Two-Photon Theory: Inelastic Effects and Partonic Approach

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Plan of talk

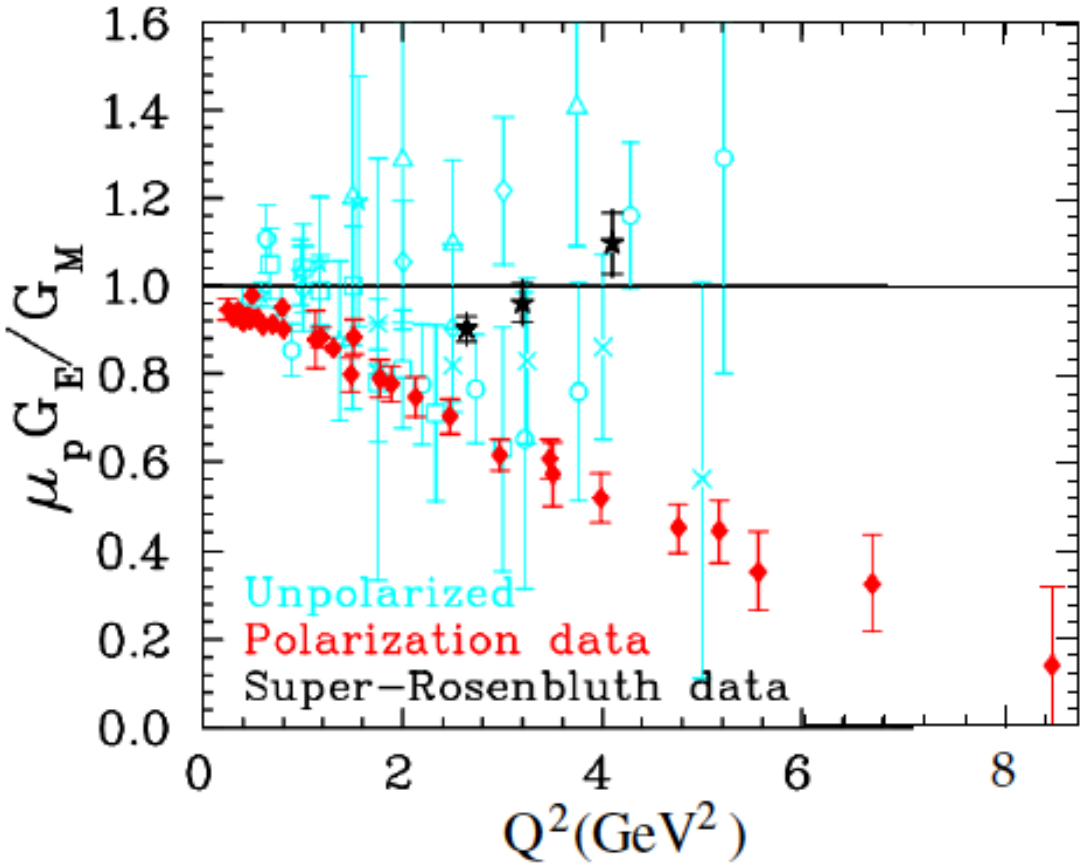
Radiative corrections for charged lepton scattering

Two-photon exchange effects (unpolarized and polarized)

T-violation

Summary

Ge/Gm Ratio: Polarization vs Rosenbluth



Recent review: A. Afanasev, P. Blunden, D. Hassell, B. Raue,
https://arxiv.org/abs/1703.03874
Prog.Part.Nucl.Phys. **95** (2017) 245-278

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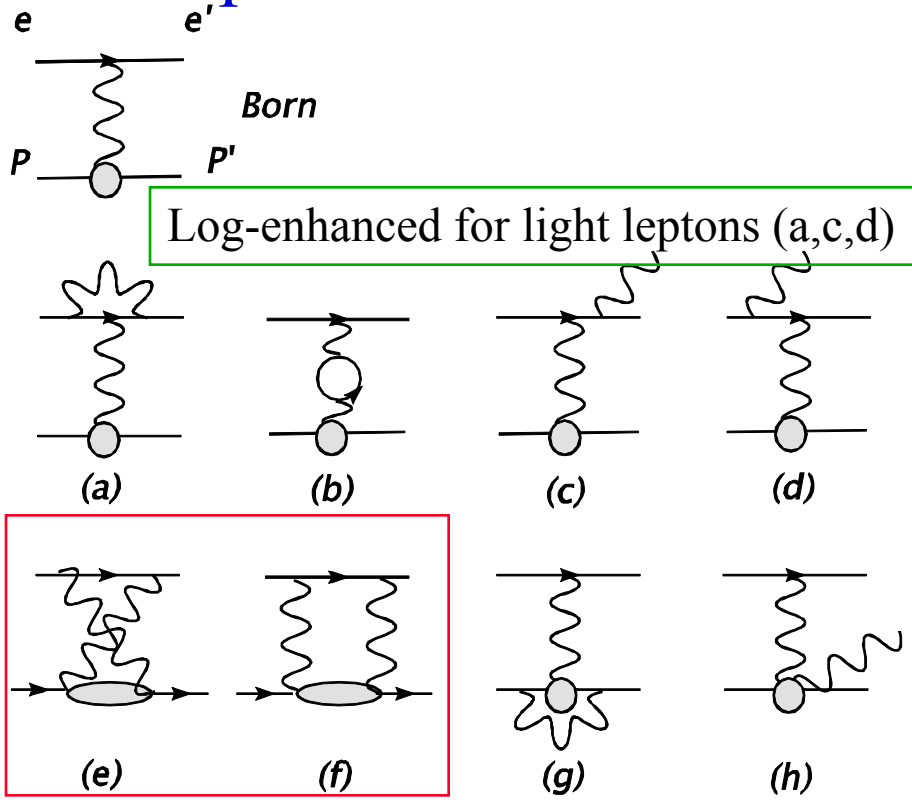
Complete radiative correction in $O(\alpha_{em})$



