Title: High-order corrections to low energy e-p and mu-p scattering

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Abstract:

Higher-Order QED Corrections to Low-Energy e-p and mu-p Scattering

Andrei Afanasev

The George Washington University, Washington, DC, USA

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Plan of talk

Radiative corrections for charged lepton scattering

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

Two-photon exchange effects

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

Summary

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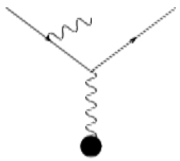
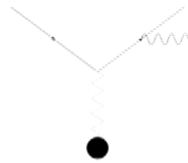
Basics of QED radiative corrections

(First) Born approximation

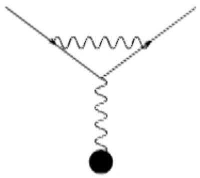


Initial-state radiation



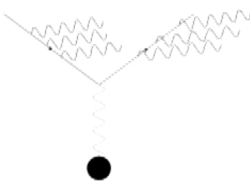
Final-state radiation

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

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

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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).

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Elastic Nucleon Form Factors

•Based on one-photon exchange approximation

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

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

•Two techniques to measure

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

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

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

$$(P_y = 0)$$

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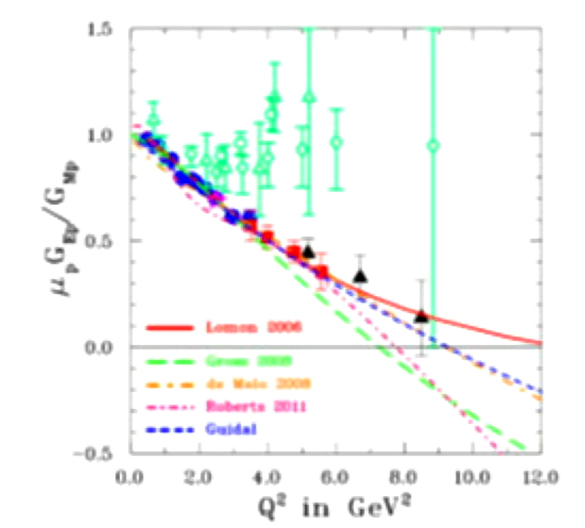
Measuring Proton Form Factors



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).

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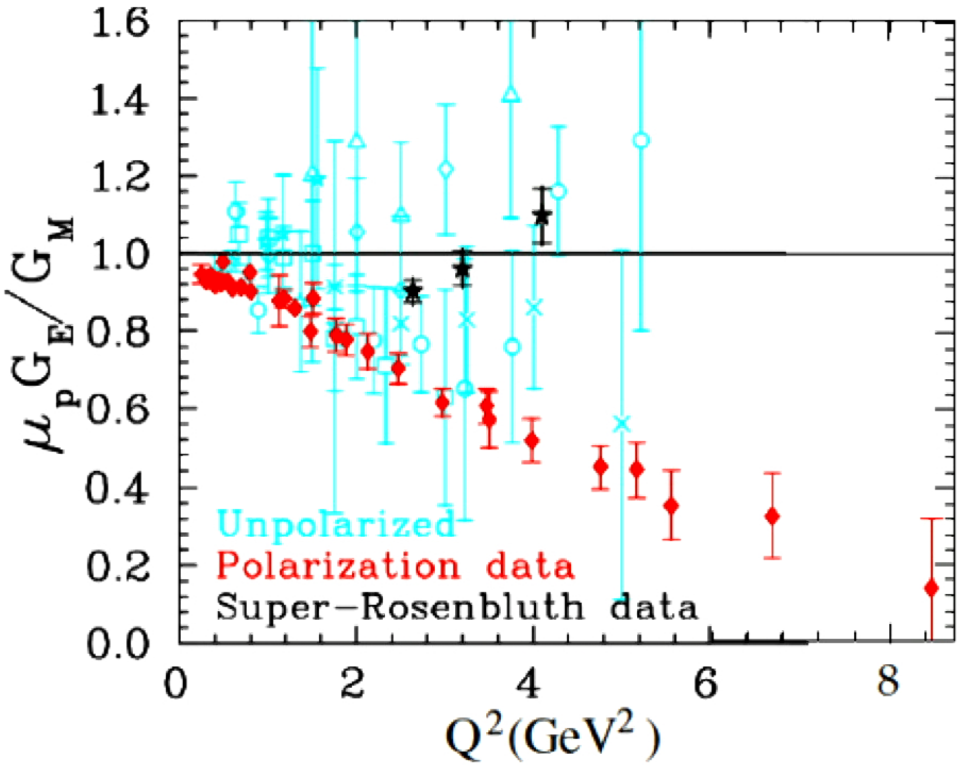
Ge/Gm Ratio: Polarization vs Rosenbluth



