the National Science Foundation.

[1]V. Cocconi, T. Fazzini, G. Fidecaro, M. Legros, N. Lipman, and A. Morrison, Phys. Rev. Letters 5, 19 (1960); V. Fitch, S. Meyer, and P. Piroue, Phys. Rev. 126, 1849 (1962).

[2]L. Azhgirei, I. Vzorov, V. Zrelov, M. Mescheriakov, B. Neganov, and A. Shabudin, Zh. Eksperim. i Teor. Fiz. 34, 1357 (1958) [translation: Soviet Phys.—JETP 6, 911 (1958)].

[3]The energy resolution of the spectrometer was 3-MeV full width at half-maximum, which is a factor of 10 better than that used in the experiment discussed in

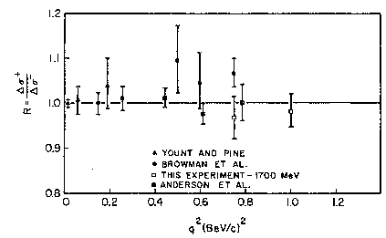


FIG. 2. Summary of experimentally obtained values of R.

itron and the electron beams had the same physical shape of 0.7 cm × 1.5 cm at the hydrogen target. The energies of the two beams differed by less than 0.2 %. The momentum distribution is normal and has a σ of 42 MeV/c. We kept the π-meson contamination of the beams to a negligible amount by maintaining the synchrotron energy below 1875 MeV. The average positron- or electron-beam intensity was about 2×10^6 sec^{-1}.

Figure 1 shows the detection apparatus which consisted of thin-foil spark chambers to measure angles of scattered particles and scintillation counters and total-absorption lead-glass Cherenkov counters, arranged symmetrically on opposite side of the liquid-hydrogen target. The spark chambers were triggered by simultaneous observation of an electron from one side and a proton from the other. The photographed spark-chamber tracks were measured and digitized onto cards on a Micrometric SP5000 image plane digitizer. Each measured event was then kinematically reconstructed with the aid of a CDC 1604 computer. By placing limits on the polar and azimuthal angles of each event and by examining the pulse height of the electrons in the Cherenkov counter, we were able to select the elastically scattered events from the inelastic events. The external radiative correction which arises from the emission and absorption of photons real or virtual contains a term which changes sign for the two scattering processes. This correction modifies the measured ratio $R_m \equiv \Delta\sigma(e^+p)/\Delta\sigma(e^-p)$ in the following way:

$$R(\text{corrected}) = R_m(1-2|\delta|),$$

where δ is given as

$$\delta = (\alpha/\pi)\ln\eta\ln[(p_e\cdot p_e')^2\Lambda^4/(M_p{}^2E_eE_e')].$$

The variables in the expression of δ are defined by Yennie and Meister.[2] In the q^2 and energy regions with our detection geometry, the correction $2|\delta|$ can be considered a constant and is found to be 0.038. The estimated error of $2|\delta|$ is about ±0.005.

The values of R after radiative correction are plotted in Fig. 2 together with all other published data.[3-5] Our result is consistent with a recent distorted-wave-approximation calculation by Greenhut,[6] who, using static magnetic-moment and charge distributions, predicted R to be less than 1.01.

We wish to thank Professor D. Yennie for many illuminating discussions. We are grateful to Dr. G. Rouse and the synchrotron staff for their help. We also wish to thank Mrs. M. Johnson and Miss G. Jackson for scanning the film.

*Work supported in part by the National Science Foundation.

†Physikalisches Institut, 5300 Bonn, Nussallee 12, Germany.

[1]H. S. Butler, S. K. Howry, and C. H. Moore, Stanford Linear Accelerator Center Report No. 29 (unpublished).

[2]N. Meister and D. Yennie, Phys. Rev. 130, 1210 (1963).

[3]D. Yount and J. Pine, Phys. Rev. 128, 1842 (1962).

[4]A. Browman, F. Liu, and C. Schaerf, Phys. Rev. 139, B1079 (1965).

[5]R. L. Anderson, B. Borgia, G. L. Cassiday, J. W. DeWire, A. Ito, and E. C. Loh, Phys. Rev. Letters 17, 407 (1966).

[6]G. Greenhut, private communication.

In addition to having large uncertainties, early papers frequently lacked detail so inclusion in global analysis is difficult.

The Modern Era of TPE Experiments

At the advent of the f.f. discrepancy the race was on to do *precision* measurements of $R_{2\gamma}$.

• CLAS (Jefferson Lab) test experiment approved in 2004; tested for one month in 2006 (1 day of data). Published: Moteabbed *et al*., PRC 88, 025210 (2013).

• CLAS full experiment approved in 2007; took data Nov. 2010-Feb. 2011. Published: Adikaram *et al*., PRL 114, 062003 (2015) and Rimal *et al*., PRC 95, 065201 (2017). (Latter includes a few more data points and δ_{even} corrections.)

• VEPP-3 (storage ring at Novosibirsk, Russia) experiment approved in 2004; took data from 2009-2012. Published: Rachek *et al*., PRL 114, 062005 (2015).

• OLYMPUS (DORIS storage ring at DESY, Germany) approved 2007; took data late 2012. Published: Henderson *et al*., PRL 118, 092501 (2017).

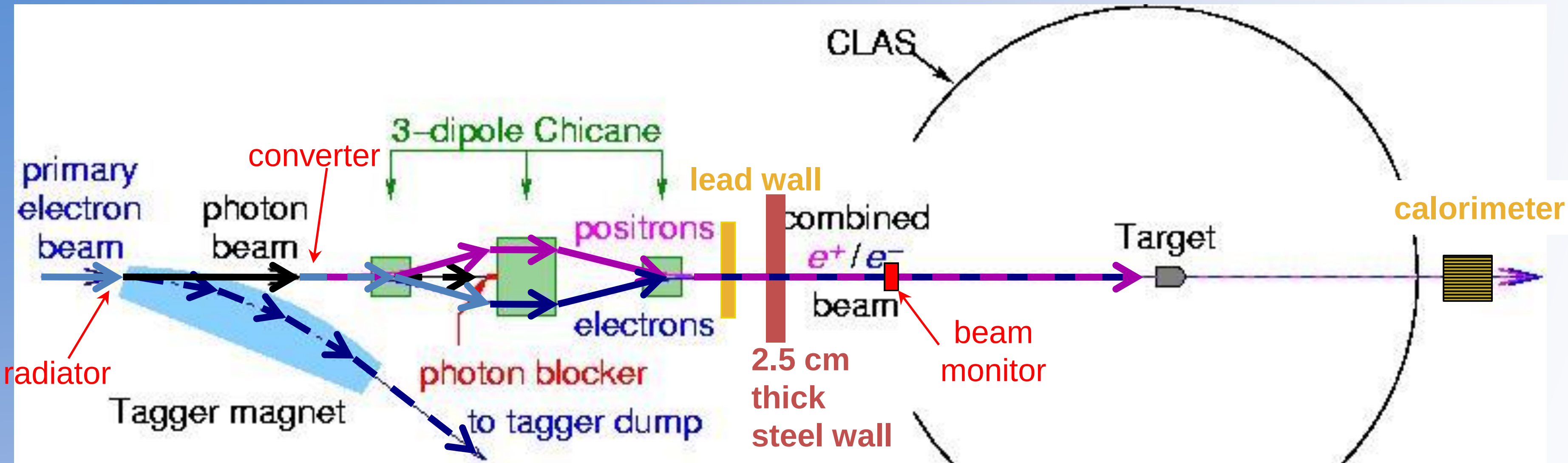
Advantages of CLAS experiment:

