Two-Photon Exchange in Precision Measurements of Proton Electromagnetic Form Factors

Theory and Experiment

Andrei Afanasev

The George Washington University, Washington, DC, USA

Talk presented at International Conference on Precision Physics and Fundamental Physical Constants FFK2023

Vienna, Austria, 22-26 May 2023

E-mail: afanas@gwu.edu

THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

Research sponsored by NSF

Plan of talk

Physics of Nucleon Form Factors

Radiative corrections for charged lepton scattering

- Model-independent and model-dependent; soft and hard photons

Two-photon exchange effects

- Theory vs experiment; data from CLAS, VEPP and OLYMPUS

Summary

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

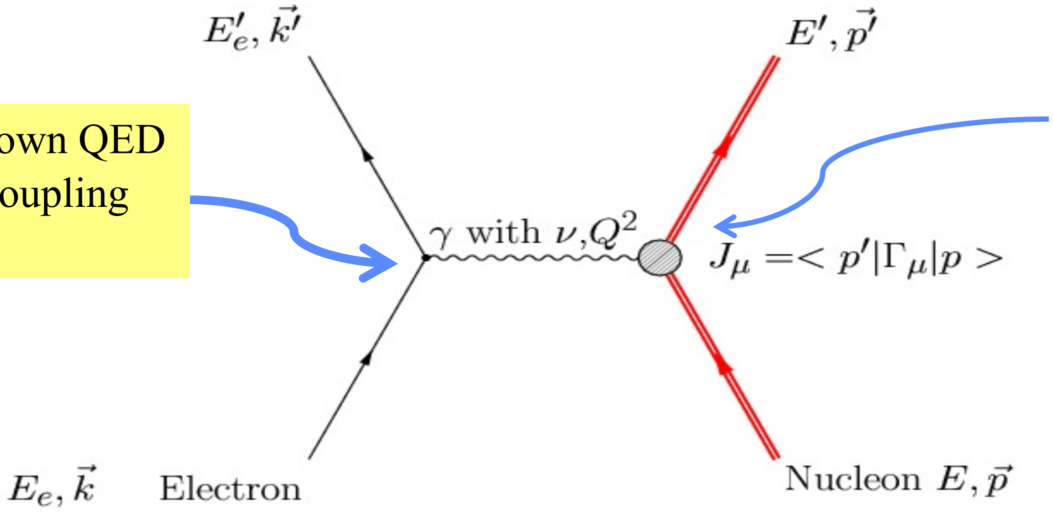
Nucleon Form Factors

- Nucleon form factors describe the distribution of charge and magnetization in the nucleon
  - This is naturally related to the fact that nucleons are made of quarks
- Why measure nucleon form factors?
  - Understand structure of the nucleon at short and long distances
  - Understand the nature of the strong interaction (Quantum Chromodynamics) at different distance scales

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Electron as probe of nucleon elastic form factors

Known QED coupling



Unknown
γ^*N
coupling

Nucleon vertex:

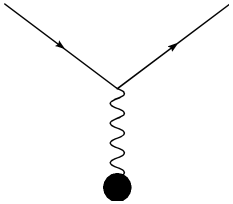
$$\Gamma_\mu(p', p) = F_1(Q^2)\gamma_\mu + \frac{i\kappa_p}{2M_p} F_2(Q^2)\sigma_{\mu\nu}q^\nu$$

Elastic Form Factors:

F_1 is helicity conserving (no spin flip)

F_2 is helicity non-conserving (spin flip)

Elastic Nucleon Form Factors



- Based on one-photon exchange approximation

$$M_{fi} = M_{fi}^{1\gamma}$$

$$M_{fi}^{1\gamma} = e^2 \bar{u}_e \gamma_\mu u_e \bar{u}_p \left(F_1(t)\gamma_\mu - \frac{\sigma_{\mu\nu} q_\nu}{2m} F_2(t)\right) u_p$$

- Two techniques to measure

$$\sigma = \sigma_0 ({G_M}^2 \tau + \varepsilon \cdot {G_E}^2) \quad : Rosenbluth \quad technique$$

By Rosenbluth (1950)

$$\frac{P_x}{P_z} = -\frac{G_E \sqrt{\tau}\sqrt{2\varepsilon(1-\varepsilon)}}{G_M \ \tau\sqrt{1-\varepsilon^2}} \quad : Polarization \quad transfer \quad technique$$

By Akhiezer and Rekalo (1968)

$$G_E = F_1 - \tau F_2, \quad G_M = F_1 + F_2$$

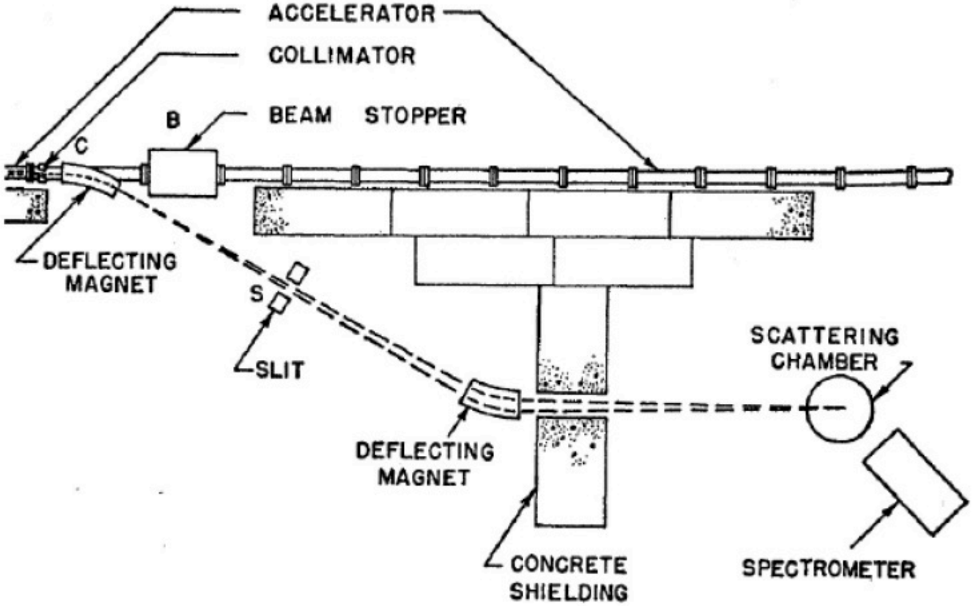
$$(P_y = 0)$$

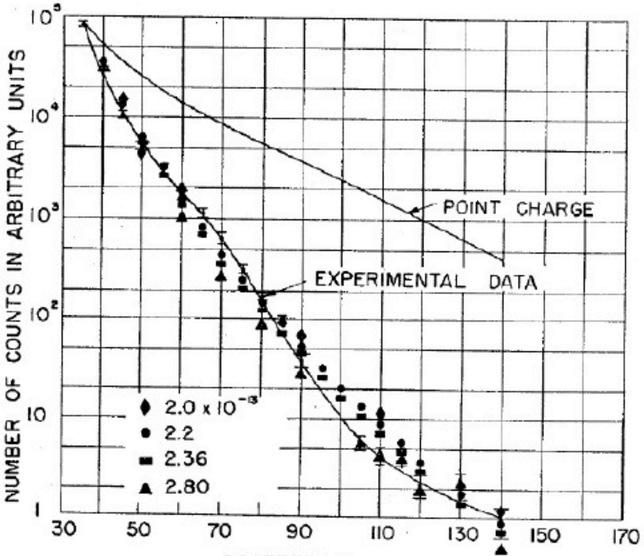
THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

Early Form Factor Measurements

Proton is an extended charge distribution





Hofstadter, R., et al., Phys. Rev. 92, 978 (1953).

Experimental equipment of electron scattering (Hofstadter 1954)

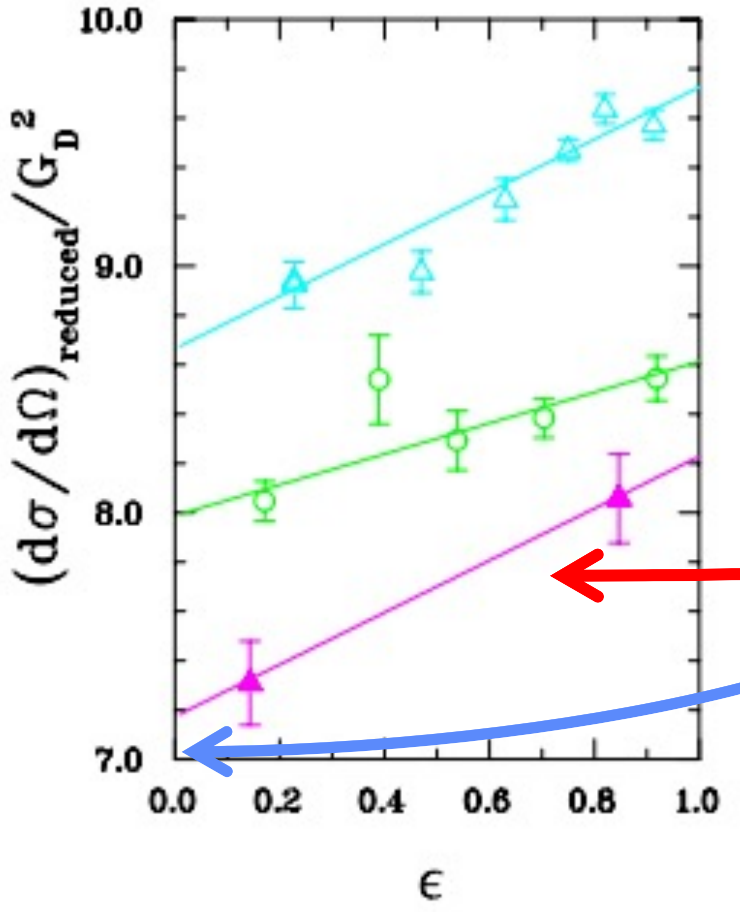
Scattering cross section of electron

Proton has a radius of ≈0.8 x 10^{-13} cm

“Dipole” shape

Elastic cross section in G_E and G_M

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \left(G_E^2 + \tau\left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]G_M^2\right)/(1+\tau)$$



$$\left(\frac{d\sigma}{d\Omega}\right)_{reduced} = \frac{\epsilon(1+\tau)}{\tau}\left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_{Mott}$$

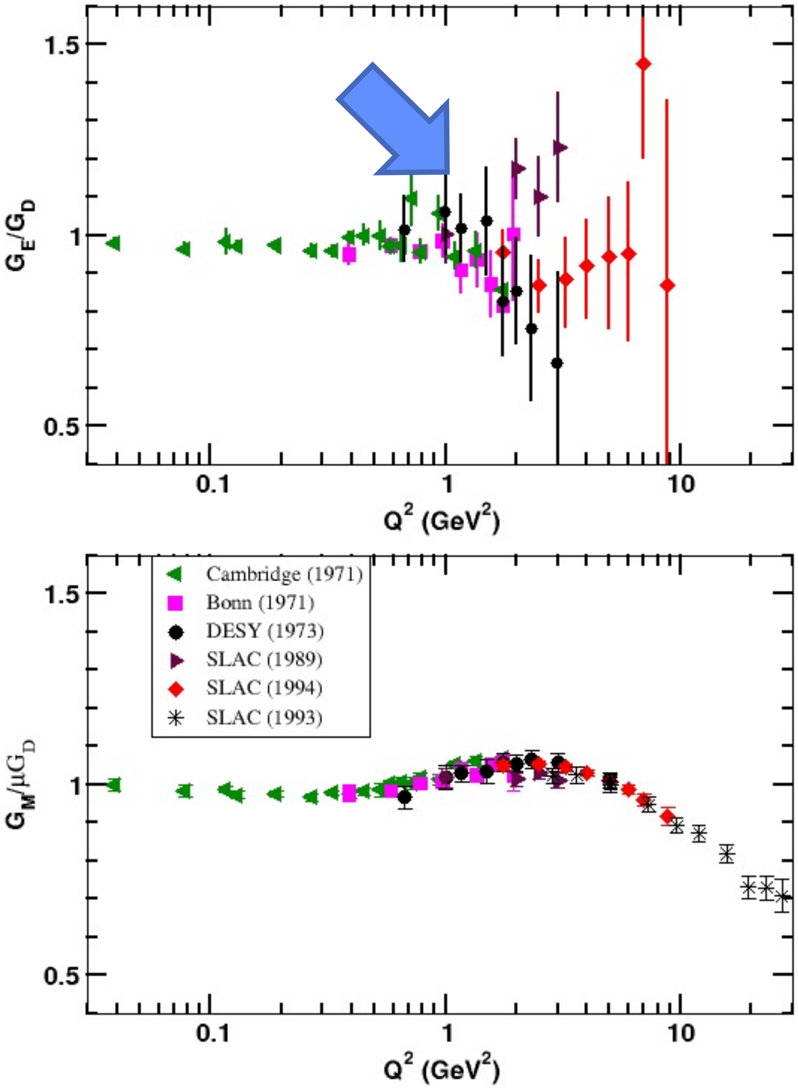
$$= G_M^2 + \frac{\epsilon}{\tau}G_E^2$$

Slope

Intercept

Proton Form Factors: G_{Mp} and G_{Ep}

$G_E > 1$ then large error bars and spread in data.



