QED (Including 2-photon) Corrections and Observables for Exclusive Processes

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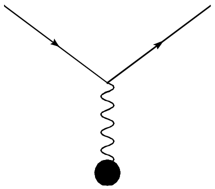
Electron-Ion Collider Workshop: Electron-Nucleon Exclusive Reactions

Rutgers University, March 14, 2010

Plan of talk

- Elastic electron-proton scattering beyond the leading order in QED
- Models for two-photon exchange
- Single-spin asymmetries
  - Diffractive mechanism in ep-scattering via two-photon exchange
  - Novel features of a single-spin asymmetry
  - Comparison with experiment
  - Possible new insights from EIC
- Summary

Elastic Nucleon Form Factors



- Based on one-photon exchange approximation

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

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

- Two techniques to measure

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

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

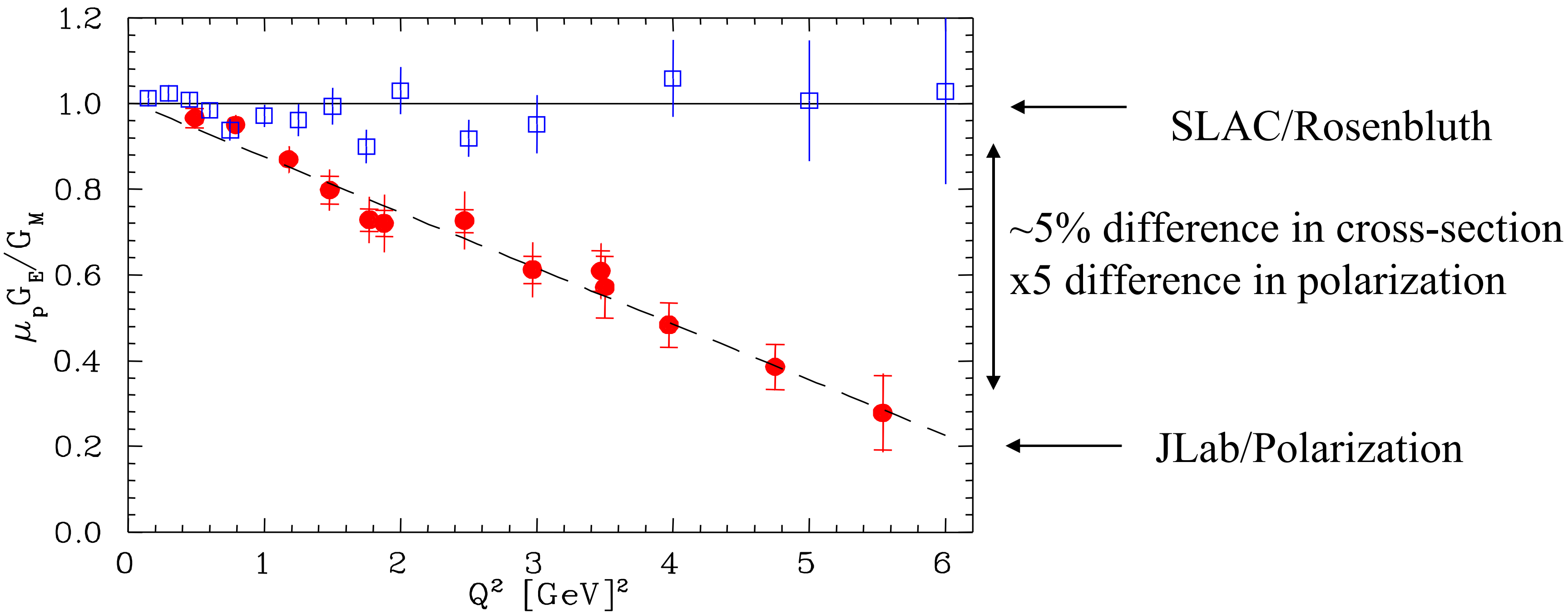
$$G_E = F_1 - \tau F_2, \quad G_M = F_1 + F_2$$

$$\tau = \frac{-q^2}{4m_N^2}, \varepsilon = (1 - 2\frac{\vec{q}_{lab}^{\,2}}{q^2}\tan^2\frac{\theta_e}{2})^{-1}$$

$$(P_y = 0)$$

Latter due to: Akhiezer, Rekalo; Arnold, Carlson, Gross

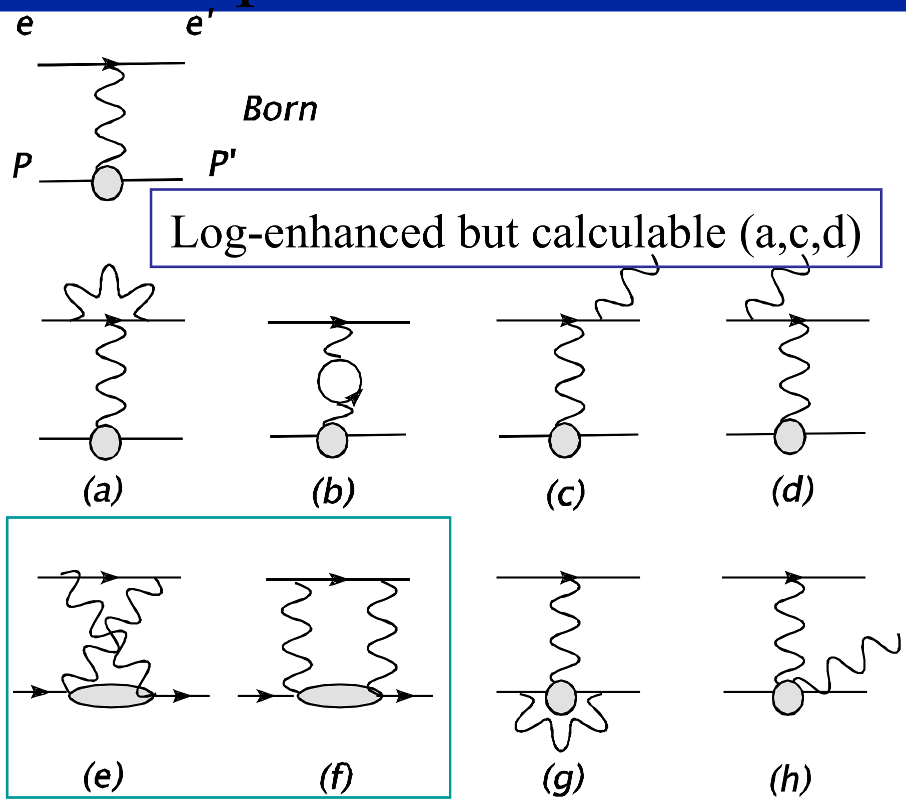
Do the techniques agree?