- Measurements at fixed values of Q^2 and ε.
- Simultaneous e^+ and e^- beams so no need for absolute normalization.

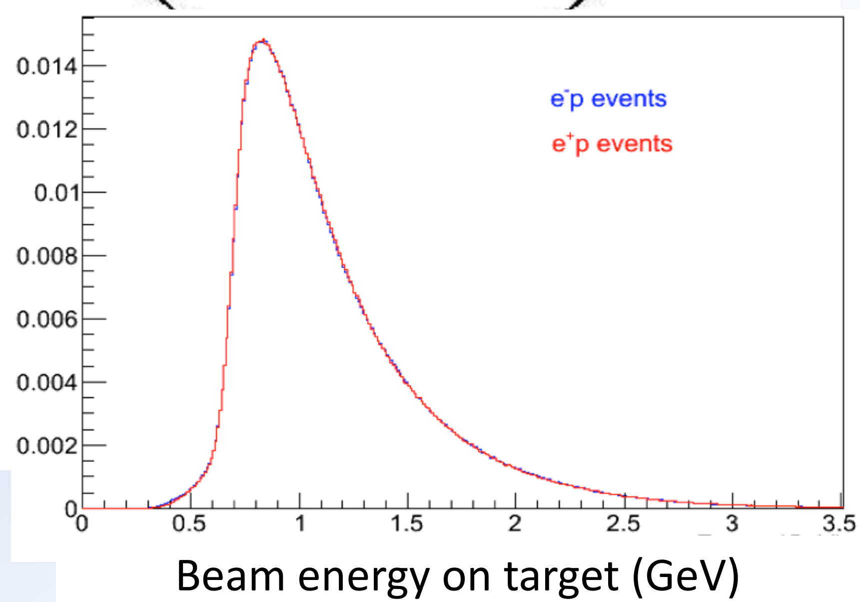
Advantages of VEPP-3 and OLYMPUS

- High luminosity so better statistical uncertainties (which also helps beat down systematic uncertainties).

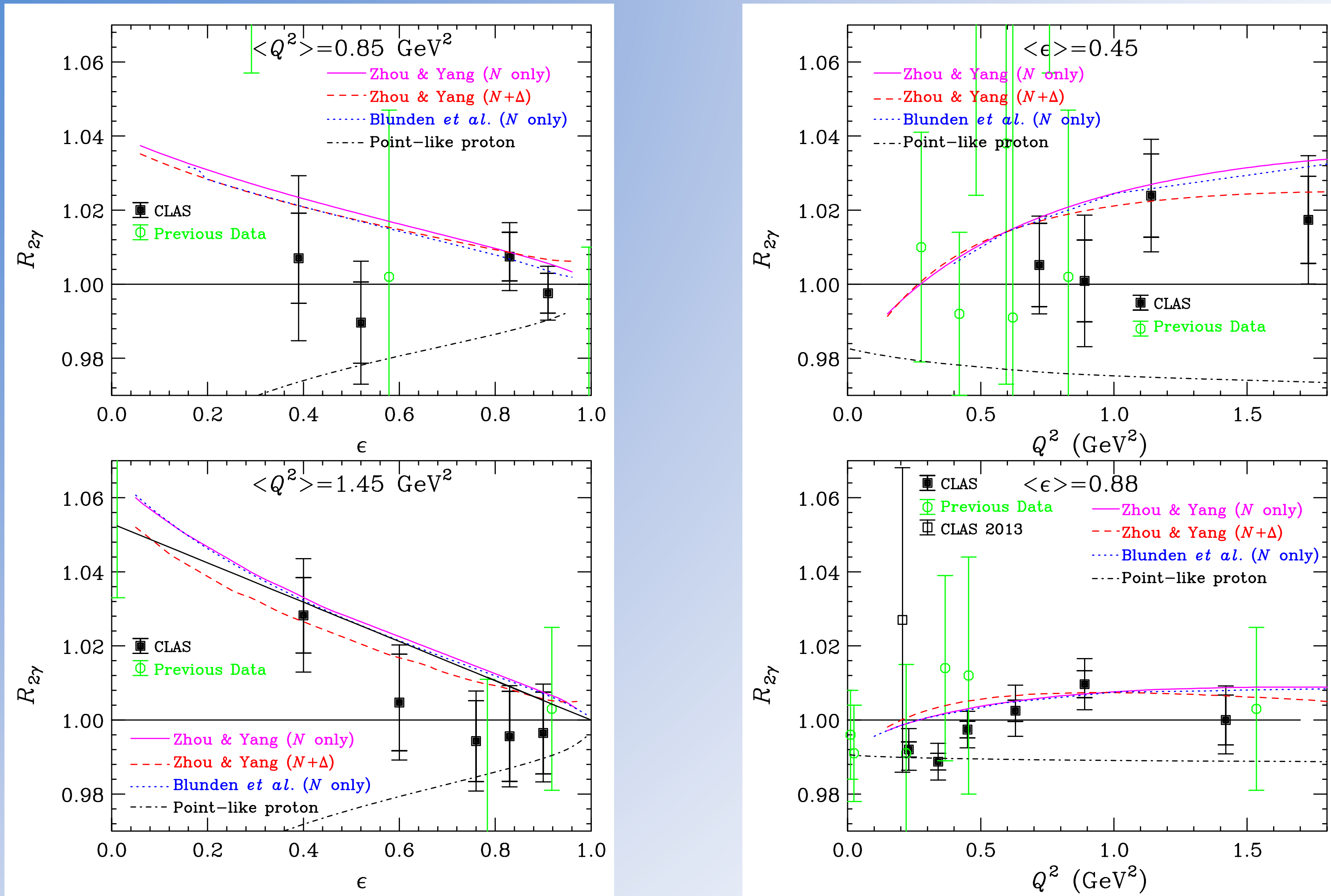
CLAS 2010-11 TPE Run



- ~110-120 nA of 5.5 GeV beam
- ~50 pA of tertiary beam current on 30cm-long LH^2 target
- About 70 days of running.
- Periodically flipped torus and chicane field polarity to cancel out acceptance and luminosity effects