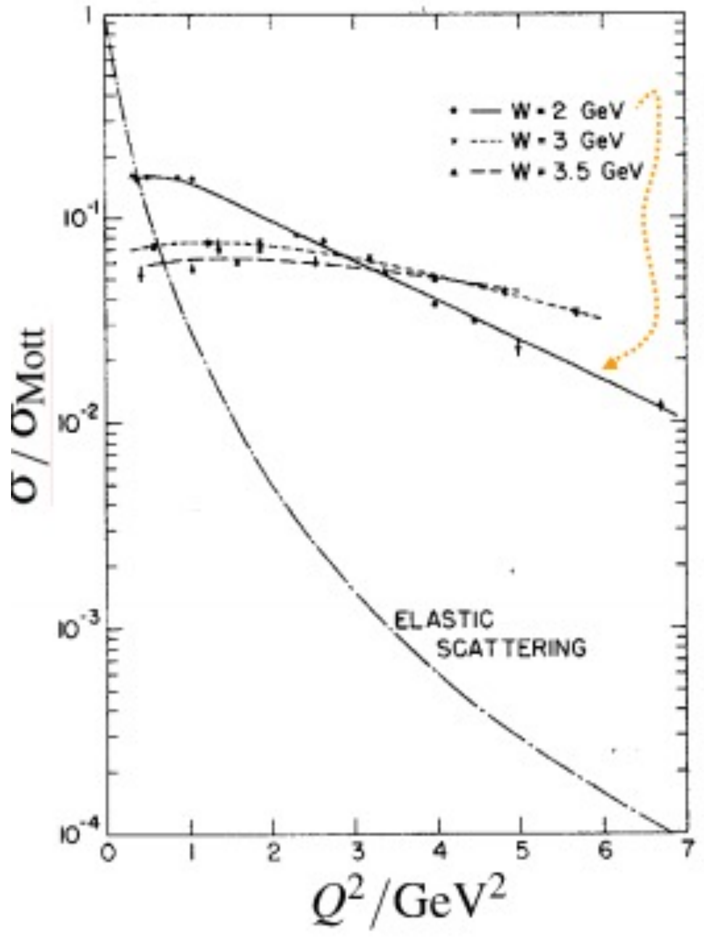
Experiments from the 1960s to 1990s gave a cumulative data set

At large Q^2, G_E contribution is smaller so difficult to extract

G_M measured to $Q^2 = 30$ GeV^2

G_E measured well only to $Q^2 = 1$ GeV^2

Q^2 dependence of elastic and inelastic cross sections



As Q^2 increases

$\sigma_{elastic} / \sigma_{Mott}$ drops dramatically

At W = 2 GeV

$\sigma_{inel} / \sigma_{Mott}$ drops less steeply

At W=3 and 3.5 GeV

$\sigma_{inel} / \sigma_{Mott}$ almost constant

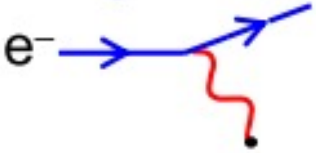
Point object inside the proton

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

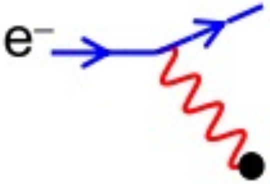
Electron as a probe of nucleon structure

★ In $e^- p \rightarrow e^- p$ scattering the nature of the interaction of the virtual photon with the proton depends strongly on wavelength

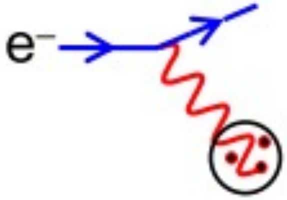
- At very low electron energies $\lambda \gg r_p$: the scattering is equivalent to that from a "point-like" spin-less object



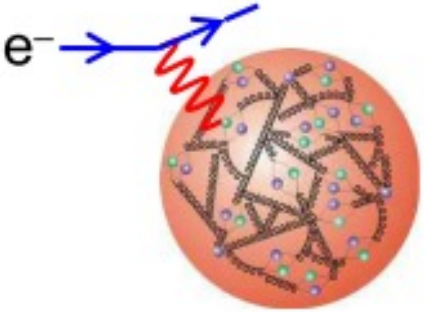
- At low electron energies $\lambda \sim r_p$: the scattering is equivalent to that from a extended charged object



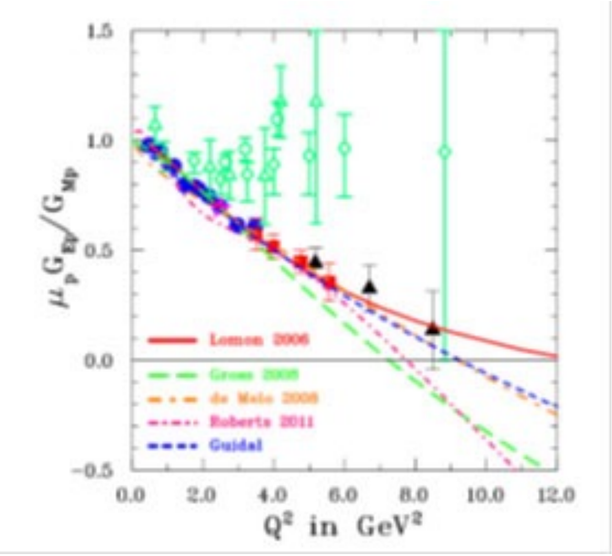
- At high electron energies $\lambda < r_p$: the wavelength is sufficiently short to resolve sub-structure. Scattering from constituent quarks

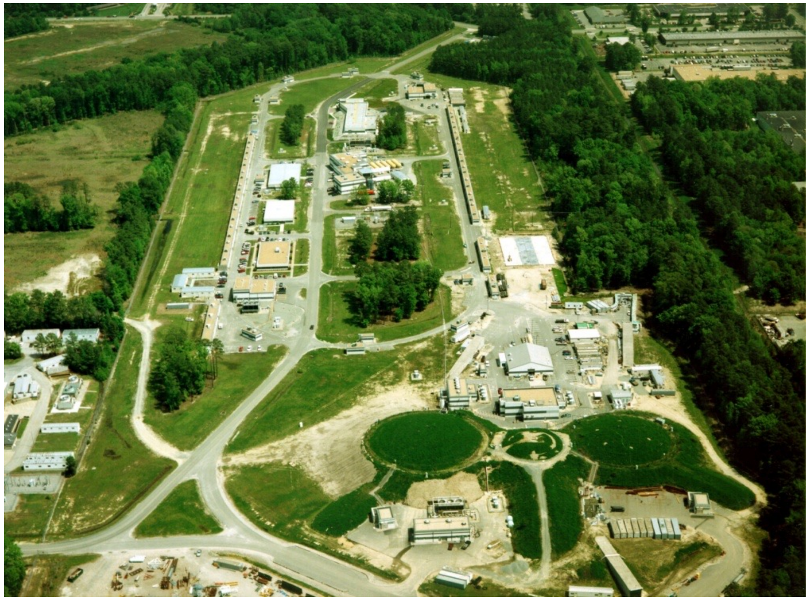


- At very high electron energies $\lambda \ll r_p$: the proton appears to be a sea of quarks and gluons.

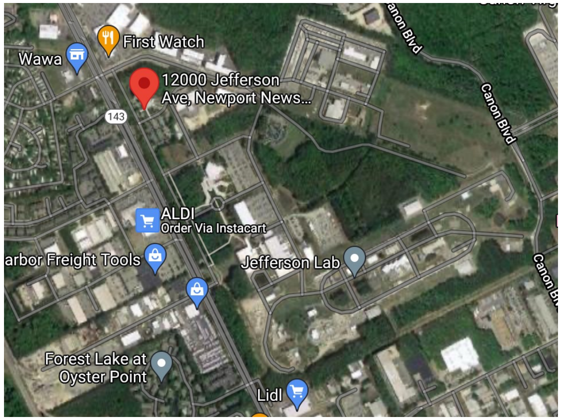


Measuring Proton Form Factors

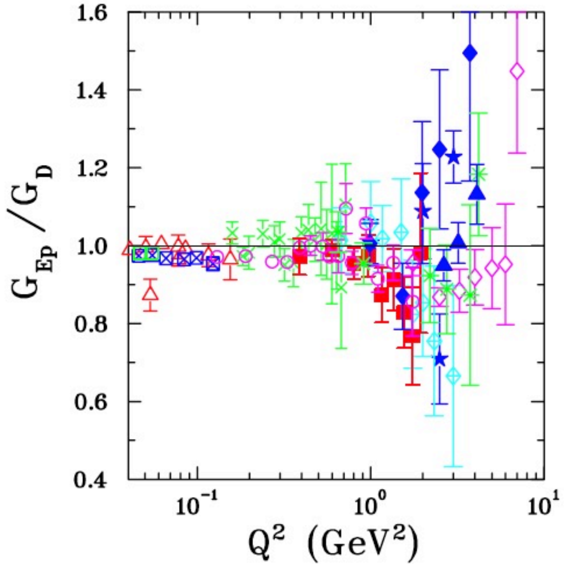


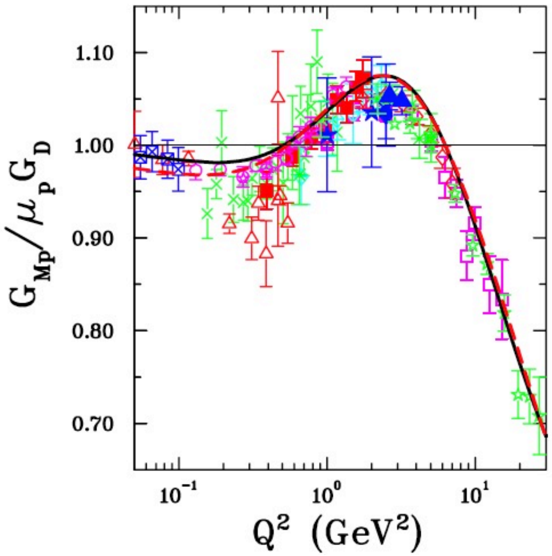


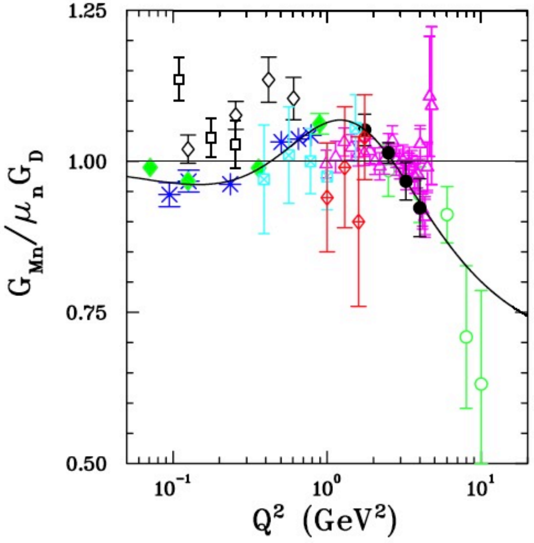
The ratio *GEp*/*GMp* obtained by the recoil polarization technique (Punjabi et al. (2005) (filled blue circle), Puckett et al. (2012) (filled red squares) and Puckett et al. (2010) (filled black triangles)) compared to ratio obtained by the Rosenbluth technique (green open points).