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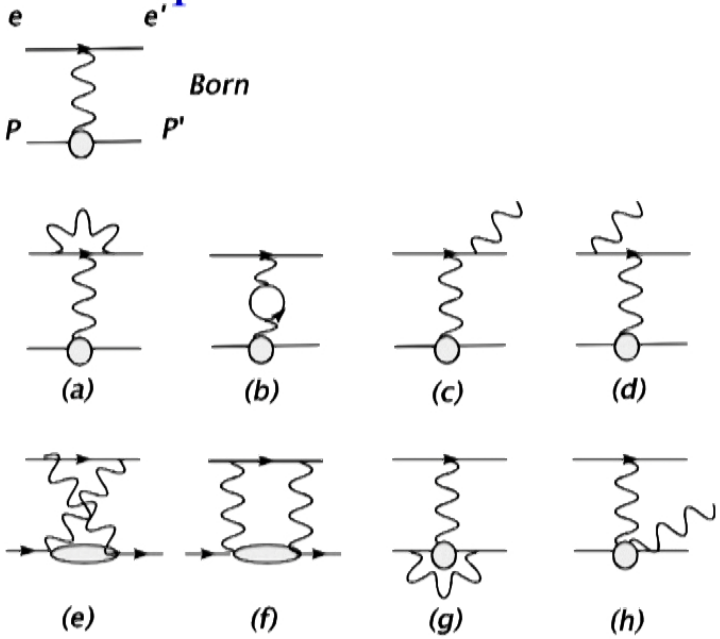
Andrei Afanasev, Radiative Corrections at the Intensity Frontier, Perimeter Institute, 14 June 2017

Complete radiative correction in O(α_{em})



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;

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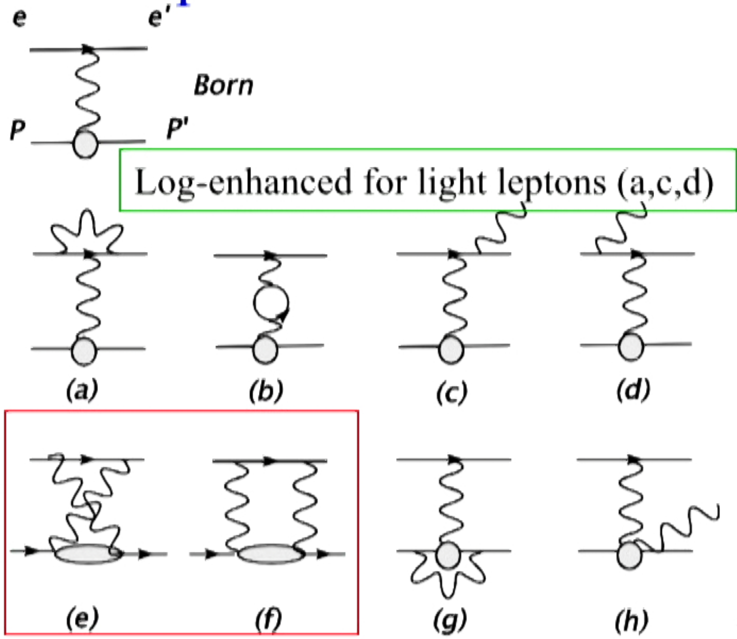

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•Guichon&Vanderhaeghen'03:
Can (e-f) account for the Rosenbluth vs. polarization experimental discrepancy? Look for ~3% ...

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

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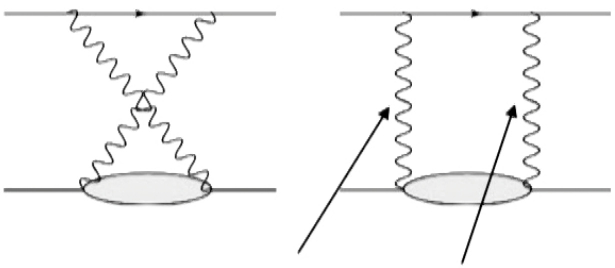
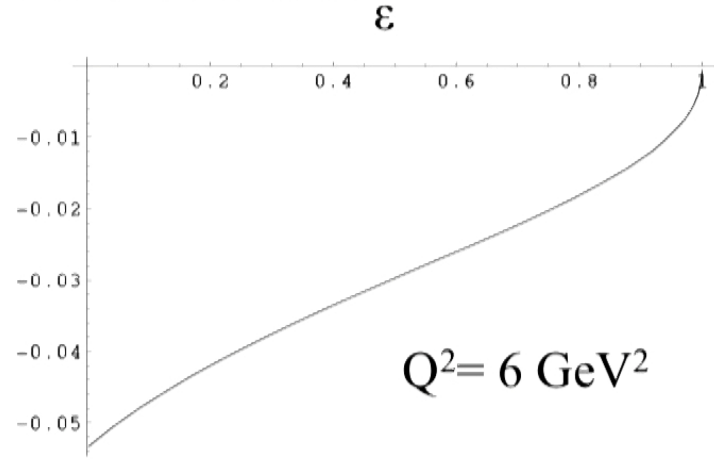
Separating *soft* 2-photon exchange

- Tsai; Maximon & Tjon ($k \to 0$); 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 for elastic ep**
  - Also done for pion electroproduction in AA, Aleksejevs, Barkanova, Phys.Rev. D88 (2013) 5, 053008 (inclusion of lepton masses is straightforward)





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Lepton mass is not essential for TPE calculation in ultra-relativistic case; Two-photon effect below 1% for lower energies and $Q^2 < 0.1 GeV^2$

General Analysis of ep->ep (including 2-photon exchange)

- Reaction e(1/2,λ_1)+p(1/2,h_1)->e(1/2,λ_2)+p(1/2,h_2) => 16 possible helicity combinations
- Parity: $T_{\lambda_1 h_1}^{\lambda_2 h_2} = (-1)^{(\lambda_1 - h_1)-(\lambda_2 - h_2)} T_{-\lambda_1 - h_1}^{-\lambda_2 - h_2}$