CLAS Results



- CLAS data favor (hadronic) TPE over no TPE
- Disfavor “point-like proton” model

VEPP-3 (Novosibirsk) 2009-2012

- Fixed beam energies of 1 and 1.6 GeV
- Alternating e^+ and e^- beams
- Internal target (1)
- Separate large (LA), medium (MA), and small angle (SA) detectors
- Non-magnetic spectrometer leading to identical e^+/e^- acceptance
- Small angle detectors to high ε, low Q^2 normalization points

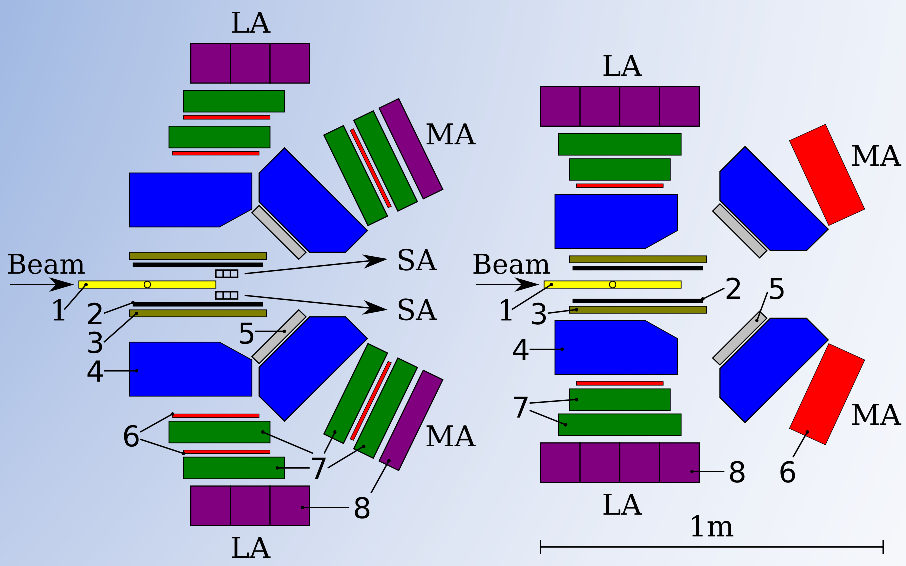
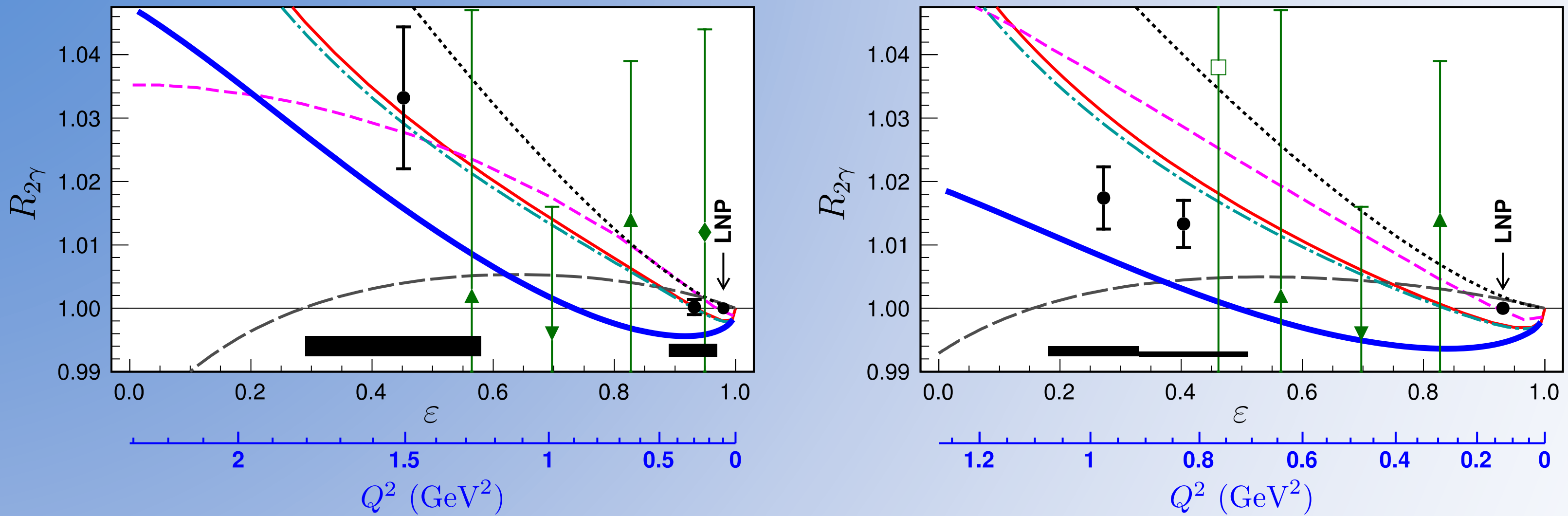


FIG. 1 (color online). The detector configurations for run I and run II (left and right panels, respectively). Labels: 1—storage cell; 2—beryllium sheet; 3—multiwire proportional chamber; 4—drift chamber; 5—acrylic glass; 6—plastic scintillator; 7—CsI crystals; 8—NaI crystals; SA, MA, LA—detector arms.