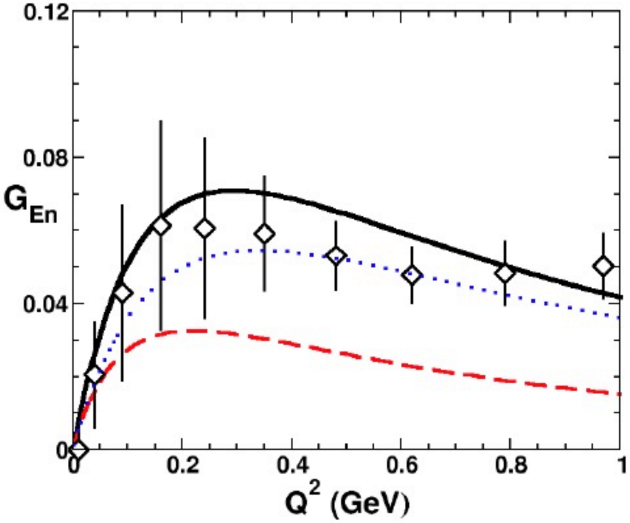


Form Factors Measured by Rosenbluth Method

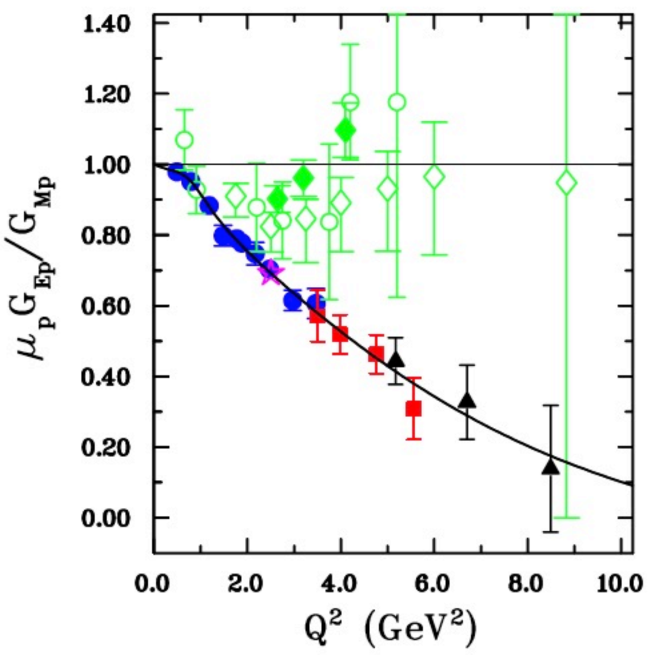


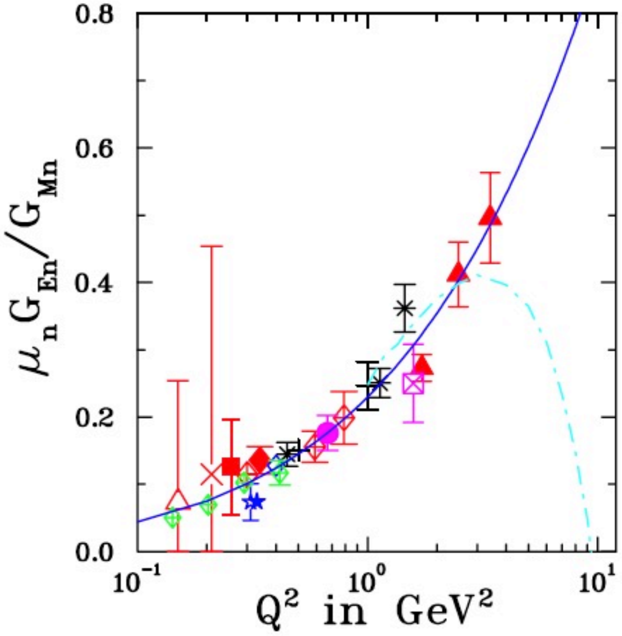






Form Factors Measured by Polarization Method



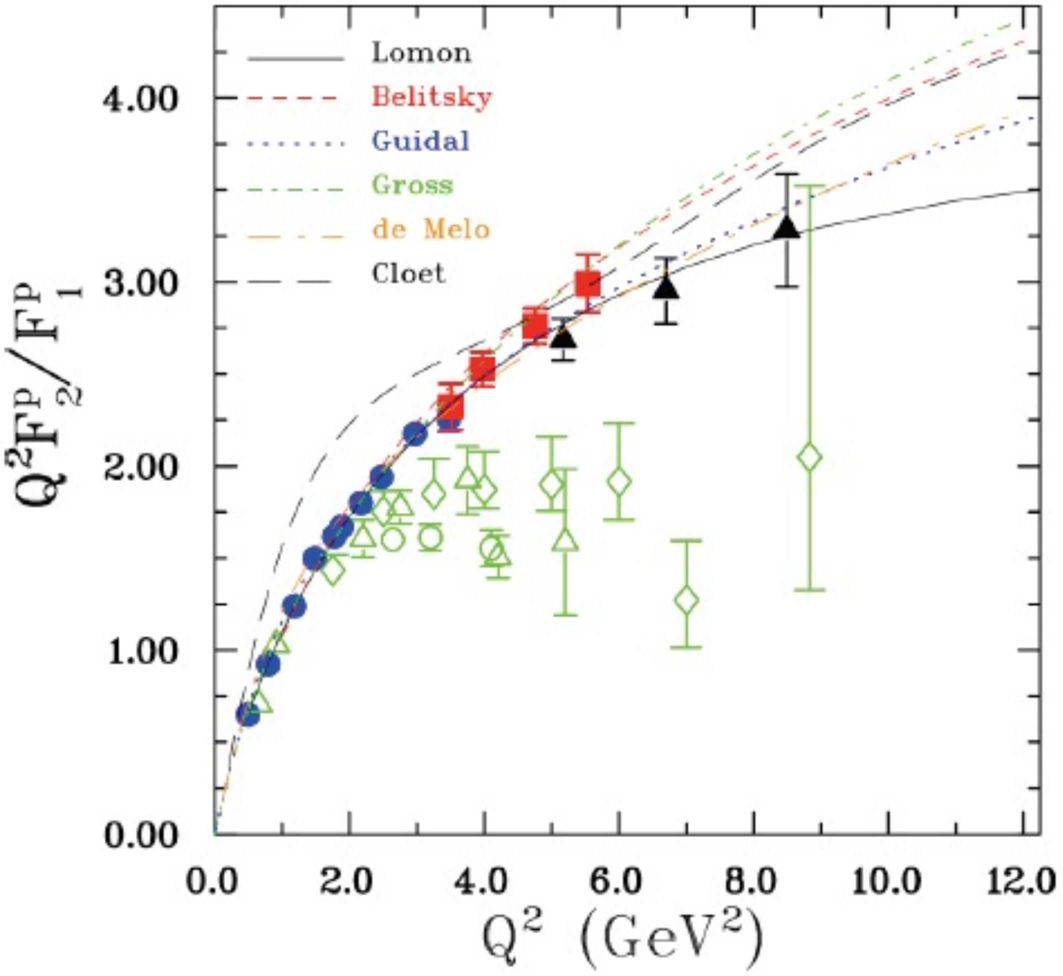


Rosenbluth method (green)
vs Polarization (Akhiezer-Rekalo)

But why are the experimental data different and what data do we trust to compare with the experiment?

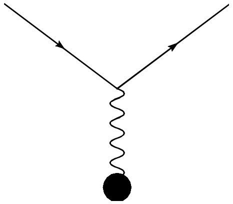
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Proton Form Factors: Experiment vs Theory

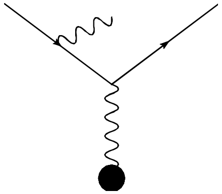


- **Theory curves:**
- Lomon 2002, 2006 (VMD)
- Belitsky 2003 (pQCD scaling)
- Guidal 2005 (GPD)
- Gross, Ramalho, Pena 2008 (covariant spectator model)
- de Melo 2009 (Bethe-Salpeter Amplitude)
- Cloet 2009 (Dyson-Schwinger/Faddeev/quark-diquark)

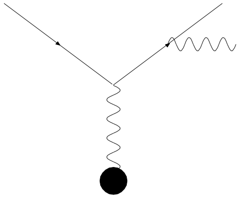
Basics of QED radiative corrections



(First) Born approximation

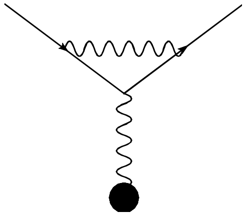


Initial-state radiation



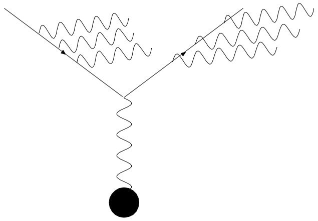
Final-state radiation

Cross section ~ dω/ω => integral diverges logarithmically: **IR catastrophe**



Vertex correction => cancels divergent terms; Schwinger (1949)
Assumed $Q^2/m_e^2 >> 1$

$$\sigma_{\exp} = (1+\delta)\sigma_{Born}, \quad \delta = \frac{-2\alpha}{\pi}\{(\ln\frac{E}{\Delta E} - \frac{13}{12})(\ln\frac{Q^2}{m_e^2} - 1) + \frac{17}{36} + \frac{1}{2}f(\theta)\}$$



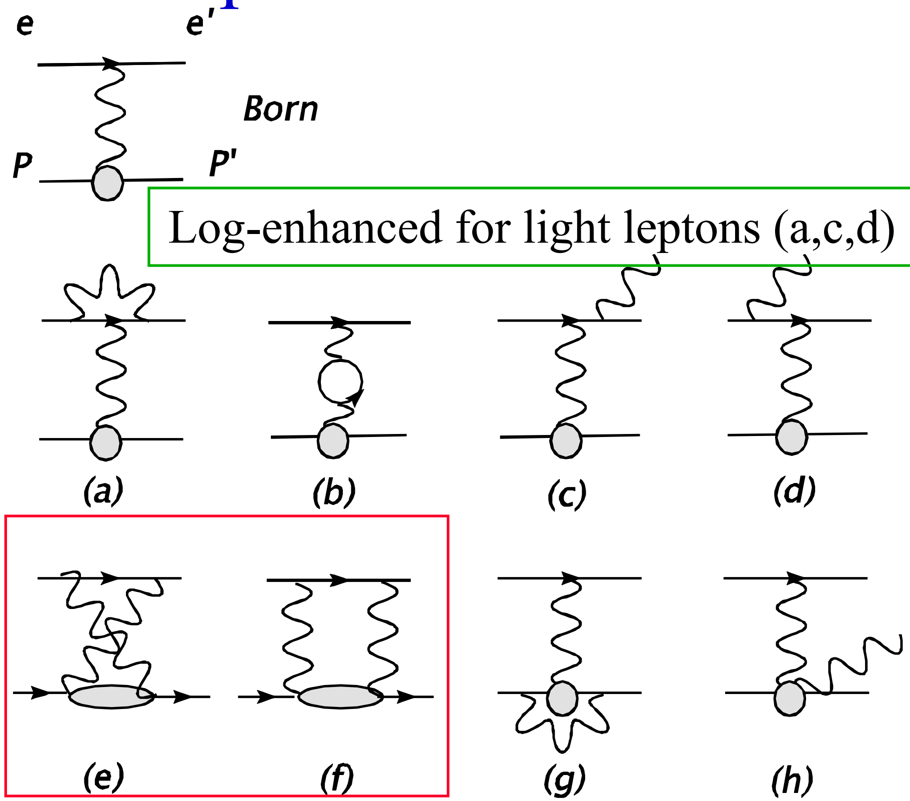
Multiple soft-photon emission: solved by exponentiation,
Yennie-Frautschi-Suura (YFS), 1961

$$(1+\delta) \rightarrow e^{\delta}$$

Basic Approaches to QED Corrections

- L.W. Mo, Y.S. Tsai, Rev. Mod. Phys. 41, 205 (1969); Y.S. Tsai, Preprint SLAC-PUB-848 (1971).
  - Considered both elastic and inelastic inclusive cases. No polarization.
- D.Yu. Bardin, N.M. Shumeiko, Nucl. Phys. B127, 242 (1977).
  - Covariant approach to the IR problem. Later extended to inclusive, semi-exclusive and exclusive reactions with polarization.
- E.A. Kuraev, V.S. Fadin, Yad.Fiz. 41, 7333 (1985); E.A. Kuraev, N.P.Merenkov, V.S. Fadin, Yad. Fiz. 47, 1593 (1988).
  - Developed a method of electron structure functions based on Drell-Yan representation; currently widely used at e^+e^- colliders
  - Applied for polarized electron-proton scattering by AA et al, JETP 98, 403 (2004).

