Charge-Asymmetric Lepton Scattering as a Probe of Hadronic Structure

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Plan of talk

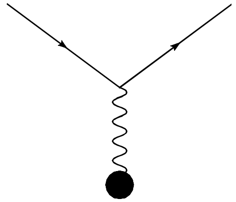
Radiative corrections for charged lepton scattering

Two-photon exchange effects

T-violation

Summary

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

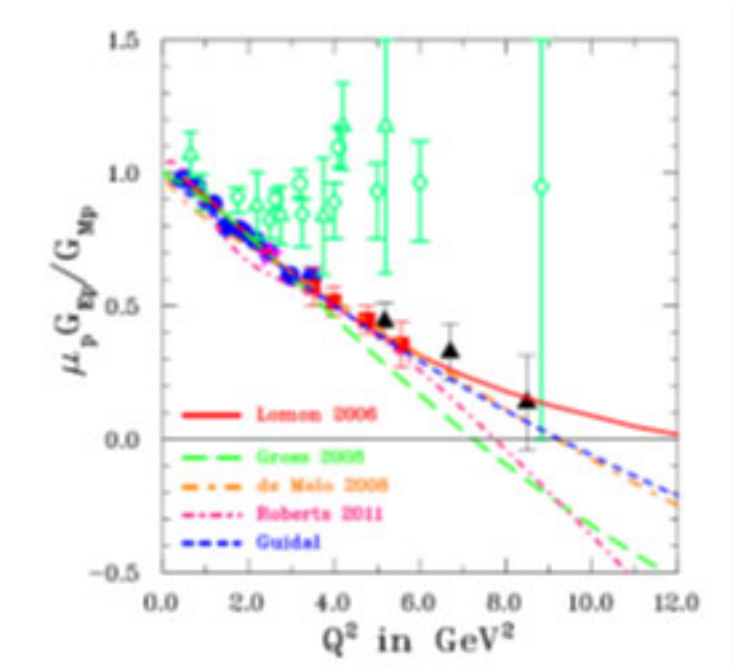
$$\sigma = \sigma_0 (G_M{}^2 \tau + \varepsilon \cdot G_E{}^2) \quad : Rosenbluth \quad technique$$

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

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

$$(P_y = 0)$$

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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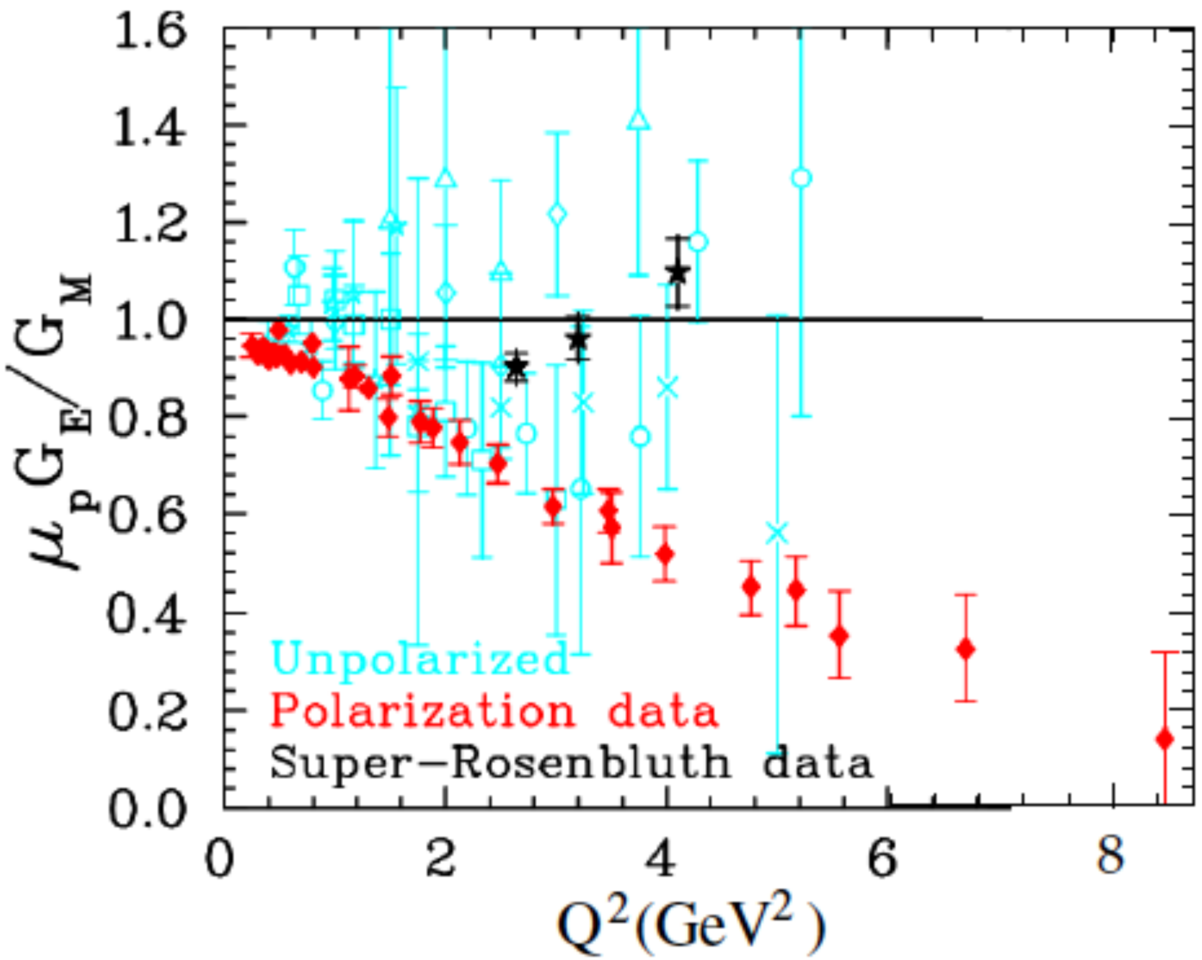
Ge/Gm Ratio: Polarization vs Rosenbluth



