Measurement of the Two-Photon Exchange Contribution to Elastic Lepton-Proton Scattering at the OLYMPUS Experiment

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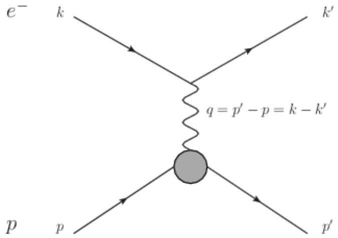
The elastic *ep* cross section and form factors

$$\frac{d\sigma}{d\Omega} = \frac{1}{\varepsilon\left(1+\frac{Q^2}{4m_p^2}\right)} \underbrace{\left(\frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)}\right)}_{\sigma_{\mathrm{Mott}}} \left(\varepsilon G_E^2\left(Q^2\right) + \frac{Q^2}{4m_p^2} G_M^2\left(Q^2\right)\right)$$

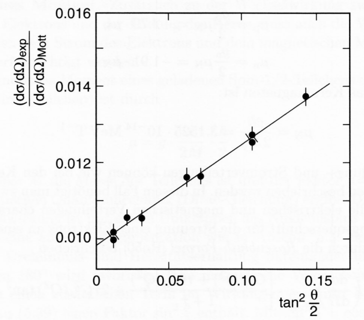
$\theta =$ Lab frame scattering angle of the lepton

$Q^2 =$ $-q_\mu q^\mu =$ Squared four-momentum transfer

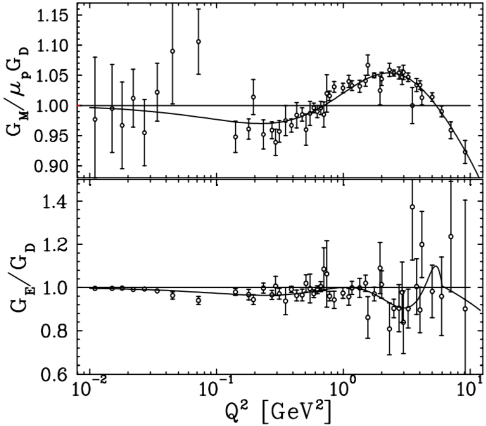
$$\varepsilon = \left(1 + 2\left(1+\frac{Q^2}{4m_p^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right)^{-1}$$



Form of cross section suggests a straightforward way to measure the form factors: fix Q^2 and vary ε (i.e., θ) using a small-acceptance spectrometer



$G_E^2(Q^2) \propto$ slope, $G_M^2(Q^2) \propto$ cross-section at $\theta = 0$



$$G_D = \left(1 + \frac{Q^2}{0.71\,\text{GeV}^2}\right)^{-2}$$

Polarized beams/targets and G_E/G_M

Availability of highly polarized e^- beams and targets starting in the mid-to-late 1990s provided a new way to measure G_E/G_M

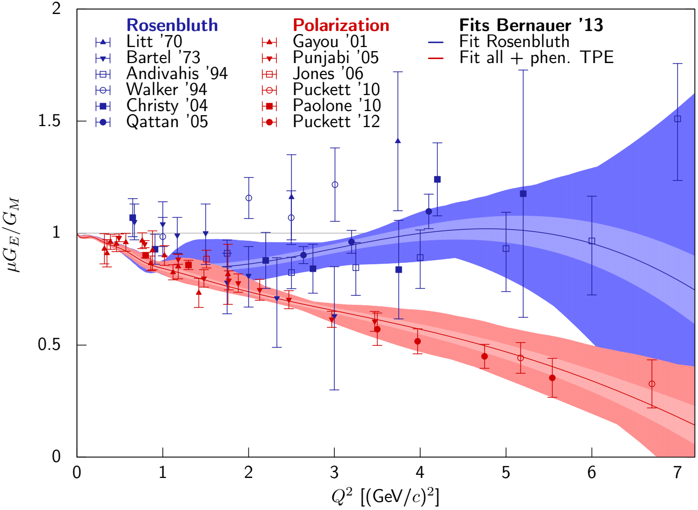
Scatter longitudinally-polarized e^- from unpolarized protons, and measure the cross-sections for the different polarizations of the outgoing lepton

$$\frac{d\sigma^{(L)}}{d\Omega} = h\sigma_{Mott}\frac{E+E'}{m_p}\sqrt{\frac{1}{1+\frac{4m_p^2}{Q^2}}}\tan^2\left(\frac{\theta}{2}\right)G_M^2$$

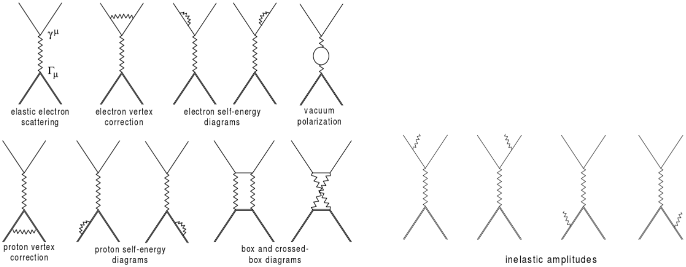
$$\frac{d\sigma^{(T)}}{d\Omega} = 2h\sigma_{Mott}\sqrt{\frac{1}{1+\frac{4m_p^2}{Q^2}}}\tan\left(\frac{\theta}{2}\right)G_EG_M$$

The G_E/G_M ratio discrepancy

The Rosenbluth and polarization form factor ratios show a large discrepancy!