Complete radiative correction in O(α_{em})



Log-enhanced for light leptons (a,c,d)

Radiative Corrections:

- Electron vertex correction (a)
- Vacuum polarization (b)
- Electron bremsstrahlung (c,d)
- Two-photon exchange (e,f)
- Proton vertex and VCS (g,h)
- Corrections (e-h) depend on the nucleon structure

•Meister&Yennie; Mo&Tsai

•Further work by Bardin&Shumeiko; Maximon&Tjon; AA, Akushevich, Merenkov;

•Guichon&Vanderhaeghen'03: *Can (e-f) account for the Rosenbluth vs. polarization experimental discrepancy? Look for ~3% ...*

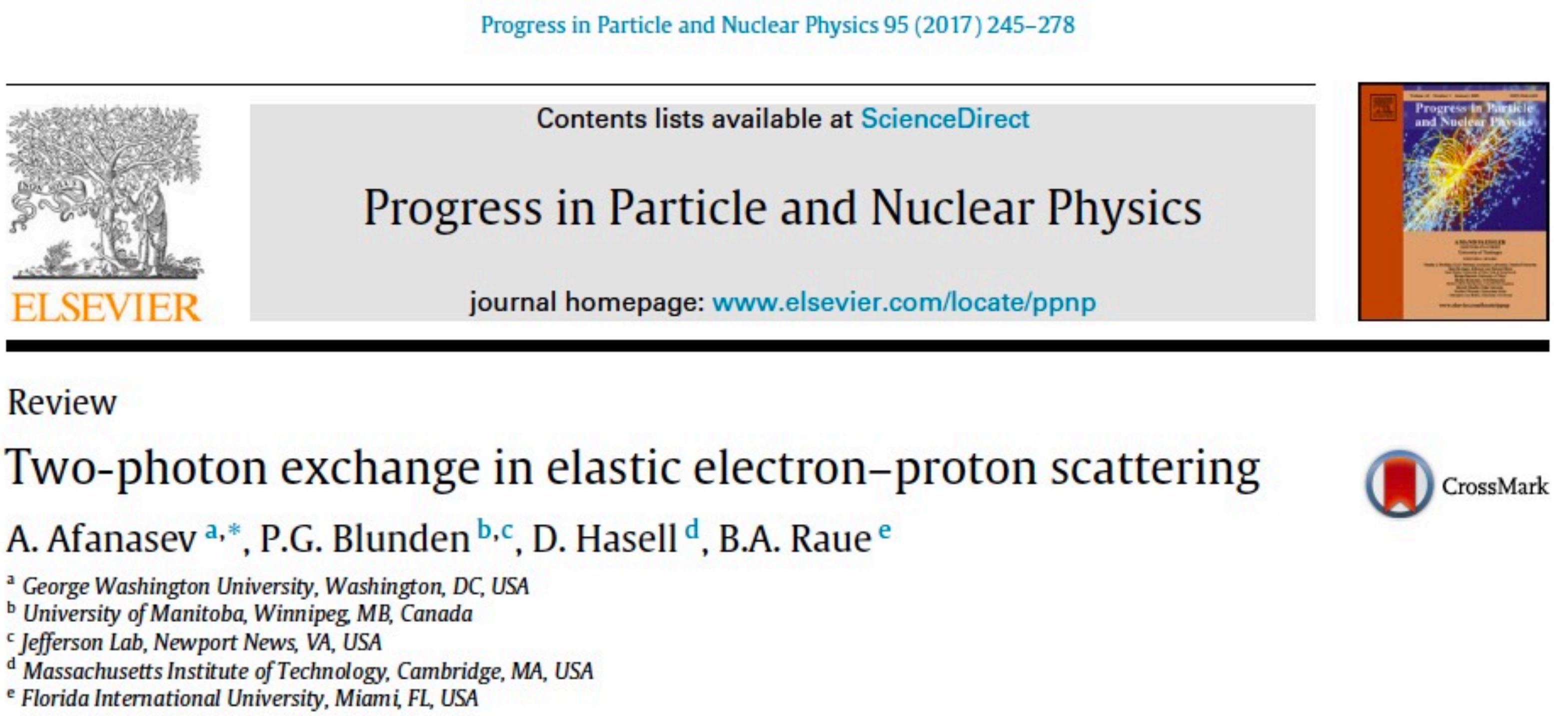
Main issue: Corrections dependent on nucleon structure

Model calculations:

•Blunden, Melnitchouk,Tjon, Phys.Rev.Lett.**91**:142304,2003

•Chen, AA, Brodsky, Carlson, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004

Two-Photon Exchange Overview



Progress in Particle and Nuclear Physics 95 (2017) 245–278

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

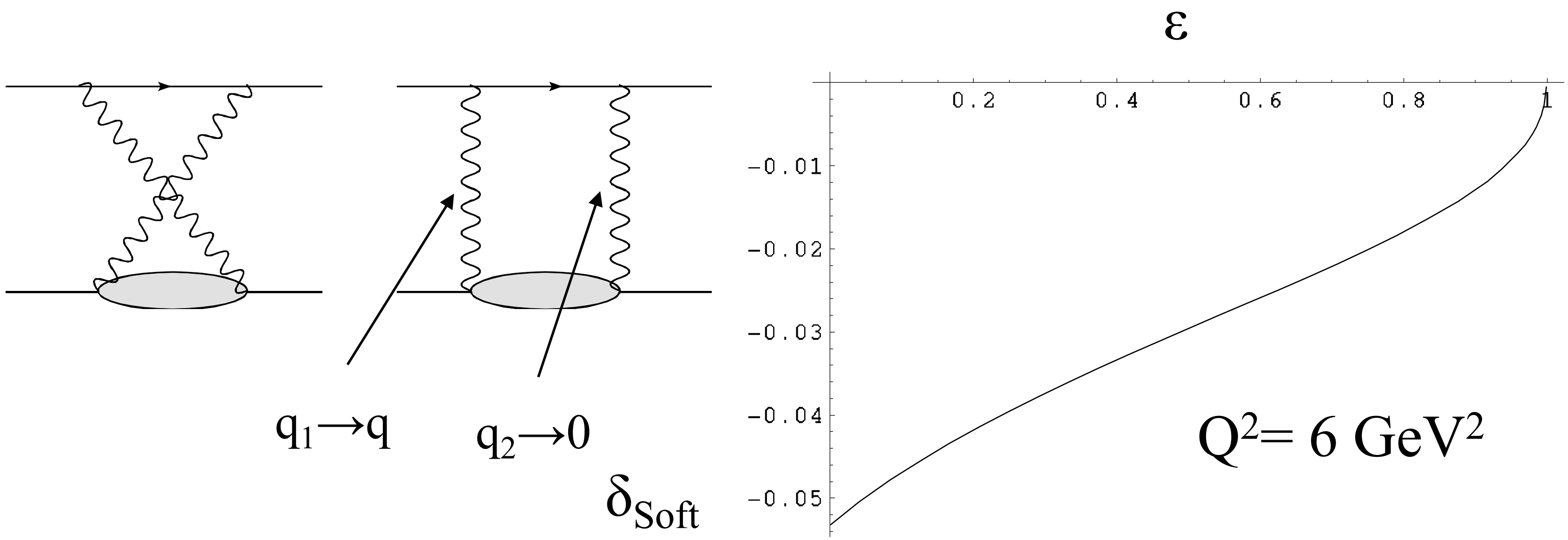
Two-photon exchange in elastic electron–proton scattering

A. Afanasev [a,*], P.G. Blunden [b,c], D. Hasell [d], B.A. Raue [e]

[a] *George Washington University, Washington, DC, USA*
[b] *University of Manitoba, Winnipeg, MB, Canada*
[c] *Jefferson Lab, Newport News, VA, USA*
[d] *Massachusetts Institute of Technology, Cambridge, MA, USA*
[e] *Florida International University, Miami, FL, USA*

Separating *soft* 2-photon exchange

- Tsai; Maximon & Tjon (k→0); similar to Coulomb corrections at low Q^2
- Grammer &Yennie prescription PRD 8, 4332 (1973) (also applied in QCD calculations)
- Shown is the resulting (soft) QED correction to cross section
- **Already included in experimental data analysis**
- NB: Corresponding effect to polarization transfer and/or asymmetry is zero



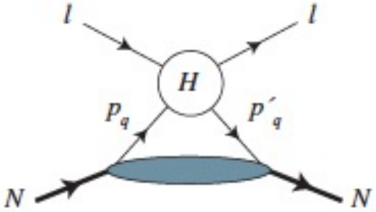
What is missing in the calculation?

- 2-photon exchange contributions for non-soft intermediate photons
  - Can estimate based on a text-book example from *Berestetsky, Lifshitz, Pitaevsky: Quantum Electrodynamics*
  - Double-log asymptotics of electron-quark backward scattering

$$\delta = -\frac{e_q e}{8\pi^3}\log^2\frac{s}{m_q^2}$$

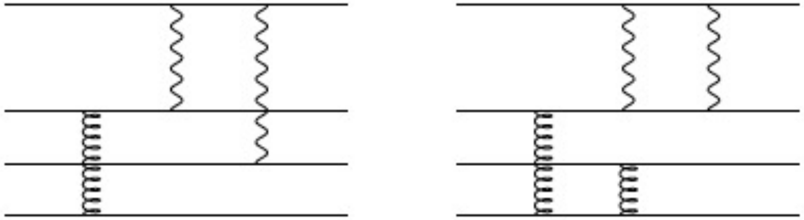
  - Negative sign for backward ep-scattering; zero for forward scattering → Can (at least partially) mimic the electric form factor contribution to the Rosenbluth cross section
  - Numerically ~3-4% (for SLAC kinematics and m_q~300 MeV)
  - **Motivates a more detailed calculation of 2-photon exchange at quark level**

Calculations using Generalized Parton Distributions

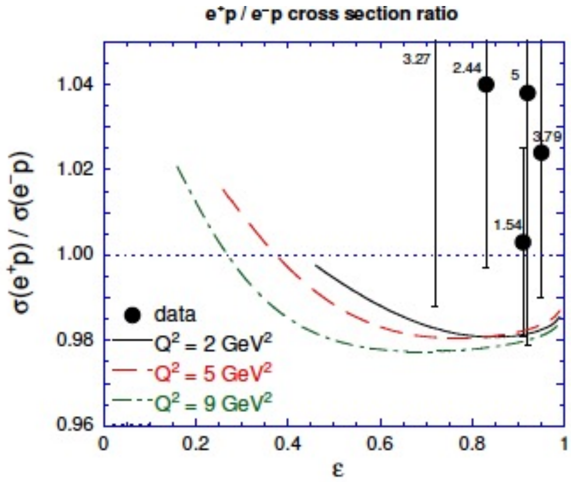


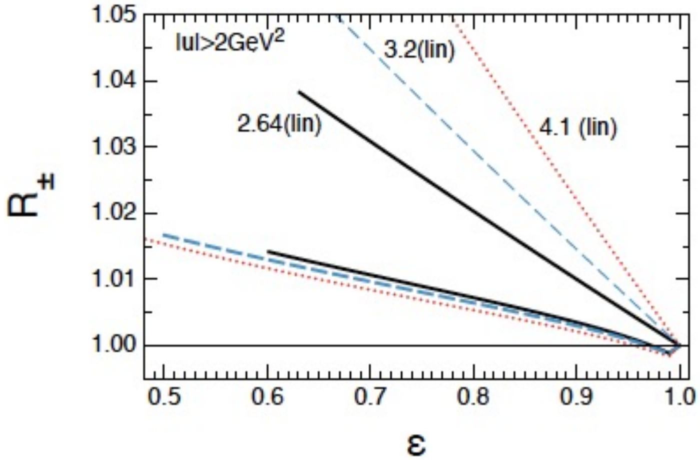
AA, Brodsky, Carlson, Chen, Vanderhaeghen,
Phys.Rev.Lett.**93**:122301,2004;