  $\Longrightarrow$8 amplitudes

  - Time-reversal: $T_{\lambda_1 h_1}^{\lambda_2 h_2} = (-1)^{(\lambda_1 - h_1)-(\lambda_2 - h_2)} T_{-\lambda_2 - h_2}^{-\lambda_1 - h_1}$

  =>6 amplitudes

  Independent helicity amplitudes:

$$A_1 = T_{\frac{1}{2}\frac{1}{2}}^{\frac{1}{2}\frac{1}{2}}, A_2 = T_{\frac{1}{2}-\frac{1}{2}}^{\frac{1}{2}-\frac{1}{2}}, A_3 = T_{\frac{1}{2}-\frac{1}{2}}^{\frac{1}{2}\frac{1}{2}},$$

$$A_4 = T_{\frac{1}{2}\frac{1}{2}}^{-\frac{1}{2}\frac{1}{2}}, A_5 = T_{\frac{1}{2}\frac{1}{2}}^{-\frac{1}{2}-\frac{1}{2}}, A_6 = T_{\frac{1}{2}-\frac{1}{2}}^{-\frac{1}{2}\frac{1}{2}},$$

$$for\ m_e = 0,\ A_{4-6} = 0$$

$$\sigma = N(|A_1|^2 + |A_2|^2 + 2|A_3|^2 + 2|A_4|^2 + |A_5|^2 + |A_6|^2)$$

$$\sigma P_y = 2N\,\mathrm{Im}(F), \quad \sigma P_x = 2N\,\mathrm{Re}(F)$$

$$F = (A_1 + A_2)A_3^* + A_4(A_6^* - A_5^*),$$

$$\sigma P_z = N(|A_1|^2 - |A_2|^2 + |A_5|^2 - |A_6|^2)$$

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

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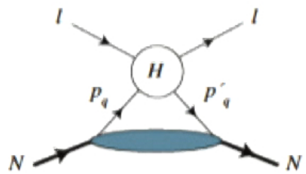
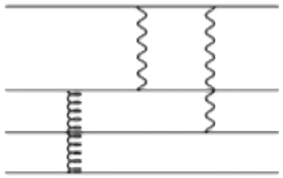
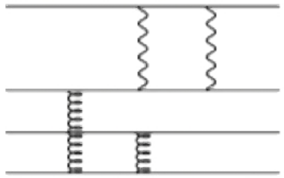
Calculations using Generalized Parton Distributions



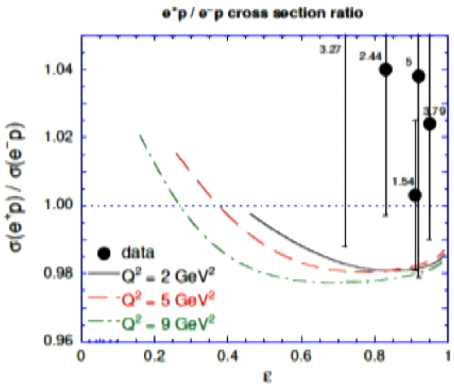


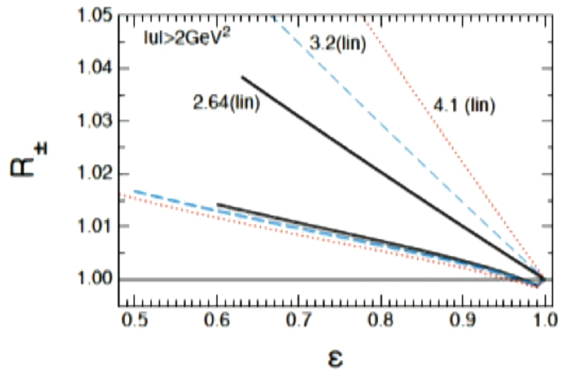


AA, Brodsky, Carlson, Chen, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004;

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

Kivel, Vanderhaeghen, PRL 103 092004 (2009)





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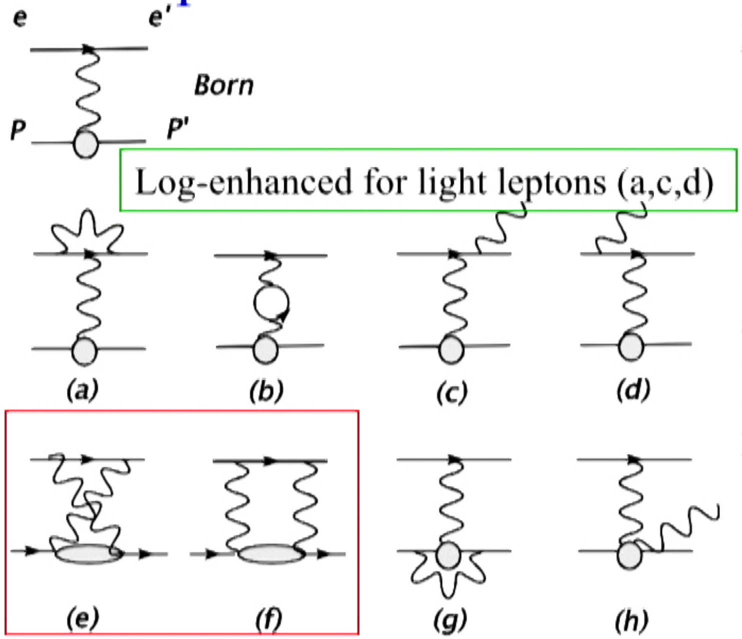
Complete radiative correction in $O(\alpha_{em})$