Results from both methods (especially Rosenbluth separation), depend heavily on radiative corrections

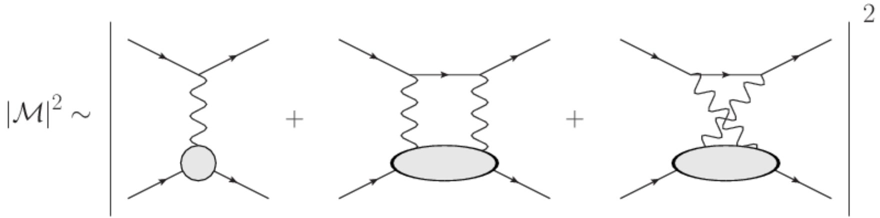


Most of these are calculable, but the two photon exchange (TPE) box and crossed-box contributions had always been "assumed to be negligible" due to the challenges of the off-shell proton propagator

Measuring TPE directly with $\sigma_{e^+p}/\sigma_{e^-p}$

A TPE correction could bring the data into agreement, but calculation of the diagrams is highly model-dependent

Can it be measured?



Interference of the tree-level and TPE diagrams changes sign with the charge of the lepton $\rightarrow$ comparing e^+ and e^- scattering gives you a direct link to the TPE contribution

The OLYMPUS experiment

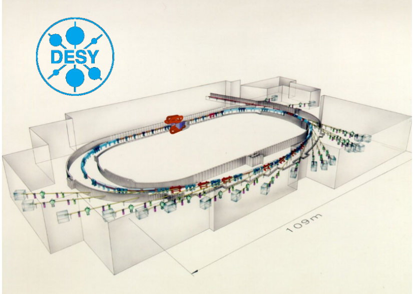
OLYMPUS seeks to provide a measurement of the e^+p/e^-p elastic cross section ratio with better than 1% uncertainty over a range of 0.6 GeV^2 $< Q^2 <$ 2.2 GeV^2 to test the TPE hypothesis

Experiment requirements:

- Strong statistics over a large θ range
- Precise monitoring of the relative e^+/e^- luminosity collected
- Complete understanding of any systematic difference between e^+ and e^- running
  - Acceptance effects
  - Beam conditions
  - Associated background/noise
  - ...
- Careful radiative corrections (especially α^3 soft effects)

OLYMPUS basics

- Located at the DORIS storage ring, DESY, Hamburg, Germany
- 2.01 GeV e^+ and e^- on a fixed internal gaseous hydrogen target
- Main tracking detectors and toroidal magnet from BLAST (MIT Bates)
- New detectors for precision luminosity monitoring
- Two other experiments: CLAS and VEPP-3

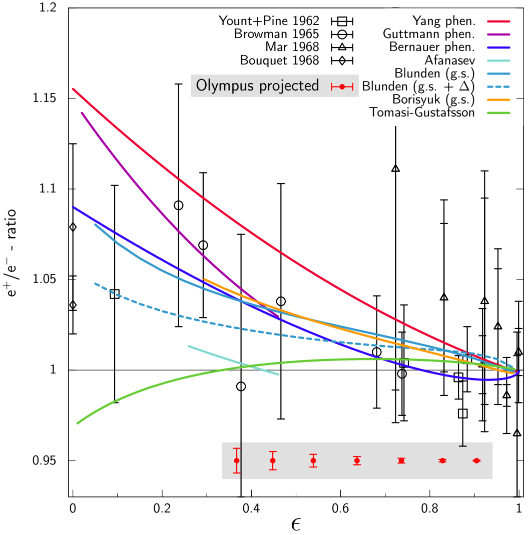


OLYMPUS basics

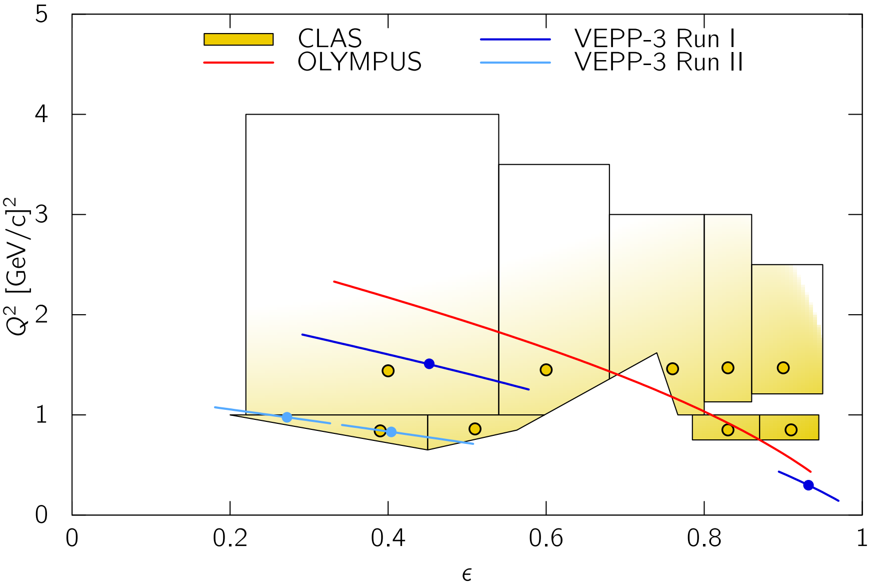
- Exclusively reconstruct elastic $e^{\pm}p$ events from $\theta \approx 20°–70°$
- Switch beam species approximately daily to control long-period systematics
- Construct an extremely detailed Monte Carlo simulation including detector efficiencies and acceptance, radiative corrections, and experiment conditions (beam current, target density, beam position, etc.)

$$R_{2\gamma} = \frac{\sigma_{e^+p}(\theta)}{\sigma_{e^-p}(\theta)} = \frac{N_{e^+,data}(\theta)}{N_{e^-,data}(\theta)} \cdot \frac{N_{e^-,MC}(\theta, \mathcal{L}_{e^-})}{N_{e^+,MC}(\theta, \mathcal{L}_{e^+})}$$

