Two-Photon Exchange Experiments: Present and Future

D.K. Hasell

Hadronic Physics with Lepton and Hadron Beams
CEBAF Center
September 5–8, 2017

Introduction

~ 100 years ago Rutherford named the nucleus of hydrogen the proton

But there are still many puzzles remaining for this fundamental particle

- proton spin

  C.A. Aidala *et al.*, Reviews of Modern Physics, 85 (2013) 655–691
- proton mass

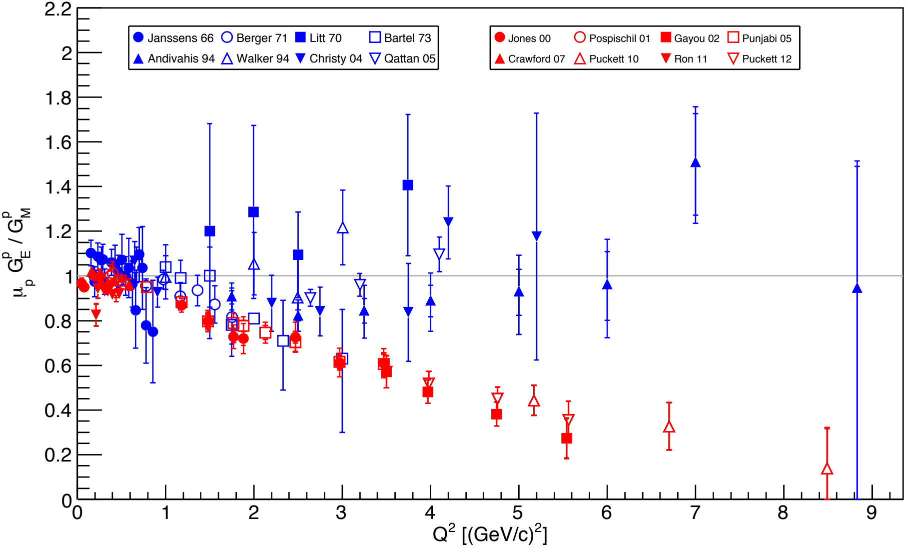
  S. Dürr *et al.*, Science, 322 (2008)1224–1227
- proton radius

  R. Pohl *et al.*, Annual Review of Nuclear and Particle Science, 63 (2013) 175–204

My talk addresses still another problem, namely the proton form factors

A. Afanasev *et al.*, Progress in Particle and Nuclear Physics, 95 (2017) 245–274

Problem with Form Factor Ratio $\mu_p G_E^p / G_M^p$ Measurements



Proposed Explanation - Two Photon Exchange (TPE)

Thought to be a small effect

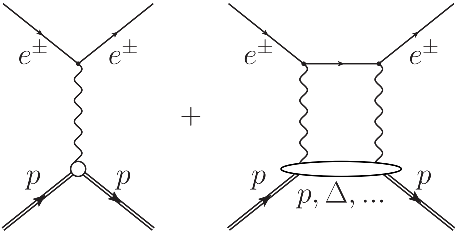
- suppressed by order α
- "soft" radiative corrections included

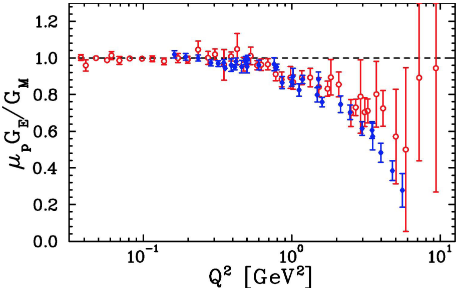
But "hard" TPE difficult

- model dependent intermediate p, Δ, ...

Calculations suggest it can resolve the discrepancy

Need a definitive experiment

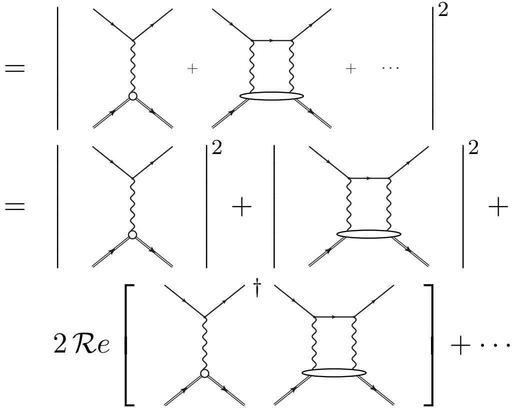




J. Arrington *et al.*, Phys. Rev. C 76 (2007) 035205

How to Measure “Hard” Two-Photon Contribution

$$\frac{d\sigma}{d\Omega} \propto |\mathcal{M}|^2 =$$



Interference term has a factor z^3, where z is the lepton charge

$\Rightarrow$ Interference term changes sign between e^+p and e^-p scattering

Definitive Measure of Two-Photon Contribution

Measure $\sigma_{e^+p}/\sigma_{e^-p}$

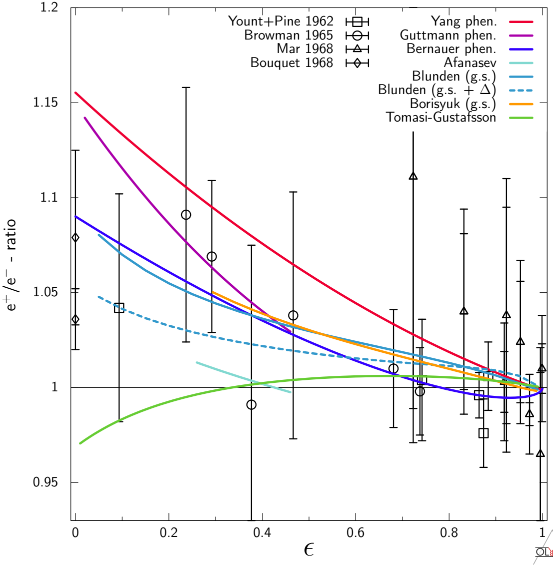
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1+4\frac{\mathcal{R}e(\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma})}{\mathcal{M}_{1\gamma}^2}$$

Existing data

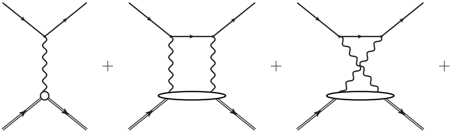
- low Q^2
- large uncertainties

Three recent experiments

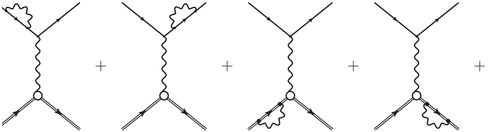
- VEPP-3 - Novosibirsk
- CLAS - JLab
- OLYMPUS - DESY



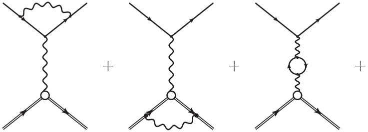
Radiative Corrections that Need to be Included



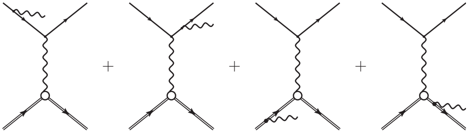
1 and 2 photon exchange



self-energy

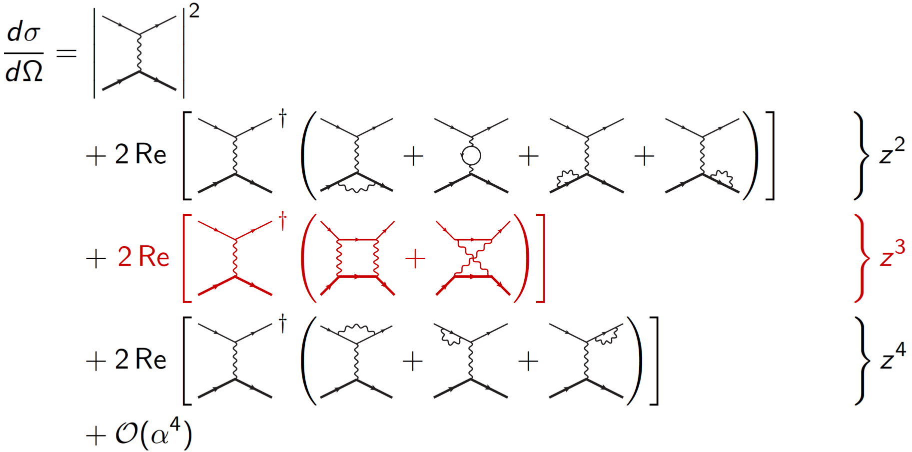


vertex corrections and
vacuum polarization



bremsstrahlung

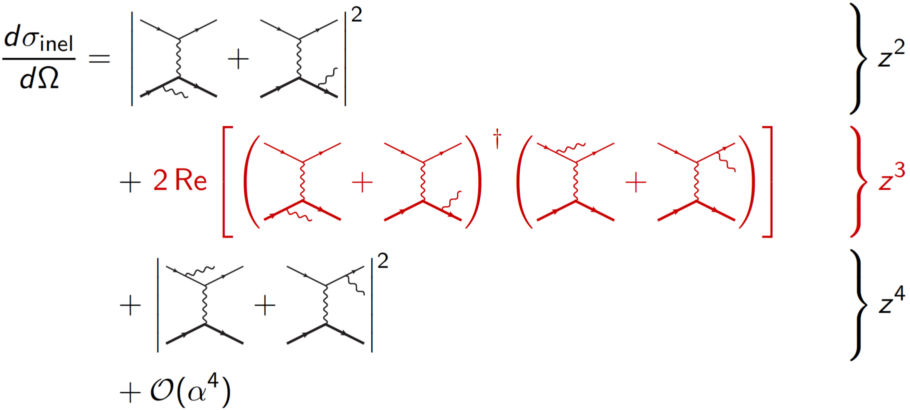
Radiative Corrections in Elastic Cross Section



Rebecca Russell, MIT

Even powers of z same for e^+p and e^-p scattering must be included

Radiative Corrections from Inelastic Processes

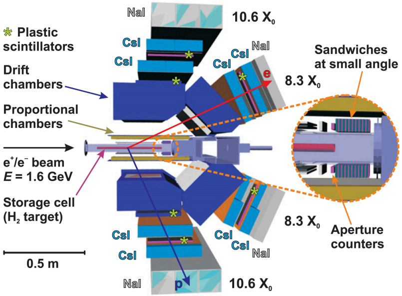


Rebecca Russell, MIT

Inelastic IR divergences cancel with elastic divergences

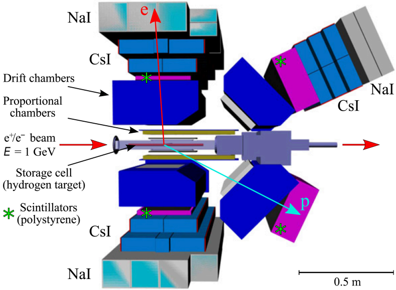
- must separate "hard" and "soft" parts in two-photon exchange
- "soft" part included in radiative corrections, "hard" part measured
- prescriptions defining "soft" - *e.g.* Mo - Tsai, Maximon - Tjon

VEPP-3 Detector Configuration



Run 1 (2009)

$E_{Beam} = 1.594$ GeV



Run 2 (2011–2012)

$E_{Beam} = 0.998$ GeV

Large acceptance, non-magnetic detector configuration

- same acceptance, efficiency for both electrons and positrons
- lepton and proton detected in coincidence
- forward angle measurement used for luminosity normalization

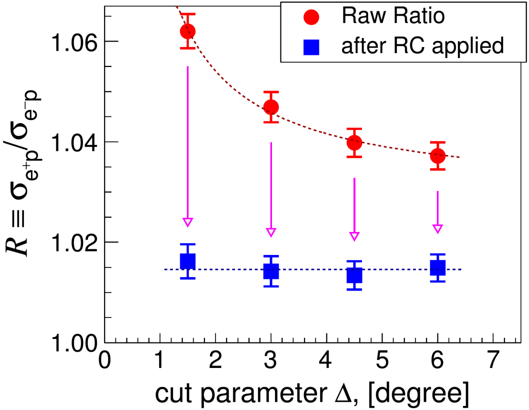
I.A. Rachek *et al.* Phys. Scr. **T166** 014017 (2015).

VEPP-3 Radiative Corrections

Dedicated event generator

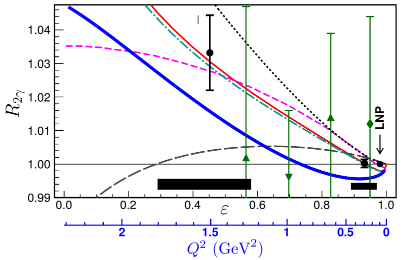
- ESEPP
- full radiative corrections
- GEANT4 detector simulation

Sensitivity of ratio to radiative corrections

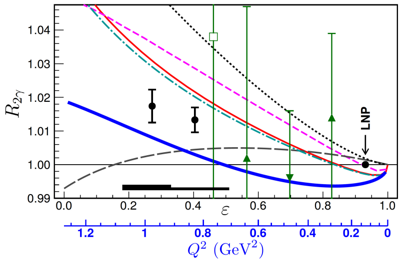


I.A. Rachek *et al.* Phys. Scr. **T166** 014017 (2015).

VEPP-3 Results



$E_{Beam} = 1.594$ GeV

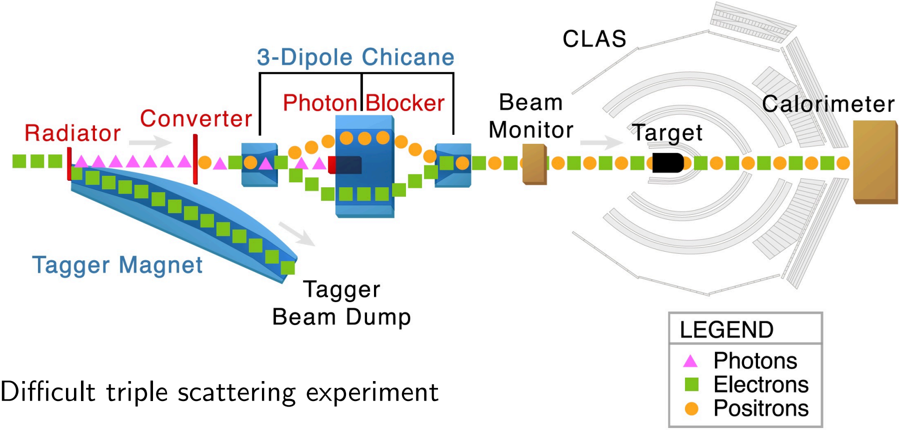


$E_{Beam} = 0.998$ GeV

dotted	*I. A. Qattan, et al.,*	Phys. Rev. C **84** (2011) 054317
solid red	*P. G. Blunden, et al.,*	Phys. Rev. C **72** (2005) 034612
dash-dot	*D. Borisyuk and A. Kobushkin,*	Phys. Rev. C **78** (2008) 025208
dashed grey	*E. Tomasi-Gustafsson, et al.,*	Phys. Atom. Nucl. **76** (2013) 937
dashed magenta	*J. Arrington and I. Sick,*	Phys. Rev. C **70** (2004) 028203
thick blue	*J. C. Bernauer, et al.,*	Phys. Rev. C **90** (2014) 015206

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

CLAS Detector Configuration

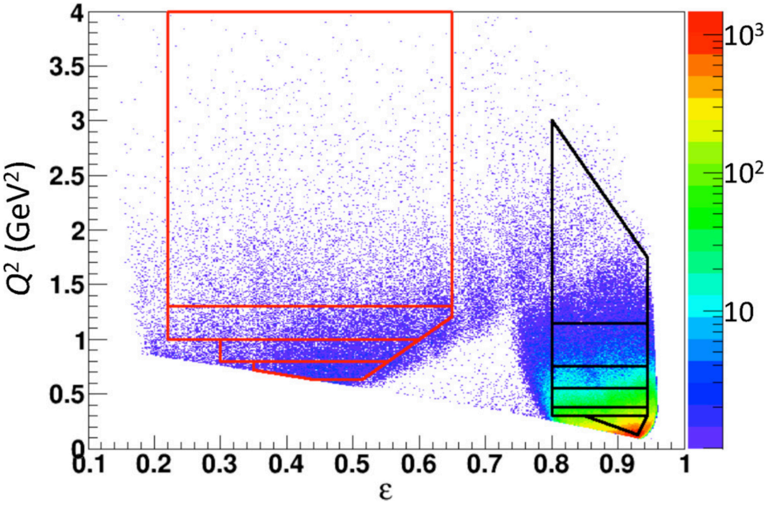


Difficult triple scattering experiment

Must reconstruct beam energy by measuring both lepton and proton

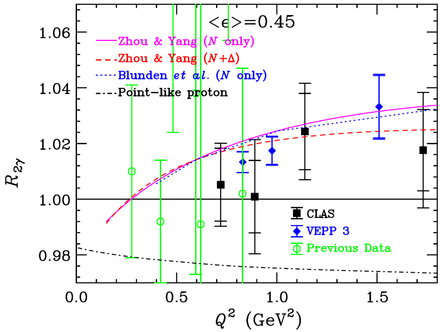
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

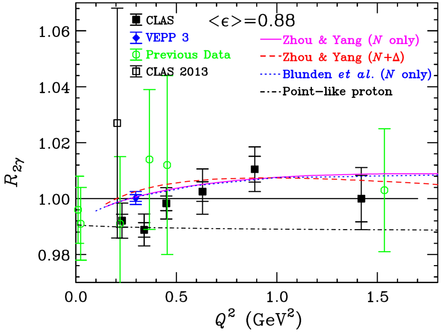
CLAS Bins for ϵ Dependence



D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

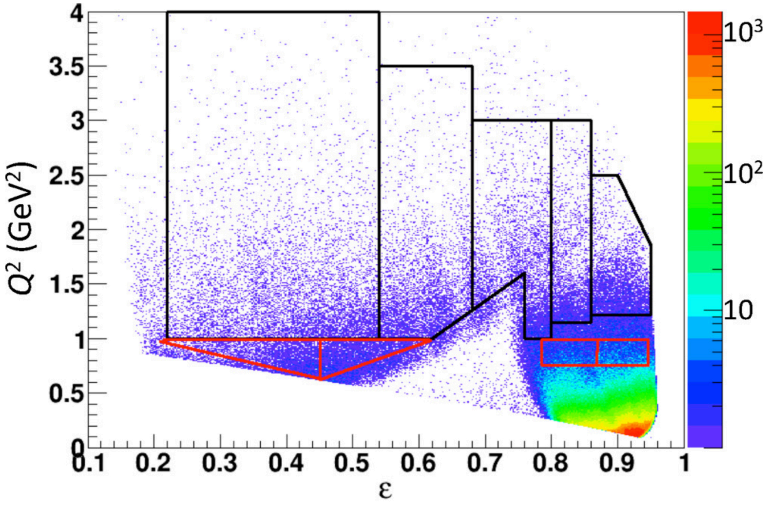
CLAS, VEPP-3, and Previous Results versus ϵ ϵ





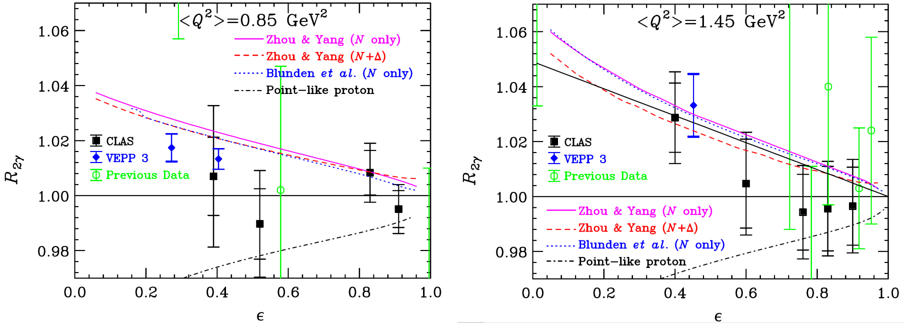
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

CLAS Bins for Q^2 Dependence



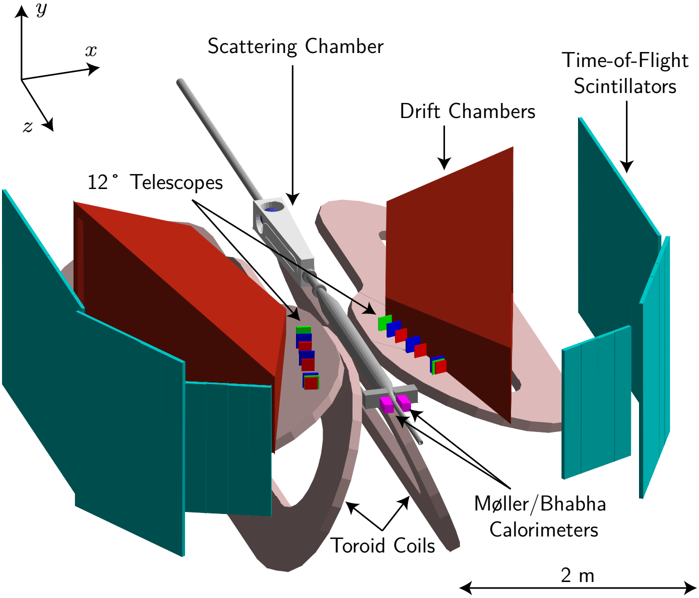
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

CLAS, VEPP-3, and Previous Results versus ϵ ϵ



D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

Detector Overview



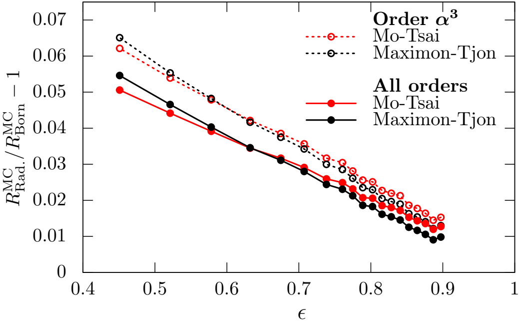
Radiative Corrections in OLYMPUS

Dedicated event generator

- checked against ESEPP - VEPP-3
- full radiative corrections
- GEANT4 detector simulation

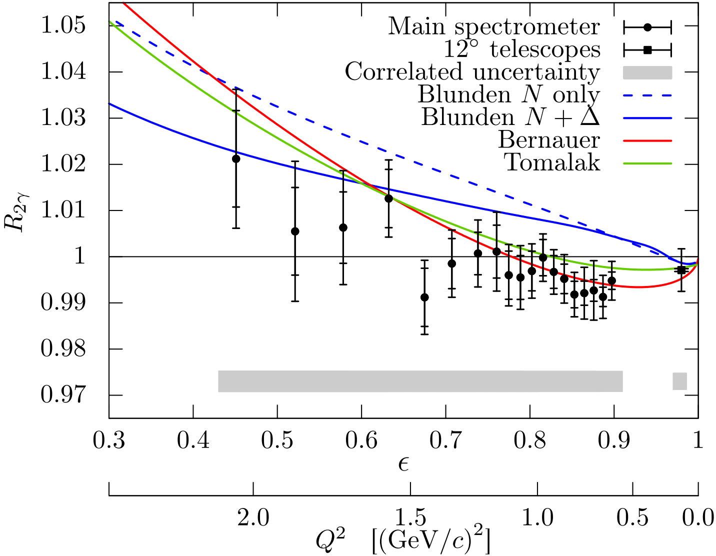
Small differences between results with different "Soft" photon definitions

Some sensitivity to α^3 or exponentiation



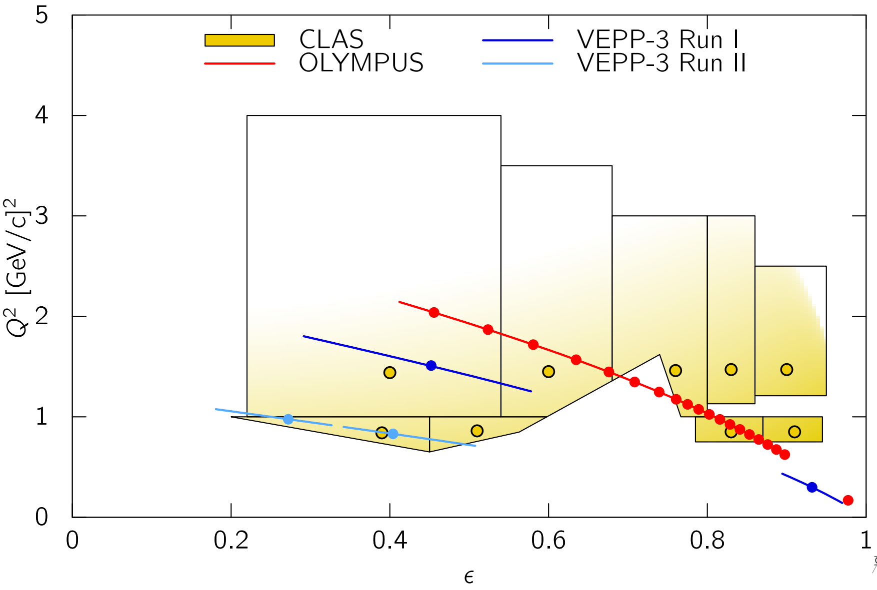
B. Henderson *et al.* Phys. Rev. Lett. **118** 092501 (2017).

OLYMPUS Results

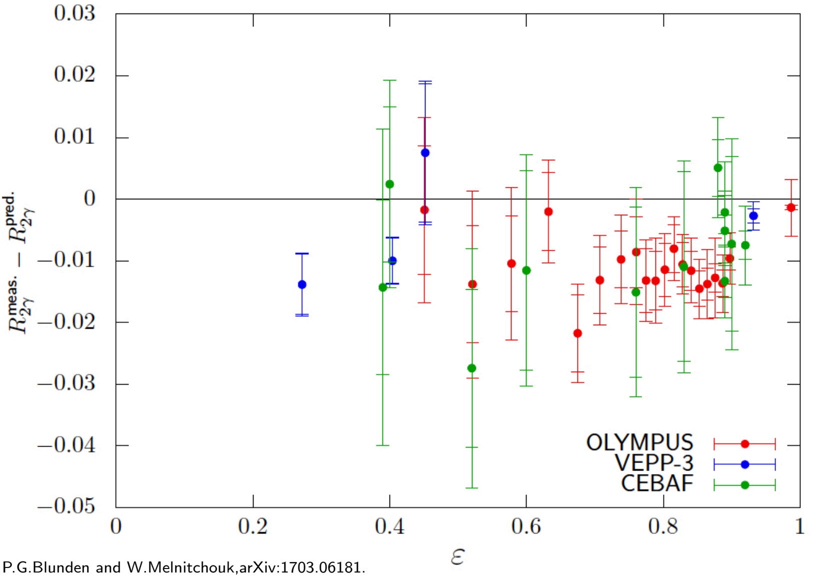


B. Henderson *et al.* Phys. Rev. Lett. **118** 092501 (2017).

Comparing the Three Experiments - (ϵ, Q^2) Reach

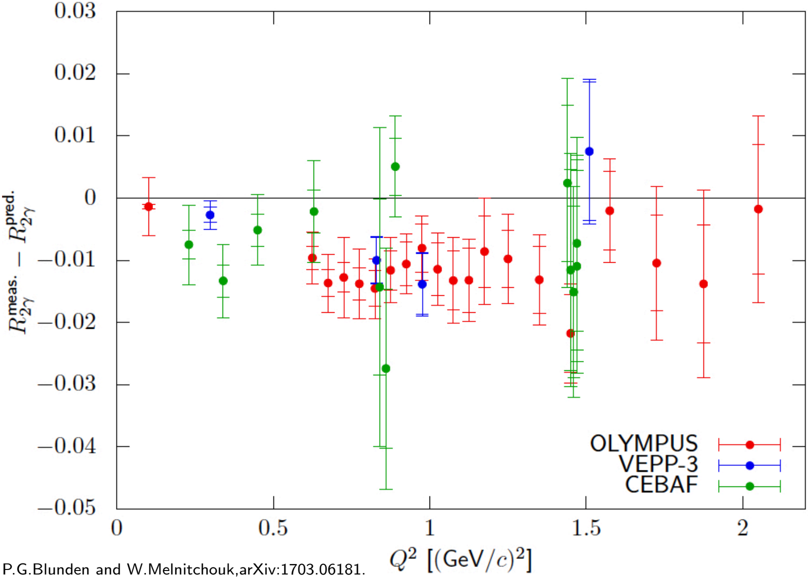


Comparison with Blunden N + Δ



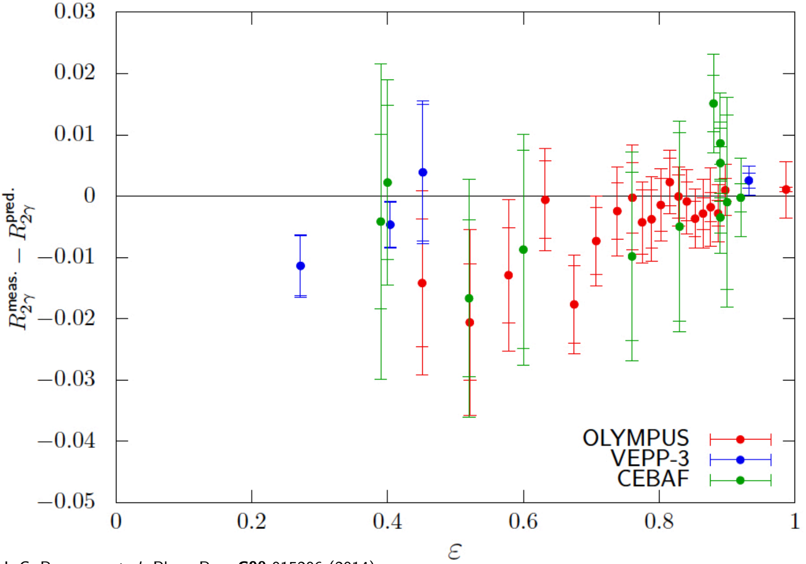
P.G.Blunden and W.Melnitchouk,arXiv:1703.06181.