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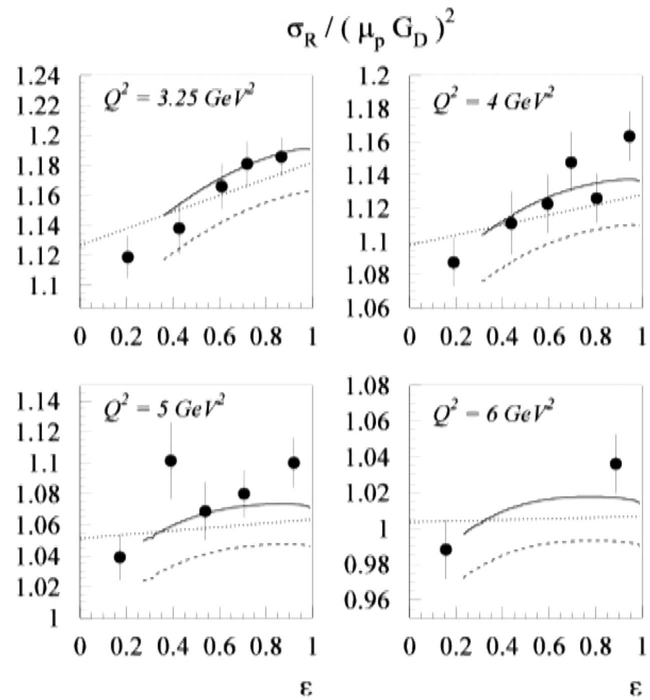
Results for cross section measurements

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



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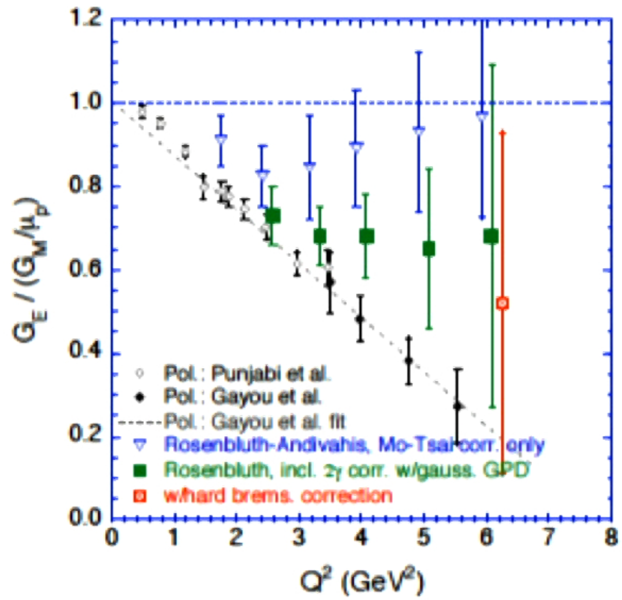
Updated Ge/Gm plot

AA, Brodsky, Carlson, Chen, Vanderhaeghen,
Phys.Rev.Lett.93:122301, 2004; Phys.Rev.D72:013008, 2005
Review: Carlson, Vanderhaeghen, Ann.Rev.Nucl.Part.Sci. 57 (2007) 171-204



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

Recent review: A. Afanasev, P. Blunden, D. Hassell, B. Raue, https://arxiv.org/abs/1703.03874, Prog.Nucl.Part.Phys. June 2017.

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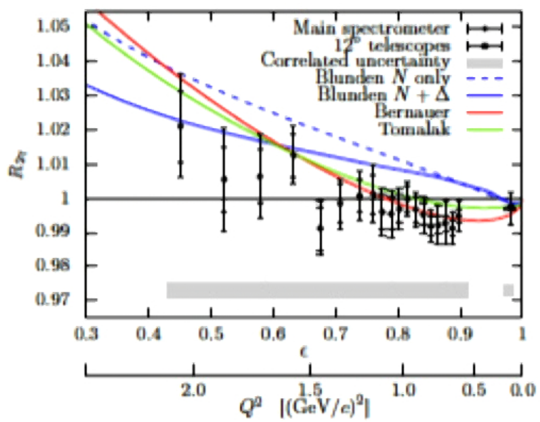
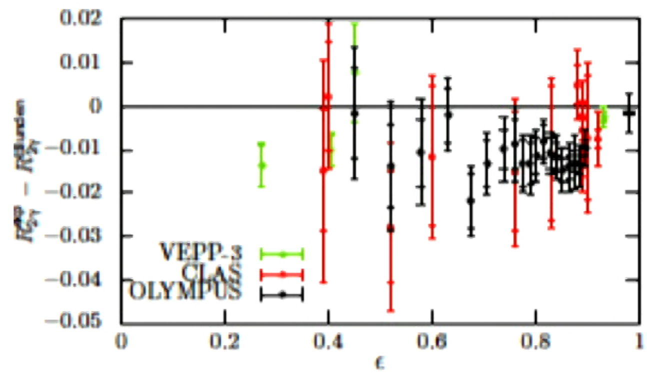
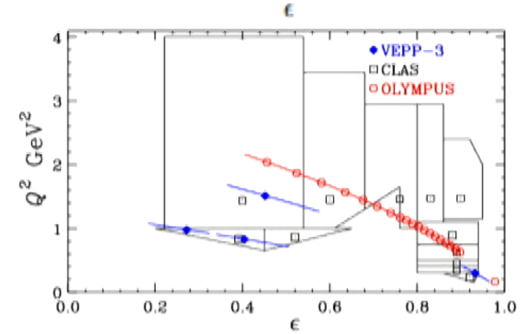
Electron/Positron Ratios

- Recent 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., https://arxiv.org/abs/1703.03874, Prog.Nucl.Part.Phys. June 2017.