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

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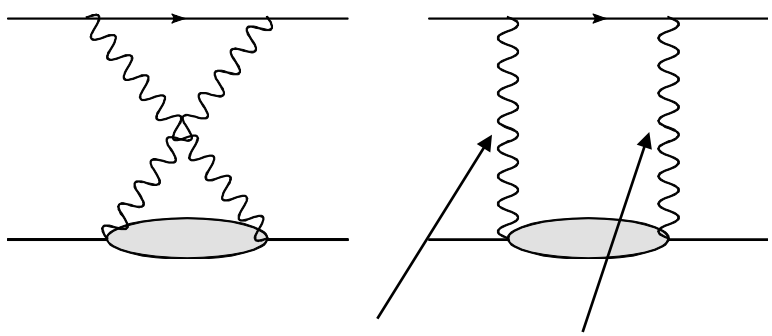
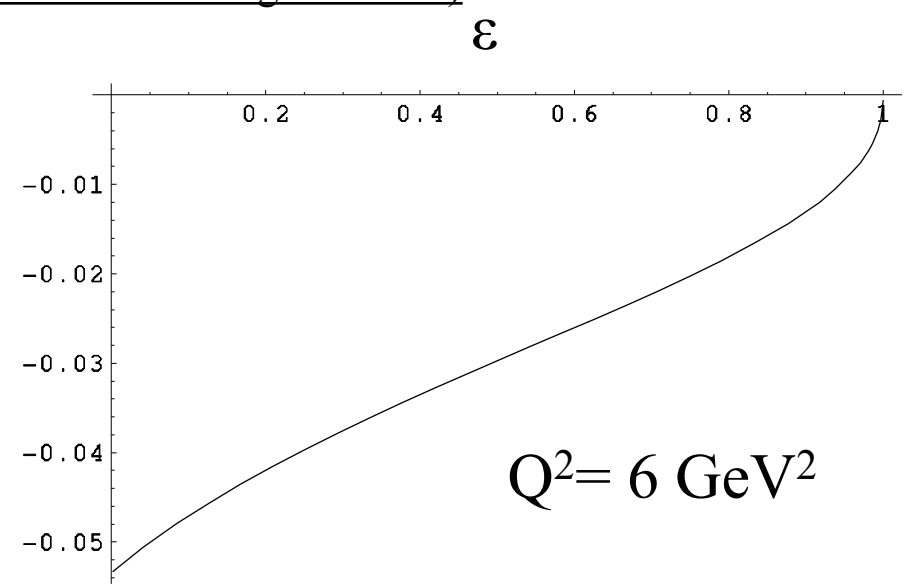
Separating *soft* 2-photon exchange

- 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
- **<u>Already included in experimental data analysis for elastic ep</u>**
  - <u>Also done for pion electroproduction in AA, Aleksejevs, Barkanova, Phys.Rev. D88 (2013) 5, 053008 (inclusion of lepton masses is straightforward)</u>



$q_1 \to q$ $q_2 \to 0$



Lepton mass is not essential for TPE calculation in ultra-relativistic case;
Two-photon effect below 1% for lower energies and Q^2<0.1GeV^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: $T^{\lambda_2 h_2}_{\lambda_1 h_1} = (-1)^{(\lambda_1 - h_1)-(\lambda_2 - h_2)} T^{-\lambda_2 - h_2}_{-\lambda_1 - h_1}$

  $\Longrightarrow$8 amplitudes
  - Time-reversal: $T^{\lambda_2 h_2}_{\lambda_1 h_1} = (-1)^{(\lambda_1 - h_1)-(\lambda_2 - h_2)} T^{-\lambda_1 - h_1}_{-\lambda_2 - h_2}$

  =>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

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

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

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

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

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

Afanasev, Brodsky, Carlson, Chen,Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004; Phys.Rev.D**72**:013008,2005

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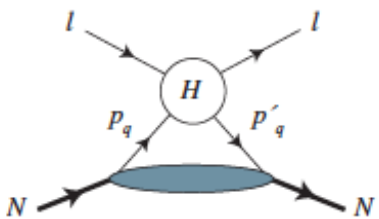
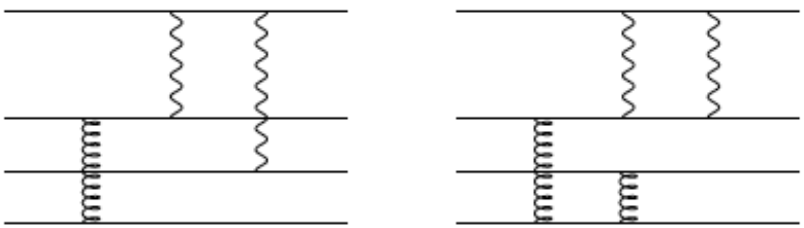
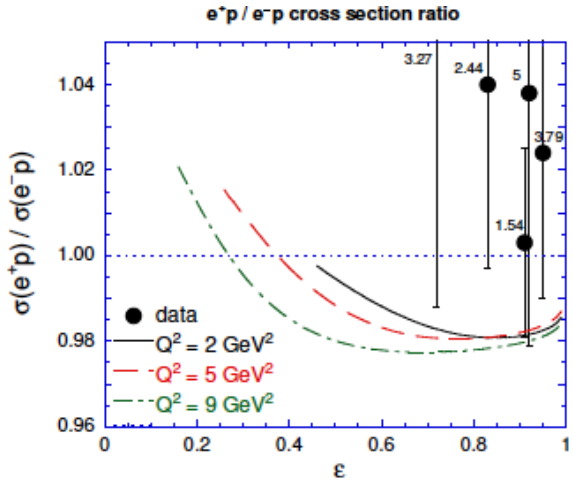
Quark-Level Calculations

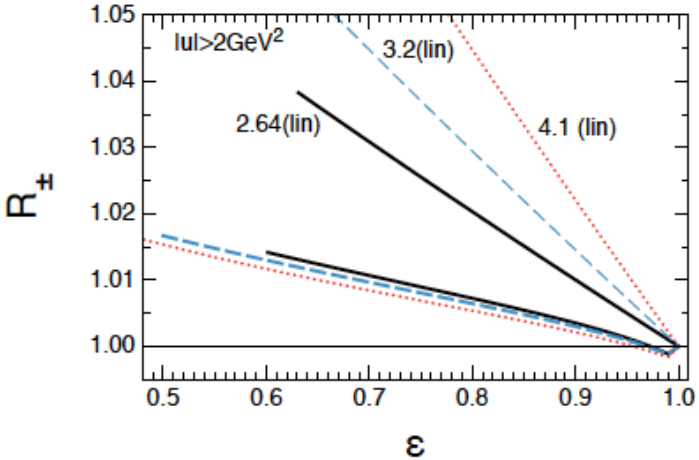




AA, Brodsky, Carlson, Chen, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004; Phys.Rev.D**72**:013008,2005