I. Rachek et al., Phys. Rev. Lett. 114, 062005 (2015)

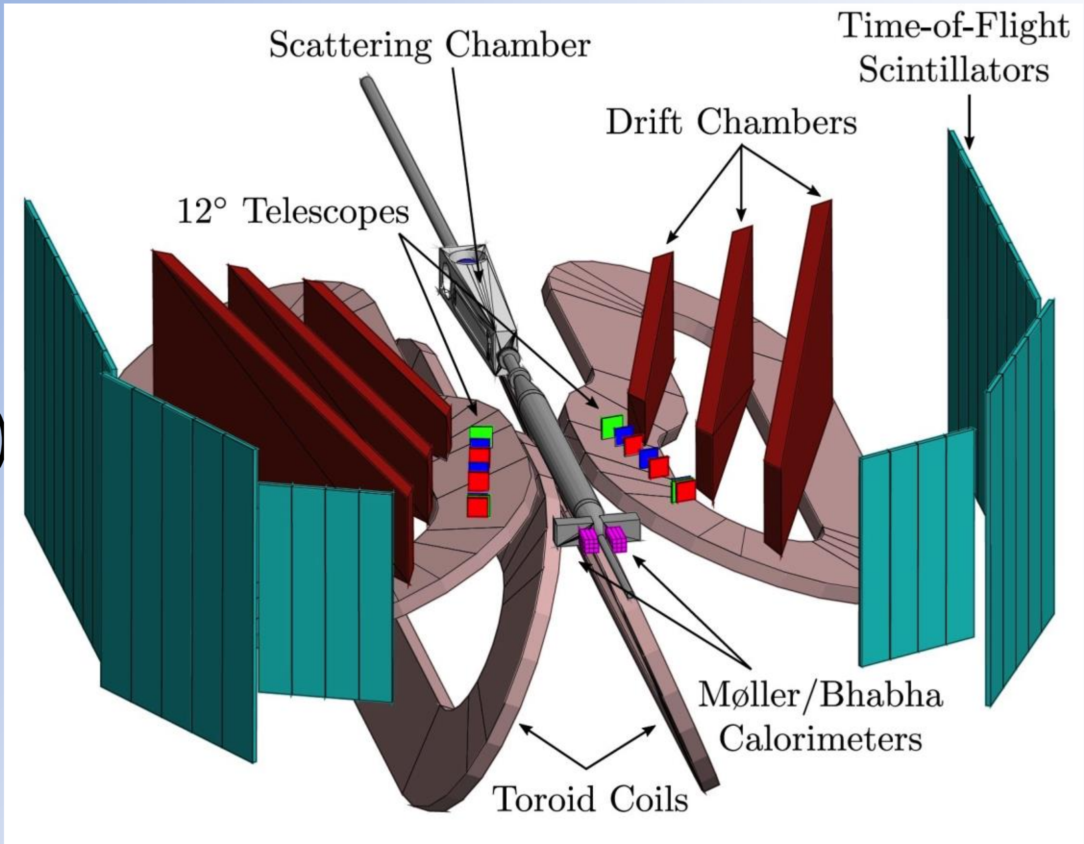
VEPP-3 Results



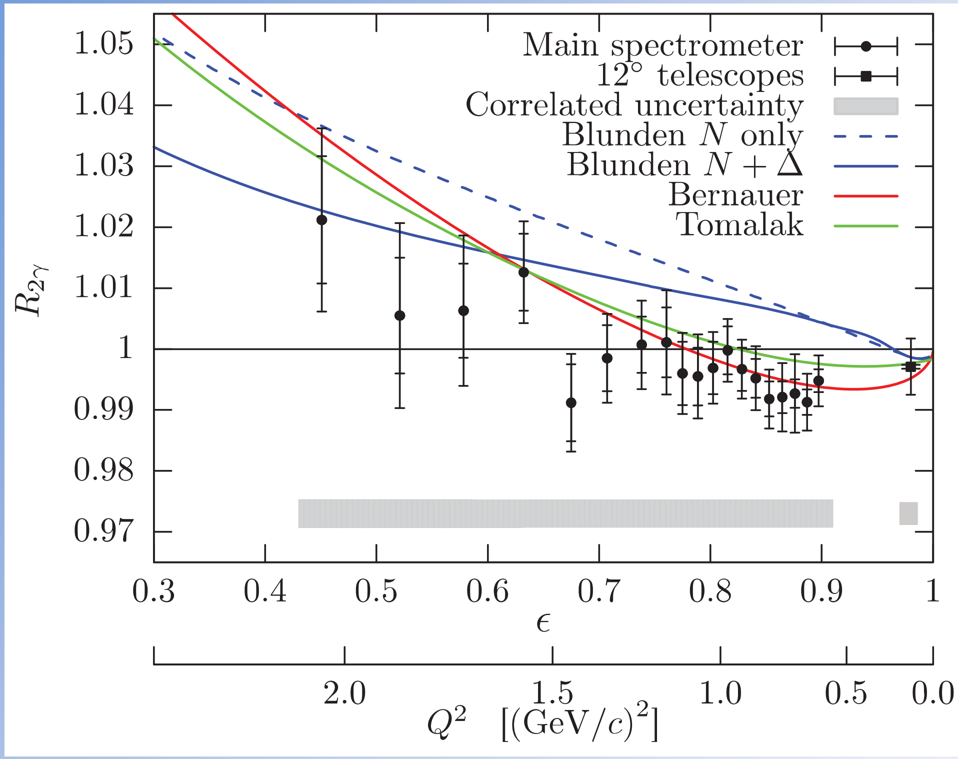
- Luminosity normalization point (LNP) at small Q^2 and εH1 assumed to be $R_{2\gamma}$=1 in these plots
- LNP scaled to model value at same kinematics
- Excludes no TPE hypothesis ($R_{2\gamma}=1$) at better than 99.9% confidence level.

OLYMPUS at DESY 2012

- E= 2 GeV
- Alternating e^+ and e^- beams
- Internal target (10^{15} atoms/cm^3)
- Small angle (1.27^o and 12^o) luminosity monitors
- Continuous angular coverage 20^o to 80^o