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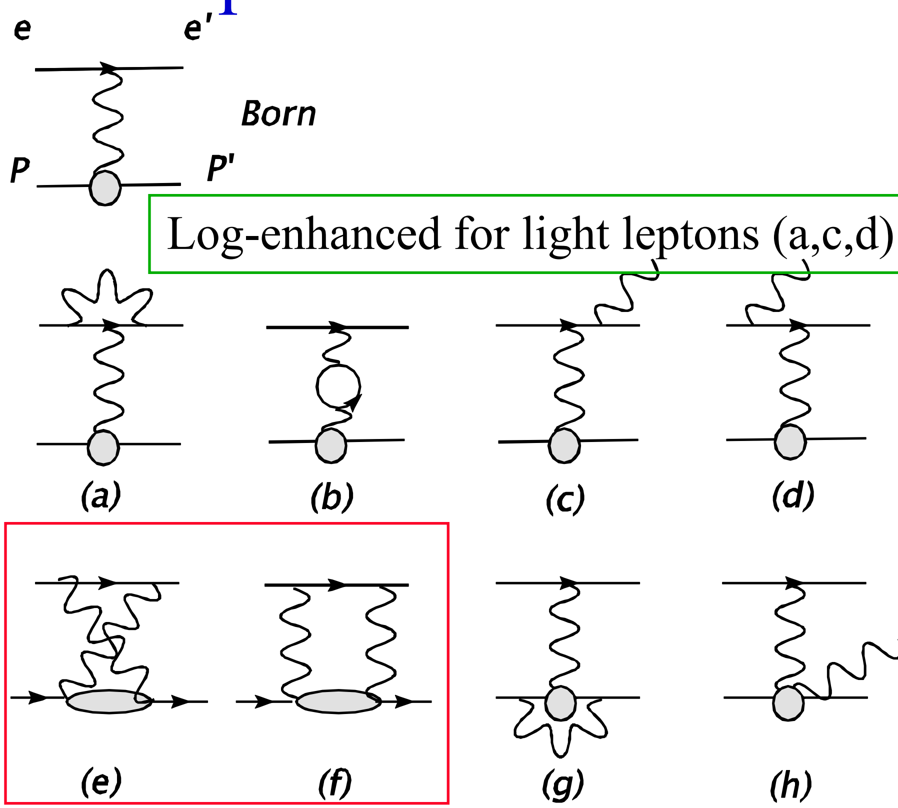
Complete radiative correction in O(α_{em})



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;

•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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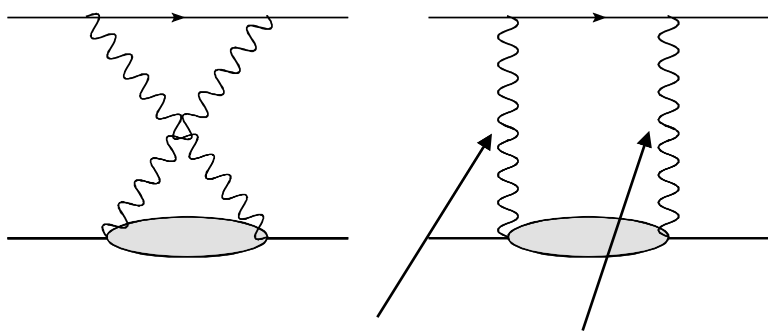
Separating *soft* 2-photon exchange

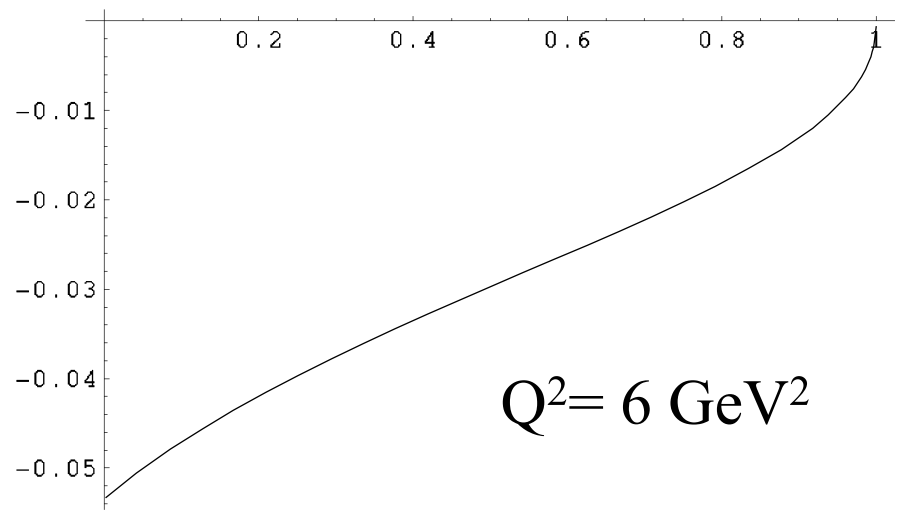
- Tsai; Maximon & Tjon ($k \rightarrow 0$); similar to Coulomb corrections at low Q^2
- Grammer &Yennie prescription PRD 8, 4332 (1973) (also applied in QCD calculations)
- Shown is the resulting (soft) QED correction to cross section
- **Already included in experimental data analysis for elastic ep**
  - Also done for pion electroproduction in AA, Aleksejevs, Barkanova, Phys.Rev. D88 (2013) 5, 053008 (inclusion of lepton masses is straightforward)



$q_1 \rightarrow q$ $q_2 \rightarrow 0$

ε

δ_{Soft}



$Q^2 = 6\ GeV^2$

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:

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

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

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

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

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

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

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

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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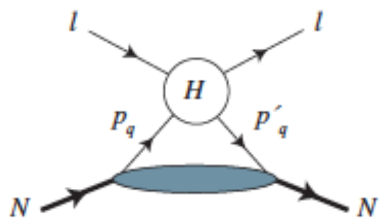
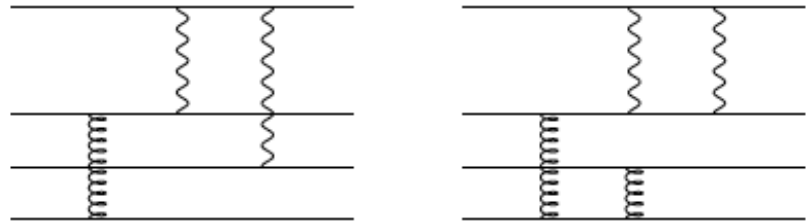
Quark-Level Calculations

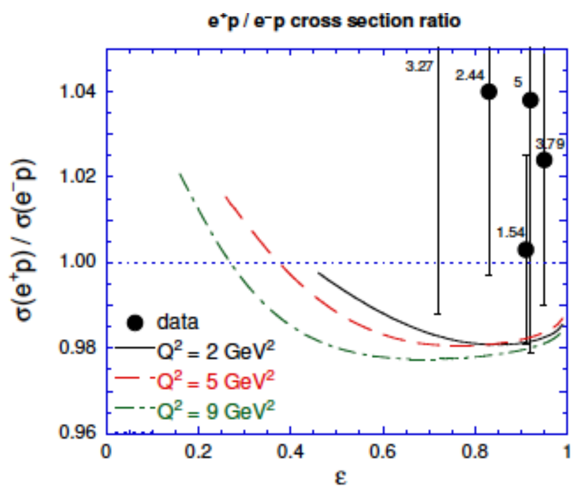


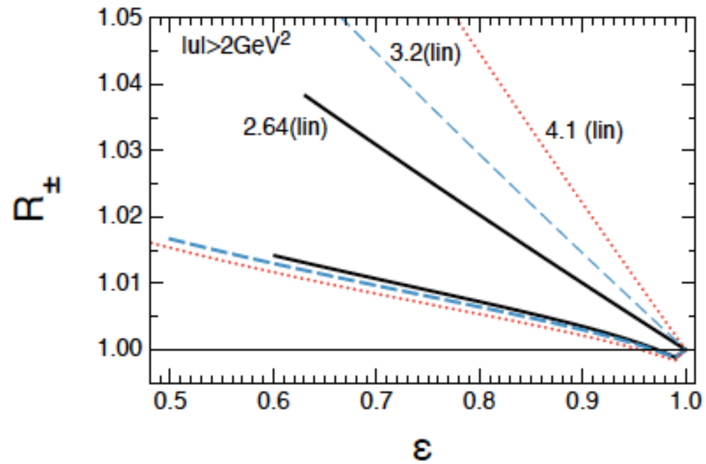


AA, Brodsky, Carlson, Chen, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004;