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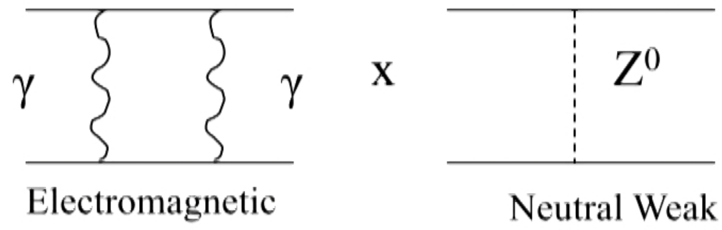
2γ-exchange Correction to Parity-Violating Electron Scattering



- Parity violating terms due to (2gamma)x(Z^0) interference should be added:

$$\mathrm{Re}\, A^{\gamma}_{AA} A^{Z}_{AV} \propto (-\tfrac{1}{2})\sqrt{\tau(1+\tau)(1-\varepsilon^2)}\,\mathrm{Re}(G^{\gamma}_{A} G^{Z}_{M})\lambda_e$$

$$\mathrm{Re}\, A^{\gamma}_{AA} A^{Z}_{VA} \propto (-\tfrac{1}{2})(1-4\sin^2\theta_W)(1+\tau)\,\mathrm{Re}(G^{\gamma}_{A} G^{Z}_{A})\lambda_e$$

AA, C.E. Carlson, Phys.Rev.Lett. 94 (2005) 212301

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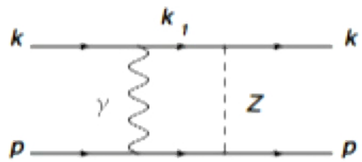
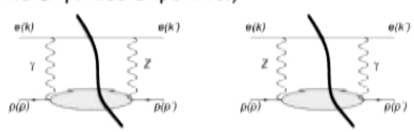
Two-boson box for Parity-Violating Electron Scattering
(as presented by C. E. Carlson)



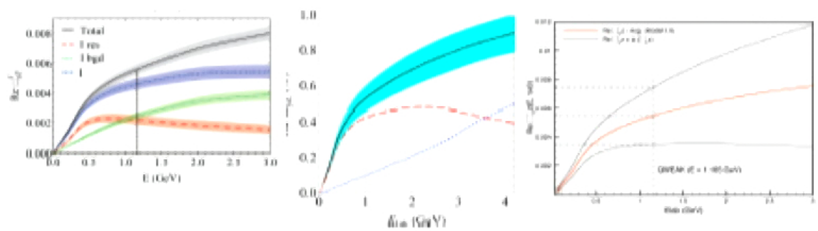
Gorchtein and Horowitz (PRL 102, 091806 (2009)) had insight to calculate the amplitude dispersively



DR → calculate whole amplitude form imaginary part.

Imaginary part comes when intermediate states on shell.

Hall *et al.* PRD 88, 013011 (2013)	Carlson and Rislow PRD 83, 113007 (2011)	Gorchtein *et al.* PRC 84, 015502 (2011)



$$\mathrm{Re}\square^{V}_{\gamma Z}(E = 1.165\ \mathrm{GeV})$$

$(5.6 \pm 0.36) \times 10^{-3}$	$(5.7 \pm 0.9) \times 10^{-3}$	$(5.4 \pm 2.0) \times 10^{-3}$

- Central values close
- Differences come from the treatment of the structure functions

- About (8.1±1.4)% of Q_W^p at E_{elec}=1.165 GeV. Proportional to E_{elec}.
- About (6.3±0.6%) of Q_W^p at E_{elec} threshold. Small dependence on E_{elec}. Might still like to improve.

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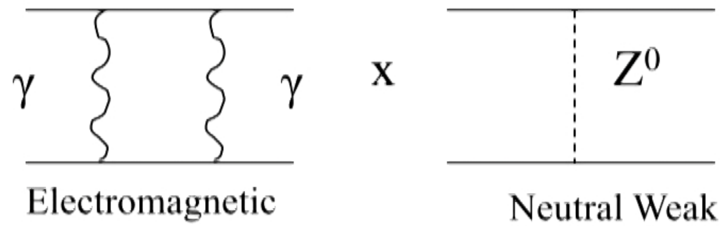

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AA, C.E. Carlson, Phys.Rev.Lett. 94 (2005) 212301

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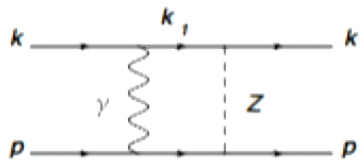

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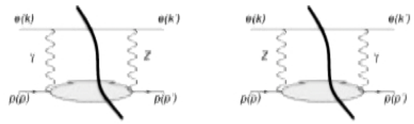