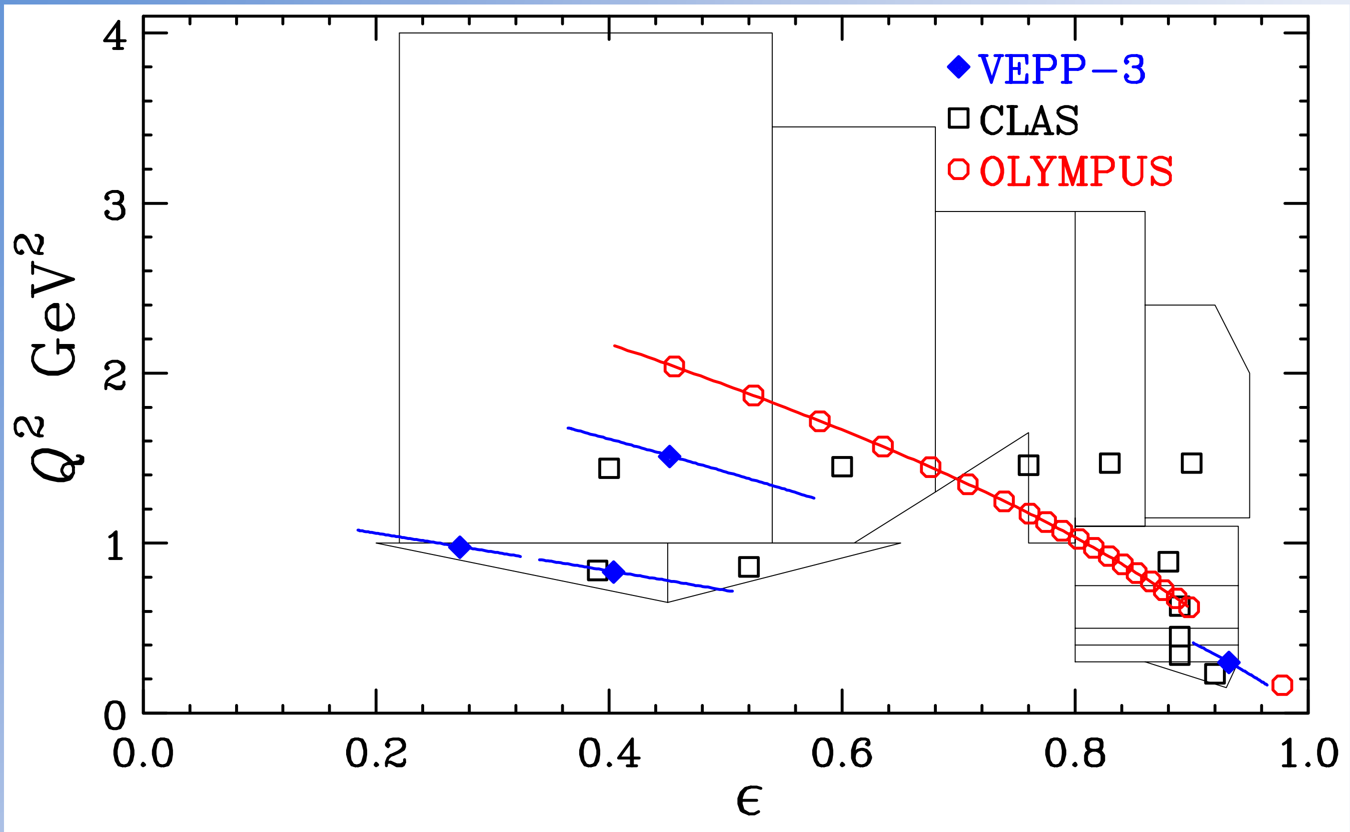


OLYMPUS Results



- *Agrees* with no TPE hypothesis ($R_{2\gamma}=1$) at 88.6% confidence level.
- Correlated uncertainty from relative normalization 0.36%—0.45%

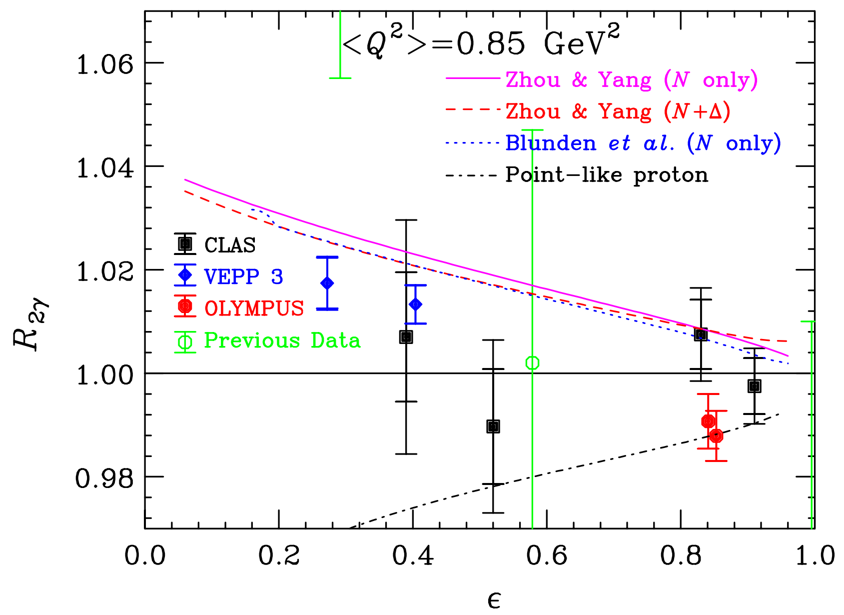
Kinematic coverage

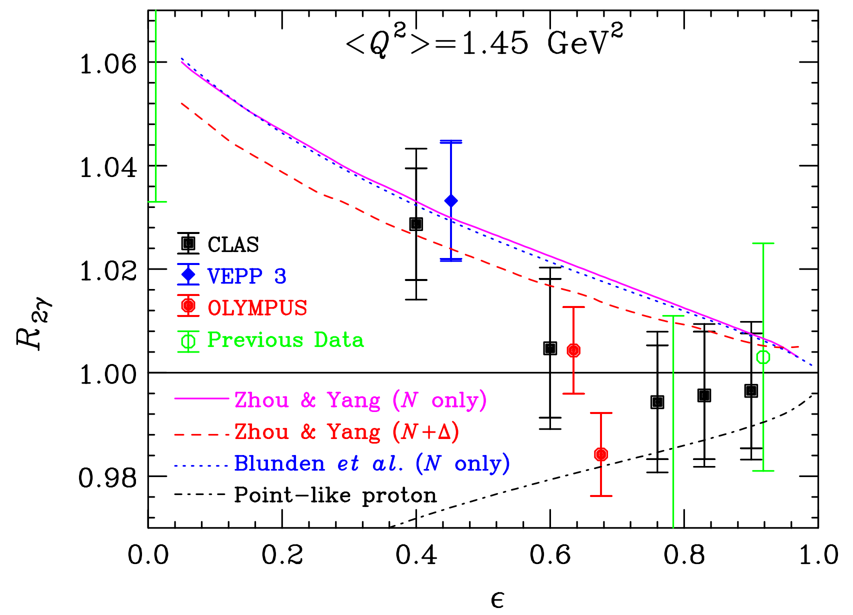


- CLAS needed larger bins in Q^2 and ε (grey boxes) because of lower statistics
- Okay if $R_{2\gamma}$ is roughly linear in Q^2 and ε over the bin
- VEPP-3 large bins in ε (blue lines)