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

Kivel, Vanderhaeghen, PRL 103 092004 (2009)





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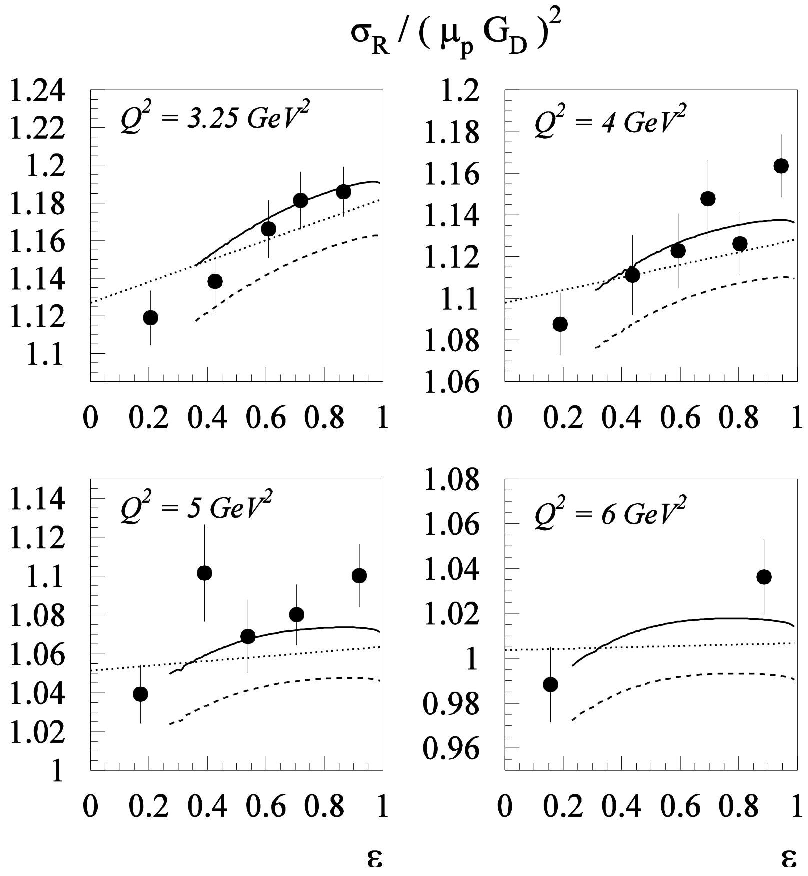
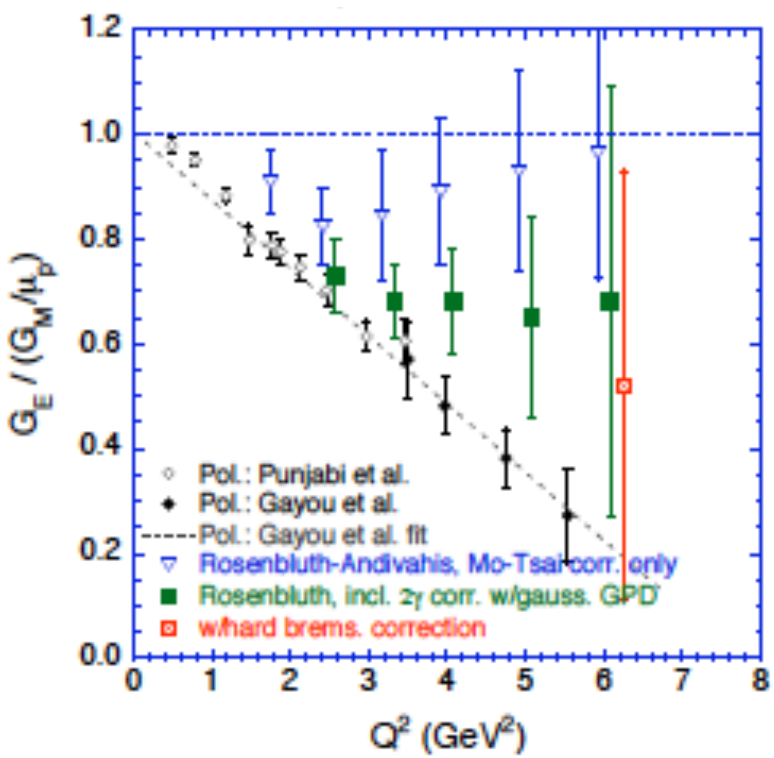
Results for cross section measurements

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



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

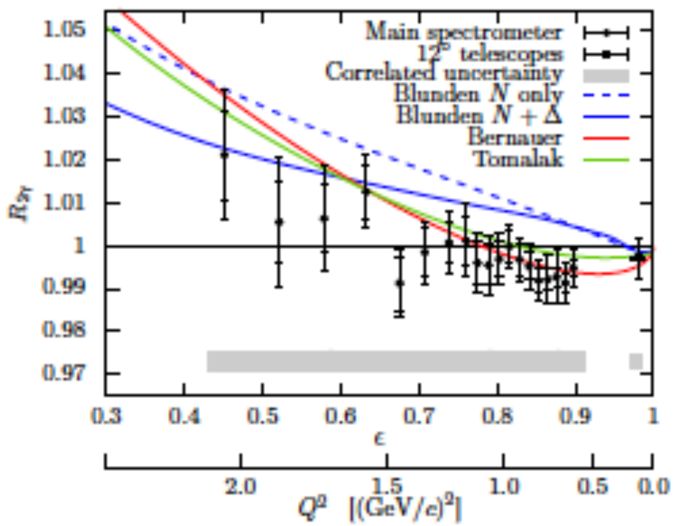


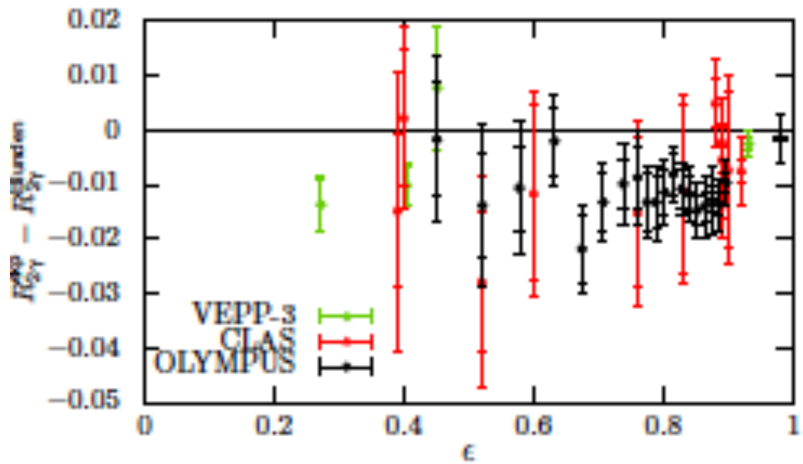
- Significant part of the discrepancy is removed by the TPE mechanism
- Verification coming from
  - VEPP: PRL 114 (2015) 6, 062005
  - CLAS: PRL 114 (2015) 6, 062003
  - OLYMPUS: PRL 118 (2017) 092501