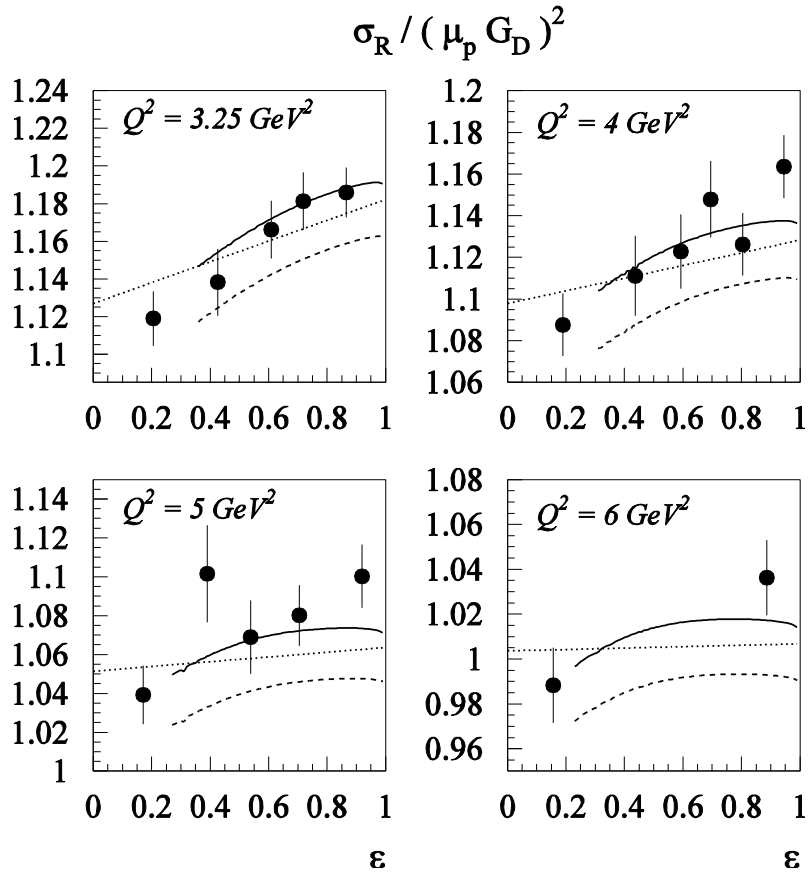
Kivel, Vanderhaeghen, PRL 103 092004 (2009)





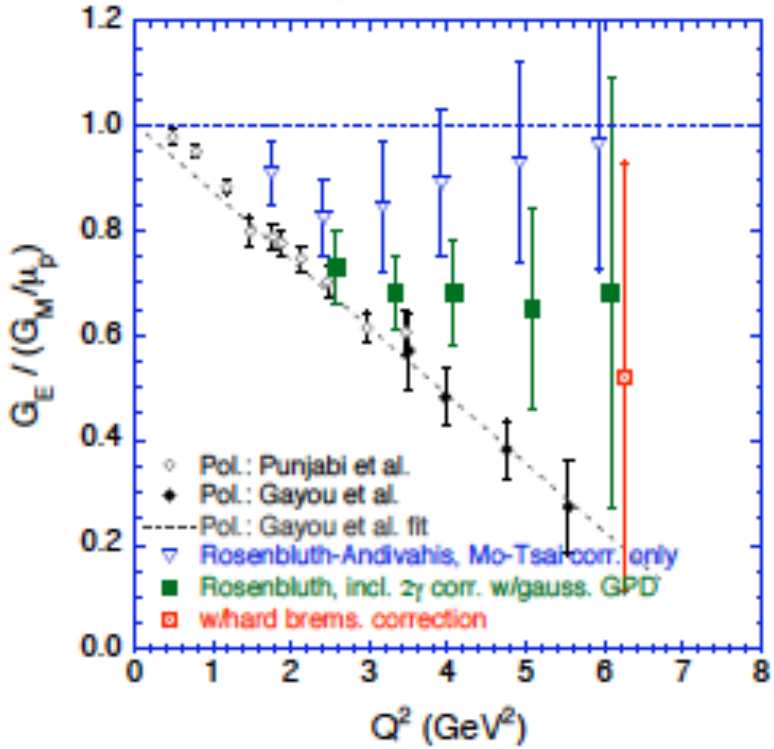
Results for cross section measurements

- 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.

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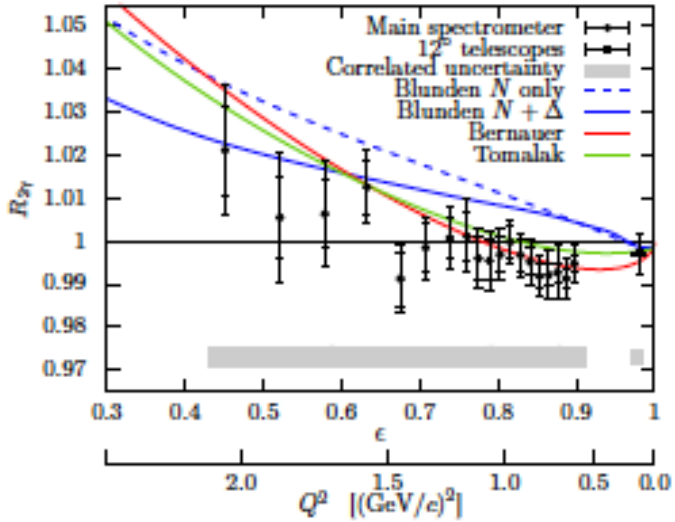
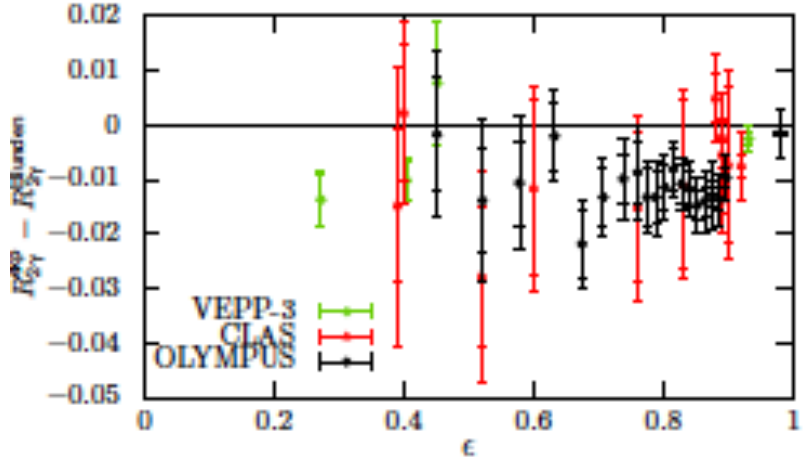
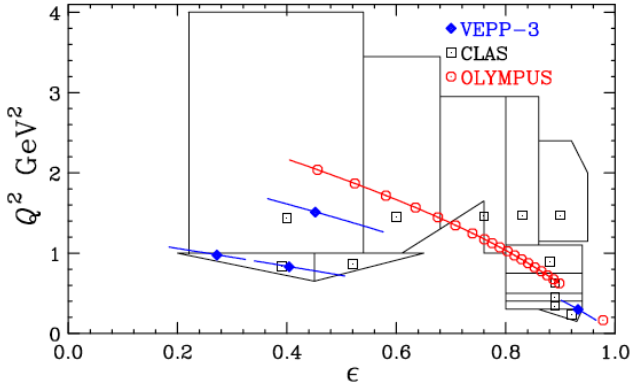
Electron/Positron Ratios