ε Dependence at fixed Q^2

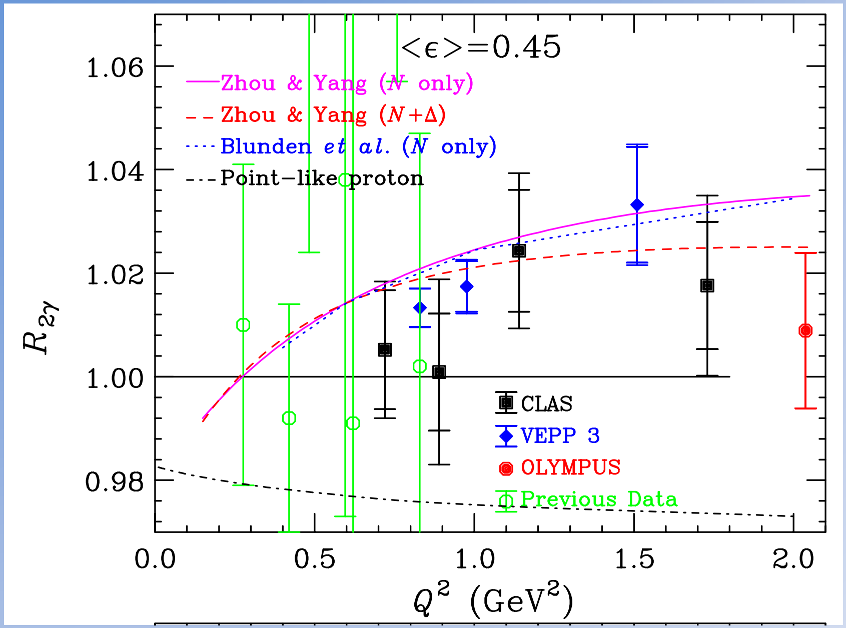
World data at *similar* kinematics

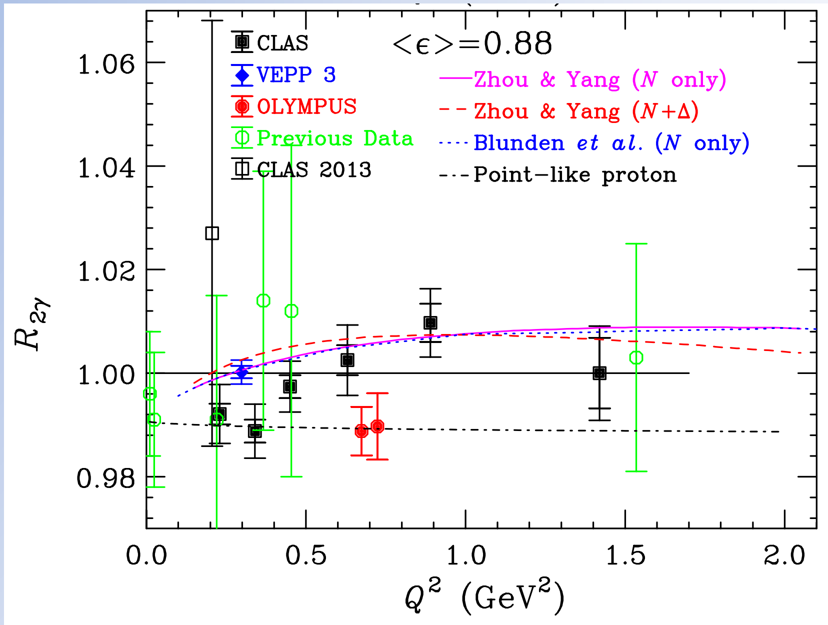




Q^2 Dependence at fixed ε

World data at *similar* kinematics





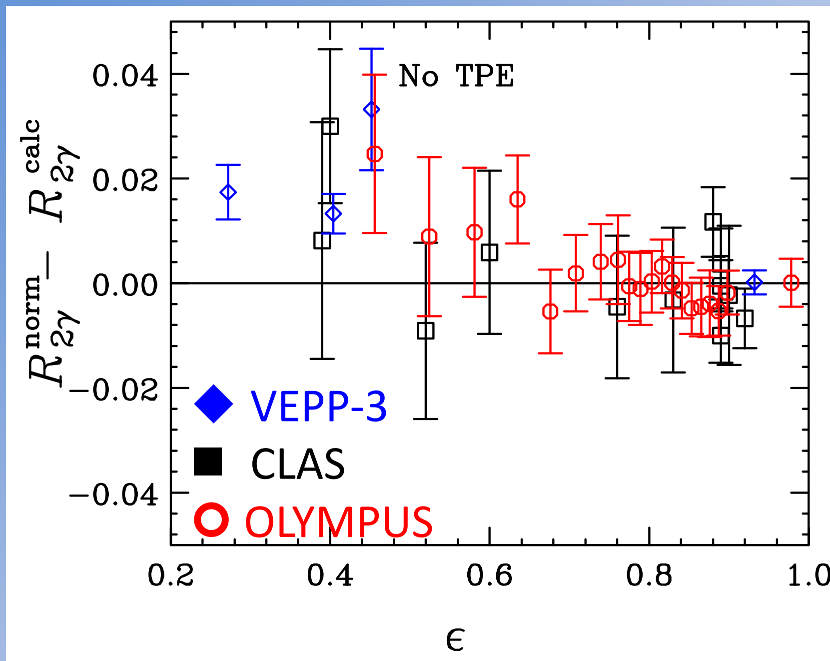
- CLAS and VEPP-3 good agreement
- Agreement with OLYMPUS is not too good
- Did the OLYMPUS results muddy the water?

Global Analysis

- Comparison to three models (Afanasev, Blunden, Hasell, Raue, Prog. Part. Nuc. Phys. 95, 245 (2017))
  1. No TPE
  2. Blunden & Melnitchouk dispersive model with N+Δ intermediate states (PRC 95, 065209 (2017))
  3. Borisyuk & Kubushkin dispersive model with πN (J= 1/2, 3/2) intermediate states (PRC 92, 035204 (2015))

  Current state of the art models that (largely) reconcile Rosenbluth and polarization-transfer discrepancy of the form factors.
- Allow for normalization (N) of CLAS and OLYMPUS data sets accounting for correlated uncertainties ($\delta R_{2\gamma}^{\mathrm{norm}}$).
- Modified χ^2: $$\chi^2 = \sum_n \left(\frac{R_{2\gamma} - R_{2\gamma}^{\mathrm{calc}}}{\delta R_{2\gamma}} \right)^2 \Rightarrow \chi^2 = \sum_n \left(\frac{R_{2\gamma} N - R_{2\gamma}^{\mathrm{calc}}}{\delta R_{2\gamma}} \right)^2 + \left(\frac{N - 1}{\delta R_{2\gamma}^{\mathrm{norm}}} \right)$$
- 34 degrees of freedom in combined data set (36 independent data points less 2 normalizations)