- **Both early SLAC and Recent JLab experiments on (super)Rosenbluth separations followed Ge/Gm~const, see I.A. Quattan et al., Phys.Rev.Lett. 94:142301,2005**
- **JLab measurements using polarization transfer technique give different results (Jones'00, Gayou'02)**

Radiative corrections, in particular, a short-range part of 2-photon exchange is a likely origin of the discrepancy

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



<u>Radiative Corrections:</u>

- 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

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

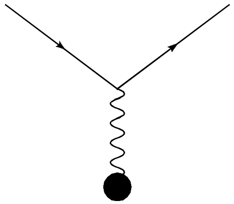
Main issue: Corrections dependent on nucleon structure

Model calculations:

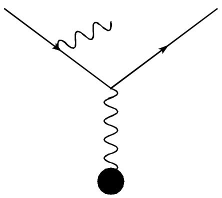
•Blunden, Melnitchouk,Tjon, Phys.Rev.Lett.**91**:142304,2003

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

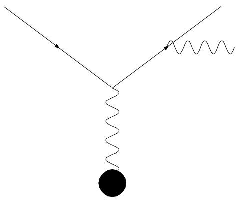
Basics of QED radiative corrections



(First) Born approximation

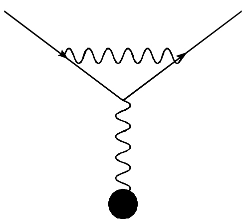


Initial-state radiation



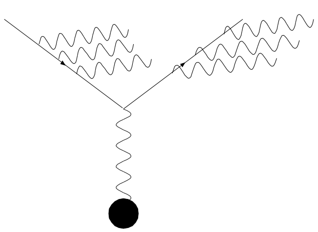
Final-state radiation

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



Vertex correction => cancels divergent terms; Schwinger (1949)

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



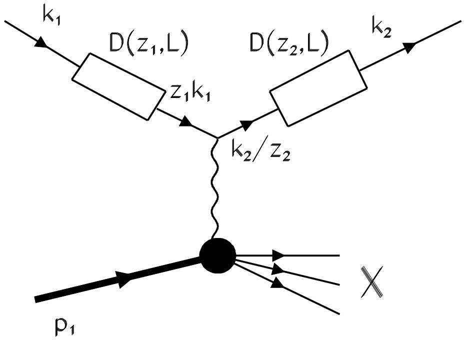
Multiple soft-photon emission: solved by exponentiation, Yennie-Frautschi-Suura (YFS), 1961

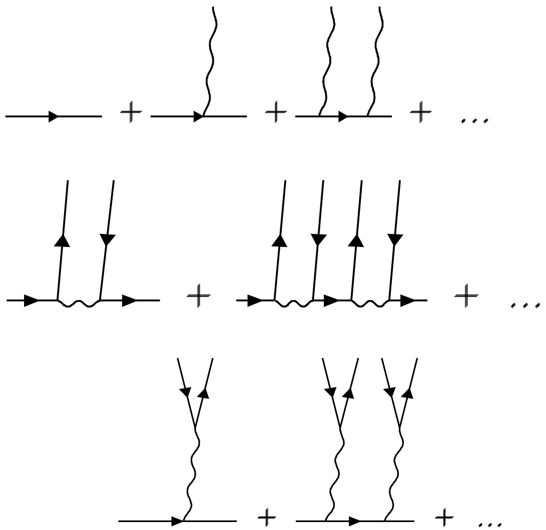
$$(1+\delta) \rightarrow e^{\delta}$$

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.

Electron Structure Functions



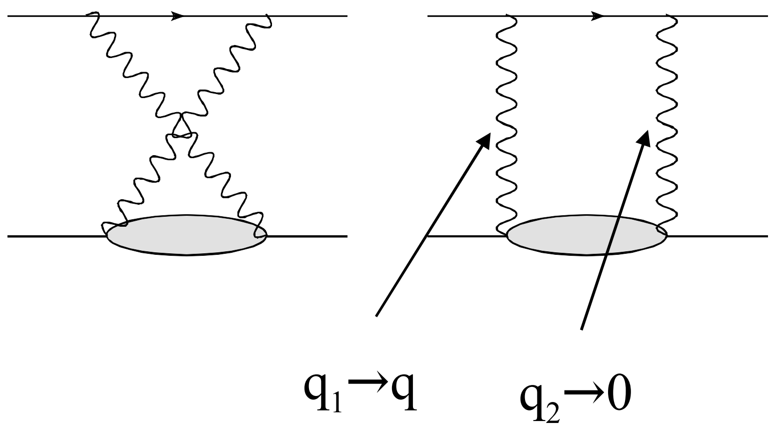


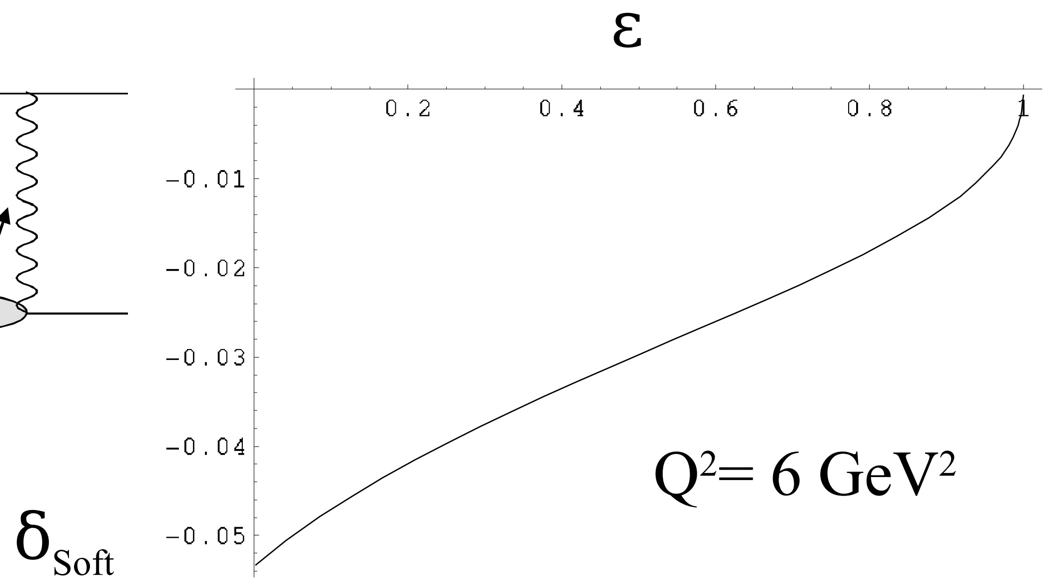
- For polarized ep->e'X scattering, AA et al, JETP 98, 403 (2004); elastic ep: AA et al. PRD 64, 113009 (2001).
  - Resummation technique for collinear photons (=peaking approx.)
  - Difference <0.5% from previous calculation including hard brem

– Bystritskiy, Kuraev, Tomasi-Gustafson (2007) claimed this approach resolves Rosenbluth vs polarization discrepancy… but used incorrect energy cutoff ΔE/E of 3% (instead of e.g. 1.5%) =>miscalculated rad.correction by ~5% (absolute)

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**
- **NB:** Corresponding effect to polarization transfer and/or asymmetry is zero





A similar approach can be applied for any exclusive reaction

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 GeV electrons and m_q~300 MeV, backward angles); zero at forward angles**
  - **Motivates a more detailed calculation of 2-photon exchange at quark level**