- 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.

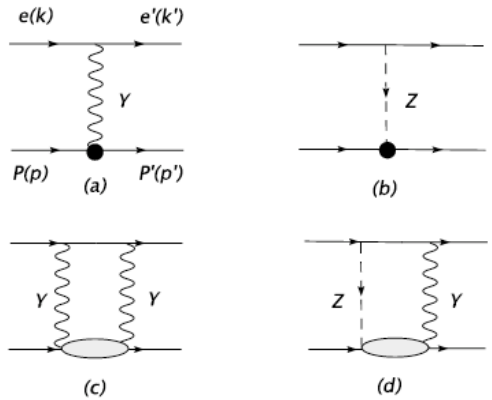






2γ-exchange Correction to Parity-Violating Electron Scattering

Afanasev, C.E. Carlson, PRL94 (2005) 212301

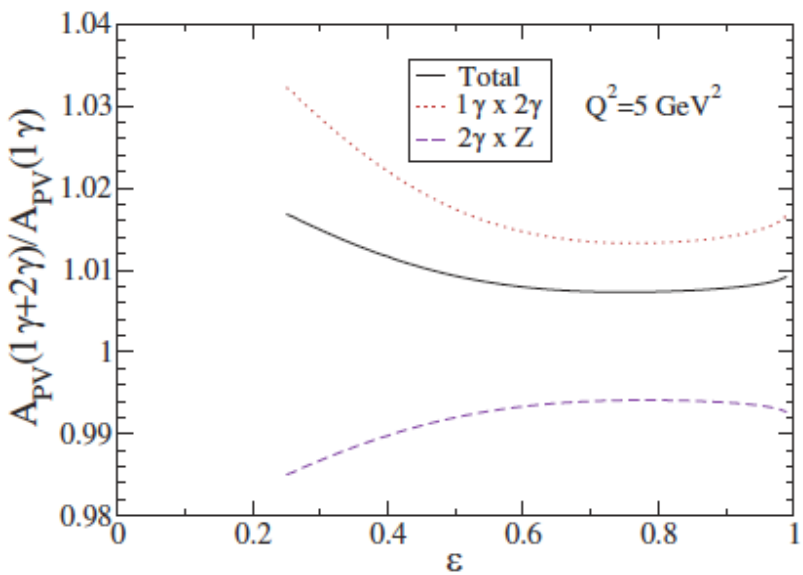


- Comes in addition to gamma-Z box (but less significant at small Q^2)
- Parity violating terms due to (TPE)x(Z^0) interference should be added:

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{A_E + A_M + A_A + A'_M + A'_A}{\epsilon|G'_{Ep}|^2 + \tau|G'_{Mp}|^2 + 2\sqrt{\tau(1+\tau)(1-\epsilon^2)}G^\gamma_{Mp}\,\mathrm{Re}(G'_{Ap})}$$

$$A'_A = 2g^e_V(1+\tau)G^Z_A\,\mathrm{Re}(G'_{Ap})$$

$$A'_M = -2g^e_A\sqrt{\tau(1+\tau)(1-\epsilon^2)}G^Z_M\,\mathrm{Re}(G'_{Ap}).$$



Results of calculation in partonic approach

FIG. 2 (color online). Two-photon-exchange correction to parity-violating asymmetry as a function of ϵ at $Q^2 = 5\ \mathrm{GeV}^2$. Also shown are separate effects from the parity-conserving $1\gamma \times 2\gamma$ interference and parity-violating $2\gamma \times Z$ interference.