Phys.Rev.D**72**:013008,2005



Kivel, Vanderhaeghen, PRL 103 092004 (2009)





Short-range effects (AA, Brodsky, Carlson, Chen,Vanderhaeghen)

Two-photon probe directly interacts with a (massless) quark

Emission/reabsorption of the quark is described by GPDs

$$A^{2\gamma}_{eq\to eq} = \frac{e_q^2}{t}\frac{\alpha_{em}}{2\pi}(V_e \otimes V_q \times f_V + A_e \otimes A_q \times f_A)$$

$$f_V = -2[\log(-\frac{u}{s}) + i\pi]\log(-\frac{t}{\lambda^2}) - \frac{t}{2}[\frac{1}{s}(\log(\frac{u}{t}) + i\pi) - \frac{1}{u}\log(-\frac{s}{t})] +$$

$$+\frac{(u^2 - s^2)}{4}[\frac{1}{s^2}(\log^2(\frac{u}{t}) + \pi^2) + \frac{1}{u^2}\log(-\frac{s}{t})(\log(-\frac{s}{t}) + i2\pi)] + i\pi\frac{u^2 - s^2}{2su}$$

$$f_A = -\frac{t}{2}[\frac{1}{s}(\log(\frac{u}{t}) + i\pi) + \frac{1}{u}\log(-\frac{s}{t})] +$$

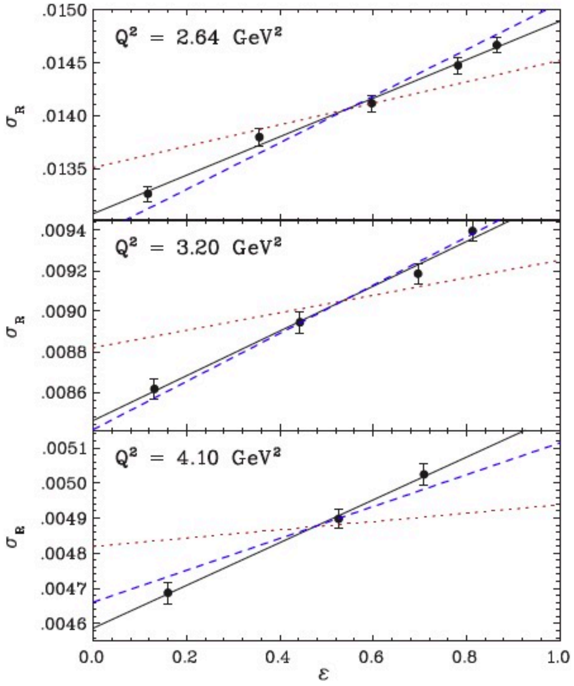
$$+\frac{(u^2 - s^2)}{4}[\frac{1}{s^2}(\log^2(\frac{u}{t}) + \pi^2) - \frac{1}{u^2}\log(-\frac{s}{t})(\log(-\frac{s}{t}) + i2\pi)] + i\pi\frac{t^2}{2su}$$

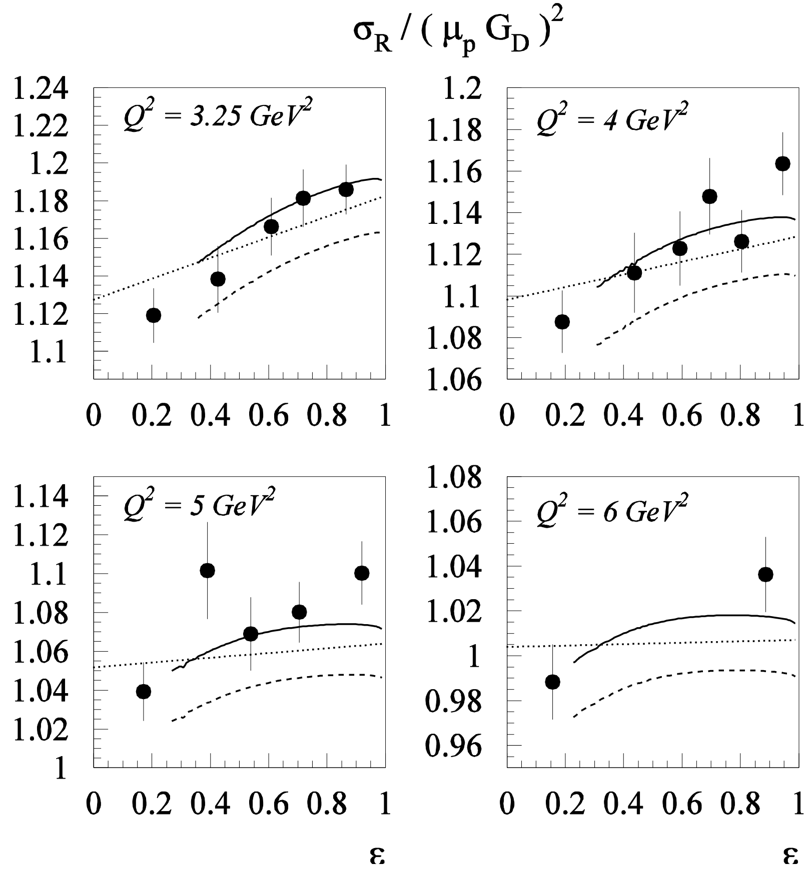
Phys.Rev.Lett.**93**:122301,2004;
Phys.Rev.D**72**:013008,2005

Note logs and double-logs

Results for cross section measurements

- New correction brings results of Rosenbluth and polarization techniques into agreement (data shown are from Andivahis et al, PRD 50, 5491 (1994)

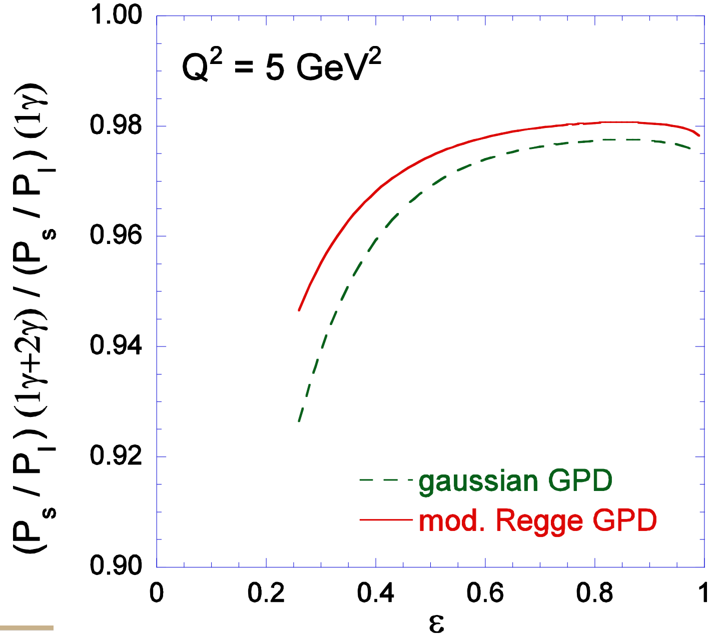




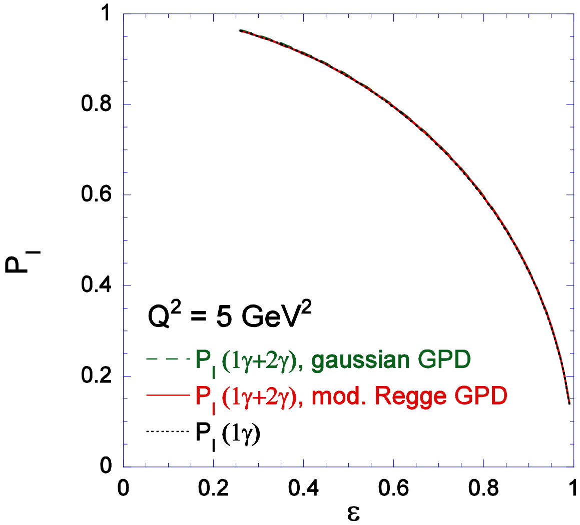
Polarization transfer

- Also corrected by two-photon exchange, but with little impact on Gep/Gmp extracted ratio

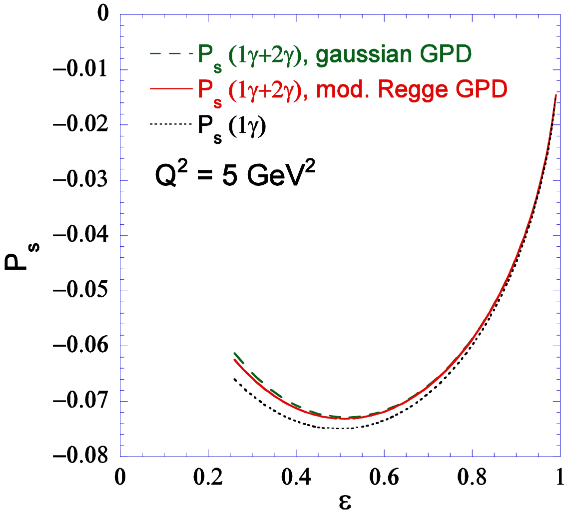
2-γ corrections to polarization ratio - proton



Longitudinal polarization - proton

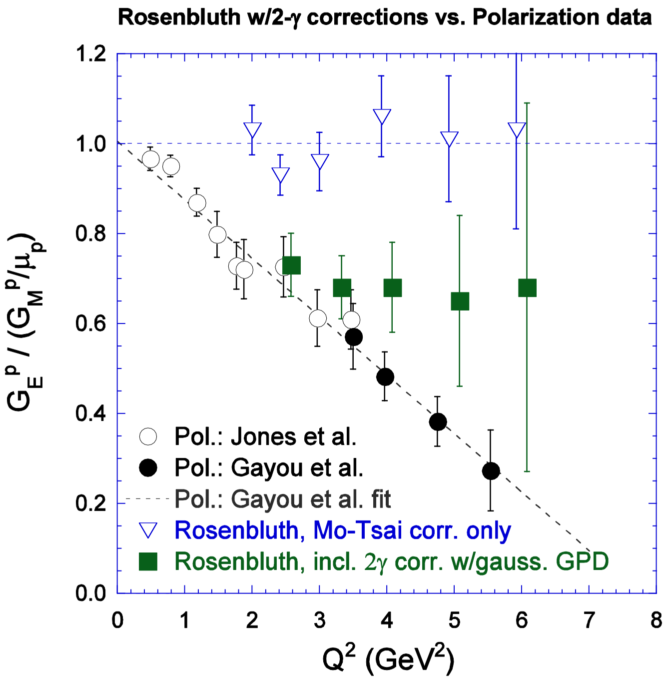


Sideways polarization - proton



Updated Ge/Gm plot

AA, Brodsky, Carlson, Chen, Vanderhaeghen,
Phys.Rev.Lett.93:122301, 2004; Phys.Rev.D72:013008, 2005



- Significant part of the discrepancy is removed by the TPE mechanism
- Verification is from the electron-positron experiments
  - VEPP: PRL 114 (2015) 6, 062005
  - CLAS: PRL 114 (2015) 6, 062003
  - OLYMPUS: PRL 118 (2017) 092501

Review: A. Afanasev, P. Blunden, D. Hassell, B. Raue,
https://arxiv.org/abs/1703.03874, Prog.Nucl.Part.Phys. **95**, 245 (2017).