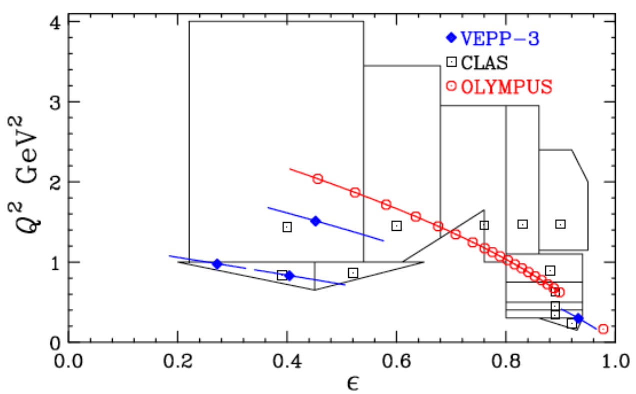
Recent review: A. Afanasev, P. Blunden, D. Hassell, B. Raue, https://arxiv.org/abs/1703.03874, Prog.Nucl.Part.Phys. June 2017.

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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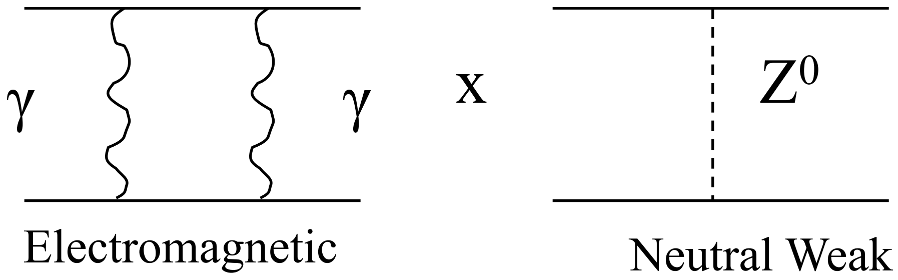
2γ-exchange Correction to Parity-Violating Electron Scattering



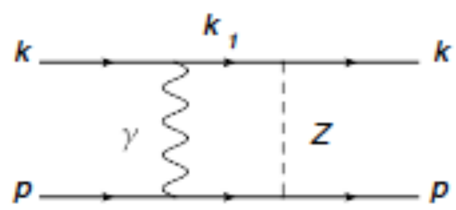
- Parity violating terms due to (2gamma)x(Z^0) interference should be added:

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

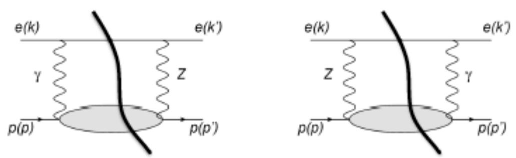
$$\mathrm{Re}\, A^{\gamma}_{AA} A^{Z}_{VA} \propto (-\tfrac{1}{2})(1-4\sin^2\theta_W)(1+\tau)\,\mathrm{Re}(G^{\gamma}_{A} G^{Z}_{A})\lambda_e$$

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

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



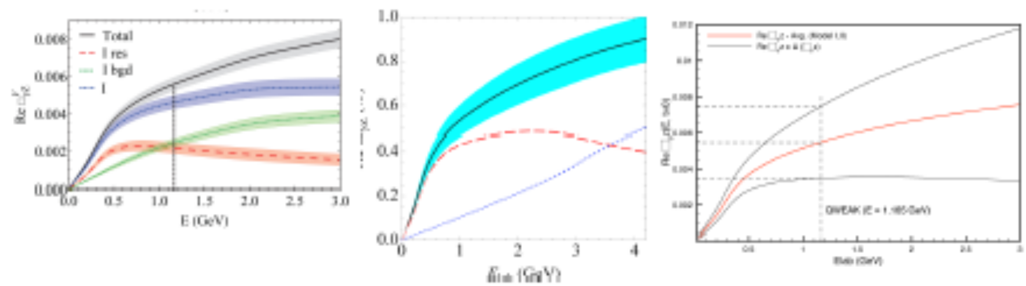
Gorchtein and Horowitz (PRL 102, 091806 (2009)) had insight to calculate the amplitude dispersively



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)



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

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

- 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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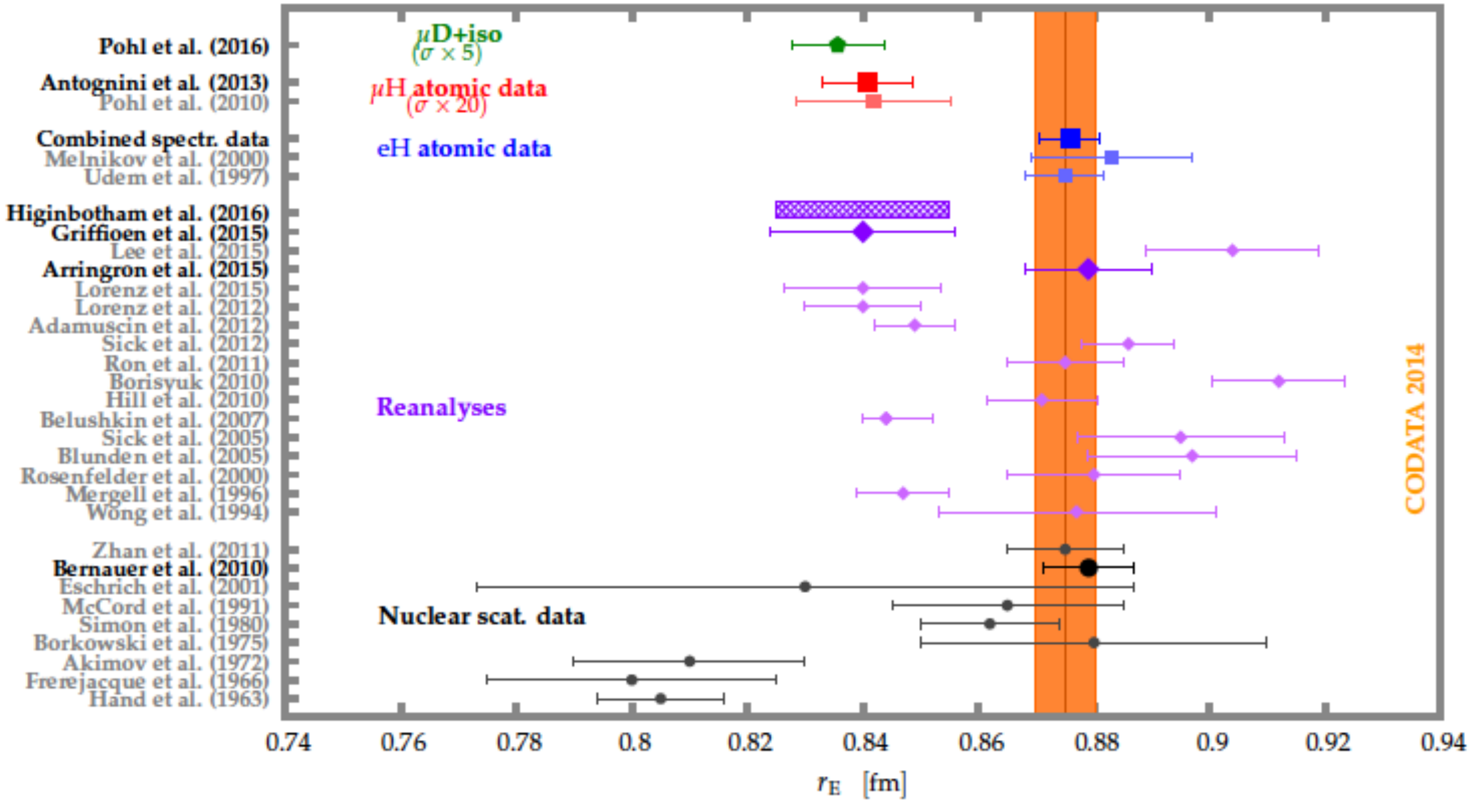
Parity violation with positrons?
High current and polarization is a challenge

Proton radius puzzle

- The 6σ discrepancy in the r_p measurements.