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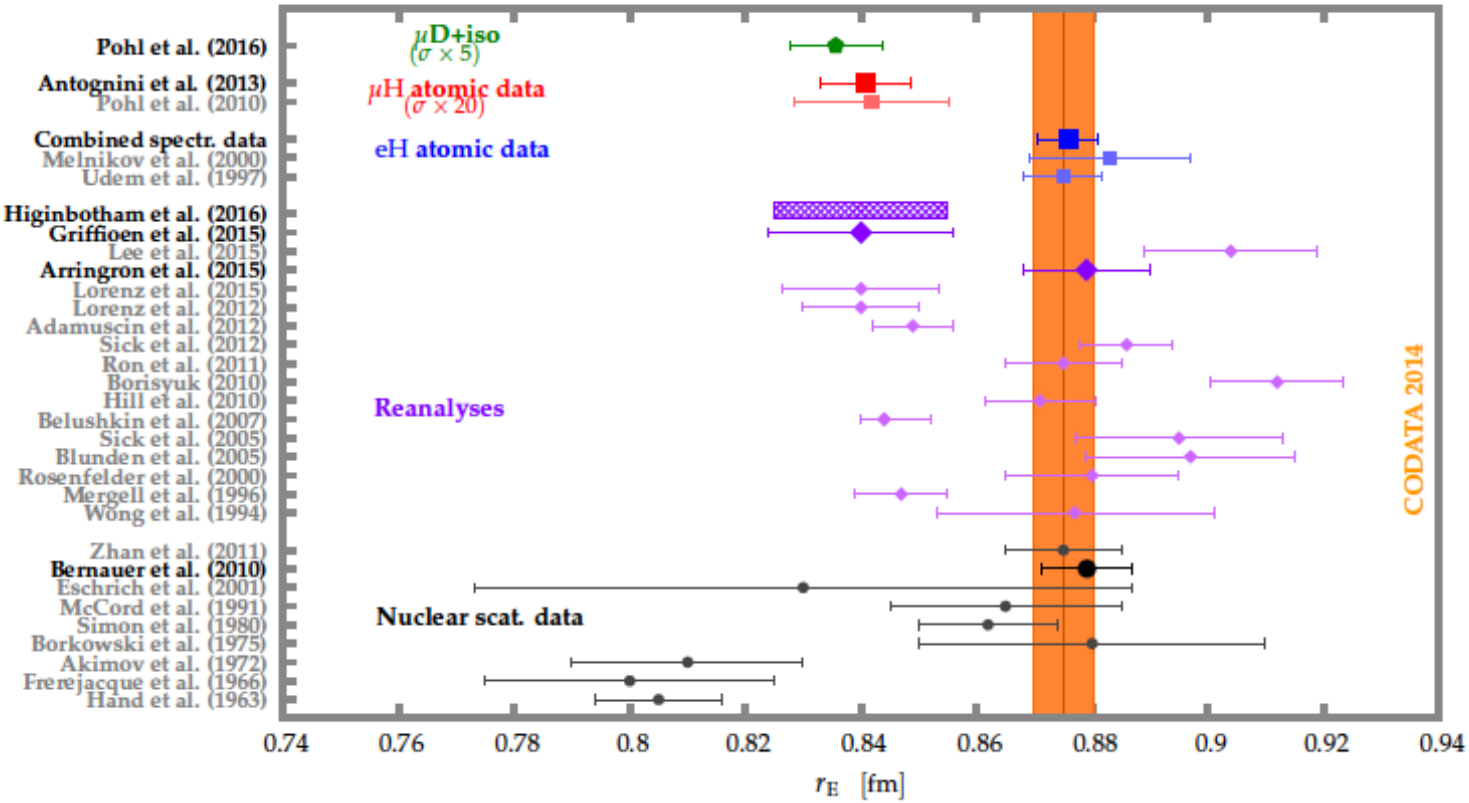
Proton radius puzzle

- The 6σ discrepancy in the r_p measurements.



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

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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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!)

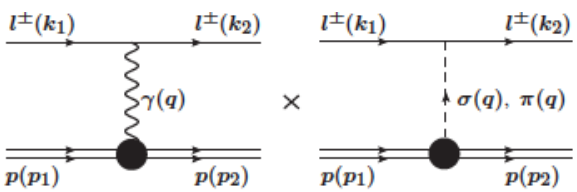
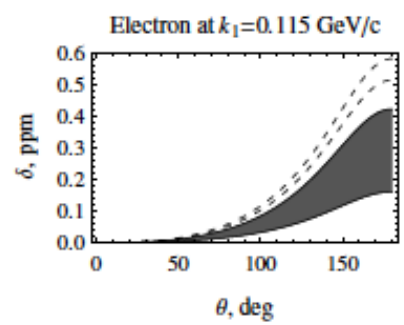
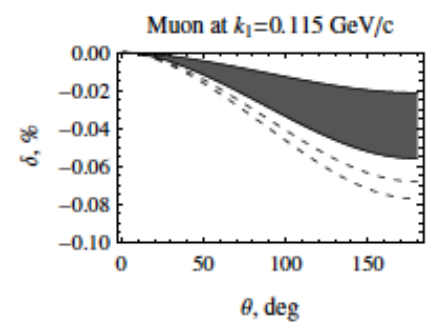


FIG. 1. One-photon and one σ (π) meson exchange diagrams





- 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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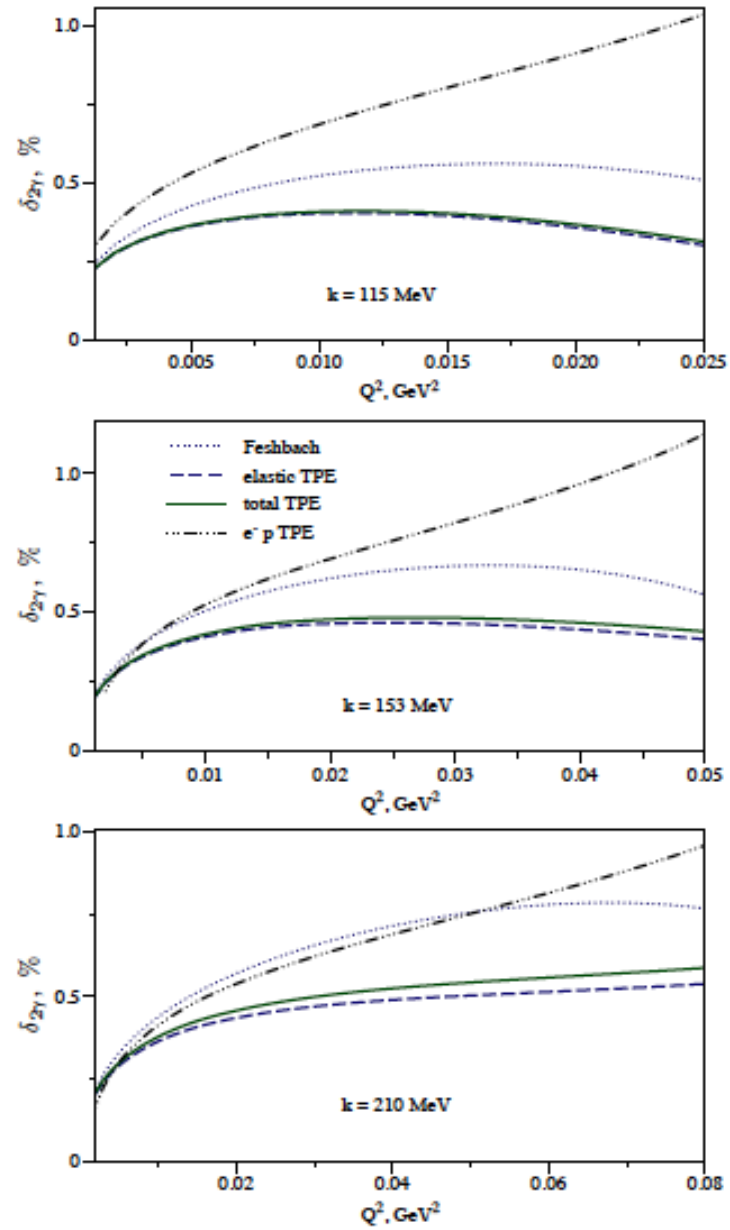
Inelastic+Elastic