Projected reach and previous data

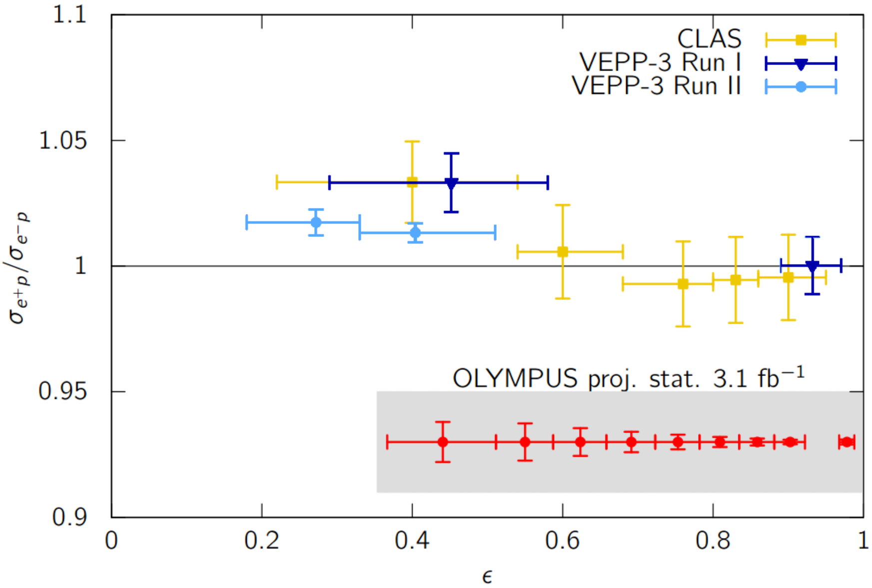


Reach of the TPE experiments

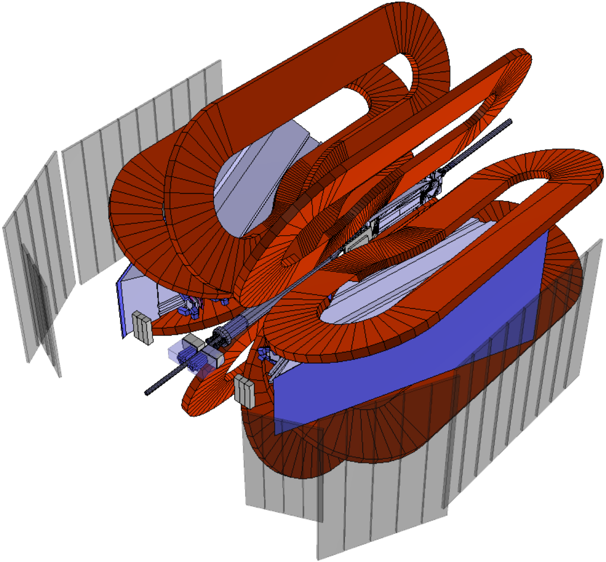


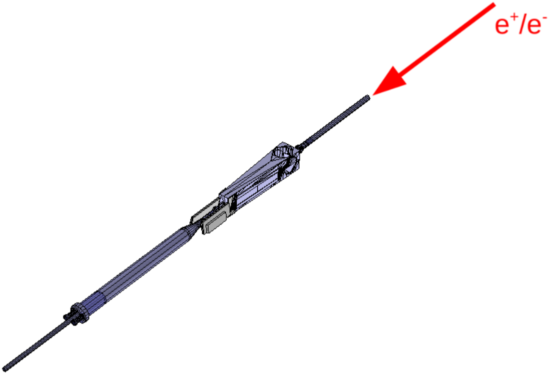
Results from CLAS and VEPP-3

OLYMPUS

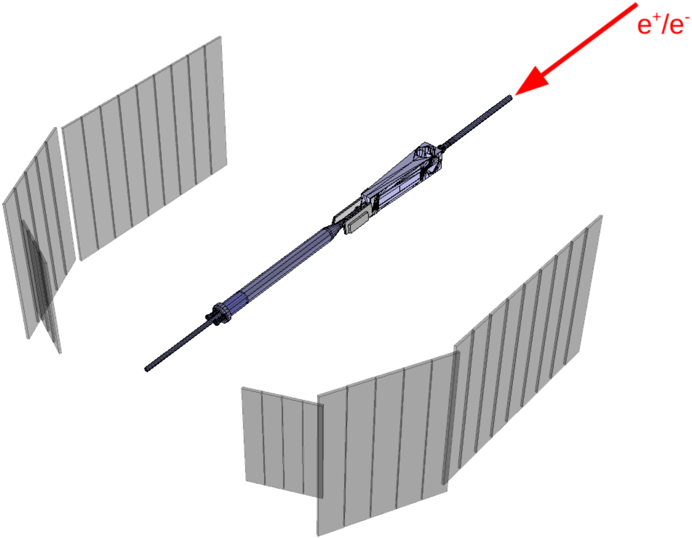


The OLYMPUS detector

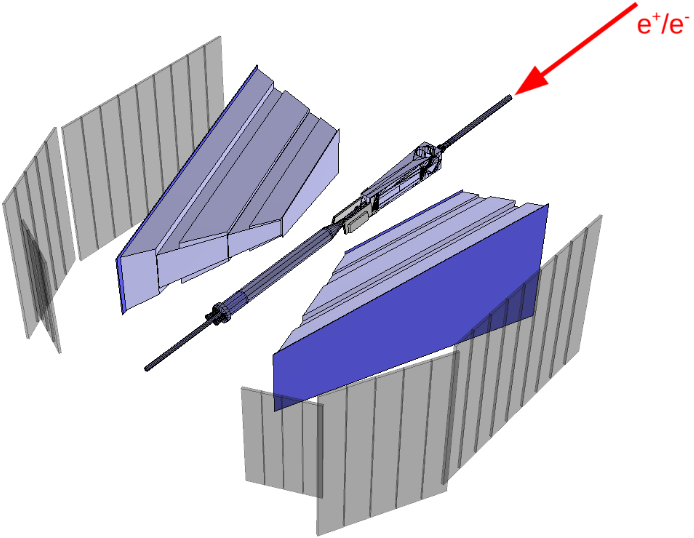



e+/e-

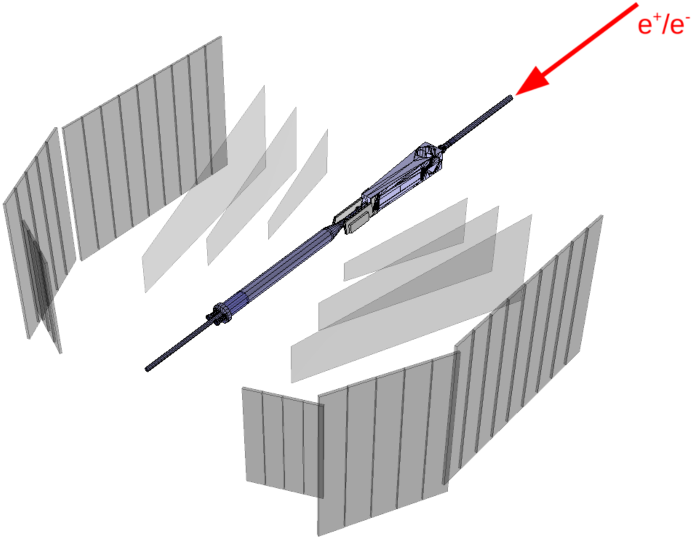
The OLYMPUS detector



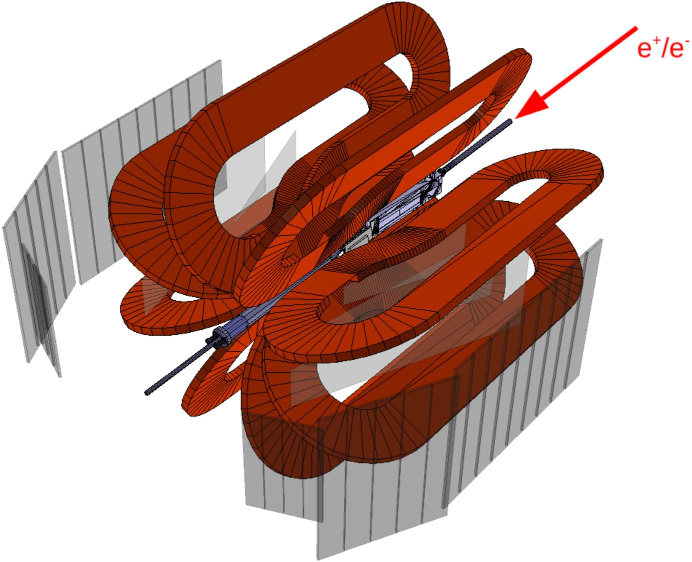