Full Calculation of Bethe-Heitler Contribution

*Additional work by AA et al., using MASCARAD (**Phys.Rev.D64:113009,2001)***
Full calculation including soft and hard bremsstrahlung

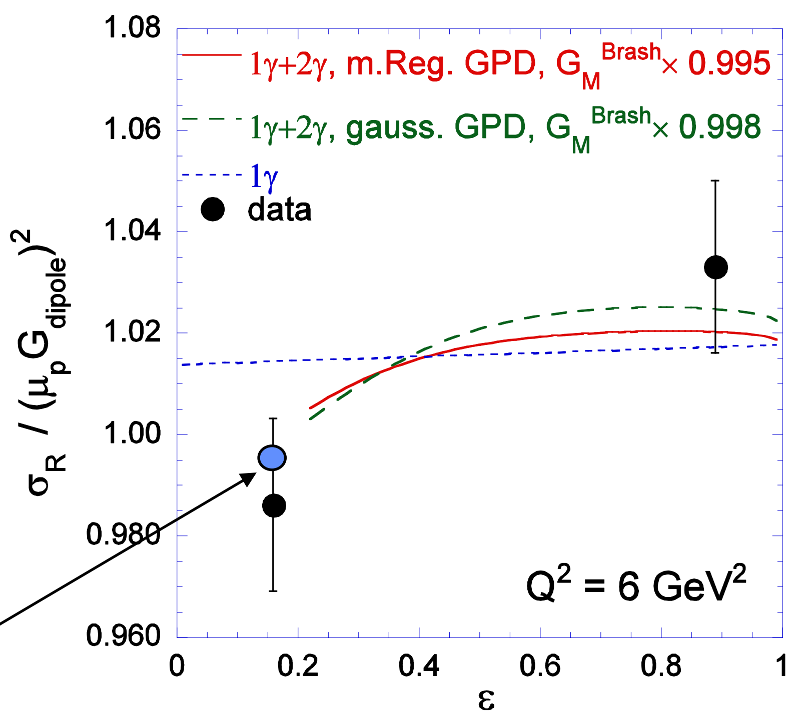
Radiative leptonic tensor in full form
AA et al, ***PLB 514, 269 (2001)***

$$L^{r}_{\mu\nu} = -\frac{1}{2} Tr(\hat{k}_2+m)\Gamma_{\mu\alpha}(1+\gamma_5\hat{\xi}_e)(\hat{k}_1+m)\overline{\Gamma}_{\alpha\nu}$$

$$\Gamma_{\mu\alpha} = \left(\frac{k_{1\alpha}}{k\cdot k_1}-\frac{k_{2\alpha}}{k\cdot k_2}\right)\gamma_\mu - \boxed{\frac{\gamma_\mu\hat{k}\gamma_\alpha}{2k\cdot k_1}-\frac{\gamma_\alpha\hat{k}\gamma_\mu}{2k\cdot k_2}}$$

$$\Gamma_{\alpha\nu} = \left(\frac{k_{1\alpha}}{k\cdot k_1}-\frac{k_{2\alpha}}{k\cdot k_2}\right)\gamma_\nu - \boxed{\frac{\gamma_\alpha\hat{k}\gamma_\nu}{2k\cdot k_1}-\frac{\gamma_\nu\hat{k}\gamma_\alpha}{2k\cdot k_2}}$$

Cross section for ep elastic scattering

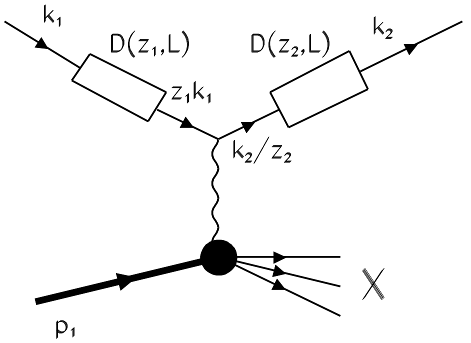


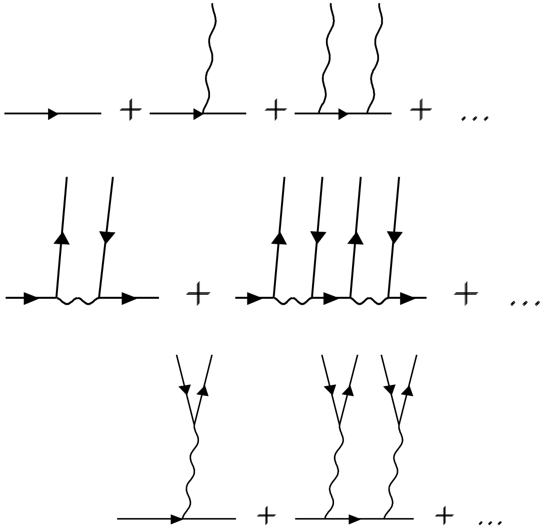
Additional effect of full soft+hard brem → +1.2% correction to ε-slope

Resolves additional ~25% of Rosenbluth/polarization discrepancy

Electron Structure Functions

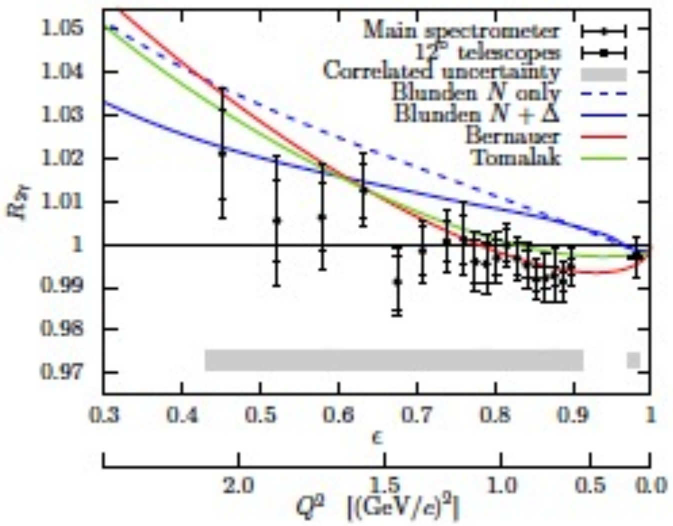
- For polarized ep->e’X scattering, AA et al, JETP 98, 403 (2004); elastic ep: AA et al. PRD 64, 113009 (2001).
  - Resummation technique for collinear photons (=peaking approx.)
  - Difference <0.5% from previous calculation including hard brem

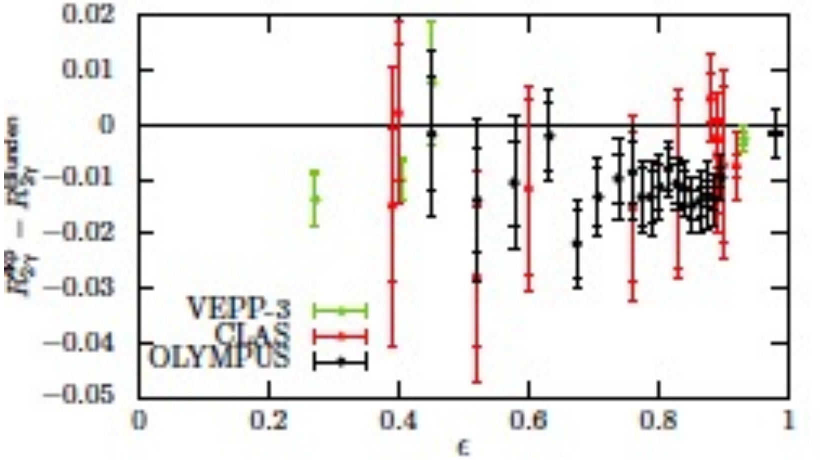




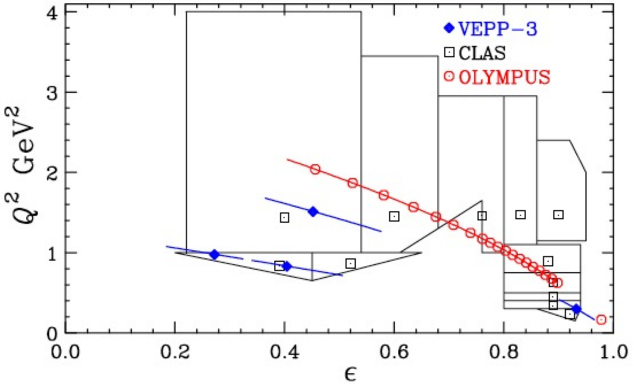
Electron/Positron Ratios

- Results from CLAS, VEPP and OLYMPUS
  - Prior results analyzed, eg, in E. Tomasi-Gustafsson, M. Osipenko, E. A. Kuraev, and Yu. Bystritsky, Phys. Atom. Nucl. 76, 937 (2013), arXiv:0909.4736
- For new discussion, see A. Afanasev et al., Prog.Nucl.Part.Phys. 95, 245 (2017)





Experiments shows nonzero TPE effects, but more data at Q2 are needed to resolve Rosenbluth-polarization puzzle



Single-Spin Asymmetries in Elastic Scattering

Parity-conserving

- Observed spin-momentum correlation of the type:

$$\vec{s} \cdot \vec{k}_1 \times \vec{k}_2$$

where $k_{1,2}$ are initial and final electron momenta, s is a polarization vector of a target OR beam

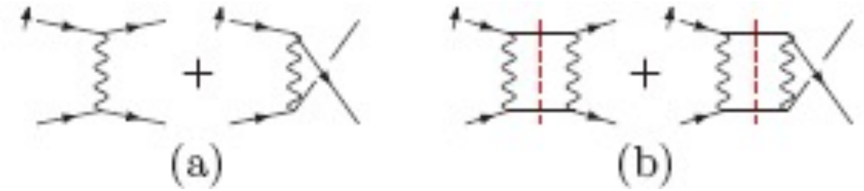
- For elastic scattering asymmetries are due to *absorptive part* of 2-photon exchange amplitude

Parity-Violating

$$\vec{s} \cdot \vec{k}_1$$

Normal Beam Asymmetry in Moller Scattering

- Pure QED process, $e^- + e^- \rightarrow e^- + e^-$
  - Barut, Fronsdal , Phys.Rev.120:1871 (1960): Calculated the asymmetry in first non-vanishing order in QED O(α)
  - Dixon, Schreiber, Phys.Rev.D69:113001,2004, Erratum-ibid.D71:059903,2005: Calculated O(α) correction to the asymmetry



$$A_n \propto \frac{2M_\gamma \,\mathrm{Im}(M_{2\gamma})}{M_\gamma^2} \xrightarrow{\sqrt{s}>>m_e} \alpha \frac{m_e}{\sqrt{s}} f(\theta)$$

SLAC E158 Results [Phys.Rev.Lett. 95 (2005) 081601]

An(exp)=7.04±0.25(stat) ppm

An(theory)=6.91±0.04 ppm

Quark+Nucleon Contributions to Target Asymmetry

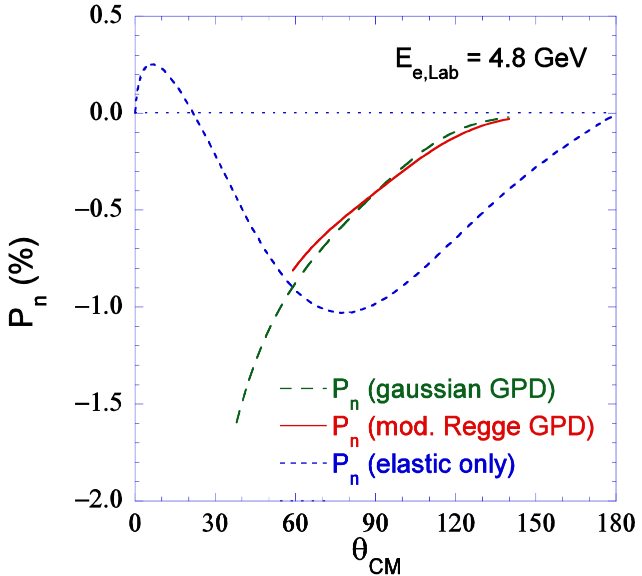
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetry of elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

$$A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_R}\left[G_E\,\mathrm{Im}(A) - \sqrt{\frac{1+\varepsilon}{2\varepsilon}}G_M\,\mathrm{Im}(B)\right]$$