- 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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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 $\mu+$ and $\mu-$, 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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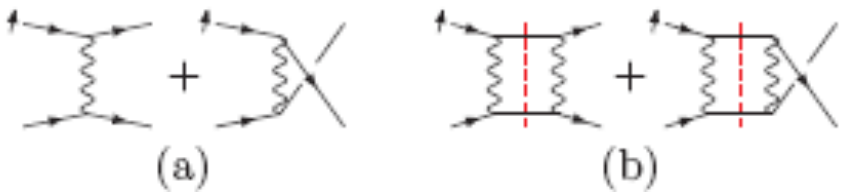
Normal Beam Asymmetry in Moller Scattering

- 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

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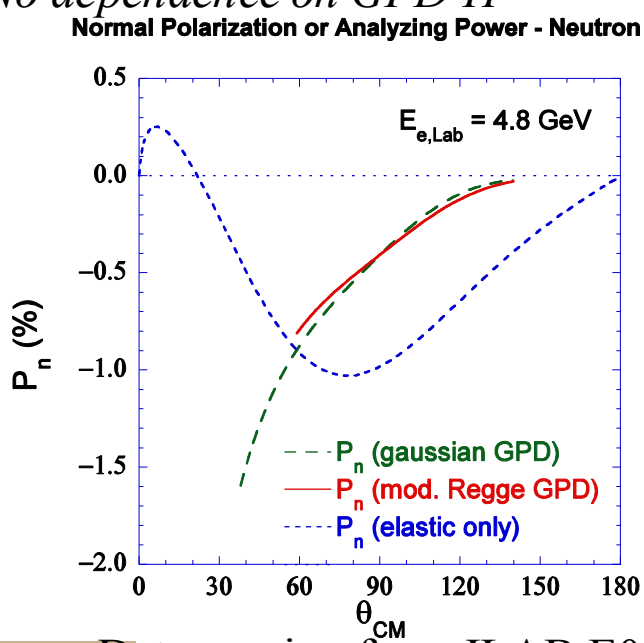
Quark+Nucleon Contributions to Target Asymmetry

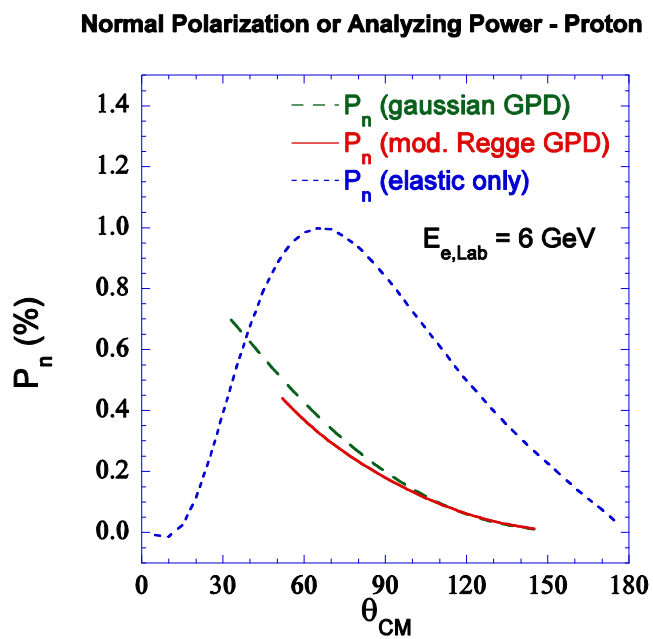
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetry of elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

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

Only minor role of quark mass

No dependence on GPD $\tilde{H}$





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

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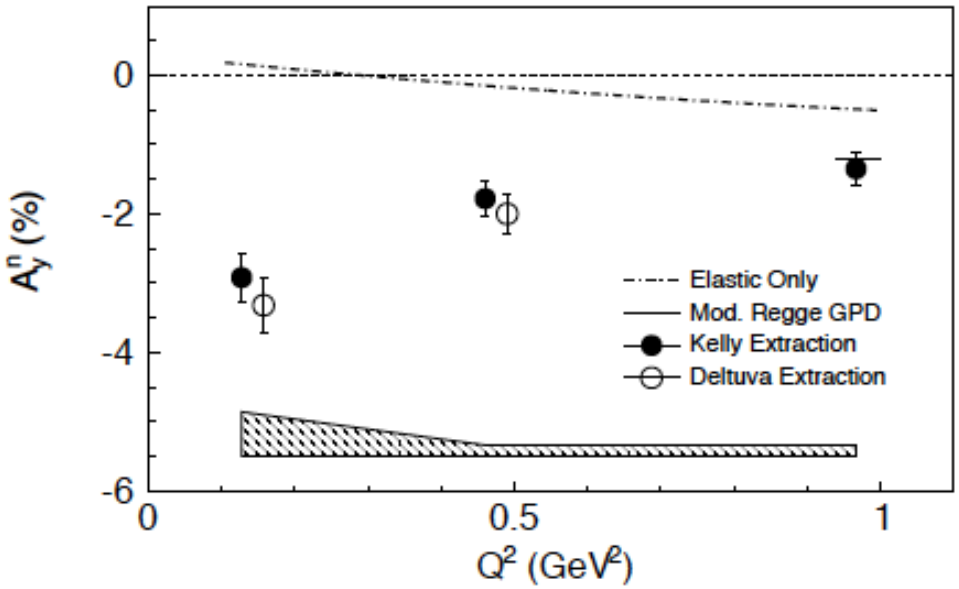
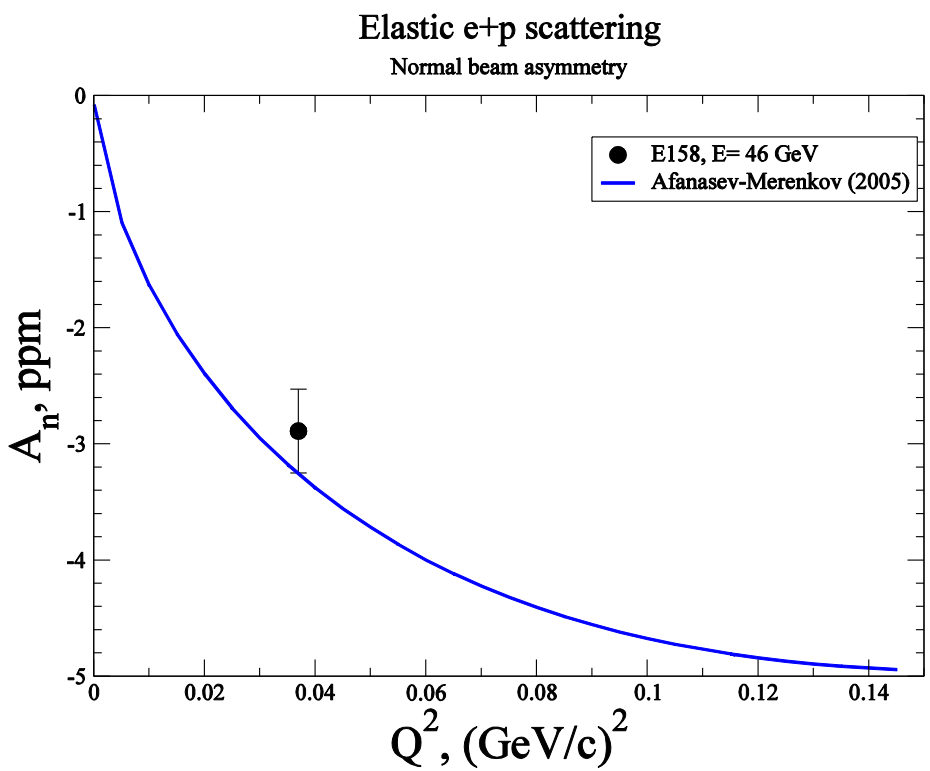
Single-spin Asymmetries at JLAB