The OLYMPUS detector



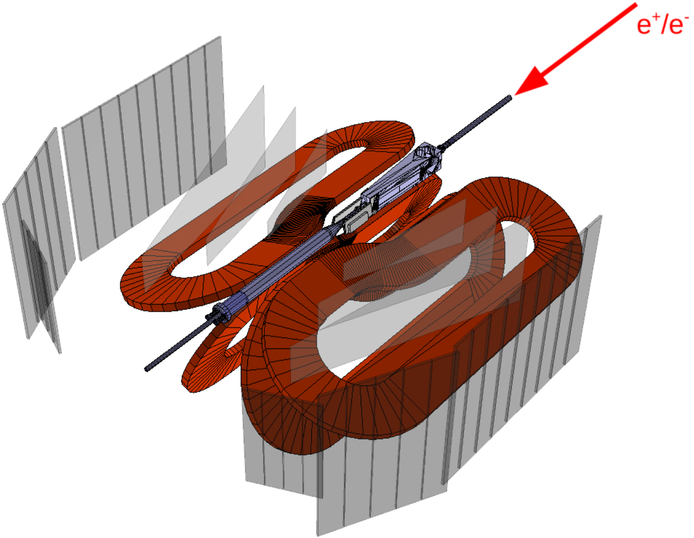
The OLYMPUS detector



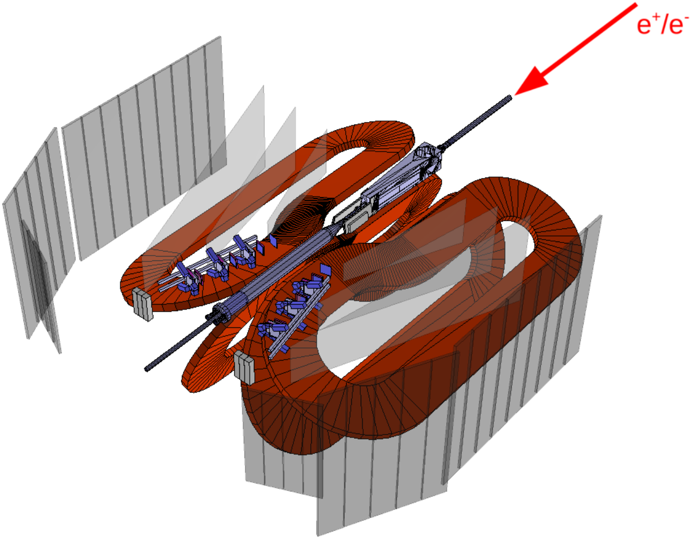
The OLYMPUS detector



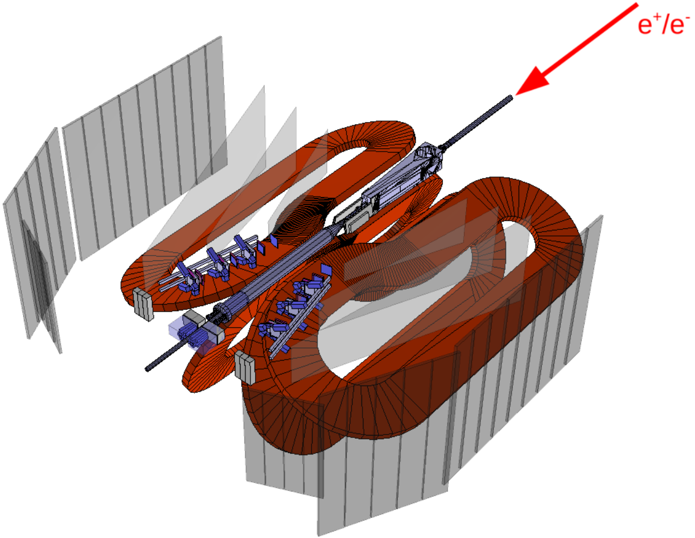
The OLYMPUS detector



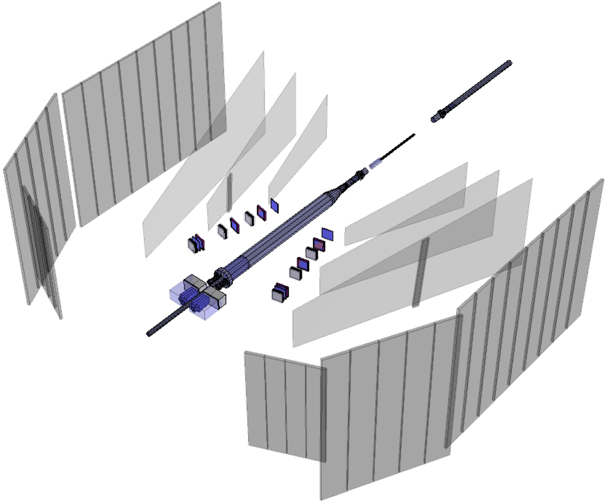
The OLYMPUS detector

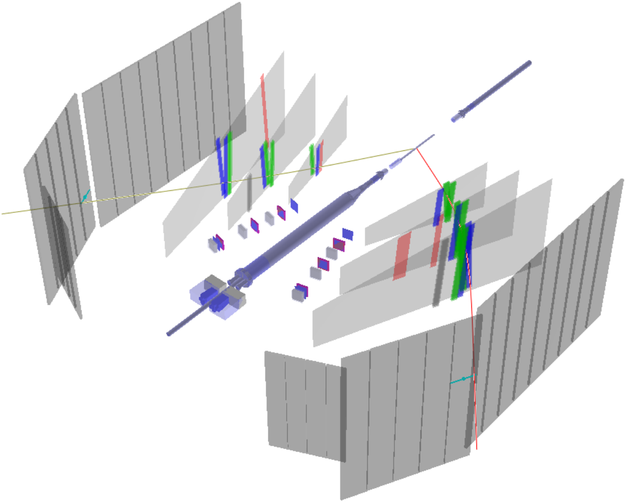


The OLYMPUS detector



The OLYMPUS detector

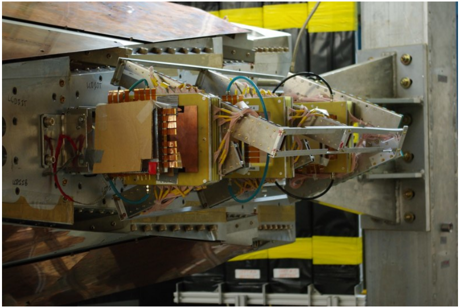




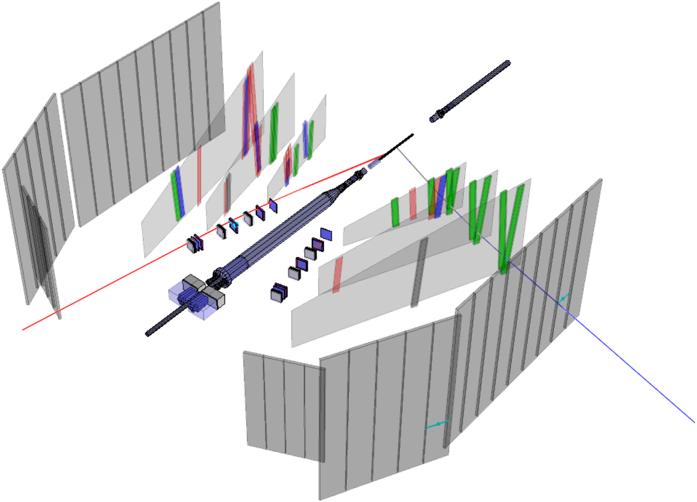