Slide credit: Miha Mihavilovic, JLAB Seminar, March'17

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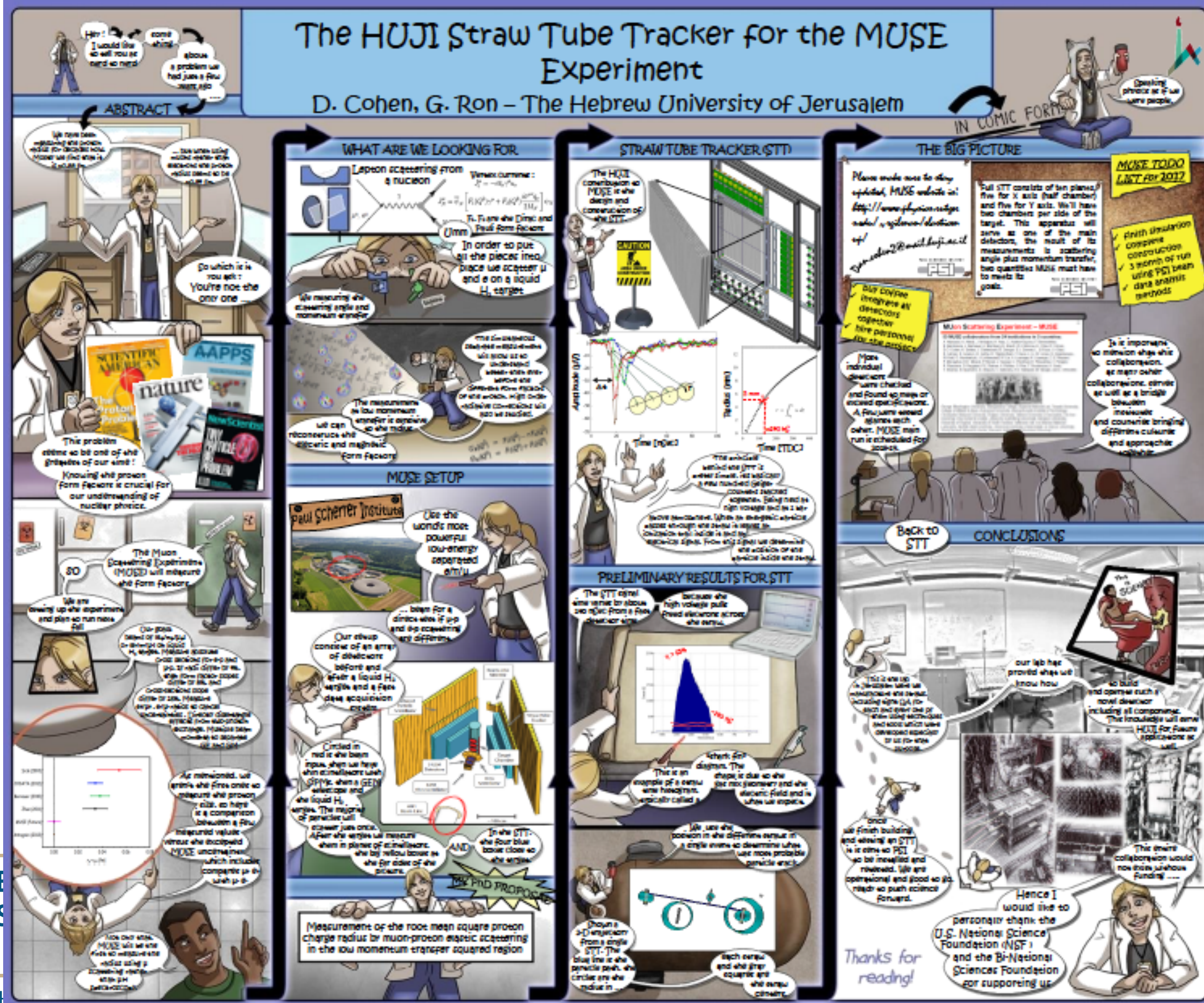

The HUJI Straw Tube Tracker for the MUSE Experiment
D. Cohen, G. Ron – The Hebrew University of Jerusalem
IN COMIC FORM
ABSTRACT
WHAT ARE WE LOOKING FOR
STRAW TUBE TRACKER (STT)
THE BIG PICTURE
Lepton scattering from a nucleon
Umm
In order to put all the pieces into place we scatter μ and e on a liquid H_2 target
So which it is you ask? You're not the only one
The problem seems to be one of the greatest of our time!
Knowing the proton form factors is crucial for our understanding of nuclear physics.
SO
The Muon Scattering Experiment (MUSE) will measure the form factors
MUSE SETUP
Paul Scherrer Institute
Use the world's most powerful low-energy separated e/π/μ
Our setup consists of an array of detectors before and after a liquid H_2 target and a fast data acquisition system
AND
In the STT: the four blue boxes close to the target.
My PhD PROPOSAL
Measurement of the root mean square proton charge radius by muon-proton elastic scattering in the low momentum transfer squared region
PRELIMINARY RESULTS FOR STT
CAUTION
Time [nSec]
Time [TDC]
MUSE TODO LIST for 2017
Back to STT
CONCLUSIONS
Hence I would like to personally thank the U.S. National Science Foundation (NSF) and the Bi-National Sciences Foundation for supporting us
Thanks for reading!

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!)