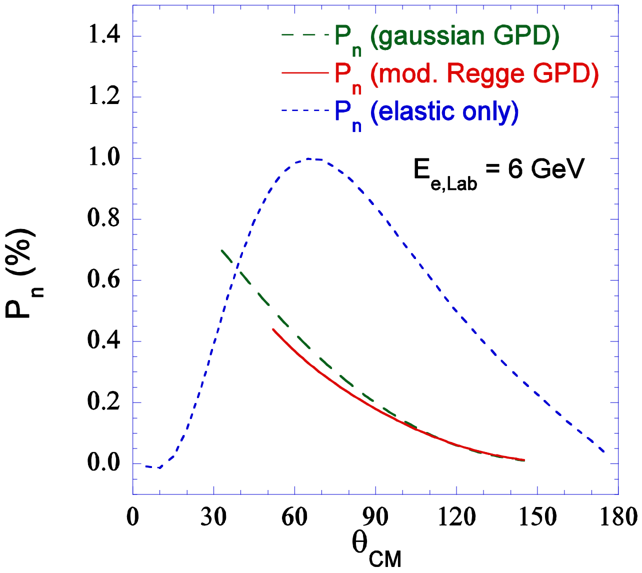
Only minor role of quark mass

No dependence on GPD $\widetilde{H}$

Normal Polarization or Analyzing Power - Neutron



Normal Polarization or Analyzing Power - Proton



Data coming from JLAB E05-015
(Inclusive scattering on normally polarized ^{3}He in Hall A)

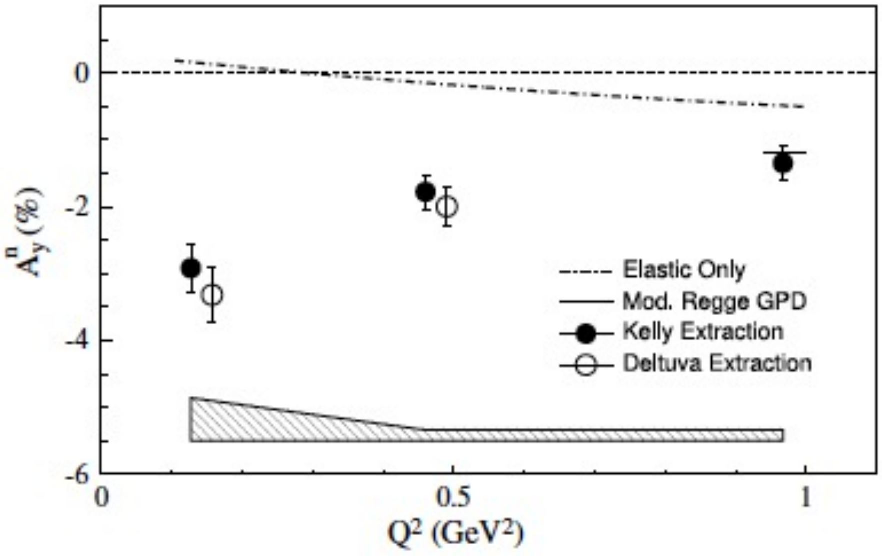
Elastic ep->ep
Quark+Nucleon Contributions to Target Asymmetry

- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetryof elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

$$A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_R}\left[G_E\,\mathrm{Im}(A) - \sqrt{\frac{1+\varepsilon}{2\varepsilon}}\,G_M\,\mathrm{Im}(B)\right]$$

Only minor role of quark mass

No dependence on GPD $\widetilde{H}$

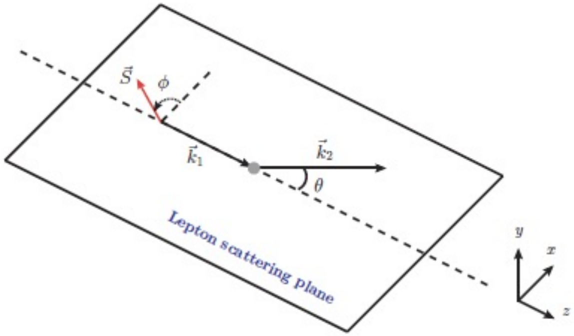


Data from JLAB E05-015 is in agreement with partonic picture.
(Inclusive scattering on normally polarized ^{3}He in Hall A)

Beam Single Spin Asymmetry

- Muons produced in pion decay are spin-polarized due to weak interactions
  - Polarizations are opposite for positive vs negative muons
  - A single-spin scattering asymmetry arises from two-photon exchange and may be a source of systematic effect in MUSE
- This effects was evaluated for MUSE kinematics by Koshchii presently at Mainz) and AA.

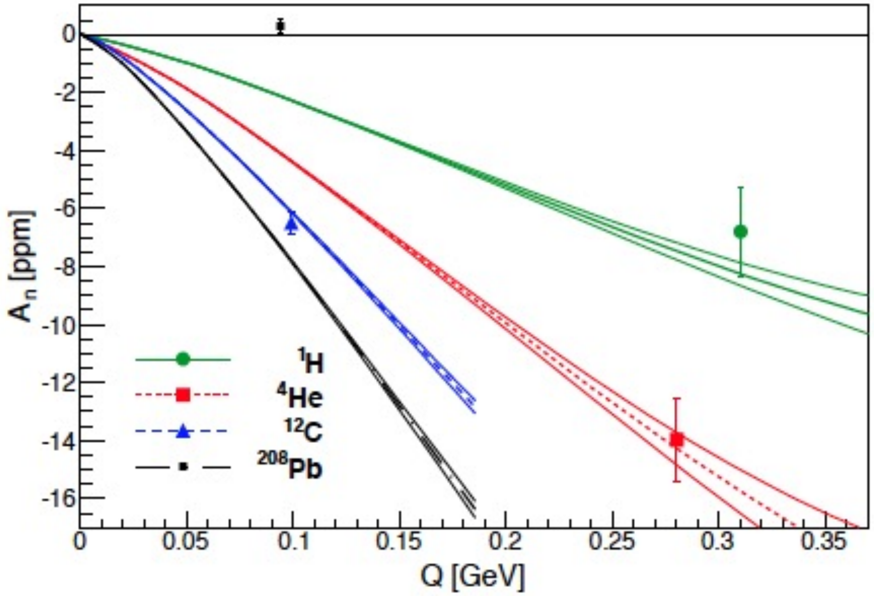
$$
\begin{aligned}
d\sigma_T(\phi) &= d\sigma_U + \frac{\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)}{|\vec{k}_1\times\vec{k}_2|}d\sigma_y \\
&= d\sigma_U + d\sigma_y \sin\phi,
\end{aligned}
$$

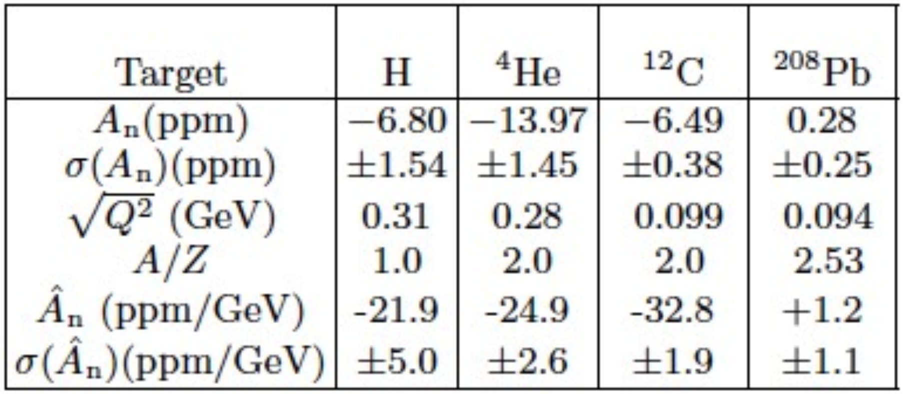


New measurements of beam SSA from Jlab on a proton arXiv:2006.12435 and Mainz arXiv:2004.14682 on 28Si and 90Zr nuclei are in good agreement with theory AA, Merenkov PRB 599, 48 (2004); Gorchtein Phys.Rev.C73:035213,2006.

Transverse Beam Asymmetries on Nuclei (HAPPEX+PREX)

- Abrahamyan et al, Phys.Rev.Lett. 109 (2012) 192501
  - Good agreement with theory for nucleon and light nuclei
  - Puzzling disagreement for ^{208}Pb measurement; if confirmed, need to include additional electron interaction with highly excited intermediate nuclear state, magnetic terms, etc (= effects of higher order in α_{em}). Interesting nuclear effect! Experimentally, need additional measurements for intermediate-mass targets (e.g., Al, Ca, Fe); Koshchii et al Phys. Rev. C 103, 064316 (+Coulomb)
- More on nuclear targets: Adhikari et al, PRL 128, 142501 (2022)





Target	H	^{4}He	^{12}C	^{208}Pb
A_n(ppm)	−6.80	−13.97	−6.49	0.28
$\sigma(A_n)$(ppm)	±1.54	±1.45	±0.38	±0.25
$\sqrt{Q^2}$ (GeV)	0.31	0.28	0.099	0.094
A/Z	1.0	2.0	2.0	2.53
$\hat{A}_n$ (ppm/GeV)	-21.9	-24.9	-32.8	+1.2
$\sigma(\hat{A}_n)$(ppm/GeV)	±5.0	±2.6	±1.9	±1.1

Comparing with positrons can help to understand disagreement or ^{208}Pb

New data from Jlab: what is wrong with ^{208}Pb theory????

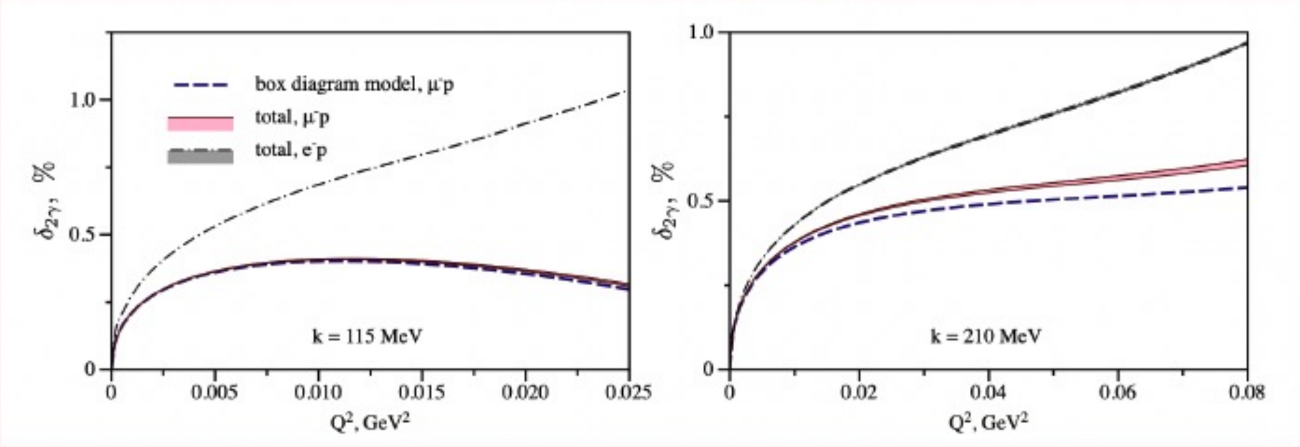
RadCor and TPE for MUSE experiments at PSI

- Radiative corrections show significant difference between electron and muon scattering in MUSE, must be properly accounted for
- Radiative corrections calculated to be about 1-1.5% for muons and varies from -4% to +3% for electrons
  - Uncertainties mainly from acceptances, need to include in detector simulations (Monte Carlo generator of radiative events was developed for MUSE) . Theory uncertainties <0.1% (muons), <0.5% (electrons)
- Two-photon exchange <1% (electrons), <0.5% (muons), ~0.01%(inelastic excitations)
- Two-photon effects can be studied directly in the ratio of μ+ and μ- , e^+ and e^- cross sections; TPE cancel in the sum of particle+antiparticle cross sections