Lorentz Structure of ep-scattering amplitude

Three generalized form factors ($m_e \to 0$ case)are functions of two Mandelstam invariants. Specific dependence is determined by nucleon structure

$$M_{fi} = M_{fi}^{1\gamma} + M_{fi}^{2\gamma}$$

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

$$M_{fi}^{2\gamma} = V_e \otimes V_p + A_e \otimes A_p$$

$$V_e = \bar{u}_e \gamma_\mu u_e, V_p = \bar{u}_p (F_1'(s,u)\gamma_\mu - \tfrac{\sigma_{\mu\nu} q_\nu}{2m} F_2'(s,u)) u_p$$

$$A_e = \bar{u}_e \gamma_\mu \gamma_5 u_e, \; A_p = \bar{u}_p G_A(s,u) \gamma_\mu \gamma_5 u_p$$

Observables in terms of generalized form factors

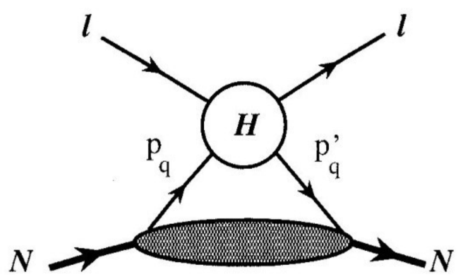
$$\sigma_R = |G'_M|^2 + \frac{\varepsilon}{\tau} |G'_E| + \sqrt{\frac{(1+\tau)(1-\varepsilon^2)}{\tau}} G_M \operatorname{Re}(G'_A) + O(\alpha^2)$$

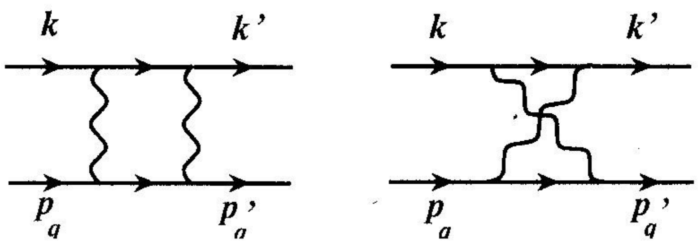
$$P_n \sigma_R = A_n \sigma_R = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}} \left[\operatorname{Im}(G_E'^* G_M') + \sqrt{\frac{(1+\tau)(1-\varepsilon)}{\tau(1+\varepsilon)}} G_E \operatorname{Im}(G_A') + O(\alpha^2) \right]$$

$$P_s \sigma_R = A_s \sigma_R = -P_e \sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}} \left[\operatorname{Re}(G_E'^* G_M') + \sqrt{\frac{(1+\tau)(1+\varepsilon)}{\tau(1-\varepsilon)}} G_E \operatorname{Re}(G_A') + O(\alpha^2) \right]$$

$$P_l \sigma_R = A_l \sigma_R = P_e \left[\sqrt{1-\varepsilon^2} \, |G_M'|^2 + 2\sqrt{\frac{1+\tau}{\tau}} G_M \operatorname{Re}(G_A') + O(\alpha^2) \right]$$

Calculations using Generalized Parton Distributions





Model schematics:

- Hard eq-interaction
- GPDs describe quark emission/absorption
- Soft/hard separation
  - Use Grammer-Yennie prescription

Hard interaction with a quark

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

Short-range effects; on-mass-shell quark

Two-photon probe directly interacts with a (massless) quark (cf *Khriplovich*, 1973; Brown et al, 1973); Emission/reabsorption of the quark is described by GPDs

$$A^{2\gamma}_{eq\to eq} = \frac{e_q^2}{t}\frac{\alpha_{em}}{2\pi}(V^e_\mu \otimes V^q_\mu \times f_V + A^e_\mu \otimes A^q_\mu \times f_A),$$

$$V^{e,q}_\mu = \bar{u}_{e,q}\gamma_\mu u_{e,q},\ A^{e,q}_\mu = \bar{u}_{e,q}\gamma_\mu\gamma_5 u_{e,q}$$

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

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

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

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

Note the additional effective (axial-vector)^2 interaction; absence of mass terms

Dimensional counting: at the quark level 2g amplitude has the same asymptotics as Born amplitude

`Hard' contributions to generalized form factors

GPD integrals

$$A \equiv \int_{-1}^{1} \frac{dx}{x} \frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)} \sum_q e_q^2 \, (H^q + E^q) \, ,$$

$$B \equiv \int_{-1}^{1} \frac{dx}{x} \frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)} \sum_q e_q^2 \, (H^q - \tau E^q)$$

$$C \equiv \int_{-1}^{1} \frac{dx}{x} \tilde{f}_1^{hard} \, \mathrm{sgn}(x) \sum_q e_q^2 \, \tilde{H}^q$$

Two-photon-exchange form factors from GPDs

$$\delta\tilde{G}_M^{hard} = C$$

$$\delta\tilde{G}_E^{hard} = -\left(\frac{1+\varepsilon}{2\varepsilon}\right)(A-C) + \sqrt{\frac{1+\varepsilon}{2\varepsilon}}\, B$$

$$\tilde{F}_3 = \frac{M^2}{\nu}\left(\frac{1+\varepsilon}{2\varepsilon}\right)(A-C)$$

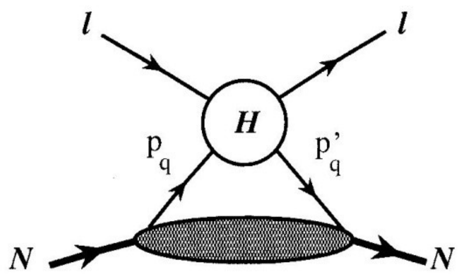
Two-Photon Contributions (cont.)

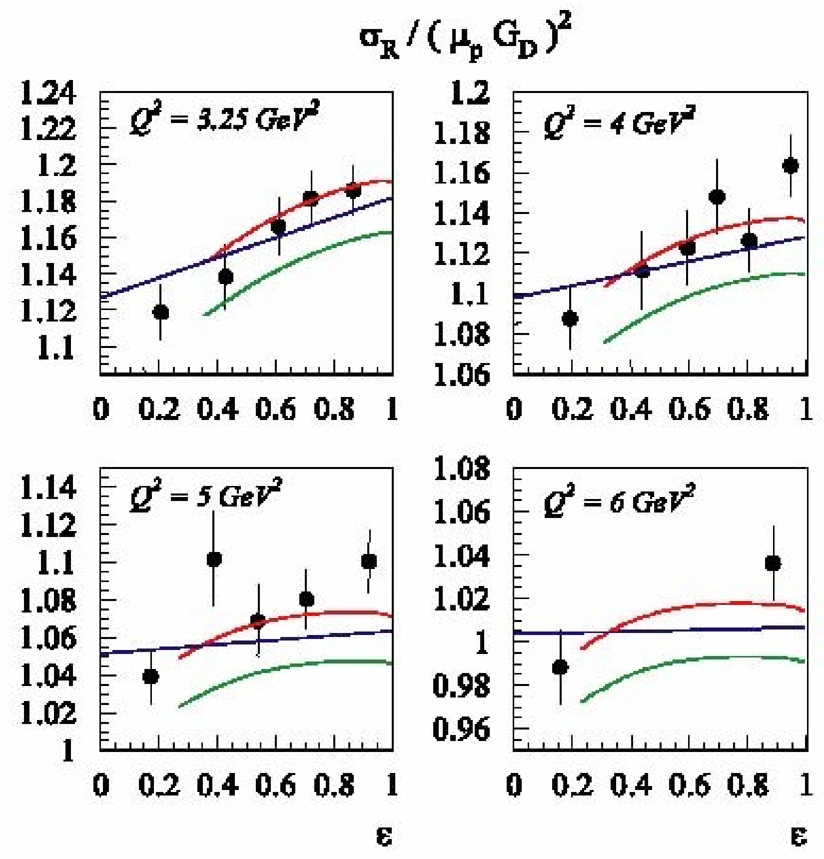
Blunden et al. have calculated elastic contribution of TPE