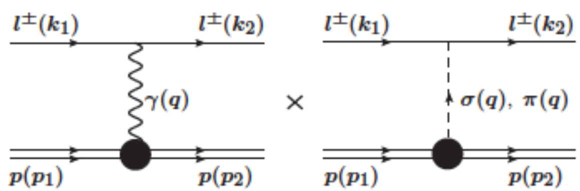
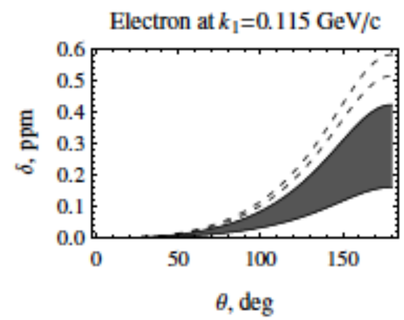
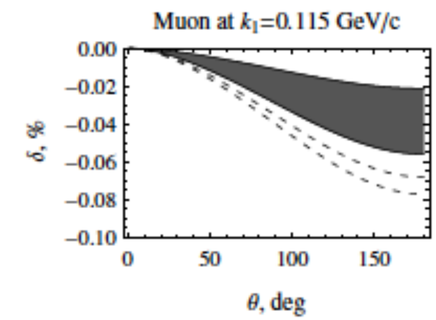


FIG. 1. One-photon and one σ (π) meson exchange diagrams





- 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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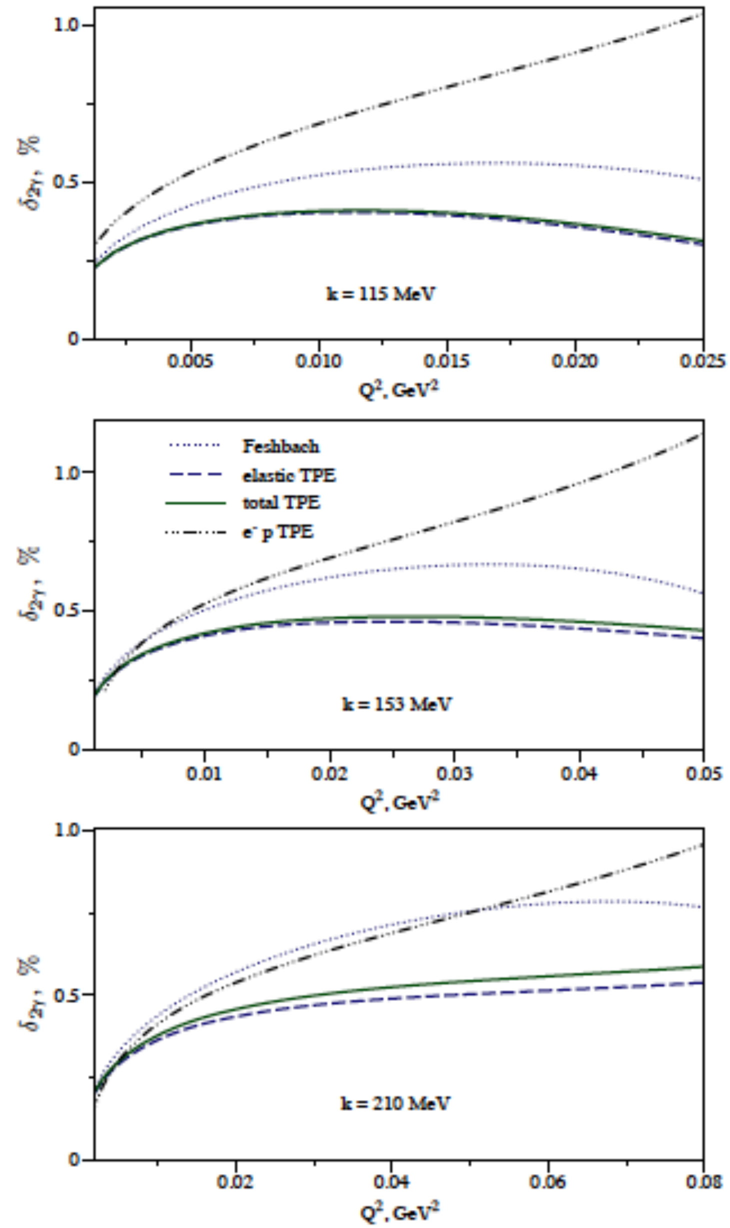
Inelastic+Elastic

- 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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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

RadCor for MUSE

- 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

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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

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

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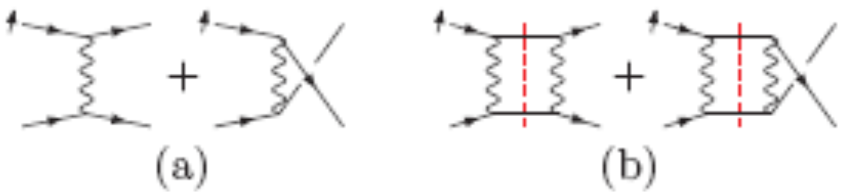
Normal Beam Asymmetry in Moller Scattering

- 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

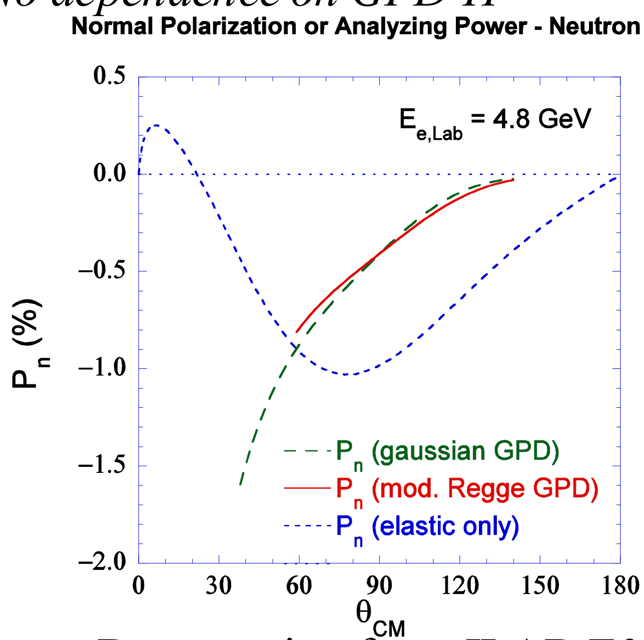
Quark+Nucleon Contributions to Target Asymmetry

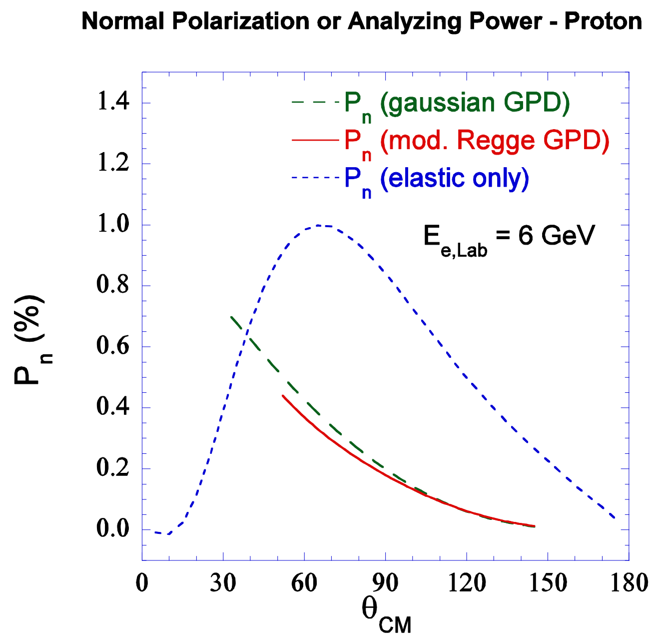
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetry of elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