Model Comparison: No TPE



Difference between $R_{2\gamma}$ and $R_{2\gamma}$=1

- CLAS norm.=1.0012

$$\frac{N-1}{dR_{2g}^{norm}} = 0.40$$

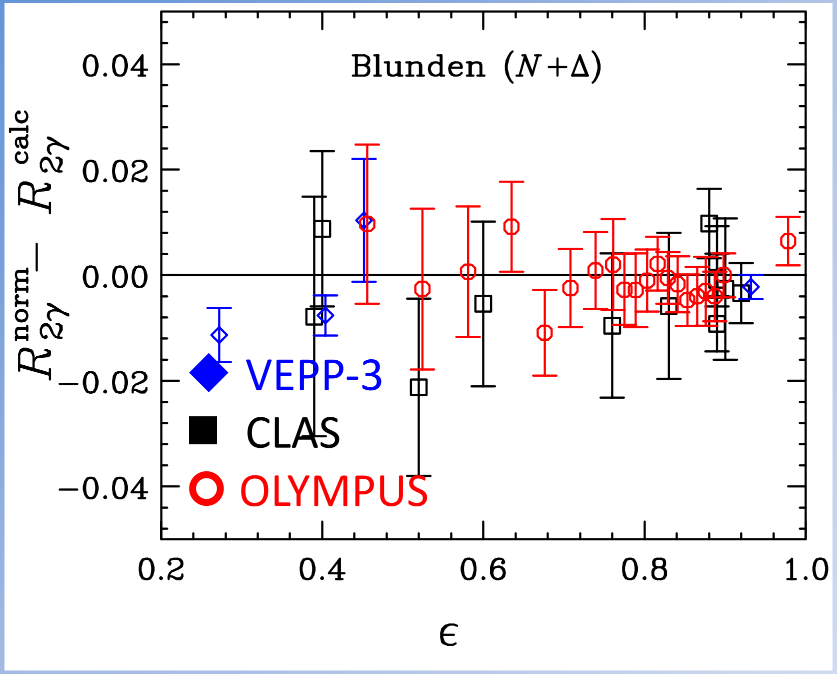
- OLYMPUS norm.=1.0034

$$\frac{N-1}{dR_{2g}^{norm}} = 0.76$$

- Overall: $c_n^2 = 1.73$

Excludes no TPE at the 99.5% confidence level

Model Comparison: Blunden & Melnitchouk



Difference between $R_{2\gamma}$ and prediction

- CLAS norm.=1.0032

$$\frac{N-1}{dR_{2g}^{\text{norm}}} = 1.07$$

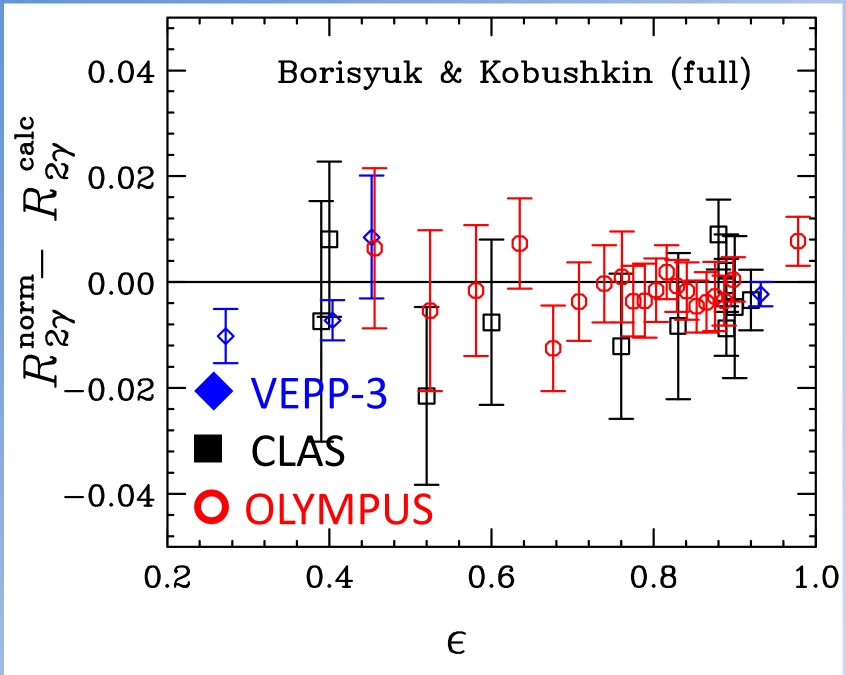
- OLYMPUS norm.=1.0082

$$\frac{N-1}{dR_{2g}^{\text{norm}}} = 1.82$$

- Overall: $c_n^2 = 0.96$

  Agrees with B&M at the 53% confidence level

Model Comparison: Borisyuk & Kobushkin



Difference between $R_{2\gamma}$ and prediction

- CLAS norm.=1.0038

$$\frac{N-1}{dR_{2g}^{\text{norm}}} = 1.27$$

- OLYMPUS norm.=1.0097

$$\frac{N-1}{dR_{2g}^{\text{norm}}} = 2.16$$

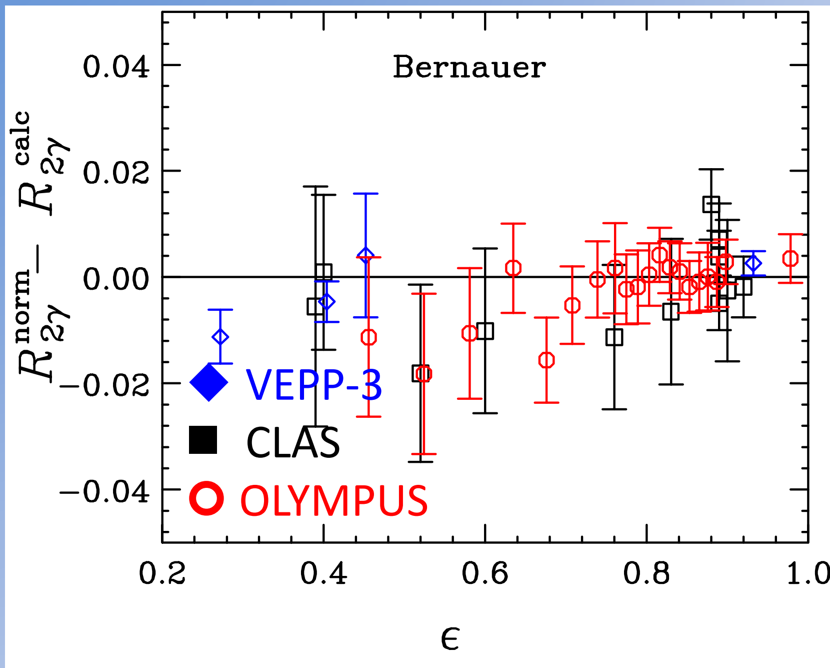
- Overall: $c_n^2 = 1.00$

  Agrees with B&K at the 48% confidence level

  B&M slightly better than B&K

Bernauer Parameterization

PRC 90, 015206 (2014)