- 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



Comparison with E158 data



- SLAC E158:

An=-2.89±0.36(stat)±0.17(syst) ppm

(K. Kumar, private communication)

- Theory (AA, Merenkov):

  An=-3.2ppm

- Good agreement justifies application of this approach to the real part of two-boson exchange (γZ box)

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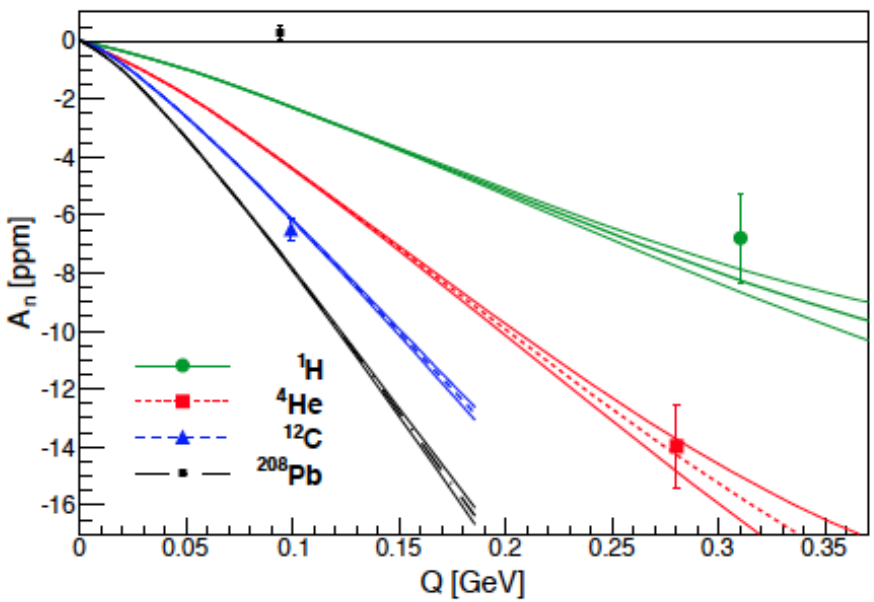
Transverse Beam Asymmetries on Nuclei (HAPPEX+PREX)

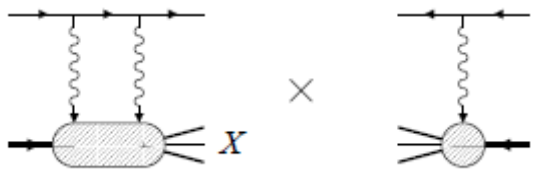
- Abrahamyan et al, Phys.Rev.Lett. 109 (2012) 192501
  - Good agreement with theory for nucleon and light nuclei
  - Puzzling disagreement for ^{208}Pb measurement; if confirmed, need to include additional electron interaction with highly excited intermediate nuclear state, magnetic terms, etc (= effects of higher order in α_{em}). Interesting nuclear effect! Experimentally, need additional measurements for intermediate-mass targets (e.g., Al, Ca, Fe)
- Low energy expansion for beam SSA: Diaconescu, Musolf, PRC70 (2004) 054003

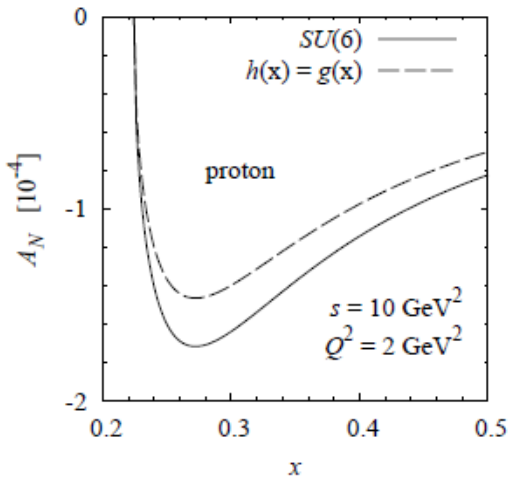


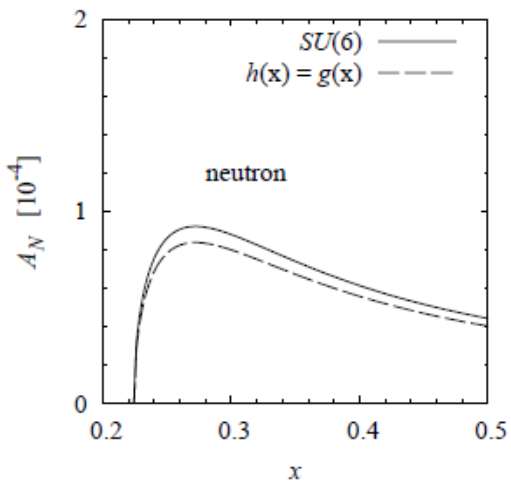
Target	H	^{4}He	^{12}C	^{208}Pb
A_n(ppm)	−6.80	−13.97	−6.49	0.28
$\sigma(A_n)$(ppm)	±1.54	±1.45	±0.38	±0.25
$\sqrt{Q^2}$ (GeV)	0.31	0.28	0.099	0.094
A/Z	1.0	2.0	2.0	2.53
$\hat{A}_n$ (ppm/GeV)	-21.9	-24.9	-32.8	+1.2
$\sigma(\hat{A}_n)$(ppm/GeV)	±5.0	±2.6	±1.9	±1.1