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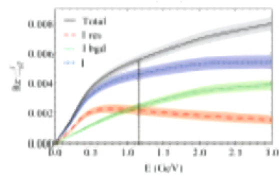

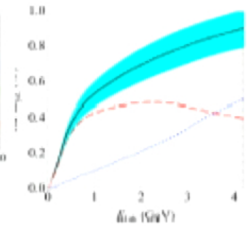

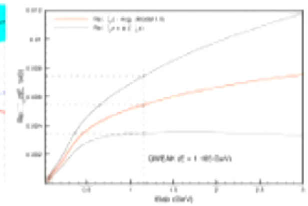

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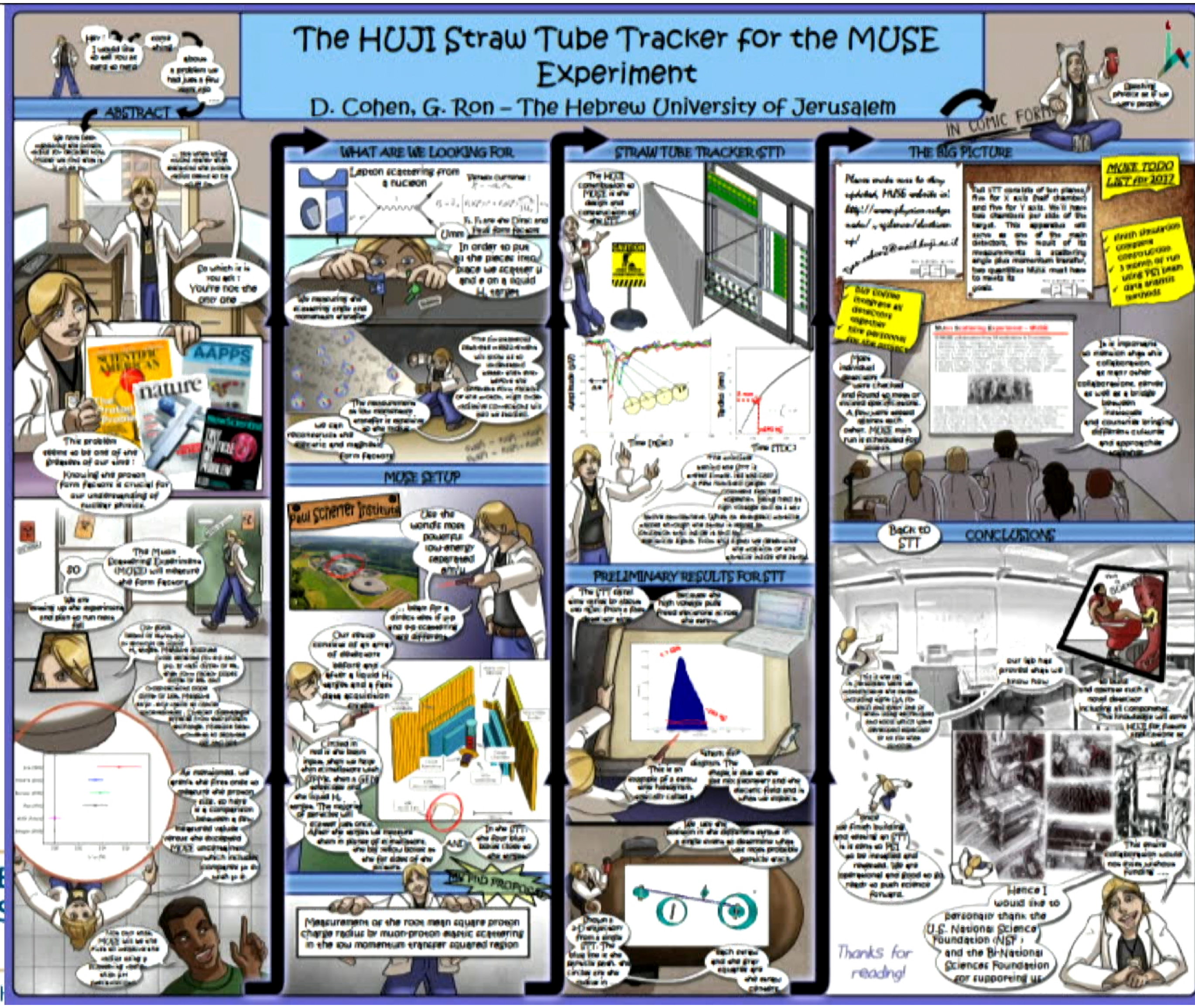

The HUJI Straw Tube Tracker for the MUSE Experiment
D. Cohen, G. Ron – The Hebrew University of Jerusalem
IN COMIC FORM
ABSTRACT
WHAT ARE WE LOOKING FOR
Lepton scattering from a nucleon
In order to put all the pieces into place we scatter μ and e on a liquid H₂ target
STRAW TUBE TRACKER (STT)
THE BIG PICTURE
MUSE SETUP
Paul Scherrer Institut
PRELIMINARY RESULTS FOR STT
Back to STT
CONCLUSIONS
Measurement of the root mean square proton charge radius by muon-proton elastic scattering in the low momentum transfer squared region
Hence I would like to personally thank the U.S. National Science Foundation (NSF) and the Bi-National Science Foundation for supporting us
Thanks for reading!