12° $e^{\pm}p$ luminosity monitoring

OLYMPUS

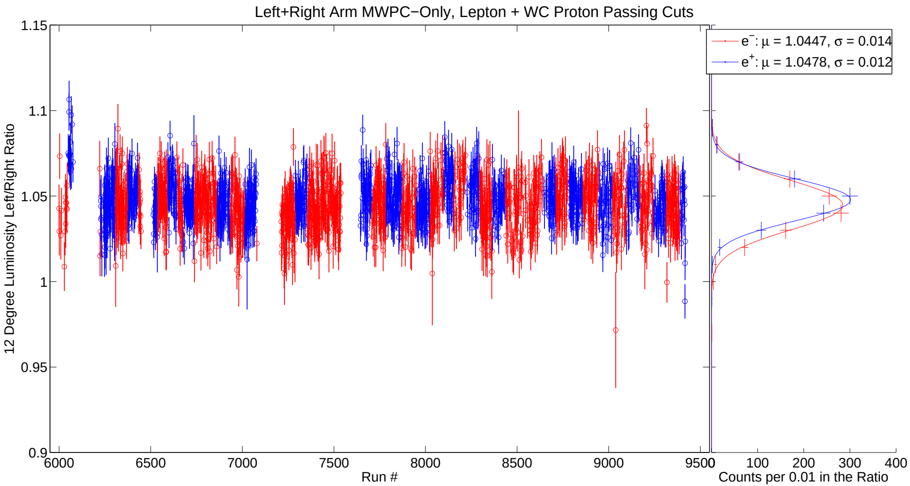
- Broad theory consensus that $R_{2\gamma} \approx 1$ at high ε
- High resolution 12° tracking telescopes with dedicated trigger provide high statistics measurement
  - 3 GEMs + 3 MWPCs per detector side
  - Exclusive $e^{\pm}p$ reconstruction
  - $\sim$1%/hour statistical uncertainty from each telescope
  - Additional $R_{2\gamma}$ point with SYMB luminosity