Difference between $R_{2\gamma}$ and prediction

- CLAS norm.=0.9985

$$\frac{N-1}{dR_{2g}^{\text{norm}}} = -0.40$$

- OLYMPUS norm.=1.0019

$$\frac{N-1}{dR_{2g}^{\text{norm}}} = 0.42$$

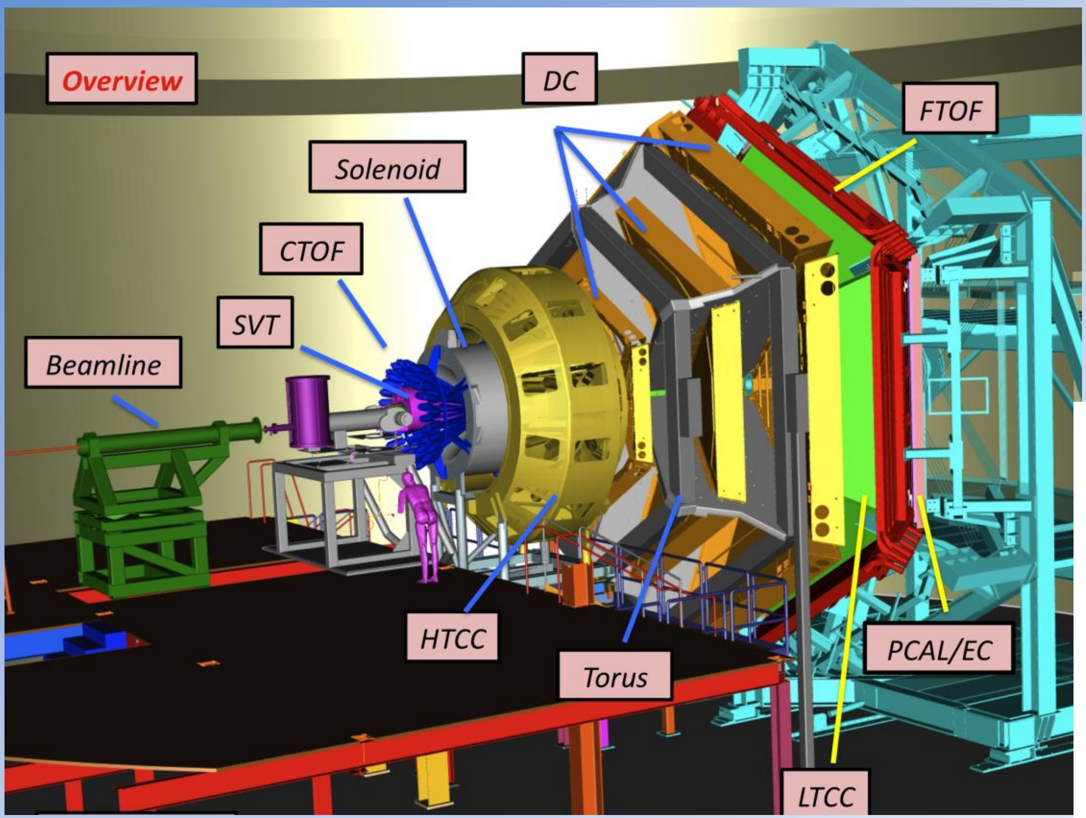
- Overall: $c_n^2 = 0.80$

  Agrees with Bernauer at the 79% confidence level

Summary of where we are

- Lots of new $R_{2\gamma}$ data at Q^2<2.0 GeV
- As published, discrepancies between OLYMPUS and the combined CLAS/VEPP-3 data
- If CLAS and OLYMPUS normalizations are allowed to float (subject to correlated/scale uncertainties)
  - No TPE ruled out at the 99.5% CL (dominated by VEPP-3 results)
  - Fair agreement with Blunden & Melnitchouk $N+\Delta$ model (53% CL), with a 1.8-sigma change to the OLYMPUS normalization
  - Agreement with Borisyuk & Kubushkin not as good (48% CL)

Future with CLAS12 and separate e^+ and e^- beams

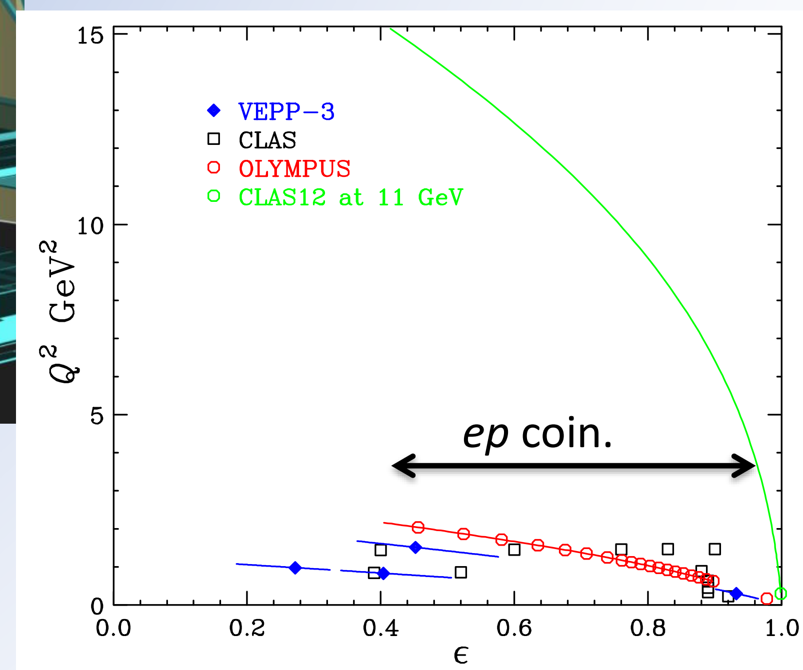


Angular acceptance

$$5° \leq \theta^e_{lab} \leq 40°$$

$$25° \leq \theta^e_{CM} \leq 122°$$

at 11 GeV



- large range of *ep* coincidence ➔ background reduction
- possibly use forward tagger or other small angle detectors to determine luminosity normalization point, a la VEPP-3

Elastic $e^{\pm}p$ Scattering in CLAS12

- Beam 8.8 GeV
- Lumi $10^{35}/cm^2/sec$ =(20 nA) • (20 cm LH_2)
- $\Delta\phi = \pi$
- 16 week run ≈ 4 PAC-weeks each $e^{\pm}$