Lepton Mass Effects

- Standard approximations keep the lepton mass in the logarithms but neglect it in power terms. May be justified in the ultrarelativistic case and Q^2>>(lepton mass)^2
- Most of analysis codes use exact mass dependence for hard brem, but use above approximations for the "soft" part of brem correction
- Revised approach is required that will NOT result in new theoretical uncertainties
- New rad.correction codes no longer use peaking approximation (justified for relatively small lepton masses)
- Formalism and Monte-Carlo generators can be adapted for this analysis (ELRADGEN; MASCARAD, etc;

more on www.jlab.org/RC); HAPRAD for SIDIS of muons

- Corrections revised with mass effects included: Koschii, AA, Phys.Rev. D94 (2016) no.11, 116007(arXiv:1608.01991) and arXiv:1705.00338

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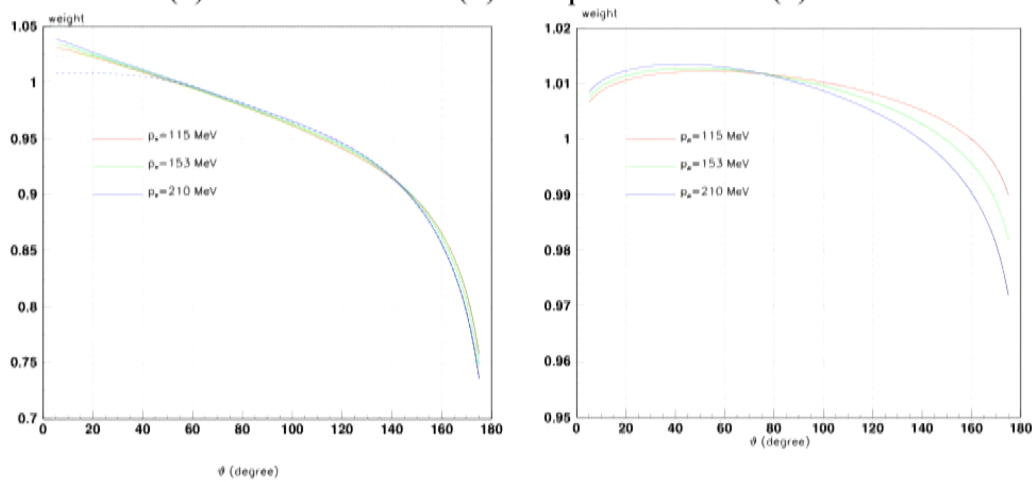
ELRADGEN Results for 100MeV-beams

MUSE: Proposed experiment at PSI to measure proton charge radius in elastic scattering of muons, arXiv:1303.2160

- Ilyichev (Minsk) and AA: updated ELRADGEN Monte Carlo (Afanasev et al., Czech. J. Phys. 53 (2003) B449; Akushevich et al., Comput. Phys. Commun. 183 (2012) 1448) to include (a) mass effects and (b) two-photon effects (c) hard brem included



Left: Radiative correction for elastic electron-proton scattering as a function of lab scattering angle in MUSE kinematics. Dashed lines show the effect of a kinematic cut. Right: Same result but for the scattering of muons.

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Helicity-Flip in TPE; estimate of inelastic contribution

- New dynamics from scalars (σ, f-mesons). No pseudo-scalar contribution for unpolarized particles
- Scalar t-channel exchange contributes to TPE (no longer setting m_{lepton} to zero!)

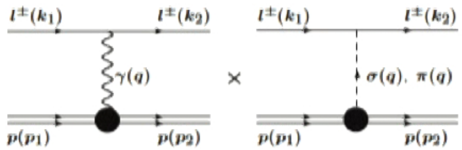
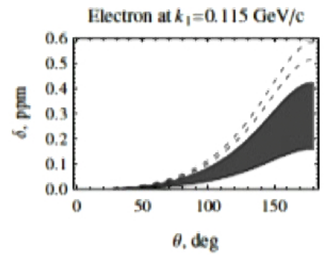
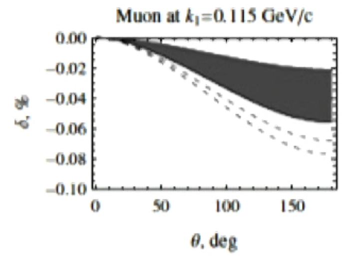


FIG. 1. One-photon and one σ (π) meson exchange diagrams





- No information on $F_{\sigma\mu\mu}$ coupling is available. Need model estimates.
- Theory analysis by AA, Koshchii, Phys.Rev. D 94, 116007 (2016).