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

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**

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Relating Inclusive SSA to TMDs

- 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

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

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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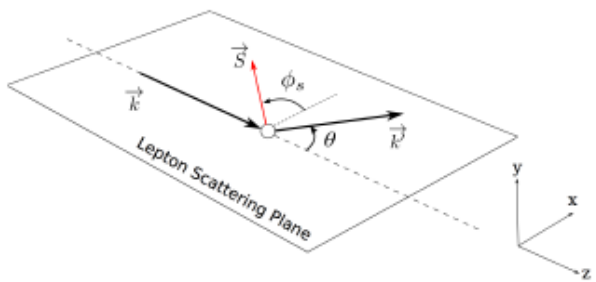
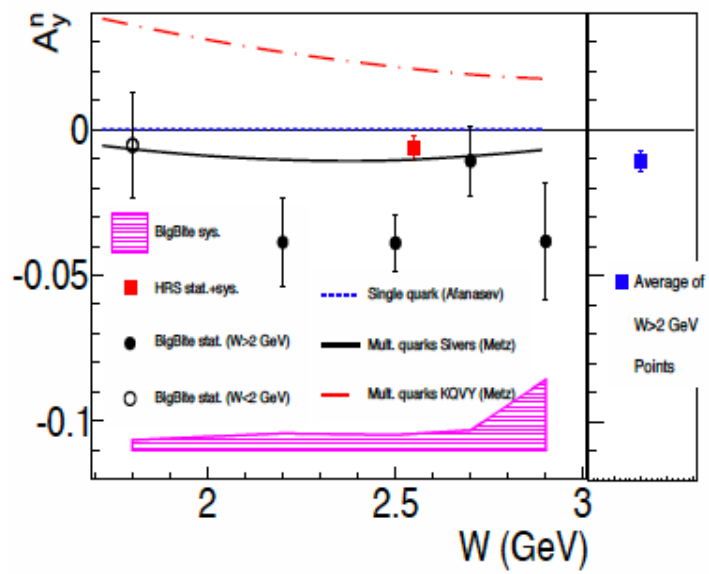
Experiment in JLAB Hall A

- Katichet al., **Phys.Rev.Lett. 113 (2014)022502**
  - Shows per-cent level asymmetry in ^{3}He↑(e,e′)X
  - Presents an issue for analysis for TMD extraction from T-odd asymmetries in SIDIS





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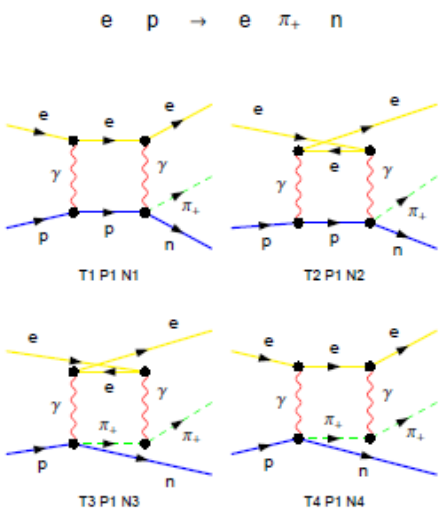
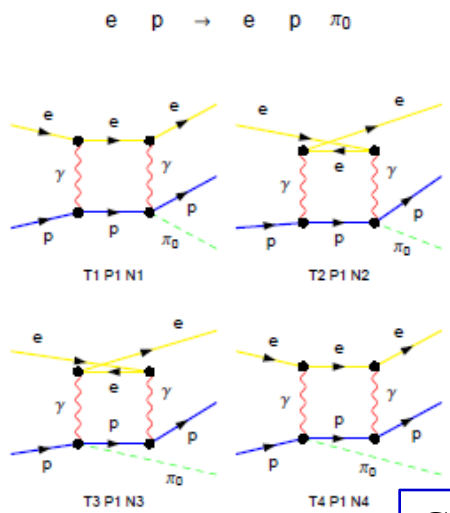
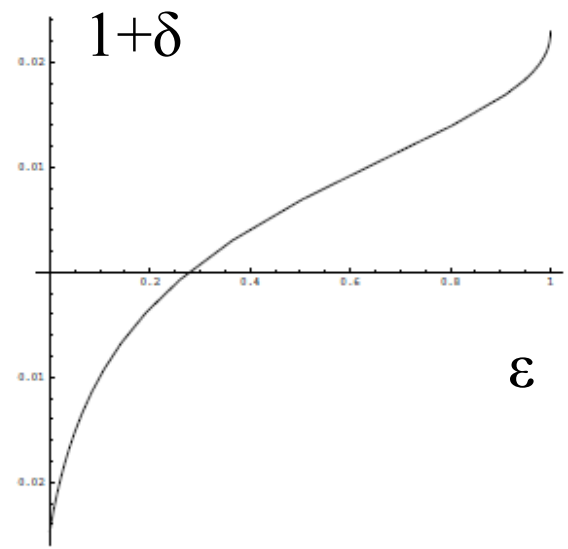
Two-Photon Exchange in Exclusive Electroproduction of Pions

- Standard contributions considered, e.g., AA, Akushevich, Burkert, Joo, PRD66:074004 (2002) also produced code EXCLURAD for data analysis)
- *Additional contributions due to two-photon exchange*, calculated by AA, Aleksejevs, Barkanova, PRD88:053008 (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.

Summary

- TPE theory consistent with available e^+/e^- data. Data at higher Q^2 is desirable to resolve Rosenbluth-polarization puzzle.
- MUSE is the only planned e+/e-, μ+/μ- proton scattering experiment. Constraining MUSE systematics due to rad.corrections is crucial for the experiment's success
- SSA due to TPE
  - Beam asymmetry in good agreement with theory except high-Z target. Raises concern for PREX. Medium-Z (CREX) is important.
  - Measured target asymmetry appears too unsuppressed (~1%) in conflict with partonic calculations => Issue for TMD program
- T-violation in lepton scattering: SSA technique works up to $\sim 10^{-4}$, limitation due to higher-order QED loops (*three*-photon exchange)

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