Afanasev, Brodsky, Carlson et al, PRD 72:013008 (2005); PRL 93:122301 (2004)

Model schematics:

- **Hard eq-interaction**
- **GPDs describe quark emission/absorption**
- **Soft/hard separation**
- **Assume factorization**





Resolves ~50% of discrepancy

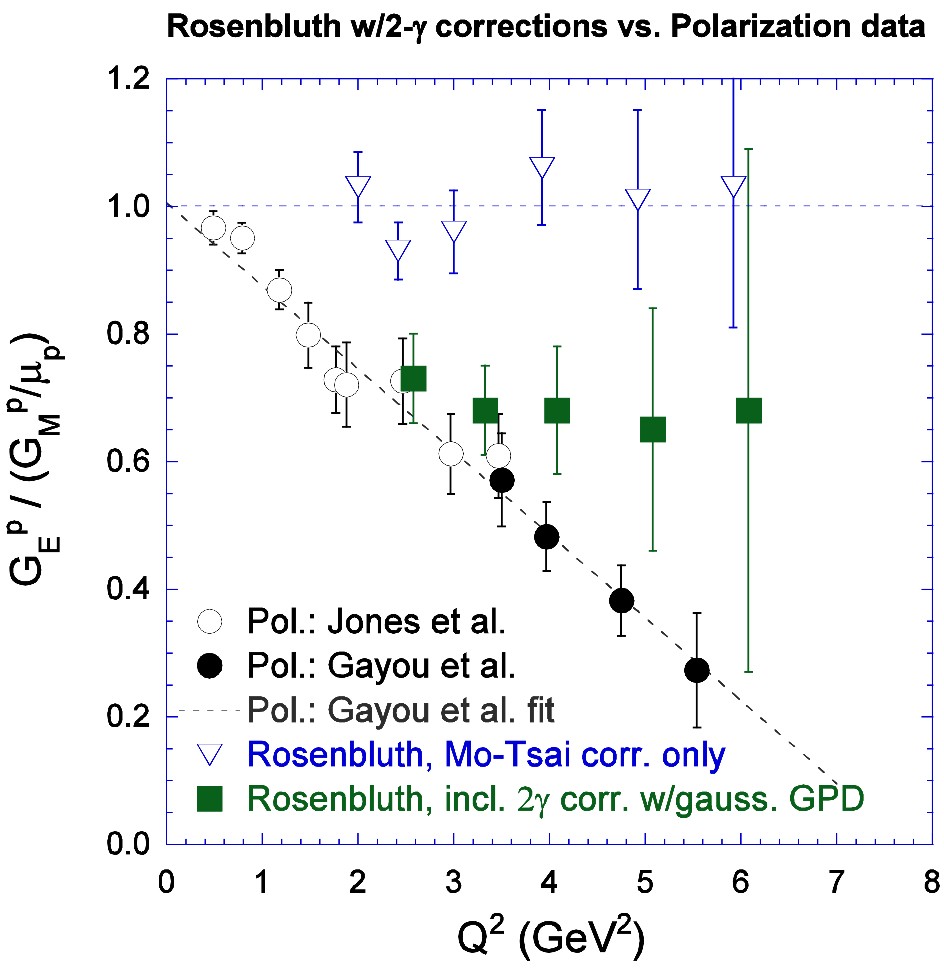
Polarization transfer

$1\gamma + 2\gamma$ (hard)

$1\gamma + 2\gamma$ (hard+soft)

Updated Ge/Gm plot

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



Full Calculation of Bethe-Heitler Contribution

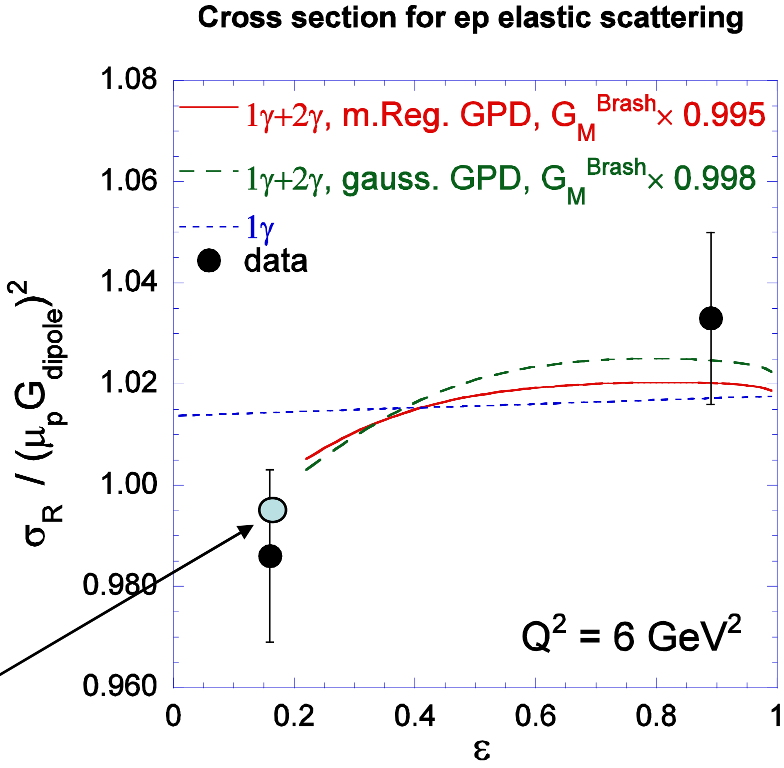
*Additional work by AA et al., using MASCARAD (**Phys.Rev.D64:113009,2001)***
Full calculation including soft and hard bremsstrahlung