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

Only minor role of quark mass

No dependence on GPD $\widetilde{H}$





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

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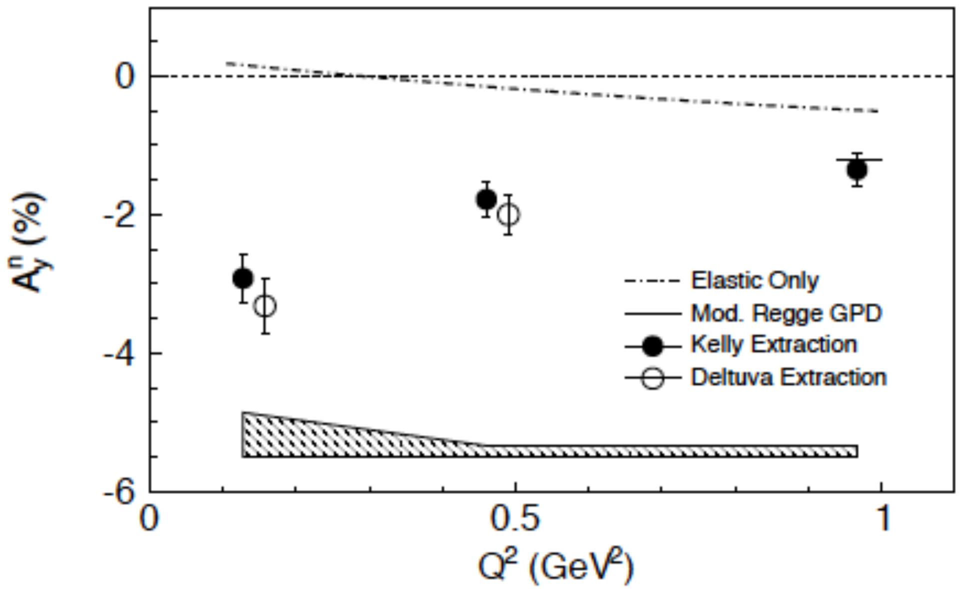
Single-spin Asymmetries at JLAB

- Polarized target (He3) JLAB E-05-015 (Zhang et al, Phys. Rev. Lett. **115**, 172502 (2015))
- Recoil polarimetry (proton): possible but challenging due to systematic corrections



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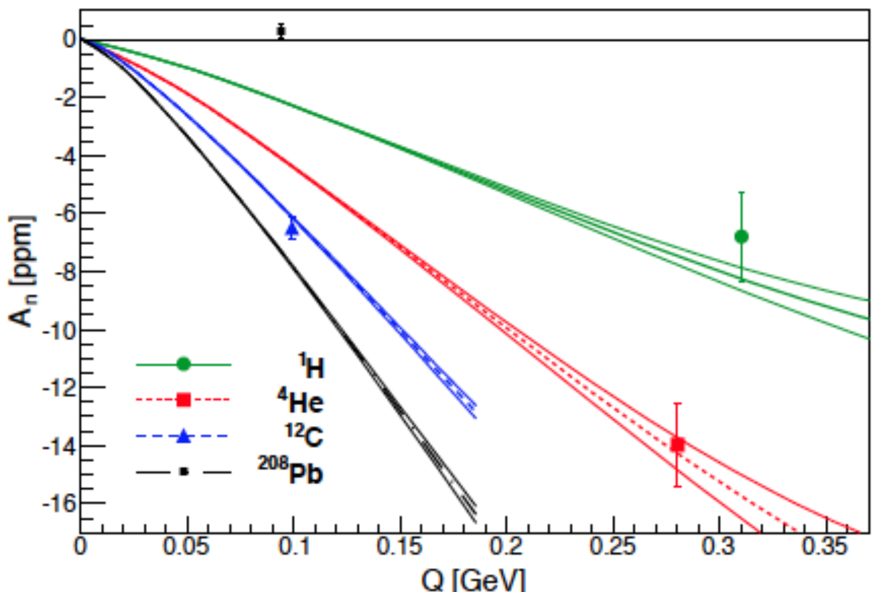
Transverse Beam Asymmetries on Nuclei (HAPPEX+PREX)

- 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)



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 settle the puzzle

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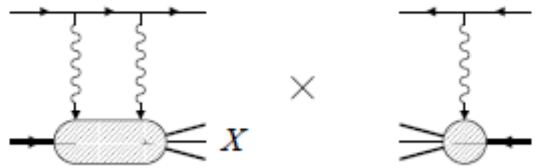
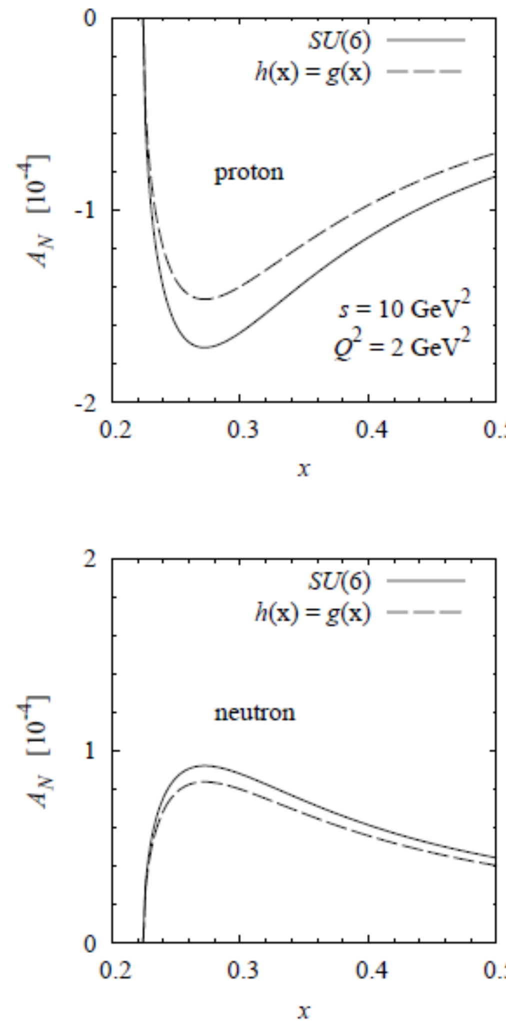
Two-Photon Exchange in inclusive DIS





- Theory: Afanasev, Strikman, Weiss, **Phys.Rev.D77:014028,2008**
  - Asymmetry due to 2γ-exchange ~1/137 suppression
  - Addional suppression due to transversity parton density => predict asymmetry at ~10^{-4} level
  - EM gauge invariance is crucial for cancellation of collinear divergence in theory predictions
  - Hadronic non-perturbative ~1% vs partonic 10^{-4}
- Prediction consistent with HERMES measurements who set upper limits ~(0.6-0.9)x10^{-3} : **Phys.Lett.B682:351-354,2010**

Work by Andreas Metz and collaborators

- Important: Inclusive asymmetries from TPE, coupling to the same quark vs different quarks A. Metz, D. Pitonyak, A. Schafer, M. Schlegel, W. Vogelsang, J. Zhou, Phys.Rev. D86 (2012) 114020

- SIDIS: Schlegel, Metz, arXiv:0902.0781

Emphasized sin(2φ) effect for SIDIS arising from two-photon exchange

$$A_{LU}^{\sin(2\phi)} = \alpha \frac{y\left(1+\frac{2-y}{1-y}\ln y\right)}{1-y+\frac{1}{2}y^2} \sin(2\phi) \frac{\sum_q e_q^3 \mathscr{C}\left[\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{2Mm_\pi} h_1^{\perp q} H_1^{\perp q}\right]}{\sum_q e_q^2 \mathscr{C}\left[f_1^q D_1^q\right]}$$