Can be studied directly in the ratio of μ+ and μ- cross sections

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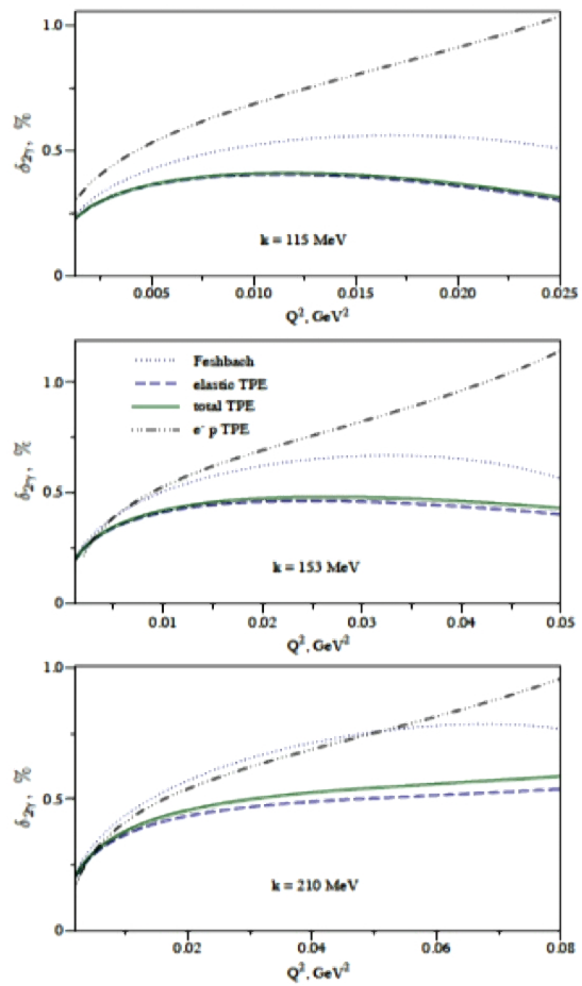
Inelastic+Elastic

- Tomalak, Vanderhaeghen, arXiv:1512.09113Eur. Phys. J. C 76, no. 3, 125 (2016)

Both inelastic and elastic contributions included

Elastic TPE dominates, Inelastic ~ 10^{-4} effects;

TPE for electrons is about twice larger than for muons.



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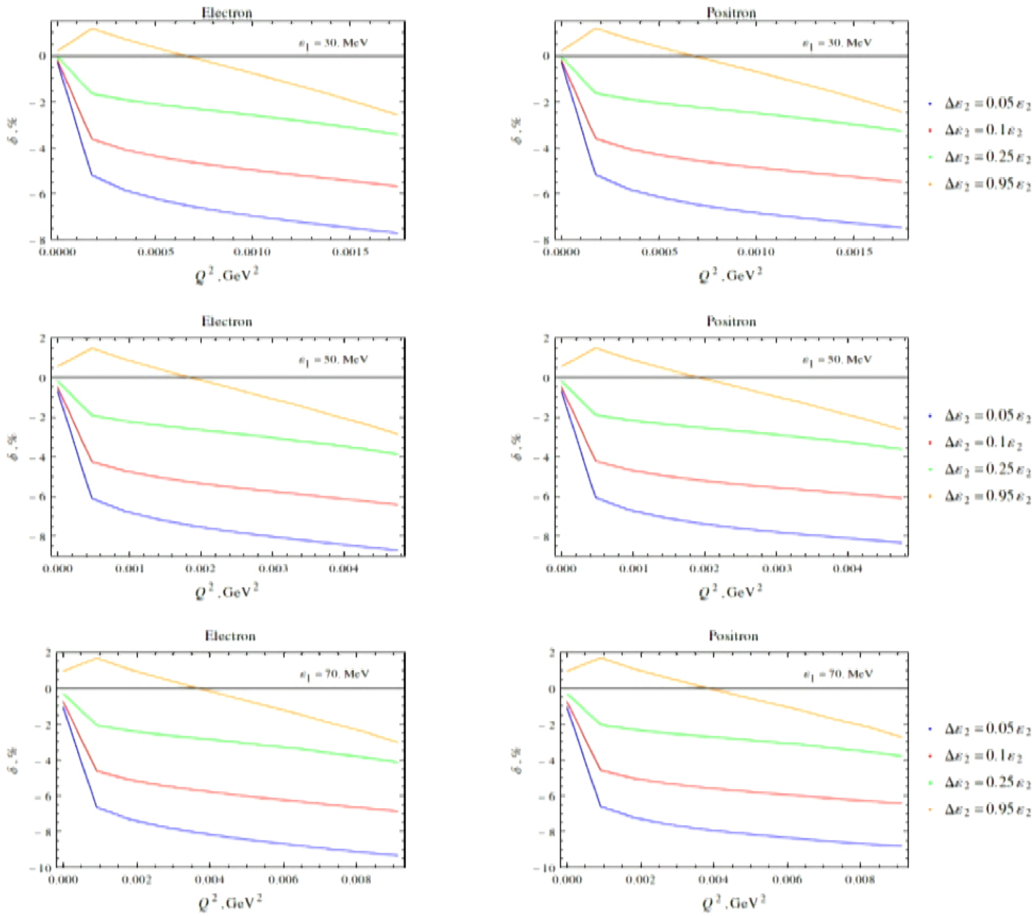
RC for low-energy electron scattering



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Andrei Afanasev, Radiative Corrections at the Intensity Frontier, Perimeter Institute, 14 June 2017

MUSE Prospectives

MUSE:

- Experiment preparation underway in PSI and MUSE collaborating institutions
- The effort on the radiative corrections aims at proper accounting of the radiative effects, that appear to show significant difference between electron and muon scattering (Afanasev, Strauch, Bernauer, Koshchii)
- Radiative corrections shown to be <1% for muons; included in MUSE analysis
- Two-photon effects can be studied directly in the ratio of μ+ and μ- cross sections

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Conclusions

- 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 $\mu+$ and $\mu-$, e^+ and e^- cross sections; TPE cancel in the sum of particle+antiparticle cross sections

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