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

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

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

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

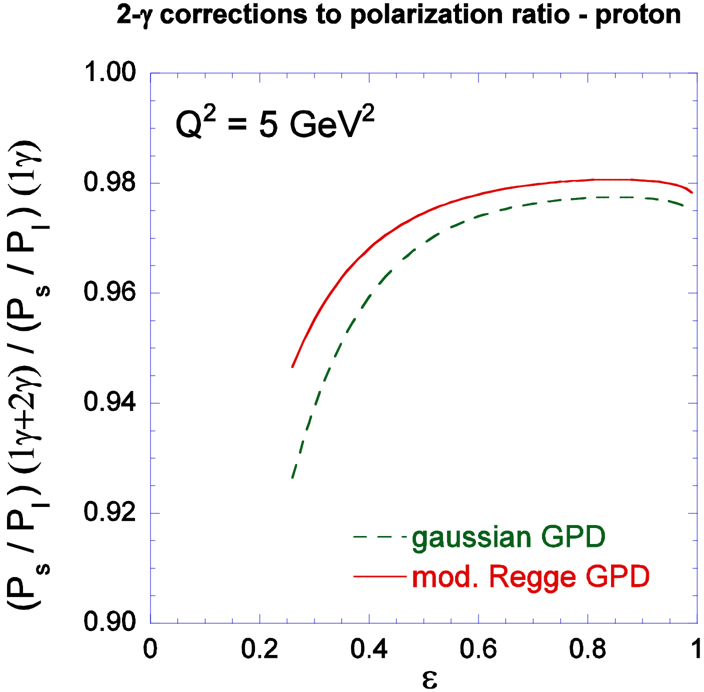


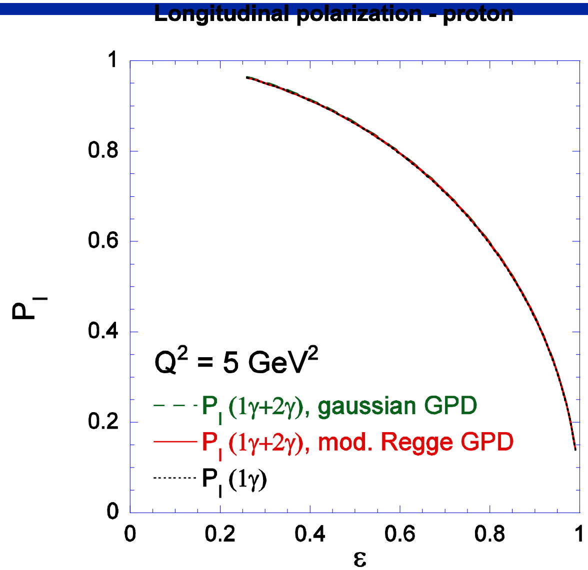
Additional effect of full soft+hard brem → +1.2% correction to ε-slope

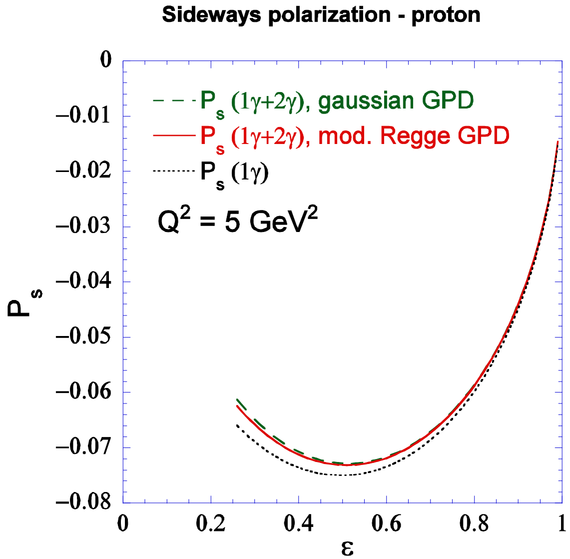
Resolves additional ~25% of Rosenbluth/polarization discrepancy!

Polarization transfer

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

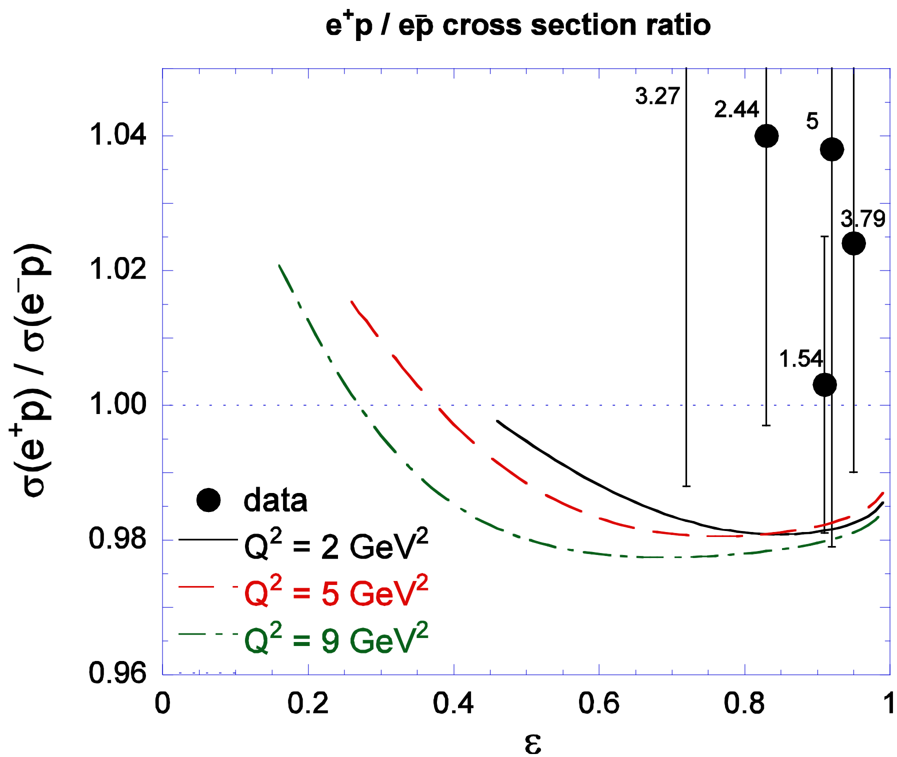






Charge asymmetry

- **Cross sections of electron-proton scattering and positron-proton scattering are equal in one-photon exchange approximation**
  - **Different for two- or more photon exchange**



To be measured in JLab Experiment 04-116, Spokepersons AA, W. Brooks, L.Weinstein, et al.
Also at DESY (Olympus) and Novosibirsk

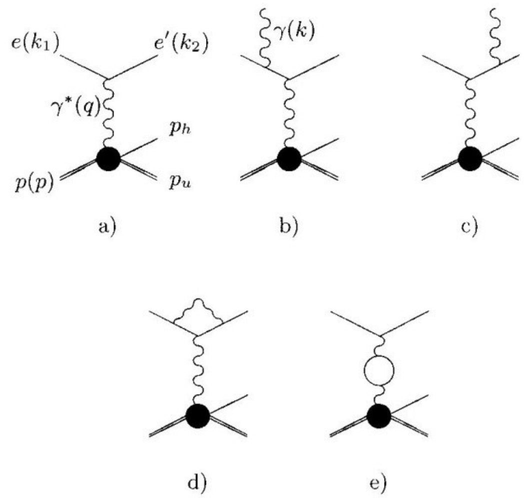
Radiative Corrections for Exclusive Processes

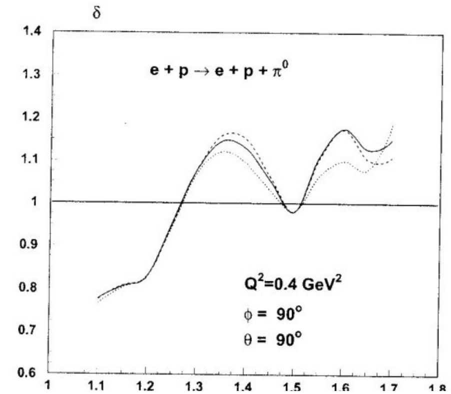
- **Photon emission is a part of any electron scattering process: accelerated charges radiate**
- **Exclusive electron scattering processes such as p(e,e'h_1)h_2 are in fact inclusive p(e,e'h_1)h_2 nγ ,**

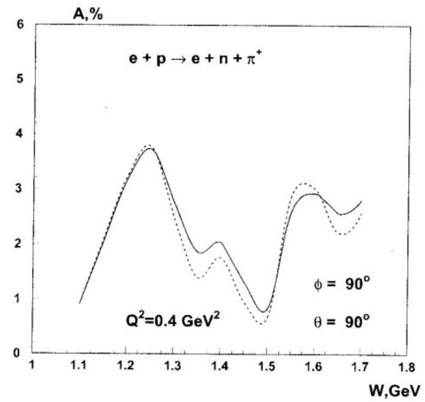
  where we can produce an infinite number of low-energy photons
- **But low-energy photons do not affect polarization observables, thanks to Low theorem**

RC for Electroproduction of Pions

- **AA, Akushevich, Burkert, Joo, Phys.Rev.D66, 074004 (2002)**
  - **Conventional RC, precise treatment of phase space, no peaking approximation, no dependence on hard/soft photon separation; <u>extension to DVMP is straightforward</u>**



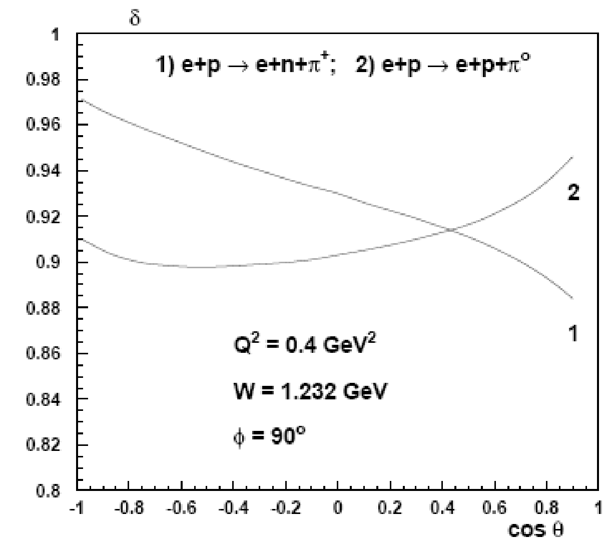


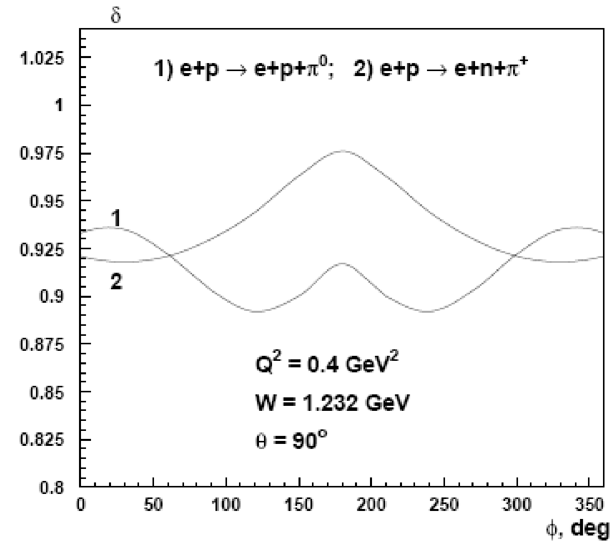


See http://www.jlab.org/RC for other codes
Used in data analysis at JLab
(and MIT, HERMES, MAMI,…)

Angular Dependence of Rad.Corrections

- **Rad.Corrections introduce additional angular dependence on the experimentally observed cross section of electroproduction processes, both exclusive and semi-inclusive**





Rad.Corrections to e^+e^- pair production

- **Usual corrections+charge asymmetric corrections**

PHYSICAL REVIEW VOLUME 173, NUMBER 4 20 SEPTEMBER 1968

Second Born Corrections to Wide-Angle High-Energy Electron Pair Production and Bremsstrahlung*

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(Received 15 April 1968)

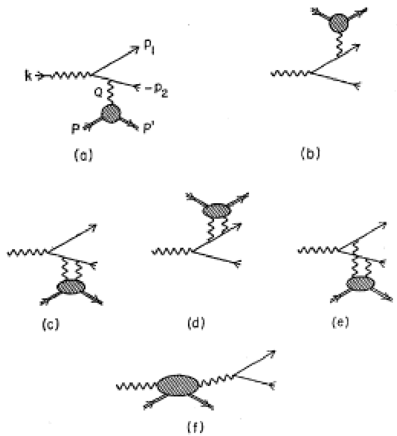


FIG. 1. Feynman diagrams for electron pair production. (a)–(e) give the Bethe-Heitler amplitude through second order in the electromagnetic interaction with the nucleus. Diagram (f) represents the virtual Compton contribution to pair production and includes contributions from the nuclear-pole terms, nucleon and nuclear excitations, and neutral vector-meson production.

Need to be re-visited in view of time-like DVCS measurements at JLAB

Single-Spin Asymmetries in Elastic Scattering

Parity-conserving

- Observed spin-momentum correlation of the type:

$$s \cdot k_1 \times k_2$$

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

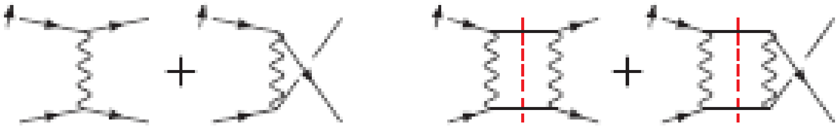
- For elastic scattering asymmetries are due to *absorptive part* of 2-photon exchange amplitude

Parity-Violating

$$s \cdot k_1$$

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) (b)

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

SLAC E158 Results (K. Kumar, private communication):
An(exp)=7.04±0.25(stat) ppm
An(theory)=6.91±0.04 ppm

Single-Spin Target Asymmetry $s_T \cdot k_1 \times k_2$

De Rujula, Kaplan, De Rafael, Nucl.Phys. B53, 545 (1973):
Transverse polarization effect is due to the absorptive part of the non-forward Compton amplitude for off-shell photons scattering from nucleons
See also AA, Akushevich, Merenkov, hep-ph/0208260

$$A_{l,p}^{el,in} = \frac{8\alpha}{\pi^2}\frac{Q^2}{D(Q^2)}\int dW^2 \frac{S+M^2-W^2}{S+M^2}\frac{dQ_1^2}{Q_1^2}\frac{dQ_2^2}{Q_2^2}\frac{1}{\sqrt{K}}\,B_{l,p}^{el,in}$$

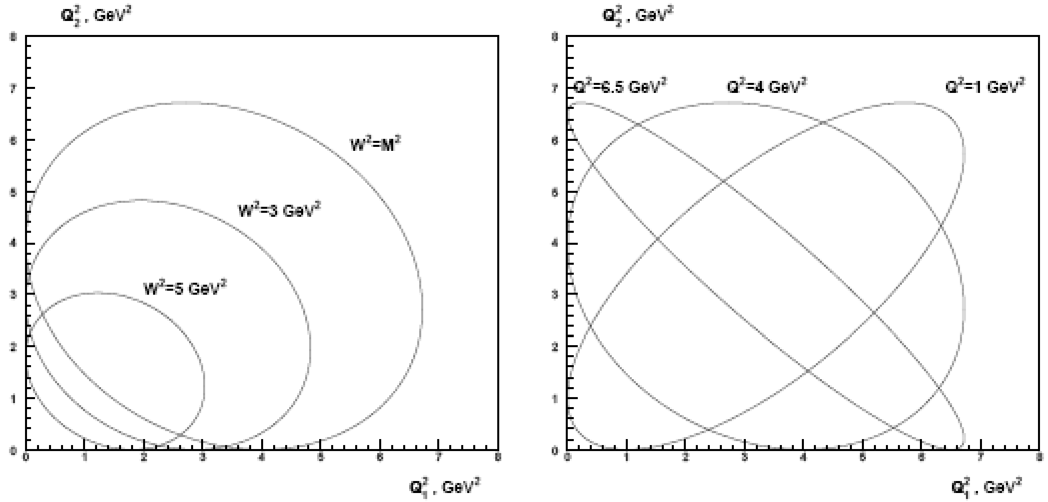


Figure 2. Integration region over Q_1^2 and Q_2^2 in Eq.(2) for elastic ($W^2 = M^2$) and inelastic contributions. The latter (left) is given for Q^2=4 GeV^2 and two values of W^2, which is an integration variable in this case. The elastic case is shown on the right as a function of external Q^2. The electron beam energy is E_b= 5 GeV.