THE GEORGE
WASHINGTON
UNIVERSITY
WASHINGTON, DC

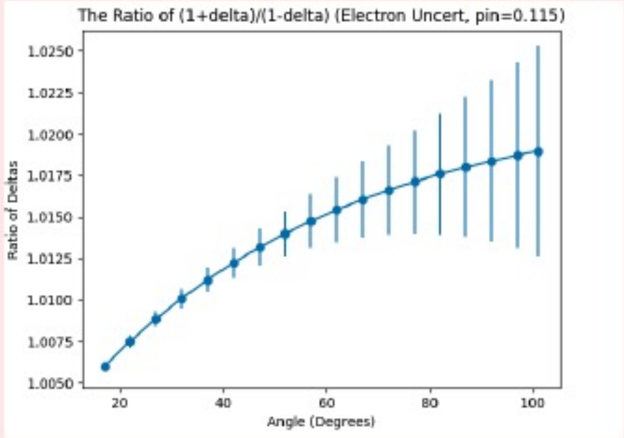
TPE Estimates for MUSE

TPE Calculations for MUSE kinematics

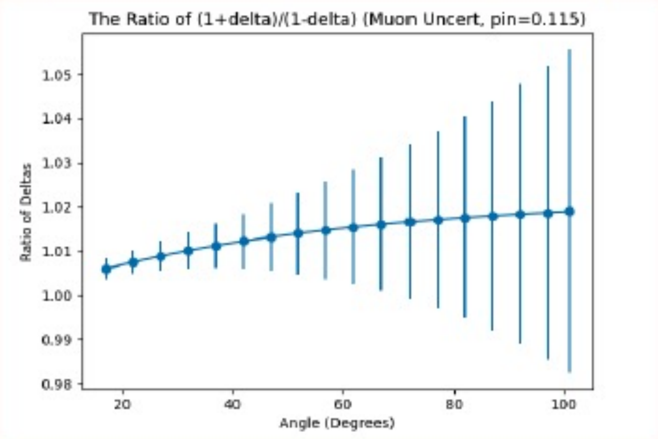


*O. Tomalak, Few-Body Systems, 59, 87 (2018)

Estimated uncertainty of TPE effect for ep scattering



Estimated uncertainty of TPE effect for μp scattering



* Plots by T. Honablew

The e+@Jlab Topical Issue (EPJ A)

- https://epja.epj.org/component/toc/?task=topic&id=1430

The European Physical Journal A

An Experimental Program with Positron Beams at Jefferson Lab

Nicolas Alamanos, Marco Battaglieri, Douglas Higinbotham, Silvia Niccolai, Axel Schmidt and Eric Voutier (Guest Editors)

☐ Open Access

Editorial

Topical issue on an experimental program with positron beams at Jefferson Lab
Nicolas Alamanos, Marco Battaglieri, Douglas Higinbotham, Silvia Niccolai, Axel Schmidt and Eric Voutier
Published online: 14 March 2022
DOI: 10.1140/epja/s10050-022-00699-6
Abstract | PDF (197.6 KB)

☐ Open Access

Two photon exchange with nuclei from e^+/e^- elastic cross section ratios
T. Kutz and A. Schmidt
Published online: 28 February 2022
DOI: 10.1140/epja/s10050-022-00682-1
Abstract | PDF (287.9 KB)

☐ **A measurement of two-photon exchange in Super-Rosenbluth separations with positron beams**
John R. Arrington and Mikhail Yurov
Published online: 29 November 2021
DOI: 10.1140/epja/s10050-021-00633-2
Abstract | PDF (752.7 KB)

☐ **Virtual Compton scattering at low energies with a positron beam**
Barbara Pasquini and Marc Vanderhaeghen
Published online: 22 November 2021
DOI: 10.1140/epja/s10050-021-00630-5
Abstract | PDF (1.142 MB)

☐ **Probing charged lepton flavor violation with a positron beam at CEBAF (JLAB)**
Y. Furletova and S. Mantry
Published online: 22 November 2021
DOI: 10.1140/epja/s10050-021-00624-3
Abstract | PDF (726.8 KB)

☐ **Deep-inelastic scattering with positron beams**
W. Melnitchouk and J. F. Owens
Published online: 11 November 2021
DOI: 10.1140/epja/s10050-021-00622-5
Abstract | PDF (1.066 MB)

☐ **Deeply virtual Compton scattering using a positron beam in Hall-C at Jefferson Lab**
A. Afanasev, I. Albayrak, S. Ali, M. Amaryan, J. R. M. Annand, A. Asaturyan, V. Bellini, V. V. Berdnikov, M. Boer, K. Brinkmann et al. (64 more)
Published online: 29 October 2021
DOI: 10.1140/epja/s10050-021-00581-x
Abstract | PDF (2.691 MB)

☐ **Direct TPE measurement via e^+p/e^-p scattering at low ε in Hall A**
Ethan Cline, Jan C. Bernauer and Axel Schmidt
Published online: 18 October 2021
DOI: 10.1140/epja/s10050-021-00597-3
Abstract | PDF (1.071 MB)

☐ **Radiative corrections to the lepton current in unpolarized elastic *lp*-interaction for fixed Q^2 and scattering angle**
A. Afanasev and A. Ilyichev
Published online: 30 September 2021
DOI: 10.1140/epja/s10050-021-00582-w
Abstract | PDF (529.9 KB)

The e+@Jlab Topical Issue (EPJ A), continued

Deeply virtual Compton scattering off Helium nuclei with positron beams
Sara Fucini, Mohammad Hattawy, Matteo Rinaldi and Sergio Scopetta
Published online: 15 September 2021
DOI: 10.1140/epja/s10050-021-00580-y
Abstract | PDF (547.3 KB)

An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab
A. Accardi, A. Afanasev, I. Albayrak, S. F. Ali, M. Amaryan, J. R. M. Annand, J. Arrington, A. Asaturyan, H. Atac, H. Avakian et al. (220 more)
Published online: 28 August 2021
DOI: 10.1140/epja/s10050-021-00564-y
Abstract | PDF (1.318 MB)

Light dark matter searches with positrons
M. Battaglieri, A. Bianconi, P. Bisio, M. Bondì, A. Celentano, G. Costantini, P. L. Cole, L. Darmé, R. De Vita, A. D'Angelo et al. (21 more)
Published online: 11 August 2021
DOI: 10.1140/epja/s10050-021-00524-6
Abstract | PDF (832.8 KB)

Impact of a positron beam at JLab on an unbiased determination of DVCS Compton form factors
H. Dutrieux, V. Bertone, H. Moutarde and P. Sznajder
Published online: 05 August 2021
DOI: 10.1140/epja/s10050-021-00560-2
Abstract | PDF (1.491 MB)

Double deeply virtual Compton scattering with positron beams at SoLID
S. Zhao, A. Camsonne, D. Marchand, M. Mazouz, N. Sparveris, S. Stepanyan, E. Voutier and Z. W. Zhao
Published online: 19 July 2021
DOI: 10.1140/epja/s10050-021-00551-3
Abstract | PDF (3.624 MB)

Deeply virtual Compton scattering on the neutron with positron beam
S. Niccolai, P. Chatagnon, M. Hoballah, D. Marchand, C. Munoz Camacho and E. Voutier
Published online: 08 July 2021
DOI: 10.1140/epja/s10050-021-00541-5

Target-normal single spin asymmetries measured with positrons
G. N. Grauvogel, T. Kutz and A. Schmidt
Published online: 29 June 2021
DOI: 10.1140/epja/s10050-021-00531-7
Abstract | PDF (444.2 KB)

Elastic positron–proton scattering at low Q_2
Tyler J. Hague, Dipangkar Dutta, Douglas W. Higinbotham, Xinzhan Bai, Haiyan Gao, Ashot Gasparian, Kondo Gnanvo, Vladimir Khachatryan, Mahbub Khandaker, Nilanga Liyanage et al. (4 more)
Published online: 19 June 2021
DOI: 10.1140/epja/s10050-021-00508-6
Abstract | PDF (1.674 MB)

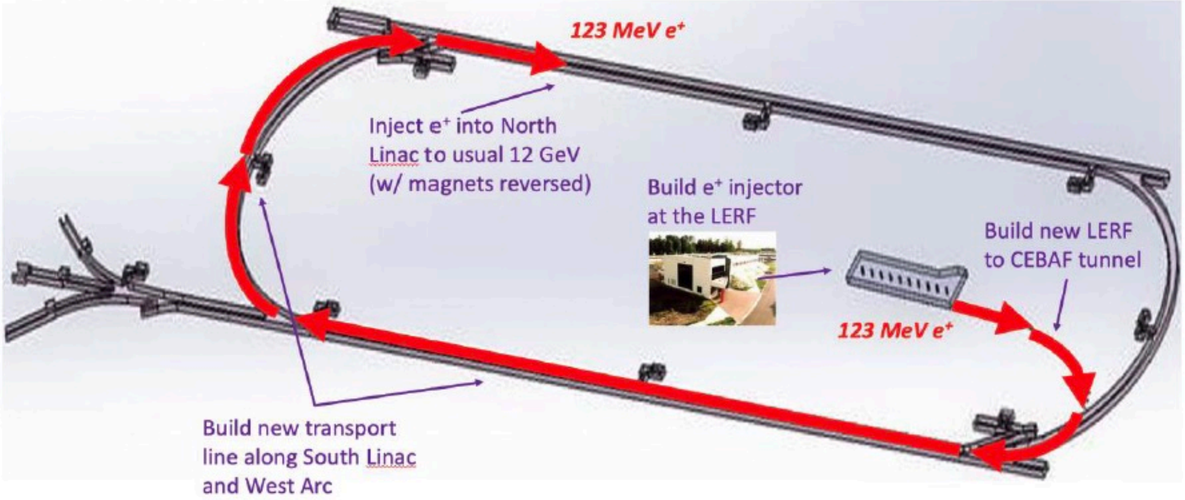
Polarization transfer in $e^+p \to e^+p$ scattering using the Super BigBite Spectrometer
A. J. R. Puckett, J. C. Bernauer and A. Schmidt
Published online: 09 June 2021
DOI: 10.1140/epja/s10050-021-00509-5
Abstract | PDF (500.2 KB)

Beam charge asymmetries for deeply virtual Compton scattering off the proton
V. Burkert, L. Elouadrhiri, F.-X. Girod, S. Niccolai, E. Voutier, A. Afanasev, L. Barion, M. Battaglieri, J. C. Bernauer, A. Bianconi et al. (50 more)
Published online: 08 June 2021
DOI: 10.1140/epja/s10050-021-00474-z
Abstract | PDF (3.413 MB)

Accessing weak neutral-current coupling g_{AA}^{eq} using positron and electron beams at Jefferson Lab
Xiaochao Zheng, Jens Erler, Qishan Liu and Hubert Spiesberger
Published online: 27 May 2021
DOI: 10.1140/epja/s10050-021-00490-z
Abstract | PDF (647.0 KB)

Determination of two-photon exchange via e^+p/e^-p scattering with CLAS12
Jan C. Bernauer, Volker D. Burkert, Ethan Cline, Axel Schmidt and Youri Sharabian
Published online: 23 April 2021
DOI: 10.1140/epja/s10050-021-00462-3

Positrons at Jlab
See https://indico.jlab.org/event/680/ for the latest info



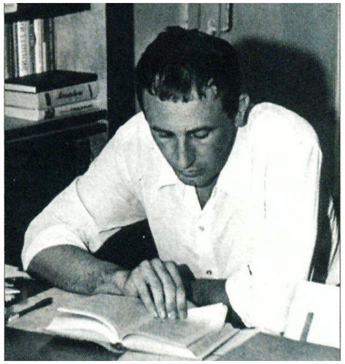
Machine Parameter	Electrons	Positrons
Hall Multiplicity	4	1 or more
Max. Energy (ABC/D)	11/12 GeV	11/12 GeV
Beam Repetition	249.5/499 MHz	249.5/499/1497 MHz
Duty Factor	100% cw	100% cw
Unpolarized Intensity	170 μA**	> 1 μA
Polarized Intensity	170 μA**	> 50 nA
Beam Polarization	> 85%	> 60%

** Total beam power at Jefferson Lab is limited to 1.1 MW with a max. of 0.9 MW to individual high power dumps.

Summary

- Nucleon form factors provide information on the structure of nucleons, their composition in terms of strongly-interacting quarks and QCD
- Measurements of the form factors are possible by two methods: using polarization or unpolarized cross sections
  - However, experimental data obtained with these two methods appeared in conflict with each other
  - Experiments using positron beams provided comparison with electron-scattering data and indicated presence of higher-order QED corrections (two-photon exchange) that are responsible for the discrepancy
- Current programs for nucleon-structure studies with electron and muon probes incorporate detailed analysis and computations of QED radiative corrections at a sub-per cent level

A.I. Akhiezer



M.P. Rekalo

THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC