Positron Beams for Elastic Form Factors

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2018-06-30

Outline

- elastic $p(e^+, e^+p)$ scattering to determine 2γ radiative corrections

- prospects of a quasielastic $d(e^+, pp)\bar{\nu}$ measurement of $F_A(Q^2)$

OLYMPUS - Measuring Two-Photon Exchange

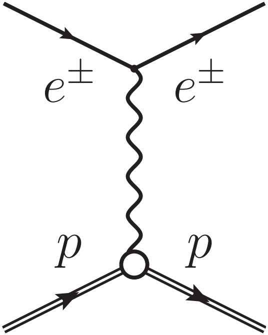
D.K. Hasell

June 26, 2018

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

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

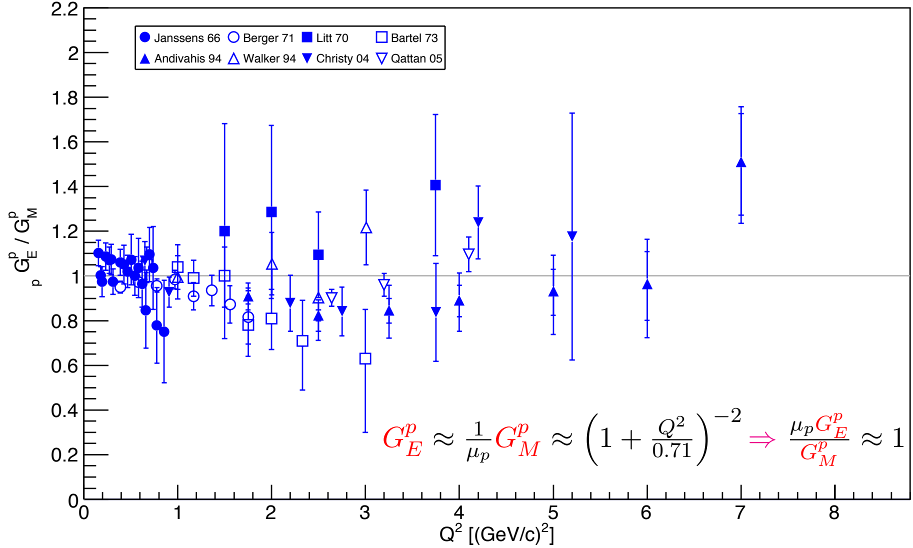
$$G_M^N(Q^2) = F_1^N(Q^2) + \kappa F_2^N(Q^2)$$

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 $\vec{e}p \to e\vec{p}$

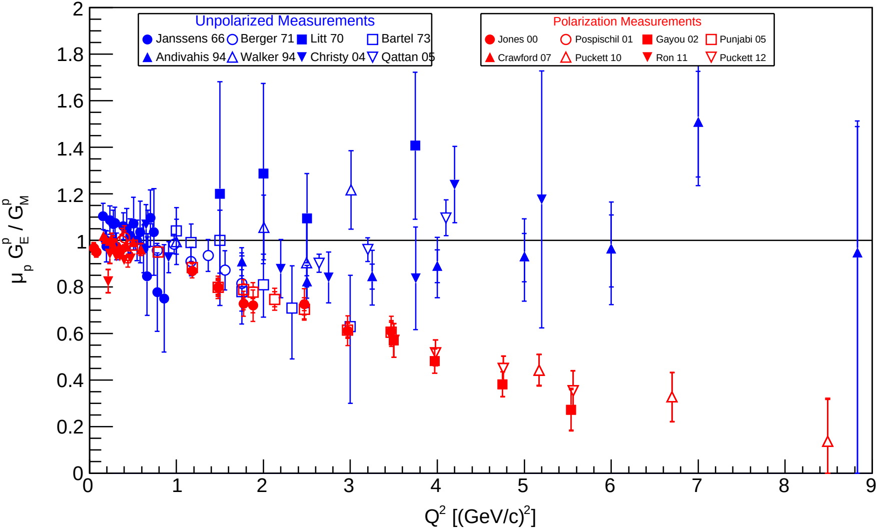
$$\mu_p \frac{G_E}{G_M} = -\mu_p \sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}\,\frac{P_T}{P_L} = -\mu_p \frac{E+E'}{2M_p} \tan\frac{\theta_e}{2}\,\frac{P_T}{P_L}$$

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

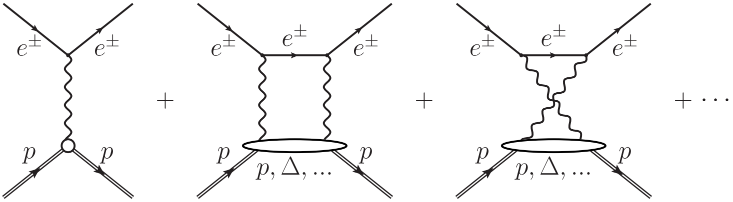
This is a simpler and more accurate measurement for $\mu_p G_E/G_M$ particularly at higher Q^2

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

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



Proposed Explanation - Two Photon Exchange (TPE)

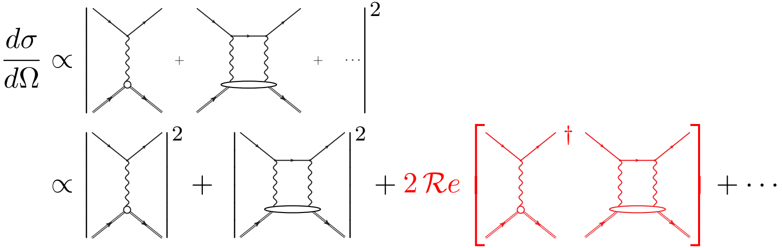


Two-photon exchange (TPE) typically thought to be a small effect

- "soft" TPE radiative corrections generally included in calculations
- "hard" TPE radiative corrections difficult to calculate
- intermediate state (p, Δ, . . .) model dependent

Need to measure "hard" TPE

How to Measure “Hard” Two-Photon Contribution



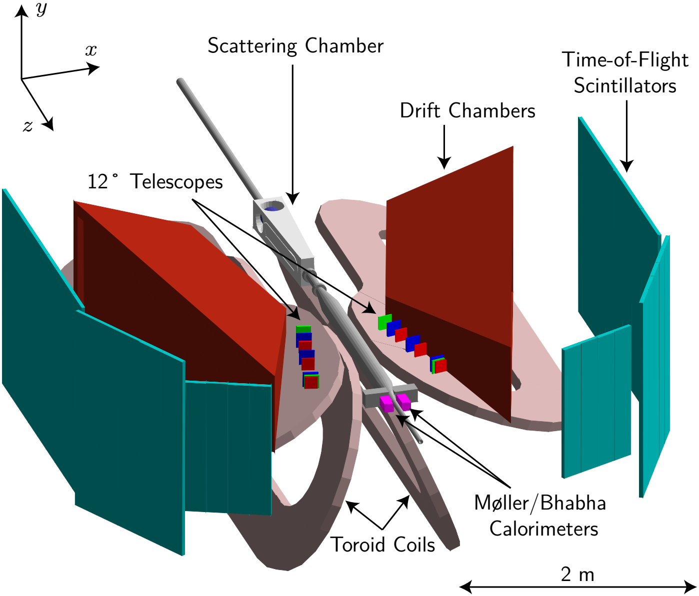
Interference term has a factor z^3, where z is the lepton charge

⇒ Interference term changes sign between e^+p and e^-p scattering

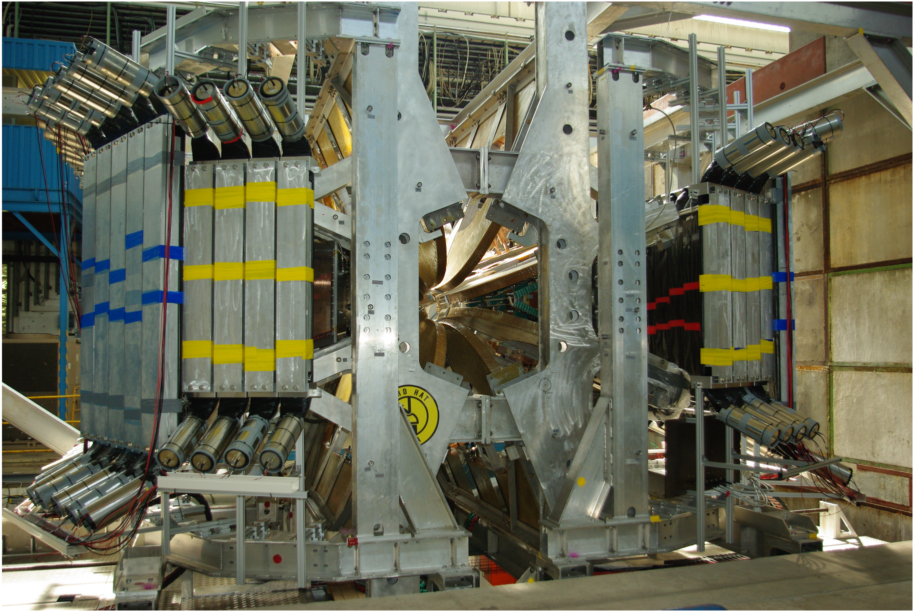
⇒ Measure ratio $R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}}$

VEPP-3 (Novosibirsk), CLAS (JLab), and OLYMPUS (DESY)

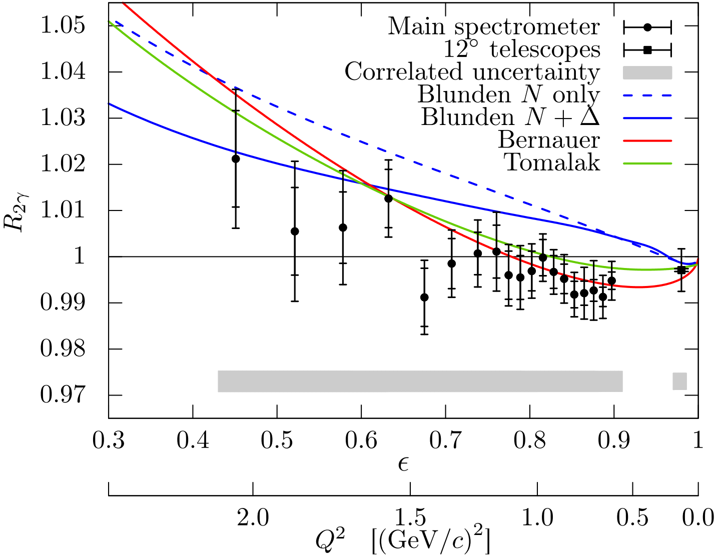
OLYMPUS Experiment - Re-Tasked the BLAST Detector



OLYMPUS Detector

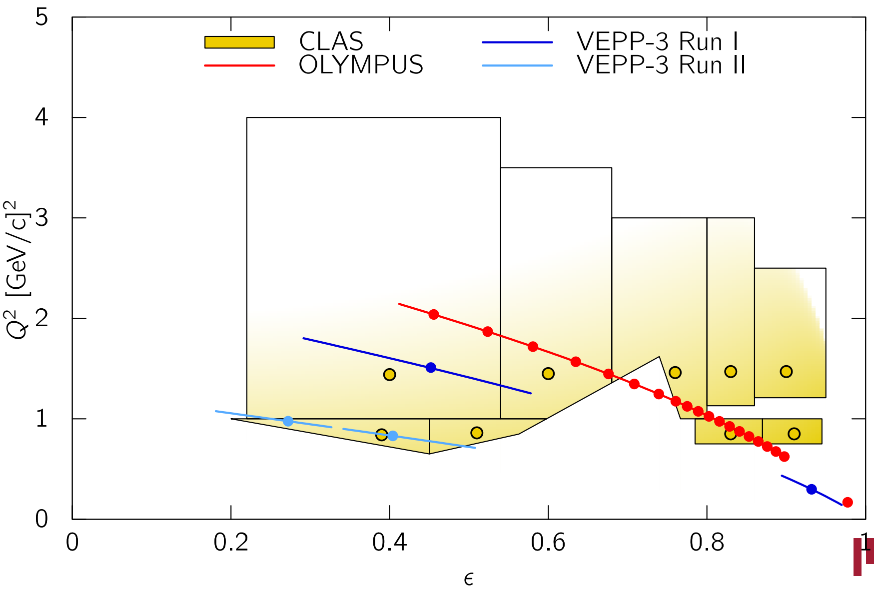


OLYMPUS Results

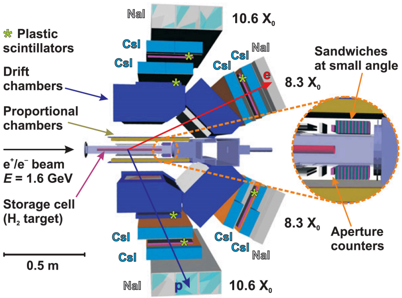


B. Henderson *et al.* Phys. Rev. Lett. **118** 092501 (2017).

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

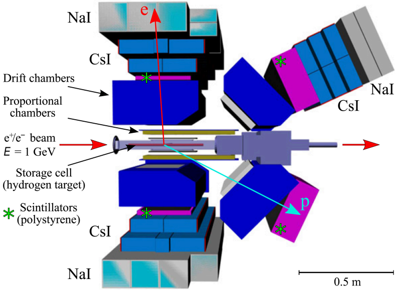


VEPP-3 Detector Configuration



Run 1 (2009)

$E_{Beam} = 1.594$ GeV



Run 2 (2011–2012)

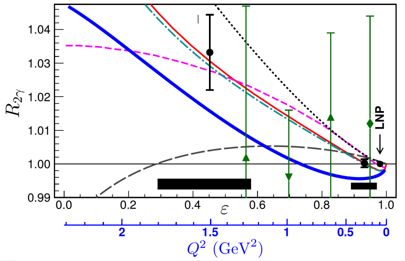
$E_{Beam} = 0.998$ GeV

Large acceptance, non-magnetic detector configuration

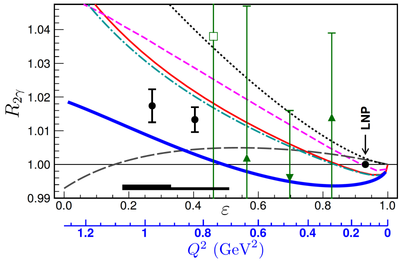
- same acceptance, efficiency for both electrons and positrons
- lepton and proton detected in coincidence
- forward angle measurement used for luminosity normalization

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

VEPP-3 Results



$E_{Beam} = 1.594$ GeV

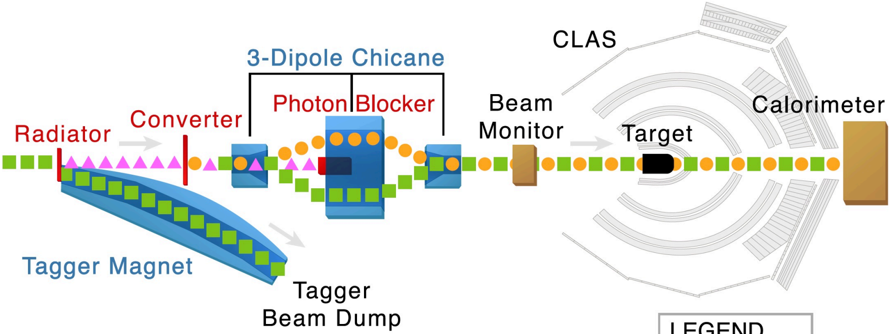


$E_{Beam} = 0.998$ GeV

⋯⋯	*I. A. Qattan, et al.,*	Phys. Rev. C **84** (2011) 054317
——	*P. G. Blunden, et al.,*	Phys. Rev. C **72** (2005) 034612
-·-·-	*D. Borisyuk and A. Kobushkin,*	Phys. Rev. C **78** (2008) 025208
- - -	*E. Tomasi-Gustafsson, et al.,*	Phys. Atom. Nucl. **76** (2013) 937
- - -	*J. Arrington and I. Sick,*	Phys. Rev. C **70** (2004) 028203
━━	*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

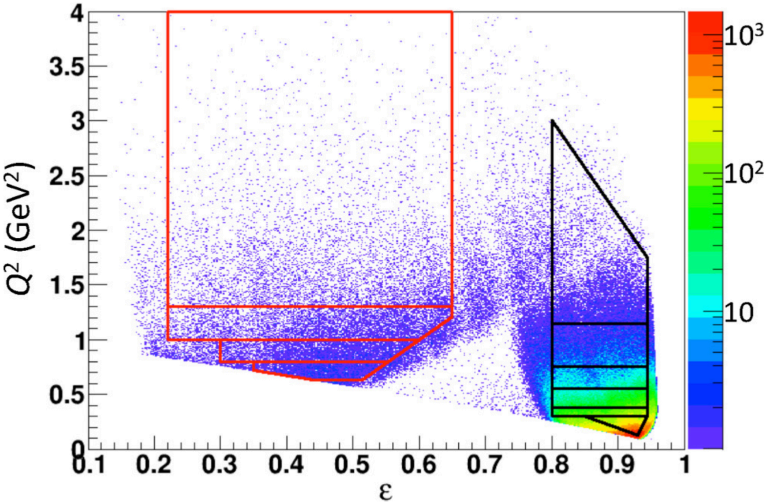


Difficult triple scattering experiment

Must reconstruct beam energy by measuring both lepton and proton

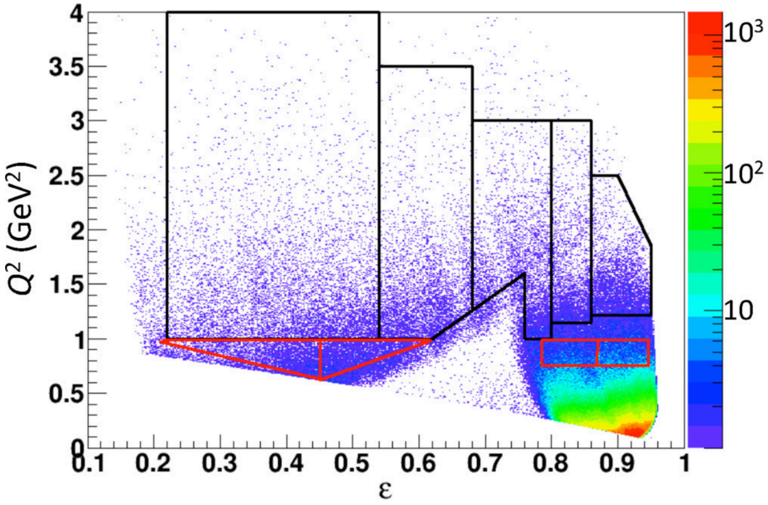
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

CLAS Bins for ϵ Dependence



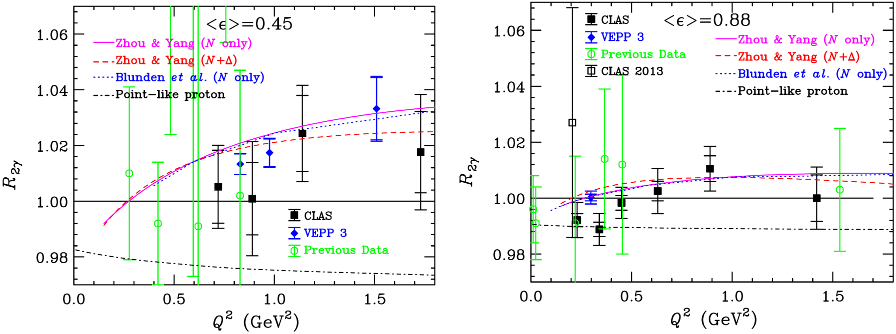
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

CLAS Bins for Q^2 Dependence



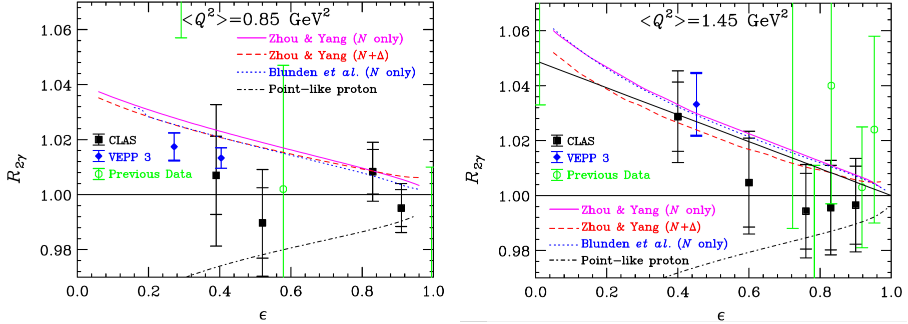
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

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



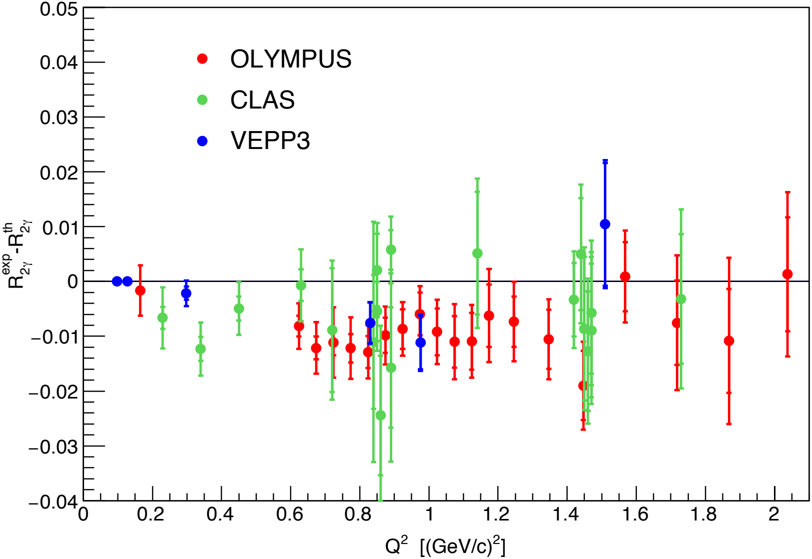
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

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



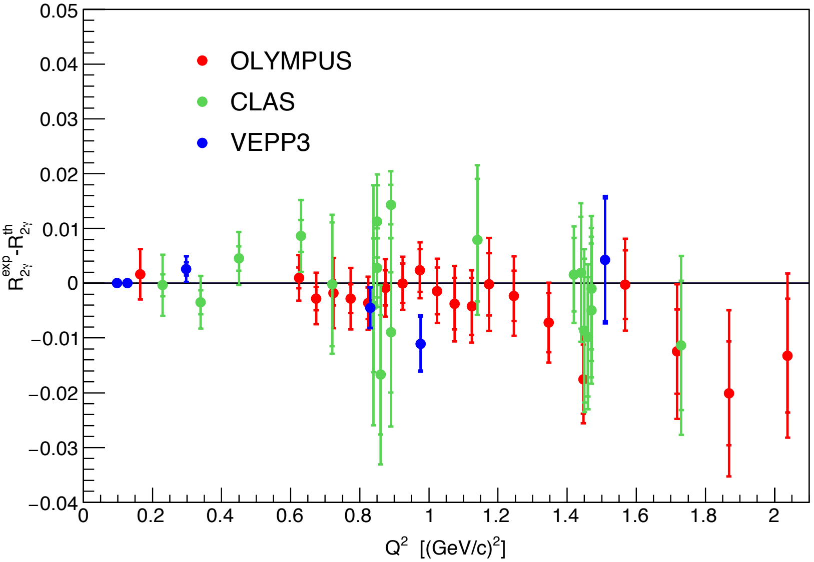
D. Rimal *et al.* Phys. Rev. **C95** 065291 (2017).

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).

Summary of Experimental Results

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

- all experiments in reasonable agreement with each other
- all found radiative corrections to be significant and important

Small, $< 1\%$, hard TPE observed, increasing with Q^2 (decreasing ϵ)

Results less than expected from theoretical calculations

- better agreement with phenomenological predictions

Does not resolve form factor discrepancy !

Further theoretical effort needed

Experiments at higher energy required

Possible Future Two-Photon Experiments

JLab ?

- possibly the best place (they caused the problem, they should fix it)
- but no positron source, plans for one ~ 10 years away

DESY planning new test beam hall

- 0.5–6.3 GeV electrons (60 nA) or positrons (30 nA)

Currently investigating a proposal for DESY

- liquid hydrogen target - Mainz (need new cell and chamber design)
- high resolution, fine granularity PbWO_4 crystals - Mainz and Bonn
- at 2 GeV, 1 week e^- / e^+, reach $0.83 < Q^2 < 2.78$ $(\text{GeV/c})^2$
- at 3 GeV, 1 month e^- / e^+, reach $1.69 < Q^2 < 4.57$ $(\text{GeV/c})^2$
- improvement options, higher energies (6 GeV $\rightarrow Q^2 = 10.1$)

TPE and Form Factor Discrepancy Still Topical

7 OLYMPUS PhD Theses:

- Axel Schmidt (MIT), Brian Henderson (MIT), Rebecca Russell (MIT), Colton O'Connor (MIT), Lauren Ice (ASU), Ozgur Ates (HU), and Dmitry Khaneft (Mainz)

Other publications:

- Physics Today
- Nuclear Physics News International
- Progress in Particle and Nuclear Physics
- 5 refereed papers

2017 Conferences and Workshops:

- NSTAR, Hadronic Physics with Lepton and Hadron Beams, JPos, Two-Boson Exchange, EINN, DIS, 12th International Spring Seminar on Nuclear Physics, APS, Bormio, Hadron, FFK, Lomonosov, PANIC

Thank You

Work supported by the United States Department of Energy.

Jefferson Lab Positron Working Group

JLab PWG Announcement – JPos17

The JPos17 International Workshop will be held in Summer/Fall 2017 at Jefferson Lab, Newport News, Virginia. It will cover innovative ideas and experimental projections that can take advantages of the unique positron source PEPPo at Jefferson Lab featuring 100 nA-10µA (CW) polarized positrons

JLab PWG Topics and Subgroups

Joe Grames (grames@jlab.org) & Eric Voutier (voutier@ipno.in2p3.fr)

John Arrington, Charles Hyde	**-**	**Interference Physics**
Yulia Furletova, Wally Melnitchouk	**-**	**Charged Current Physics**
Marco Battaglieri, Xiaochao Zheng	**-**	**Test of the Standard Model**
Tony Forest, Farida Selim	**-**	**Positron Applications**
Joe Grames, Vasiliy Morozov	**-**	**Positron Source and Beam Physics**

http://wiki.jlab.org/pwg ***pwg@jlab.org***

Charged Current Physics Sub-Group

1. Structure Functions with Charged and Neutral Current

a) The flavor separation of the pion and kaon structure could be achieved by comparing the difference between electron and positron interactions involving the Sullivan process with neutral and charged currents.

b) Neutral current. The xF3 nucleon structure function, which is charge-conjugation odd and mostly dominated by the γZ interference contribution, will be directly sensitive to valence quark distributions.

c) The charged-current deep inelastic scattering (DIS) cross section measurements provide possibly the most direct information on the flavor dependence of quark and anti-quark distributions. Depending on the charge of the exchanged W boson, the charged current process will be sensitive to either up-type or down-type flavors.

d) The charm and anticharm production in charged current DIS offers the best way to obtain information on strangeness in the nucleon, and the availability of polarized positron and electron beams would provide the necessary tools to extract strange and anti-strange distributions unambiguously.

e) The production of Ds+ mesons in diffractive charged current DIS could provide information on the gluon structure of the diffraction mechanism in QCD.

2. Electroweak form factors.

a) In connection with the study of axial form factors measured with neutrino scattering, reactions like p(e,n)nu with the neutrino being reconstructed by missing mass would bring new information. However n + neutrino is a challenging final state to reconstruct. With a positron beam, d(e+,pp)nubar might be much more feasible. It requires detecting 2 low-momentum protons (and nothing else), and while there are issues to be worked out, it looks like the proposed ALERT detector with CLAS12 might be ideal.

Luminosity of e^+ source/targets

- VEPP-3 10^{-7} fb^{-1}/s (0.32 pb^{-1} @ 1.6 GeV, 0.60 pb^{-1} @ 1.0 GeV)
- JLAB – CLAS similar statistics
- DESY – Doris $1.1\text{x}10^{-6}$ fb^{-1}/s (60 mA, 4.5 pb^{-1} @ 2.0 GeV)

- DESY II synchrotron $0.77\text{x}10^{-4}$ fb^{-1}/s (30 nA, 0.6-6.3 GeV, 10 cm LD$_2$)
- JLab – PEPPo (proposed R&D) (100 nA-10µA, CW pol, 10 cm LD$_2$)

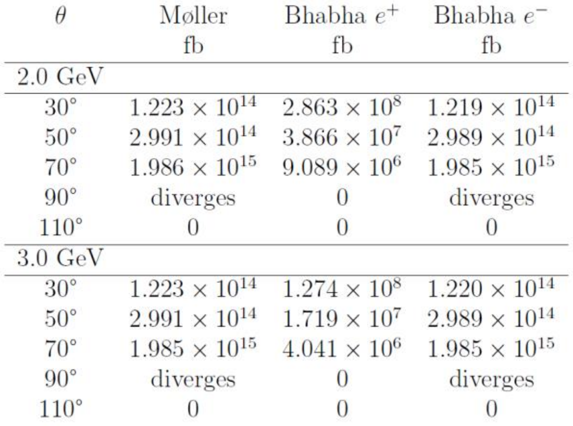
Rates

Assuming $L =$ 0.77x10−4 fb^{-1}/s

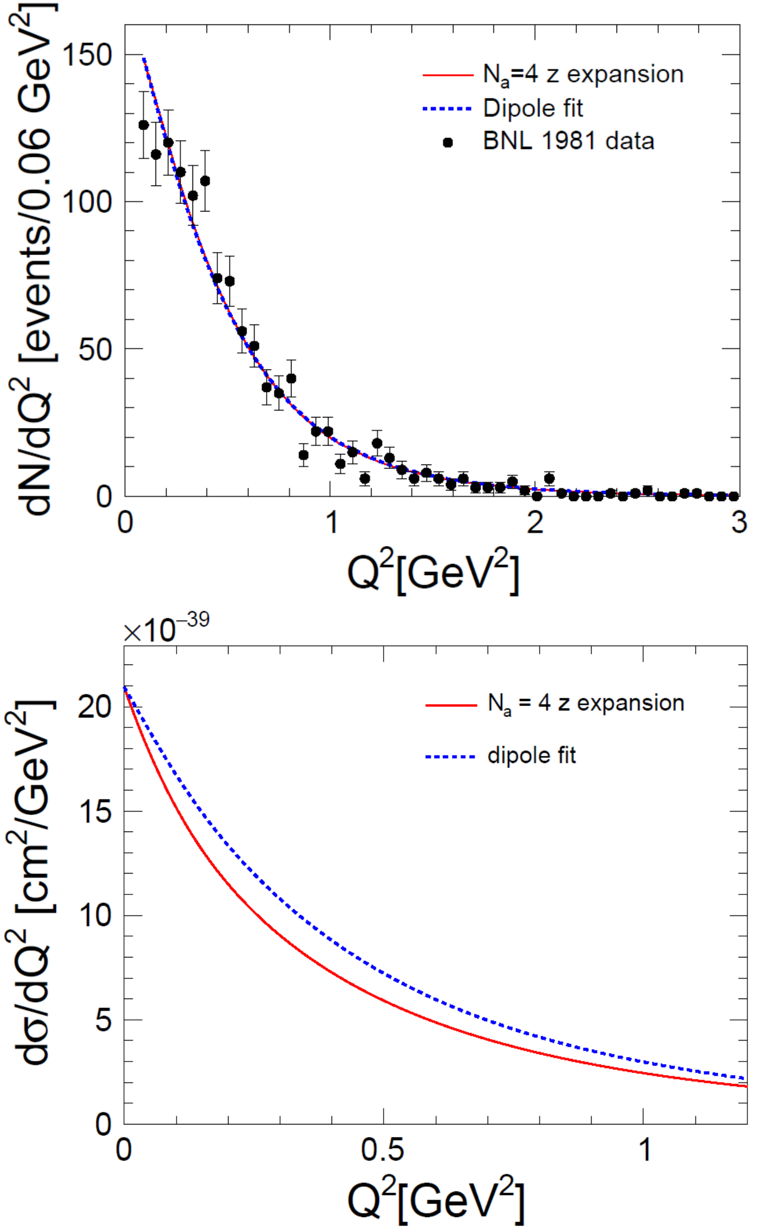
$E =$ 1 GeV @ DESY

- $d(e^+, pp)\bar{\nu}$ QE-CC

  could retake BNL1981 dataset of
  120 ev at 0.10-0.16 GeV^2 in **15.8 day**
- $d(e^+, e^+p)$ EQ-EM
  - **7.6x10^8** x larger cross section [$\sim\mu$b]
  - 562 Hz in the 0.1 GeV^2 bin
- $e^-(e^+, e^+e^-)$ [Desy II proposal]

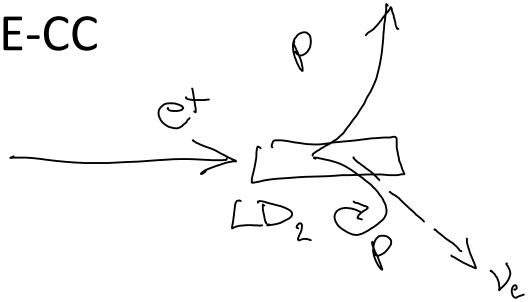


θ	Møller fb	Bhabha e^+ fb	Bhabha e^- fb
2.0 GeV			
30°	1.223×10^{14}	2.863×10^{8}	1.219×10^{14}
50°	2.991×10^{14}	3.866×10^{7}	2.989×10^{14}
70°	1.986×10^{15}	9.089×10^{6}	1.985×10^{15}
90°	diverges	0	diverges
110°	0	0	0
3.0 GeV			
30°	1.223×10^{14}	1.274×10^{8}	1.220×10^{14}
50°	2.991×10^{14}	1.719×10^{7}	2.989×10^{14}
70°	1.985×10^{15}	4.041×10^{6}	1.985×10^{15}
90°	diverges	0	diverges
110°	0	0	0



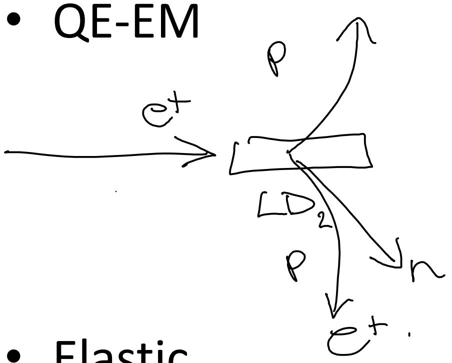
Meyer et al, PRD 93, 113015 (2016)

- QE-CC

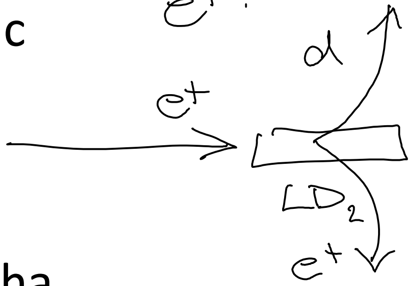


Backgrounds

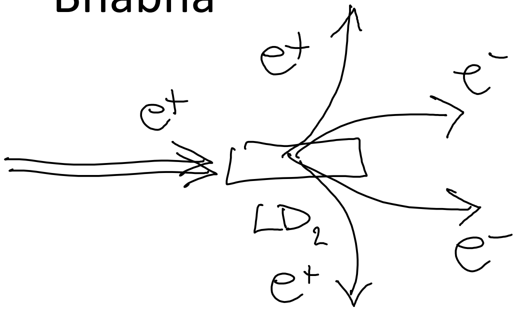
- QE-EM

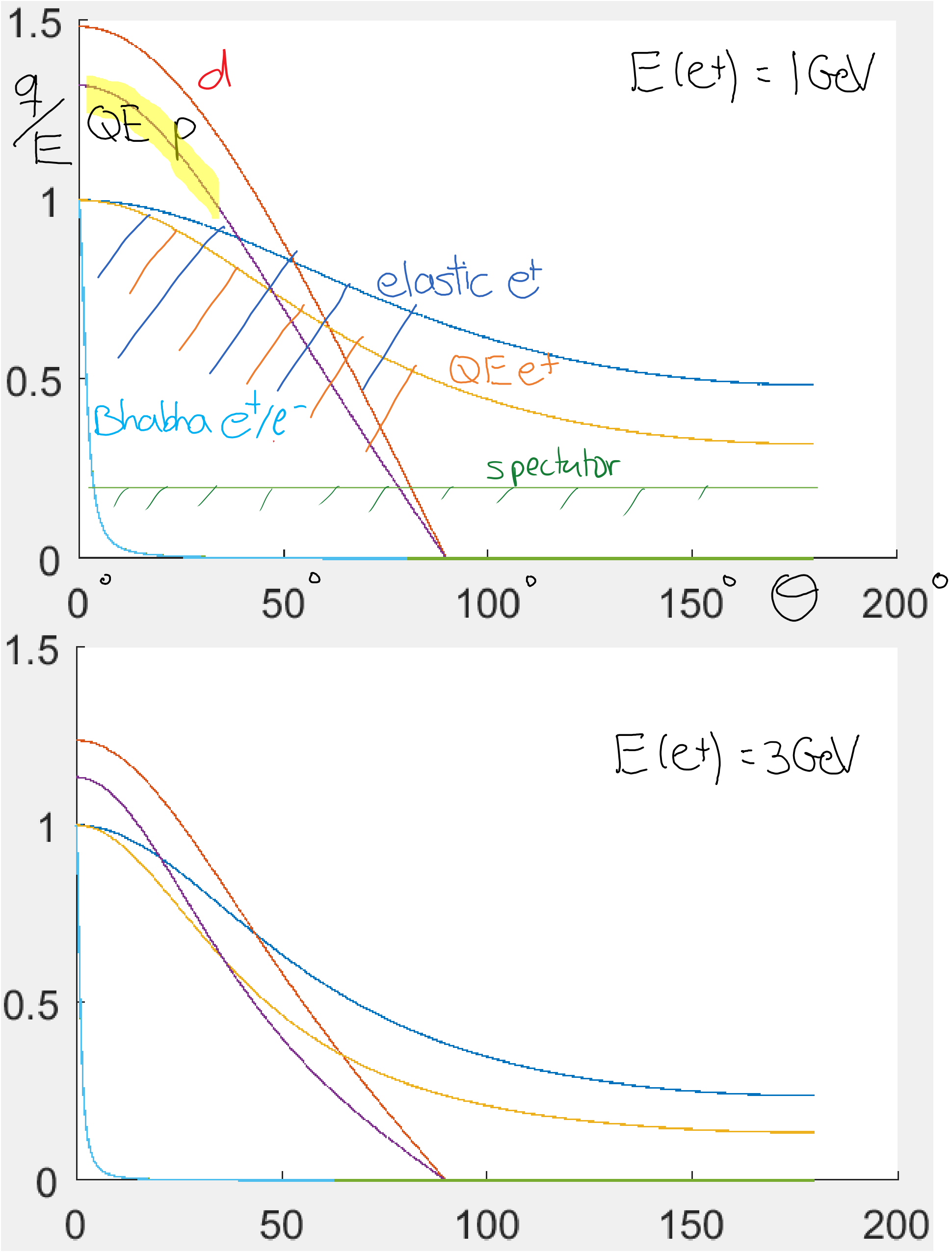


- Elastic



- Bhabha





Cuts

1. Fermi momentum of spectator
2. Quasielastic kinematics of E vs θ of $(\overrightarrow{p_{p1}} + \overrightarrow{p_{p2}})$
    - 1 instead of 4 constraints, since $\overrightarrow{p_{\nu}}$ unknown
3. No other particle
    - must include kinematics of QE-EM e^{+} in fiducial acceptance
    - Čerenkov veto

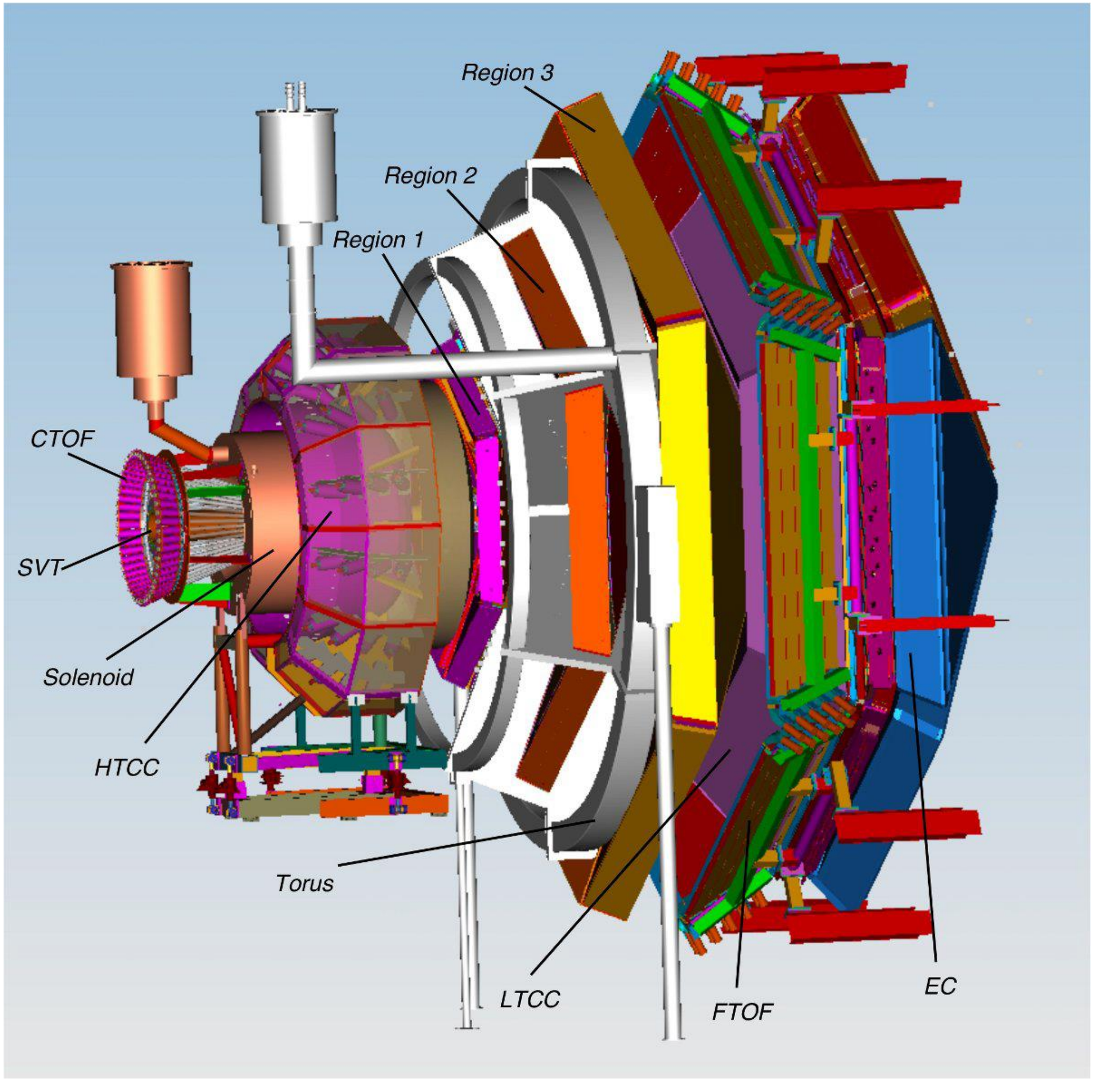
- NEED 10^8 REJECTION !!!

CLAS Detector Package

Forward detector

- High Threshold Cherenkov Counters (HTCC)
- Drift Chambers (DC)
- Low Threshold Cherenkov Counters (LTCC)
- Time-of-Flight scint. (TOF)
- Forward Calorimeter
- Preshower Calorimeter

- pion rejection factor >2000 up to momentum 4.9 GeV/c



ALERT detector

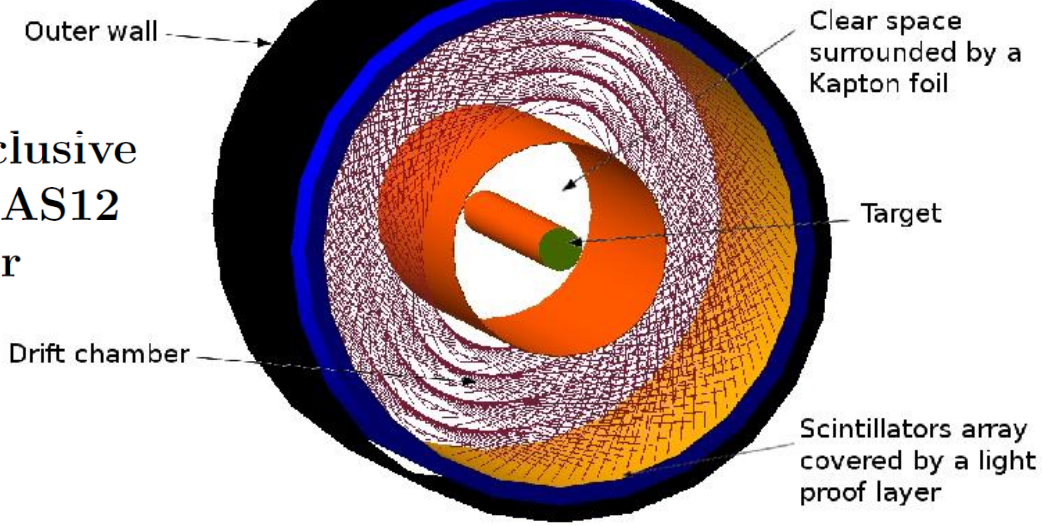
- 30 cm long, 6 mm radius cylindrical target @ 3 atm, 25μm Kapton wall
- clear space to outer radius of 30 mm, filled with helium to reduce secondary scattering from the high rate Moller electrons
- drift chamber, radius 32 – 85 mm to track low energy nuclear recoils
- two rings of plastic scintillators placed inside the gaseous chamber total thickness ~20 mm.

PR12-16-011C

Jefferson Lab PAC 44

Nuclear Exclusive and Semi-inclusive
Measurements with a New CLAS12
Low Energy Recoil Tracker

ALERT Run Group[†]

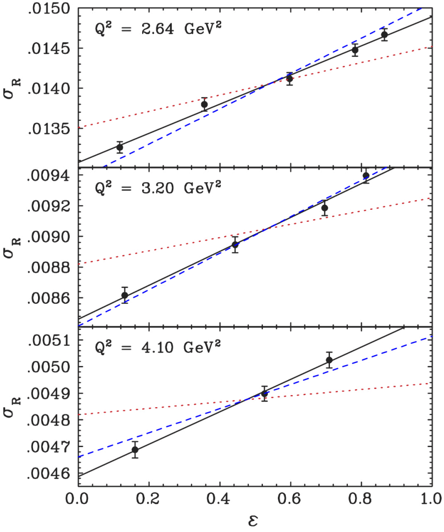


Conclusion

- hint of small 2γ radiative corrections
  must go to higher Q^2 for definitive results
  new proposal at DESY-II, 100x luminosity
  JLab PEPPo in the far future

- quasielastic $d(e^+,pp)\bar{\nu}$ dominated by EM background
  although cuts in principle could separate $F_A(Q^2)$,
  noise-to-signal ratio overwhelming

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

Blue dashed → FF ratio = 1

Red dotted → polarized measure

Definitive Measure of Two-Photon Contribution

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

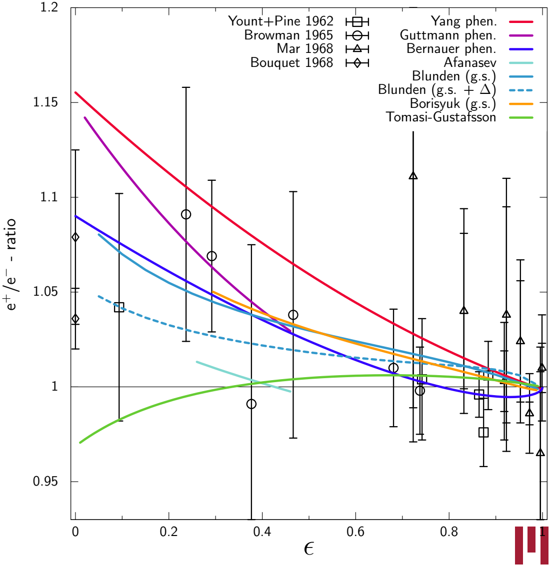
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\mathcal{R}e(\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma})}{\mathcal{M}_{1\gamma}^2}$$

Existing data

- low Q^2
- large uncertainties

Three recent experiments

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

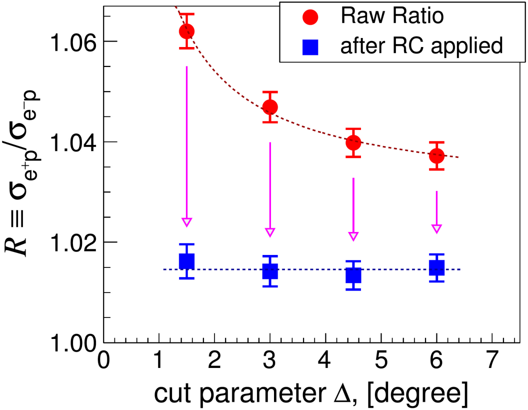


VEPP-3 Radiative Corrections

Dedicated event generator

- ESEPP
- full radiative corrections
- GEANT4 detector simulation

Sensitivity of ratio to radiative corrections



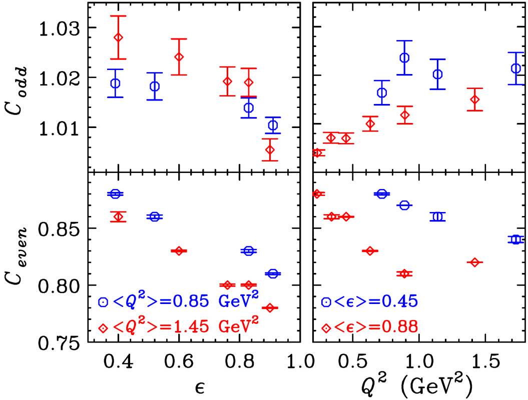
I.A. Rachek *et al.* Phys. Scr. **T166** 014017 (2015).

CLAS Radiative Corrections

Calculated following R. Ent *et al.*

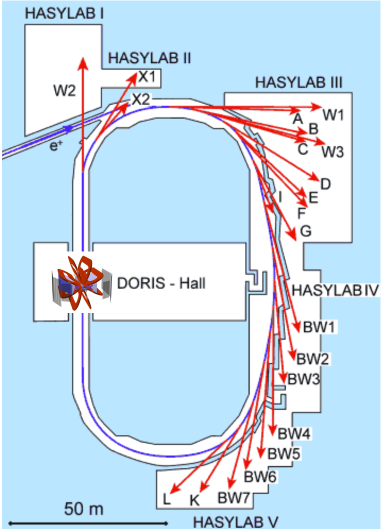
$$\frac{1+\delta_{even}-\delta_{2\gamma}-\delta_{epbrem}}{1+\delta_{even}+\delta_{2\gamma}+\delta_{epbrem}}$$

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



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 !

Luminosity

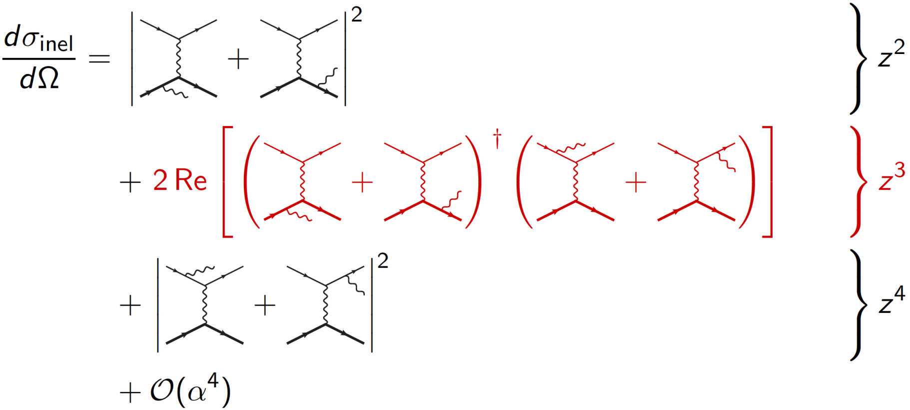
Three independent and consistent measures of luminosity:

- 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 $(e^{\pm}e \rightarrow e^{\pm}e) + (e^{\pm}p \rightarrow e^{\pm}p)$ 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 from Inelastic Processes

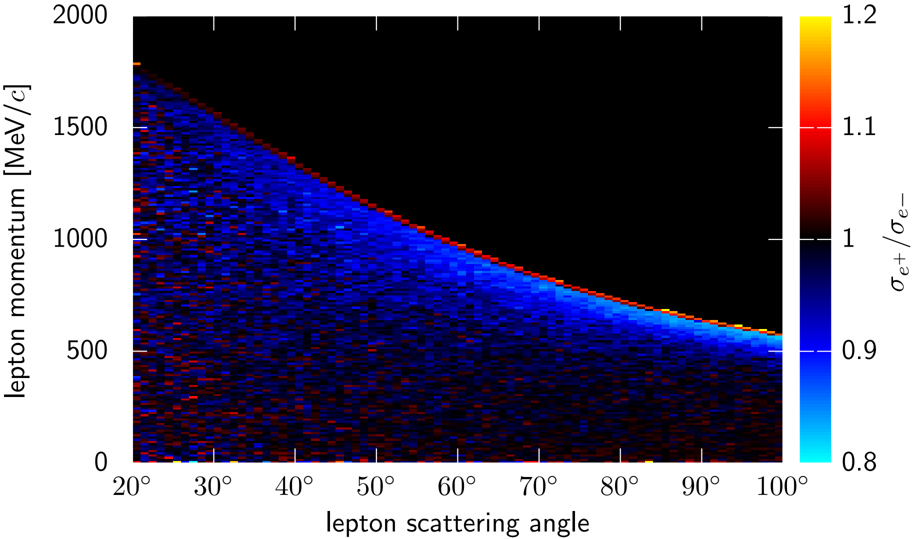


Rebecca Russell, MIT

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

Radiative Corrections



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