Comparison with Blunden N + Δ



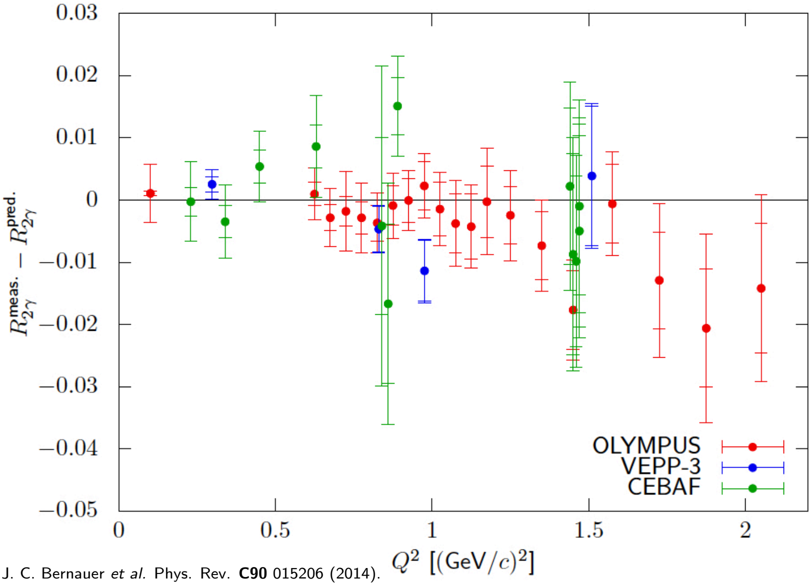
P.G.Blunden and W.Melnitchouk,arXiv:1703.06181.

Comparison with Bernauer



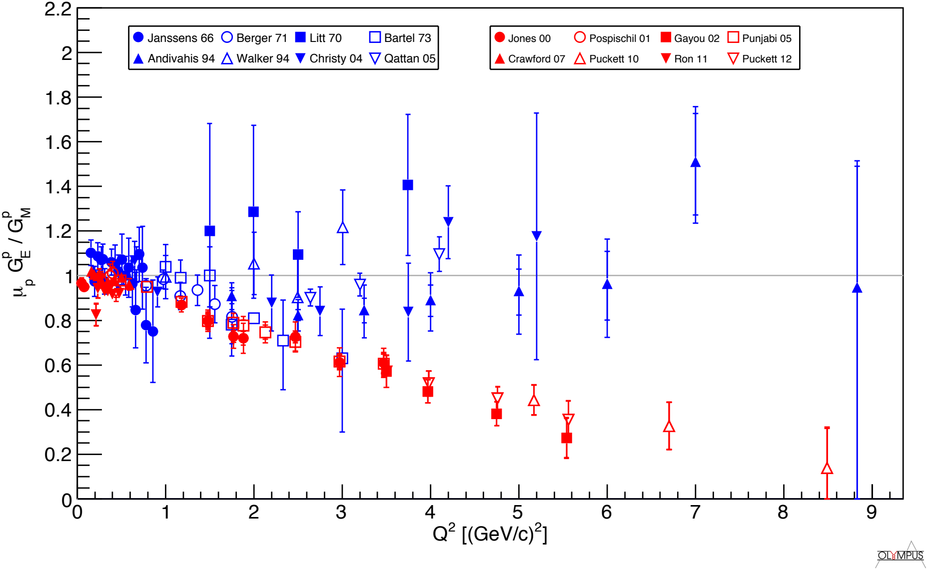
J. C. Bernauer *et al.* Phys. Rev. **C90** 015206 (2014).

Comparison with Bernauer

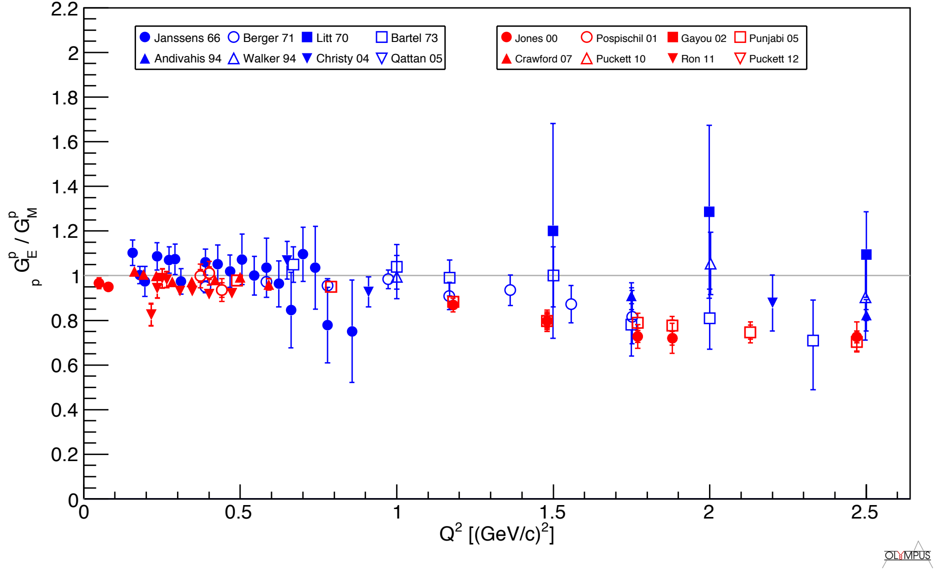


J. C. Bernauer *et al.* Phys. Rev. **C90** 015206 (2014).

Should we be surprised ?



Discrepancy in $\mu_p G_E^p / G_M^p$ at $Q^2 < 2.5\ (\text{GeV/c})^2$



Summary of Experimental Results

$R_{2\gamma}$ measured for $Q^2 < 2.3$ (GeV/c)^2

Radiative corrections and prescription for handling TPE important.

Small, $< 1\%$, hard two-photon exchange observed

Evidence for effect increasing with increasing Q^2 (decreasing ϵ)

Results less than expected from theoretical calculations

In better agreement with phenomenological predictions

Further theoretical effort on radiative corrections needed

Experiments at higher energy required to resolve discrepancy

- When ? Where ?

Possible Future Two-Photon Experiments at JLab

CLAS12 ?

Positrons ?

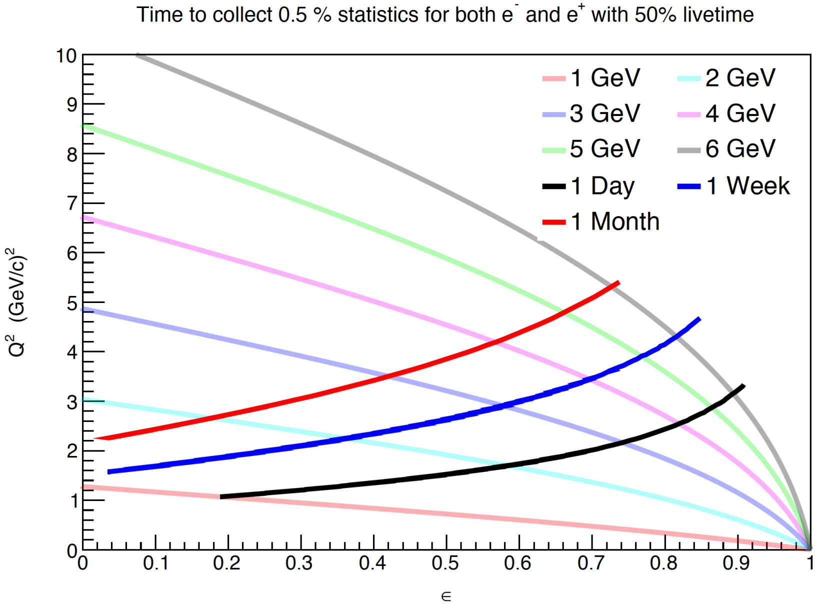
- J. Grames (NSTAR2017), polarized positrons, 100 nA
- higher unpolarized positron current ?
- JPos17 - September 12-15, JLab
    - good idea and not just for two-photon exchange
    - DVCS, full flavor decomposition of structure functions

Hall A

- 10 cm liquid hydrogen target
- HRS 6 msr

Event rate $\sim 1.6 \times 10^{-6}$ per second per femtobarn

Time to Measure $R_{2\gamma}$ at One Point in (ϵ, Q^2)



Possible Future Two-Photon Experiments at DESY

OLYMPUS 2 ?

Electrons and positrons available directly from DESY synchrotron

- 1–6 GeV electrons or positrons
- 30 nA
- higher current ?

Test hall

- 10 cm liquid hydrogen target
- high resolution, fine granularity calorimeter ($PbWO_4$) 10 msr
    - increase coverage with more calorimeter modules

Event rate $\sim 7.9 \times 10^{-7}$ per second per femtobarn

$\sim 2 \times$ slower than JLab Hall A with HRS

Recent and Future Meetings

Two parallel session on experiment and theory of two-photon exchange

- NSTAR Conference, Columbia, SC, August 20-23

Hadronic Physics with Lepton and Hadron Beams

- JLab, Newport News, VA September 5–8

International Workshop on Physics with Positrons at Jefferson Lab

- JLab, Newport News, VA September 12–15

Workshop on Two-Boson Exchange

- UMass, Amherst, MA September 28–30

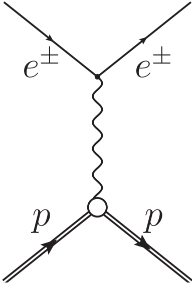
Thank You

Work supported by the United States Department of Energy.

Nucleon Form Factors from Elastic Electron Scattering

One photon exchange approximation

$$\gamma^\mu F_1^N(Q^2) + i\sigma^{\mu\nu} q_\nu \frac{\kappa}{2M} F_2^N(Q^2)$$



Electric and magnetic form factors

$$G_E^N(Q^2) = F_1^N(Q^2) - \tau\kappa F_2^N(Q^2)$$

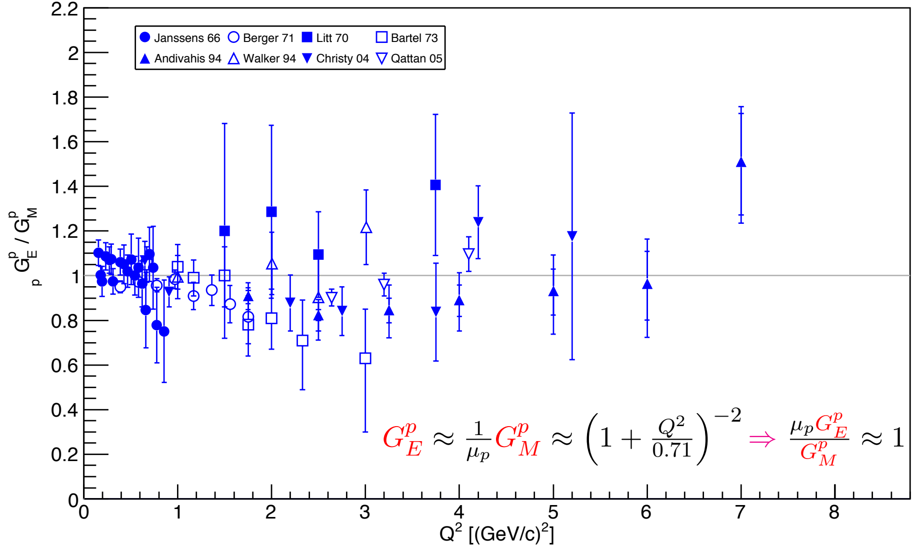
$$G_M^N(Q^2) = F_1^N(Q^2) + \kappa F_2^N(Q^2)$$

Rosenbluth cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\left(\frac{{G_E^N}^2 + \tau {G_M^N}^2}{1+\tau}\right) + 2\tau {G_M^N}^2 \tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{Q^2}{4M_N^2}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{\tau {G_M^N}^2 + \epsilon {G_E^N}^2}{\epsilon(1+\tau)} \qquad \epsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$

Form Factor Ratio $\mu_p G_E^p / G_M^p$ - Rosenbluth Technique



$$G_E^p \approx \frac{1}{\mu_p} G_M^p \approx \left(1 + \frac{Q^2}{0.71}\right)^{-2} \Rightarrow \frac{\mu_p G_E^p}{G_M^p} \approx 1$$

Measuring Form Factors - Polarized Techniques

Advent of polarized beams and targets provided another technique

In polarization transfer experiments $\vec{e}p \rightarrow e\vec{p}$

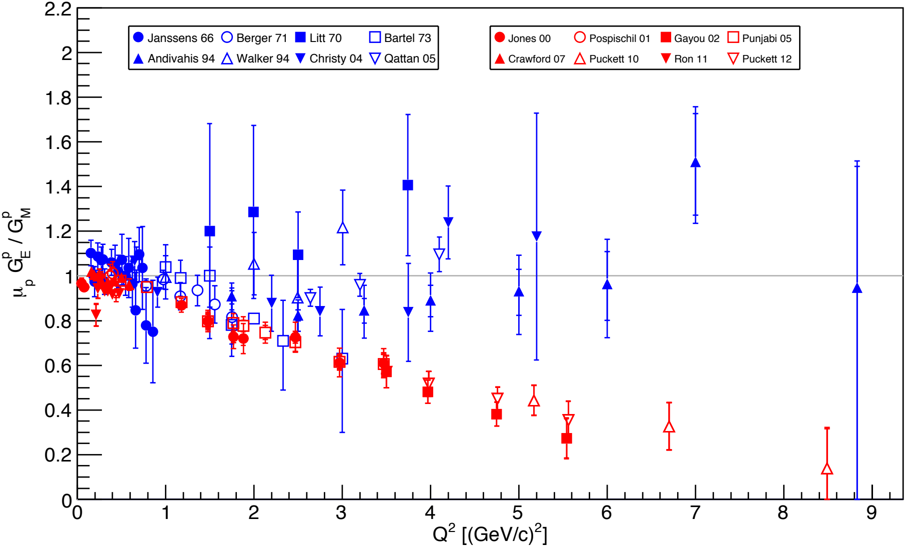
$$\mu_p \frac{G_E}{G_M} = -\mu_p \sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}\, \frac{P_T}{P_L} = -\mu_p \frac{E+E'}{2M_p} \tan\frac{\theta_e}{2}\, \frac{P_T}{P_L}$$

where P_T and P_L are the polarizations of the recoil proton.

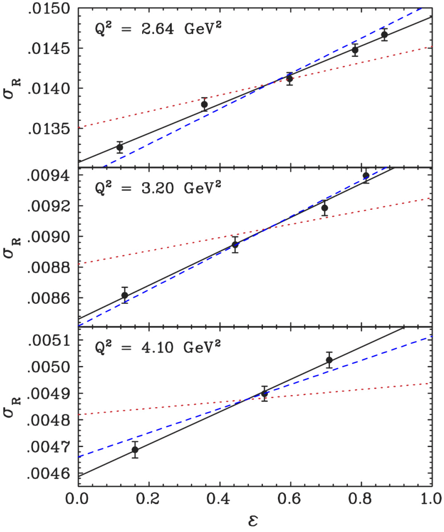
This is a simpler and more accurate measurement for $\mu_p G_E/G_M$ particularly at higher Q^2

It is also possible to determine $\mu_p G_E/G_M$ from $\vec{e}\,\vec{p} \rightarrow e\,p$ by measuring the asymmetries (see Crawford 07).

Discrepancy in Form Factor Ratio $\mu_p G_E^p / G_M^p$?



Measuring Form Factors - Rosenbluth Technique



I.A. Qattan, Phys. Rev. Lett. **94** (2005) 142301.

$$\sigma_R = \epsilon(1+\tau)\left(\frac{d\sigma}{d\Omega}\right) / \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \tau {G_M^N}^2 + \epsilon {G_E^N}^2$$

Vary E and θ to measure σ_R at different ϵ but same Q^2 and plot:

- Slope $\rightarrow$ ${G_E^N}^2$
- Intercept $\rightarrow$ ${G_M^N}^2$
- G_M^N dominates at high Q^2
- σ_R decreases quickly with Q^2

Blue dashed $\rightarrow$ FF ratio $= 1$

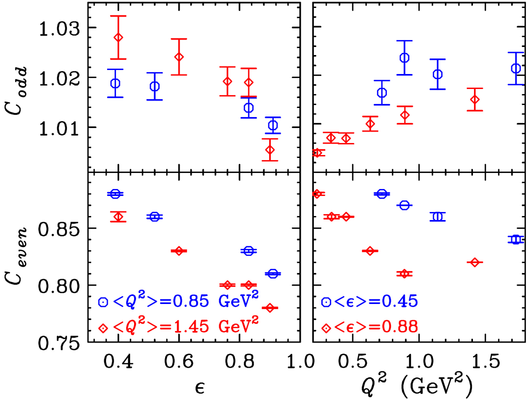
Red dotted $\rightarrow$ polarized measure

CLAS Radiative Corrections

Calculated following R. Ent *et al.*

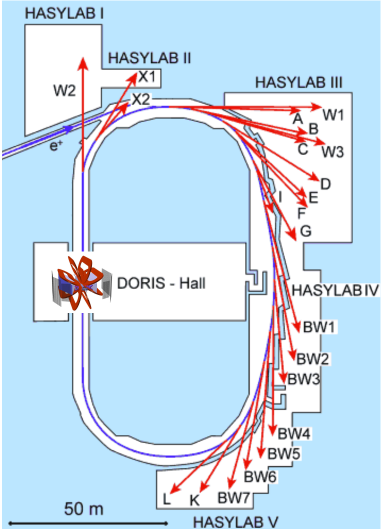
$$\frac{1+\delta_{even}-\delta_{2\gamma}-\delta_{epbrem}}{1+\delta_{even}+\delta_{2\gamma}+\delta_{epbrem}}$$

$$R_{2\gamma}=1-2\delta_{2\gamma}$$



D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

DORIS Storage Ring at DESY, Hamburg, Germany



Extensive modifications to DORIS

- move RF cavities, ARGUS
- provide cooling water, power
- open pit, move shielding walls
- optics, synchrotron radiation
- automated polarity switches

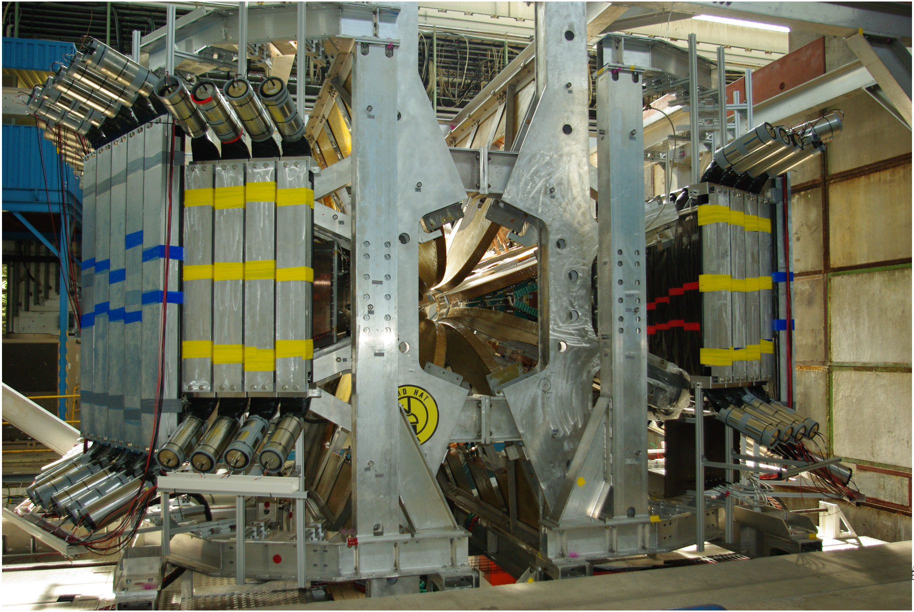
Great support from DESY !

- MEA, MKK, DORIS operators
- Jan Hausschildt, Frank Brinker

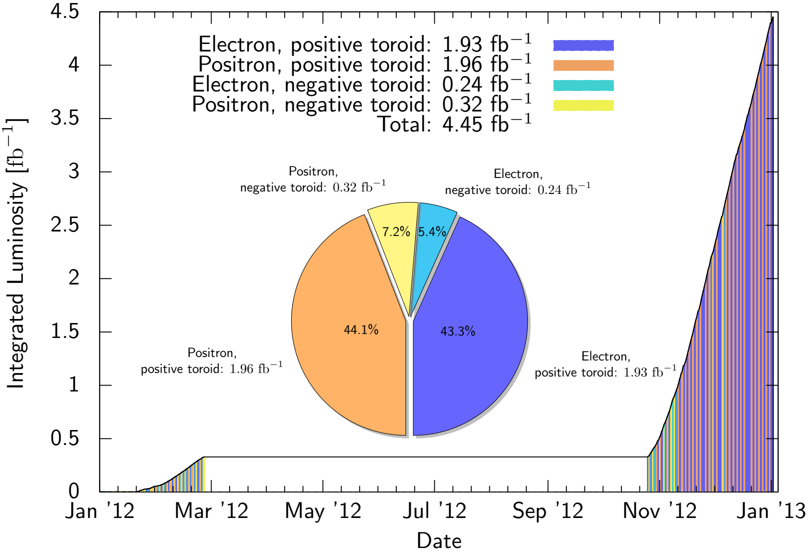
Tight schedule shutdown end 2012

OLYMPUS funded end 2009 !

OLYMPUS Detector



Luminosity


Electron, positive toroid: 1.93 fb^{-1}
Positron, positive toroid: 1.96 fb^{-1}
Electron, negative toroid: 0.24 fb^{-1}
Positron, negative toroid: 0.32 fb^{-1}
Total: 4.45 fb^{-1}
Positron, negative toroid: 0.32 fb^{-1}
Electron, negative toroid: 0.24 fb^{-1}
7.2%
5.4%
44.1%
43.3%
Positron, positive toroid: 1.96 fb^{-1}
Electron, positive toroid: 1.93 fb^{-1}
Integrated Luminosity [fb^{-1}]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Jan '12
Mar '12
May '12
Jul '12
Sep '12
Nov '12
Jan '13
Date

Luminosity

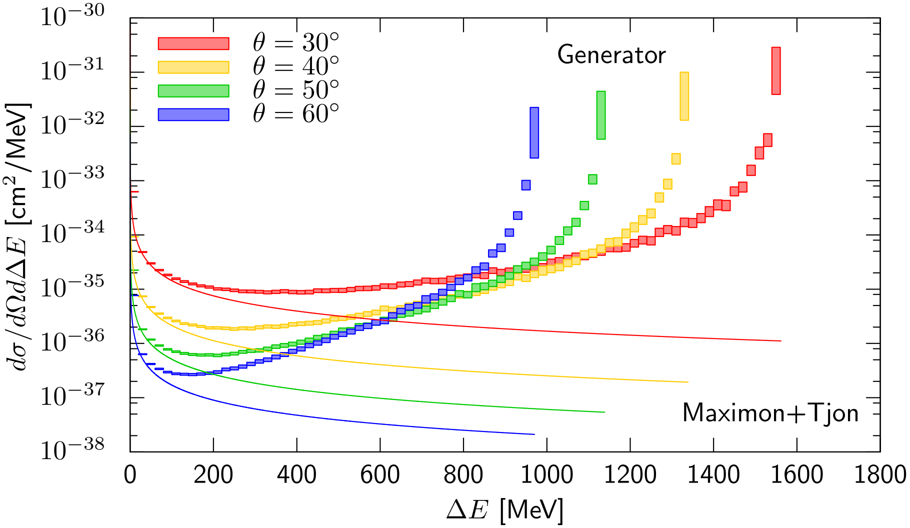
Three independent and consistent measures of luminosity:

- slow control using molecular flow calculation
  - 2 % between beam species, 5 % absolute
- 12° MWPC with coincident proton in WC
  - 0.46 % between beam species, 2.4 % absolute
- multi-interaction events $(e^\pm e \to e^\pm e) + (e^\pm p \to e^\pm p)$ in SYMB
  - 0.1 % statistical, 0.36 % systematic

Chose to use multi-interaction events, MIE, as the most accurate:

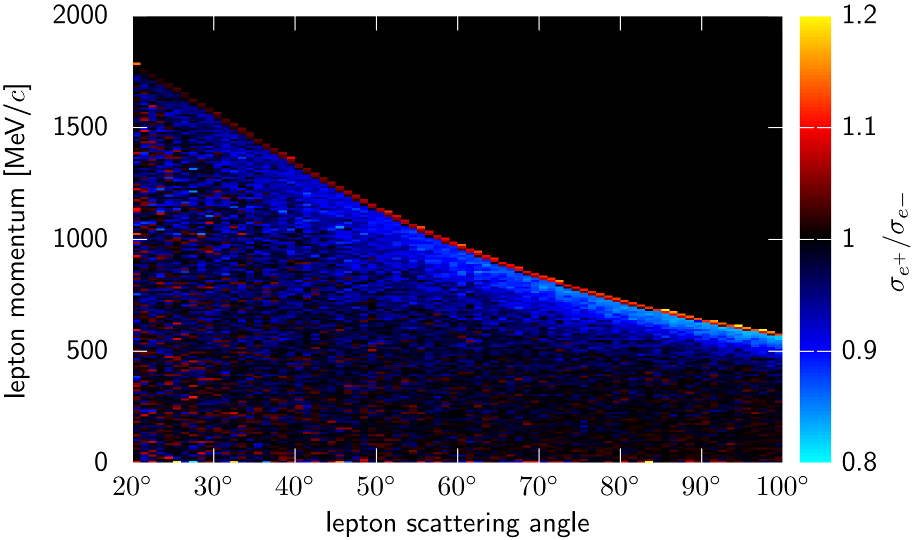
- negligible TPE at 1.29°
  - $\langle Q^2 \rangle = 0.002$ GeV^2, $\langle \epsilon \rangle = 0.99975$
- allows additional measurement of TPE at 12°
  - $R_{2\gamma} = 0.9975 \pm 0.010 \pm 0.0053$
  - $\langle Q^2 \rangle = 0.165$ GeV^2, $\langle \epsilon \rangle = 0.98$

Radiative Corrections and Initial State Radiation



Jan Bernauer, Rebecca Russell, and Axel Schmidt, MIT

Radiative Corrections



Analysis Procedure

All analyses share the following:

- based on the same run list and same tracked data files
- use the same tracked, radiatively generated, MC files
  - based on the same detector calibration, simulation, and digitization
- results normalized with MIE and binned in the same Q^2 and ϵ bins

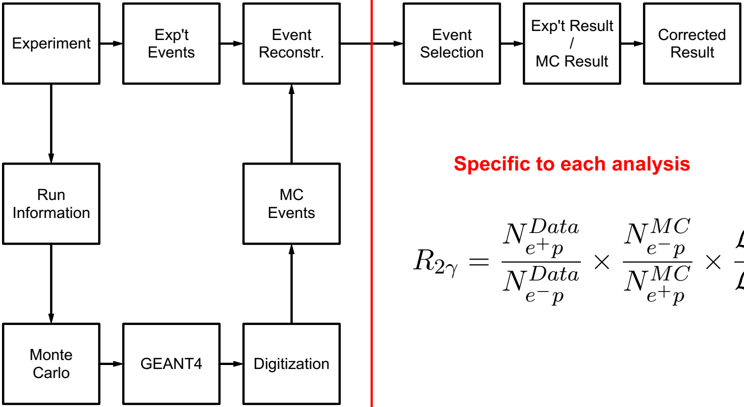
Analyses are independent in the following:

- philosophy in selecting elastic candidates vary
- selection and size of applying cuts are different

Four analyses combined for final result (Axel, Rebecca, Brian, and Jan)

- results simply averaged
- variance added to uncorrelated uncertainty in quadrature

Schematic of Analysis Procedure



Specific to each analysis

$$R_{2\gamma} = \frac{N^{Data}_{e^+p}}{N^{Data}_{e^-p}} \times \frac{N^{MC}_{e^-p}}{N^{MC}_{e^+p}} \times \frac{\mathcal{L}_{e^+p}}{\mathcal{L}_{e^-p}}$$

Common to all analyses

Systematic Uncertainties

OLYMPUS control of systematics

- left / right symmetric detector → two independent measurements
- $R_{2\gamma}$ is a ratio so many efficiencies cancel
- four independent analyses that can be examined and combined

Correlated systematic uncertainties

- luminosity (MIE) - 0.36%
- beam energy - 0.04%–0.13%
- beam and detector geometry - 0.25%
- total - 0.46%

Uncorrelated systematic uncertainties

- track efficiency - 0.25%
- event selection and background subtraction - 0.25%–1.17%
- total - 0.37%–1.20%

Timeline

2005

- May - BLAST Experiment ends
- November - BLAST@ELSA, @DORIS

2007

- May - seminars DESY, Zeuthen, and PRC
- June - Letter of Intent

2008

- September - OLYMPUS proposal
- December - cond. approval DESY + PRC

2009

- August - Technical Design Report
- September - technical review

2010

- January - approval and funding
- February - disassemble BLAST and ship
- July - start modifications and assembly

2011

- January - install target and test
- February - ring run tests
- July - roll into DORIS ring
- August–December - service day test runs

2012

- February - first data run
- July - repair target, other improvements
- October - December - second data run

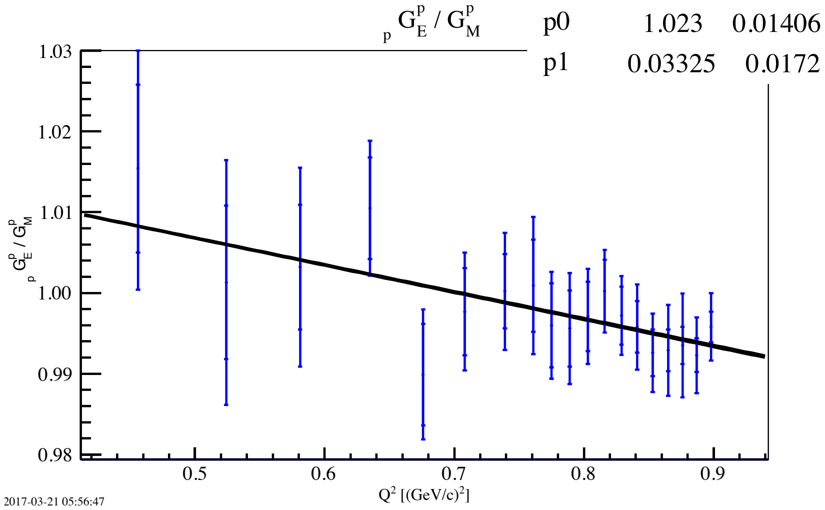
2013

- January - collected cosmic data
- February–May - optical survey, field map
- June–July - disassemble OLYMPUS

2016

- October - most of the analysis complete
- 7 PhD's

Fit to OLYMPUS $R_{2\gamma}$



Fit to Rebinned OLYMPUS $R_{2\gamma}$