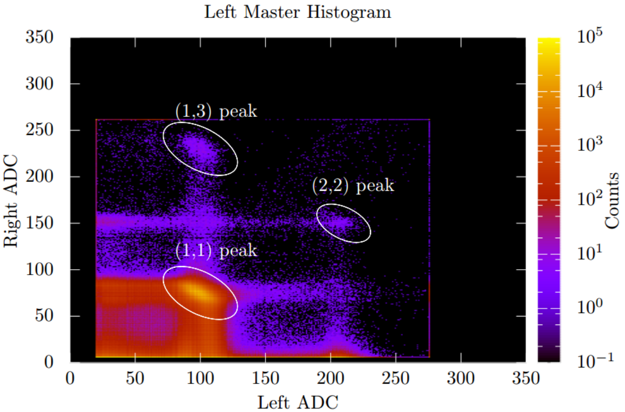
Typical 12° event



12° results

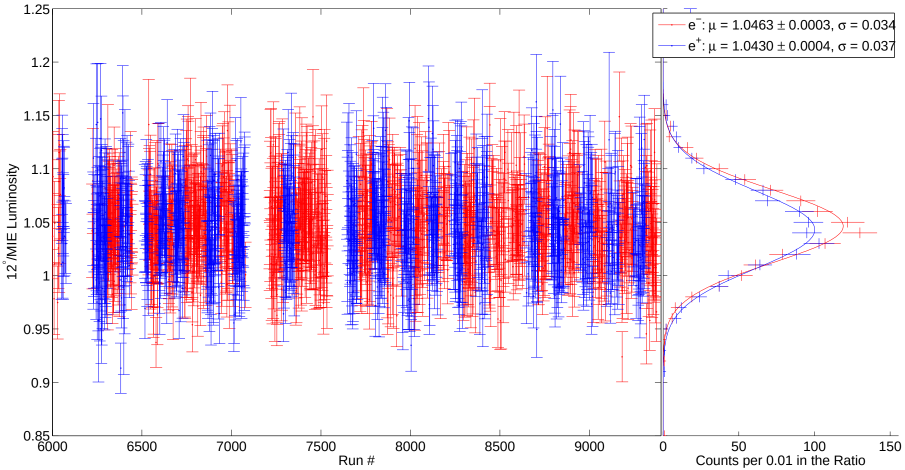

Left+Right Arm MWPC−Only, Lepton + WC Proton Passing Cuts
12 Degree Luminosity Left/Right Ratio
Run #
Counts per 0.01 in the Ratio
e⁻: μ = 1.0447, σ = 0.014
e⁺: μ = 1.0478, σ = 0.012
1.15
1.1
1.05
1
0.95
0.9
6000
6500
7000
7500
8000
8500
9000
9500
0
100
200
300
400

Multi-interaction event luminosity



$$\mathcal{L}_{\text{MIE}} = \frac{N_{(1,3)} N_b}{N_{(1,1)} \sigma^{\text{MC}}_{e^\pm p \to \text{R}}} - \frac{v_b N_b^2}{\mathcal{L}_{\text{SC}}} - N_b \sigma_{\text{tot}} \left[\left(\frac{v_b N_b}{\mathcal{L}_{\text{SC}}} + \frac{\mathcal{L}_{\text{SC}}}{N_b} \right)^2 - \frac{N_b \left\langle \mathcal{L}_b^3 \right\rangle}{\mathcal{L}_{\text{SC}}} \right]$$

Measurement of $R_{2\gamma}$ at $\theta \approx 12^\circ$

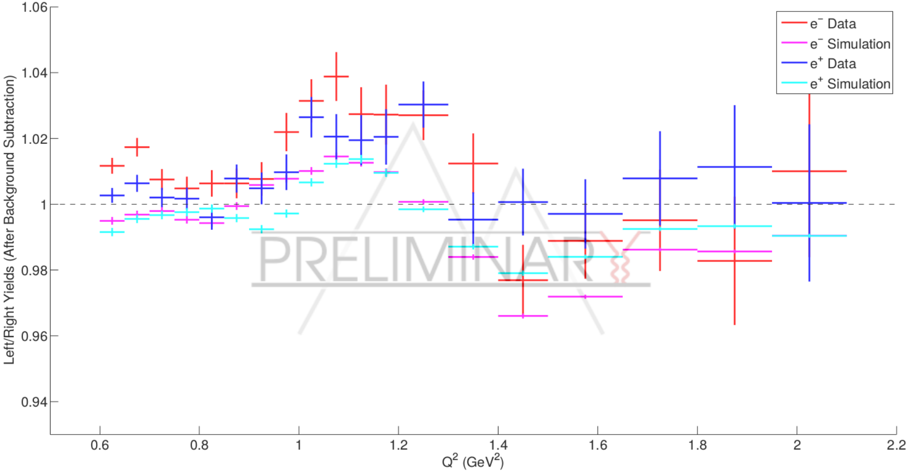


$$R_{2\gamma}\left(\epsilon = 0.98, Q^2 = 0.165\ \text{GeV}^2\right) = 0.9975 \pm 0.0010\ (\text{stat.}) \pm 0.0053\ (\text{syst.})$$