Target asymmetry:

$$A_{UT}(x_B, y, \phi_s) = \alpha \frac{x_B M}{2Q} \frac{y(1-y)\sqrt{1-y}}{1-y+\frac{1}{2}y^2} |\vec{S}_T| \sin(\phi_s) \left(\ln\frac{Q^2}{\lambda^2} + \text{finite}\right) \frac{\sum_q e_q^3 g_T^q(x_B)}{\sum_q e_q^2 f_1^q(x_B)}$$

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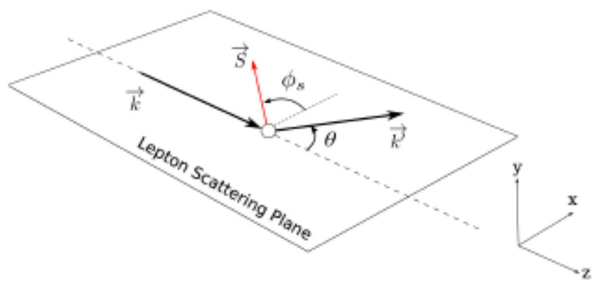
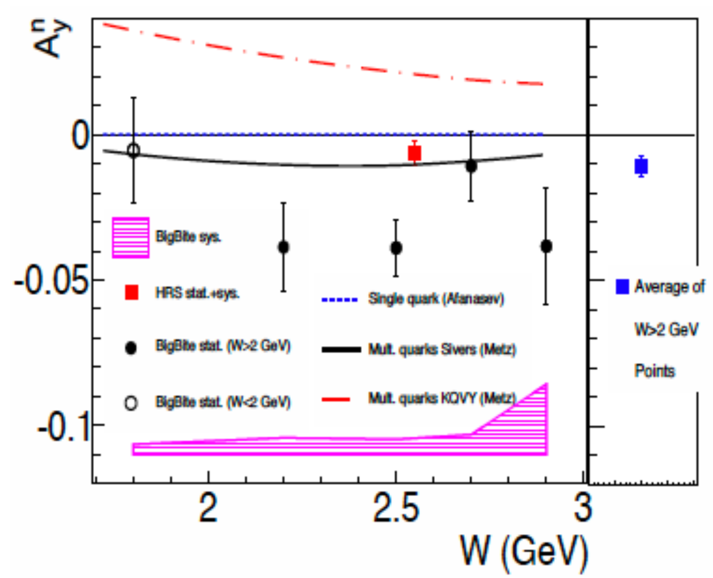
Experiment in JLAB Hall A

- Katichet al., **Phys.Rev.Lett. 113 (2014)022502**
  - Shows per-cent level asymmetry in $^3He\uparrow(e,e')X$
  - Presents an issue for analysis for TMD extraction from T-odd asymmetries in SIDIS





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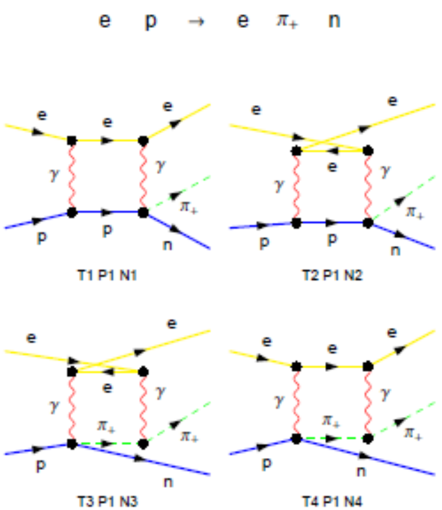
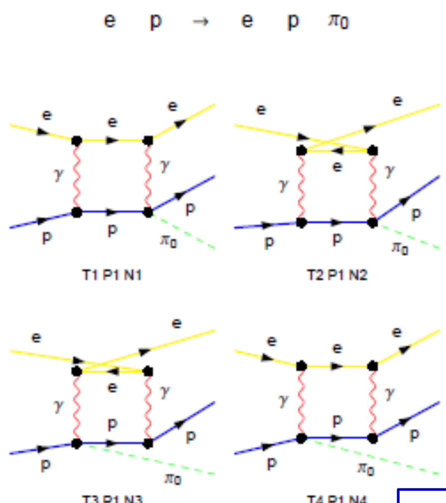
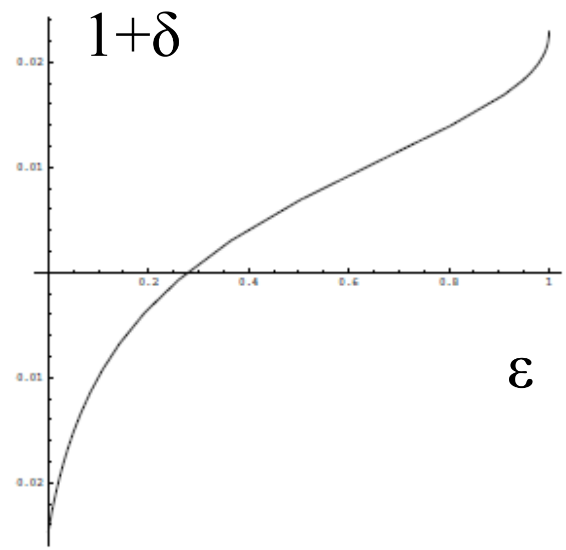
Two-Photon Exchange in Exclusive Electroproduction of Pions

- Standard contributions considered, e.g., AA, Akushevich, Burkert, Joo, **Phys.Rev.D66:074004,2002** (Code EXCLURAD used for data analysis)
- *Additional contributions due to two-photon exchange*, calculated by AA, Aleksejevs, Barkanova, arXiv:1207.1767, PRD88 (2013)
  Calculated in soft-photon approximation







Calculated ε-dependence of TPE correction.
Q^2=6 GeV^2, W=3.2 GeV, E_e=5.5 GeV .
Shows ±2% variation with ε.

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TPE vs T-violation

- Single-spin asymmetries in inclusive DIS may be caused by
  - Effects beyond Born approximation
  - Violation of time-reversal symmetry
- The effects can be separated using positron vs electron comparison
  - TPE effects are charge-odd
  - T-violation is time-even
- First suggested by Tsai
- Important Note: *if* CPT is a good symmetry, then constraints on CP-violation in leptonic sector is $<10^{-6}$. But higher-order QED loops will also produce C-even SSA (three-photon exchange) at a level of 10^{-4}.
- Possible experiment with e^+/e^-: Looking for T-violation in lepton scattering at sub-percent level.

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Summary

- Electron-positron asymmetries provide model-independent measurement of effects beyond Born approximation: an important tool for precision probes of hadronic structure
  - Elastic ep- and eA-scattering
  - Inelastic scattering: DIS, SIDIS, DVMP
  - Parity violation: need high currents and polarization
  - T-violation in lepton scattering: SSA technique works up to ~10-4, limitation due to higher-order QED loops (*three*-photon exchange)