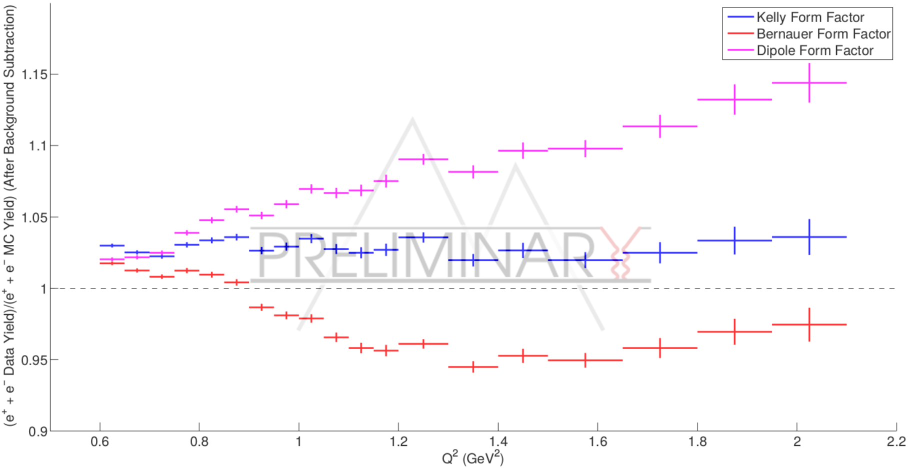
Upcoming results

- The OLYMPUS analysis is in its final stages
- Final checks on systematics prior to release of $R_{2\gamma}$ results
  - Acceptance/efficiency effects
  - Radiative corrections
  - Comparison of independent analyses
- Possible additional results on the form factors themselves
- Publication/conferences this fall

Lepton left/right yields



Form factor discrimination power

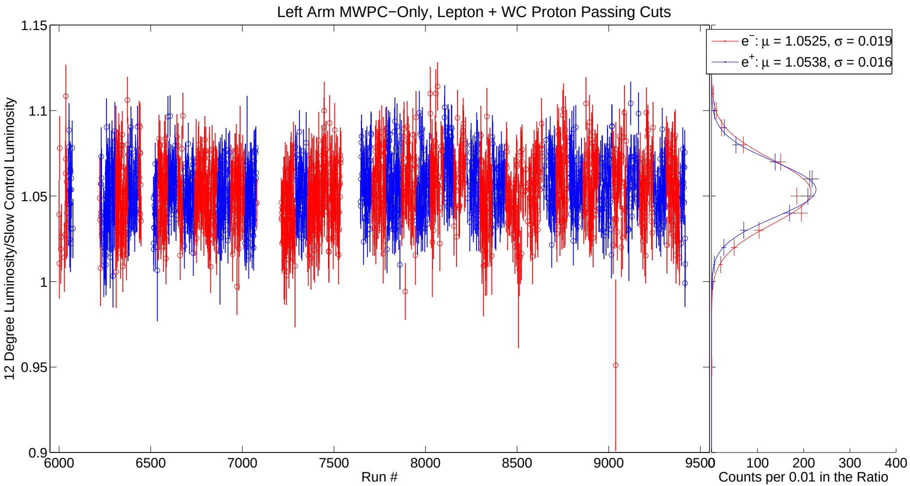


Slow control luminosity normalization, blinded common slope

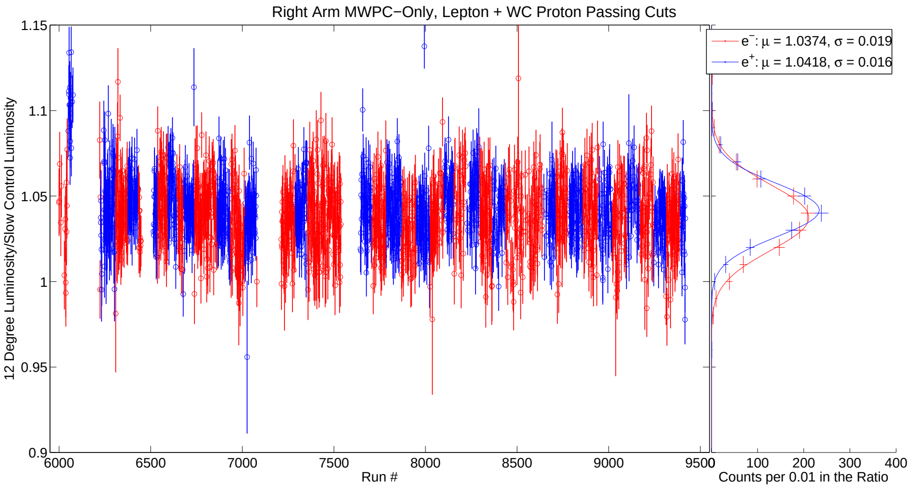
The OLYMPUS collaboration

- Arizona State University
- DESY
- INFN Bari
- INFN Ferrara
- INFN Rome
- Hampton University
- Massachusetts Institute of Technology
- Petersburg Nuclear Physics Institute
- University of Bonn
- University of Glasgow
- University of Mainz
- University of New Hampshire
- A. Alikhanyan National Laboratory (Yerevan Physics Institute)

12° left results



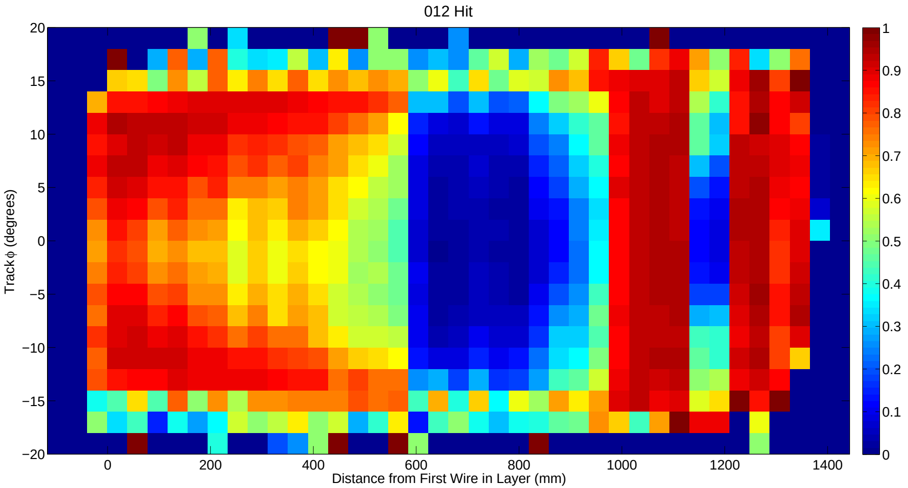
12° right results



12° systematics

Uncertainty Source	Relative (%)	Absolute (%)
ToF trigger efficiency ($\delta_{\epsilon_{\text{ToF}}}$)	± 0.19	± 0.25
SiPM trigger efficiency ($\delta_{\epsilon_{\text{SiPM}}}$)	± 0.01	± 0.10
MWPC plane efficiency ($\delta_{\epsilon_{\text{MWPC}}}$)	± 0.01	± 0.05
Magnetic field (δ_B)	± 0.15	± 0.35
Lepton tracking efficiency ($\delta_{\epsilon_{e,\text{track}}}$)	± 0.18	± 0.86
Proton tracking efficiency ($\delta_{\epsilon_{p,\text{track}}}$)	± 0.10	± 0.80
Beam position/slope (δ_{BPM})	± 0.01	± 0.01
Beam energy ($\delta_{E_{\text{beam}}}$)	± 0.02	± 0.02
Detector position (δ_{det})	± 0.02	± 0.20
Fiducial cuts (δ_{fid})	± 0.12	± 0.22
Elastic cuts (δ_{elas})	± 0.27	± 1.63
Radiative corrections (δ_{rad})	± 0.08	± 0.45
Form factors (δ_{ff})	± 0.14	± 1.20
TPE at $\theta = 12^\circ$ (δ_{TPE})*	± 0.10	± 0.10
Total including TPE uncertainty ($\delta_{12^\circ,\text{TPE}}$)	$\pm 0.47\%$	$\pm 2.44\%$
Total without TPE uncertainty (δ_{12°)	$\pm 0.46\%$	$\pm 2.44\%$

Cause of left/right difference



Other TPE experiments

Two other experiments have also completed data-taking for e^+p/e^-p ratio measurements; different systematics and kinematic coverages

CLAS, Jefferson Lab, USA

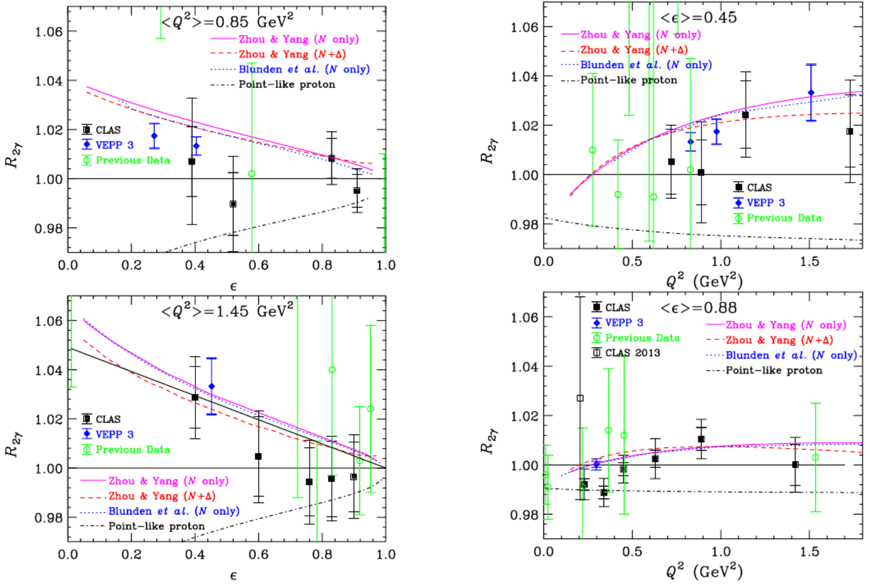
- Unique tertiary beam
- Sensitive to lower Q^2
- Very large acceptance
- Statistics limited
- Results published, long paper pending

VEPP-3, Novosibirsk, Russia

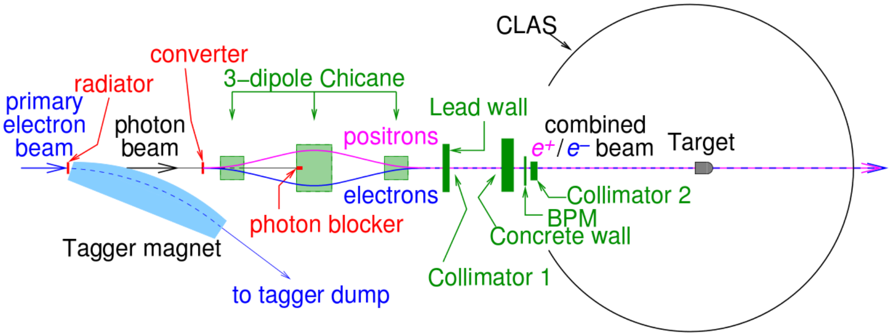
- Sensitive to lower Q^2
- Calorimetry-based detector
- Smaller acceptance
- Relatively advanced results already out

The three experiments are quite complimentary; should provide a definitive answer

CLAS and VEPP-3 results



CLAS TPE experiment



VEPP-3 TPE experiment