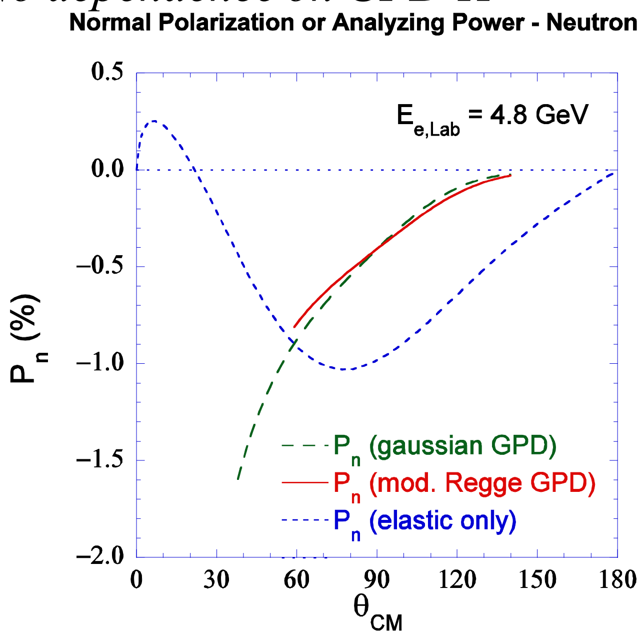
Quark+Nucleon Contributions to Target Asymmetry

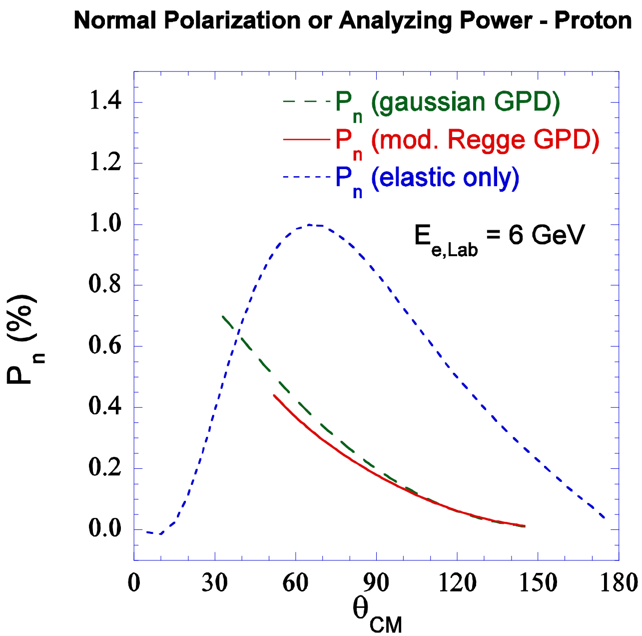
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetryof elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

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

Only minor role of quark mass

No dependence on GPD $\widetilde{H}$





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

Beam Single-Spin Asymmetry: Early Calculations

- ***Spin-orbit interaction of electron moving in a Coulomb field***
  N.F. Mott, Proc. Roy. Soc. London, Set. A 135, 429 (1932);
- ***Interference of one-photon and two-photon exchange Feynman diagrams in electron-muon scattering:*** **Barut, Fronsdal, Phys.Rev.120, 1871 (1960)**
- ***Extended to quark-quark scattering SSA in pQCD*****: Kane, Pumplin, Repko, Phys.Rev.Lett. 41, 1689 (1978)**

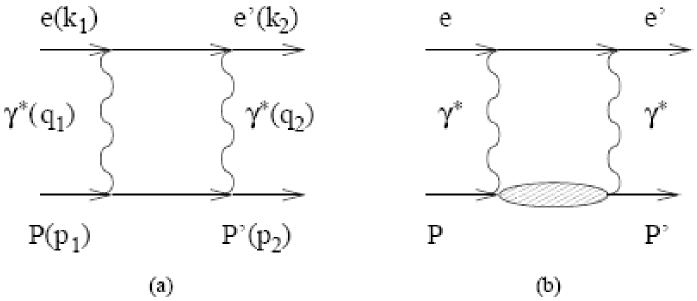
$$\Delta(\vartheta) = \mp 2Z\alpha \frac{v\sqrt{1-v^2}}{1-v^2\sin^2(\vartheta/2)} \frac{\sin^3(\vartheta/2)}{\cos(\vartheta/2)} \ln \frac{1}{\sin(\vartheta/2)} .$$

$$A_n \propto \frac{\alpha \cdot m_e \cdot \theta^3}{E}, \; for\ \theta << 1$$

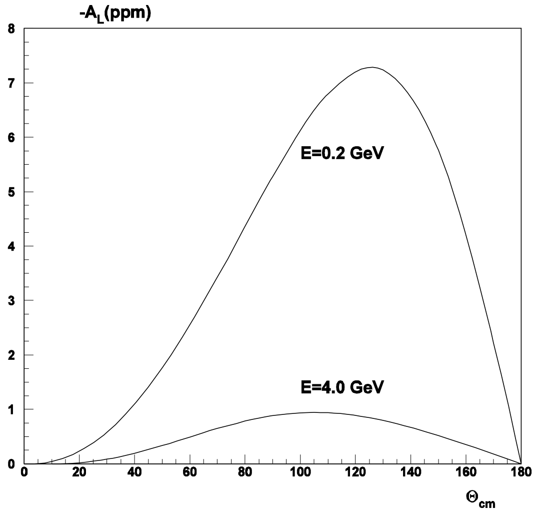
$$(small - angle\ scattering)$$

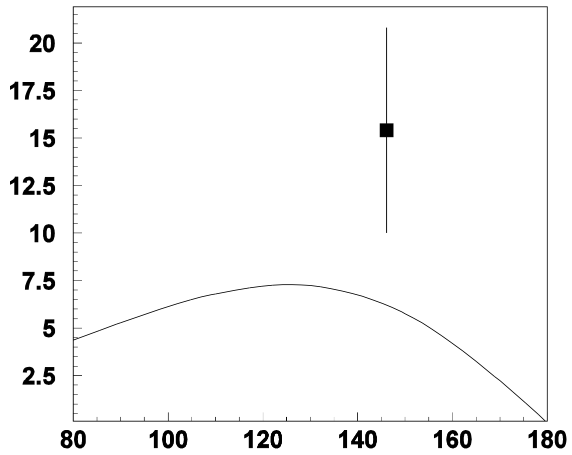
Proton Mott Asymmetry at Higher Energies

AA, Akushevich, Merenkov, hep-ph/0208260



Transverse beam SSA, units are parts per million



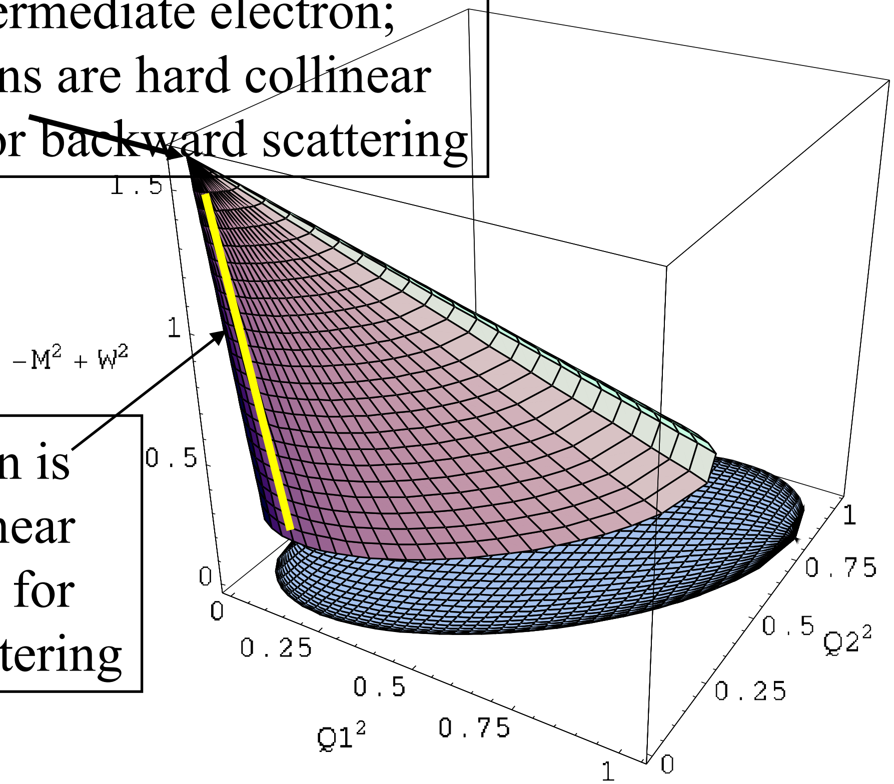


- **Asymmetry due to absorptive part of two-photon exchange amplitude; shown is elastic intermediate state contribution**
- **Nonzero effect first observed by SAMPLE Collaboration (S.Wells et al., PRC63:064001,2001) for 200 MeV electrons**

Phase Space Contributing to the absorptive part of 2γ-exchange amplitude

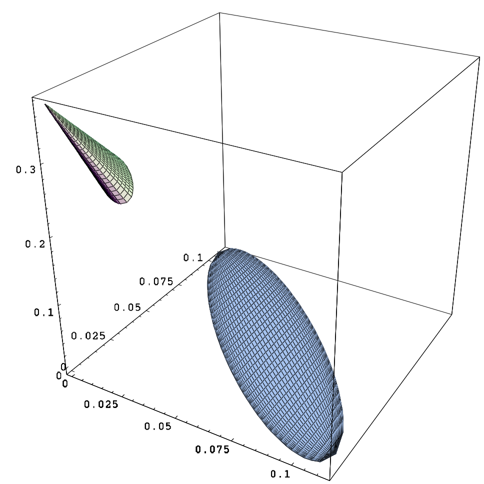
- 2-dimensional integration (Q_1^2, Q_2^2) for the elastic intermediate state
- 3-dimensional integration (Q_1^2, Q_2^2, W^2) for inelastic excitations

`Soft' intermediate electron;
Both photons are hard collinear
Dominates for backward scattering



One photon is
hard collinear
Dominates for
forward scattering

Examples: MAMI A4
E= 855 MeV
Θcm= 57 deg;
SAMPLE, E=200 MeV



Special property of Mott asymmetry

- Mott asymmetry above the nucleon resonance region
  - (a) does not decrease with beam energy
  - (b) is enhanced by large logs

(AA, Merenkov, PL B599 (2004)48; hep-ph/0407167v2 (erratum))

- Reason for the unexpected behavior: exchange of hard collinear quasi-real photons and diffractive mechanism of nucleon Compton scattering
  - For s>>-t and above the resonance region, the asymmetry is given by:

$$A_n^e(diffractive) = \sigma_{\gamma p} \frac{(-m_e)\sqrt{Q^2}}{8\pi^2} \cdot \frac{F_1 - \tau F_2}{F_1^2 + \tau F_2^2} (\log(\frac{Q^2}{m_e^2}) - 2) \cdot Exp(-bQ^2)$$

Compare with asymmetry caused by Coulomb distortion at small θ =>
may differ by orders of magnitude depending on scattering kinematics

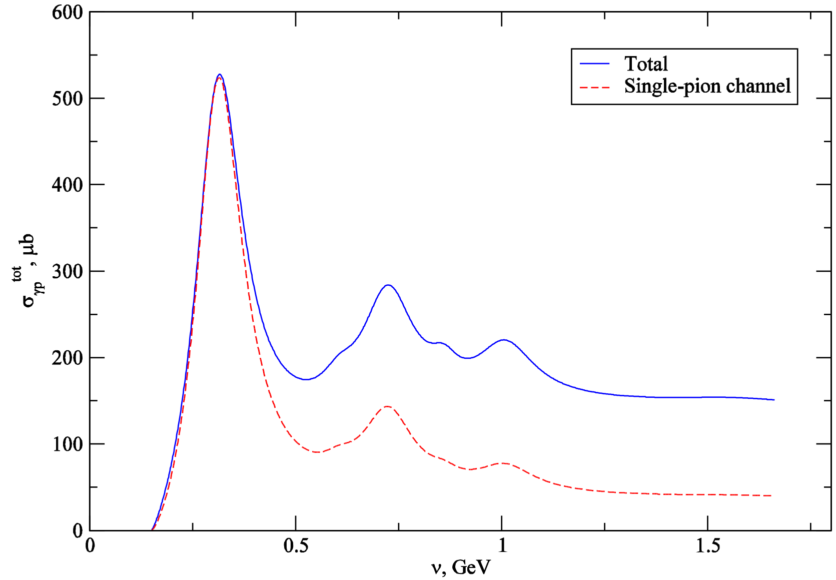
$$A_n^e(Coulomb) \propto \alpha \frac{m_e}{\sqrt{s}} \theta^3 \rightarrow A_n^e(Diffractive) \propto \alpha m_e (\sqrt{s}) \theta \cdot R_{\mathrm{int}}^2$$

Input parameters

For small-angle (-t/s<<1) scattering of electrons with energies Ee , normal beam asymmetry is given by the energy-weighted integral

$$A_n \propto \frac{1}{E_e^2} \int_{\nu_{th}}^{E_e} d\nu \cdot \nu \;\; \sigma_{\gamma p}^{tot}(\nu; q_{1,2}^2 \approx 0)$$

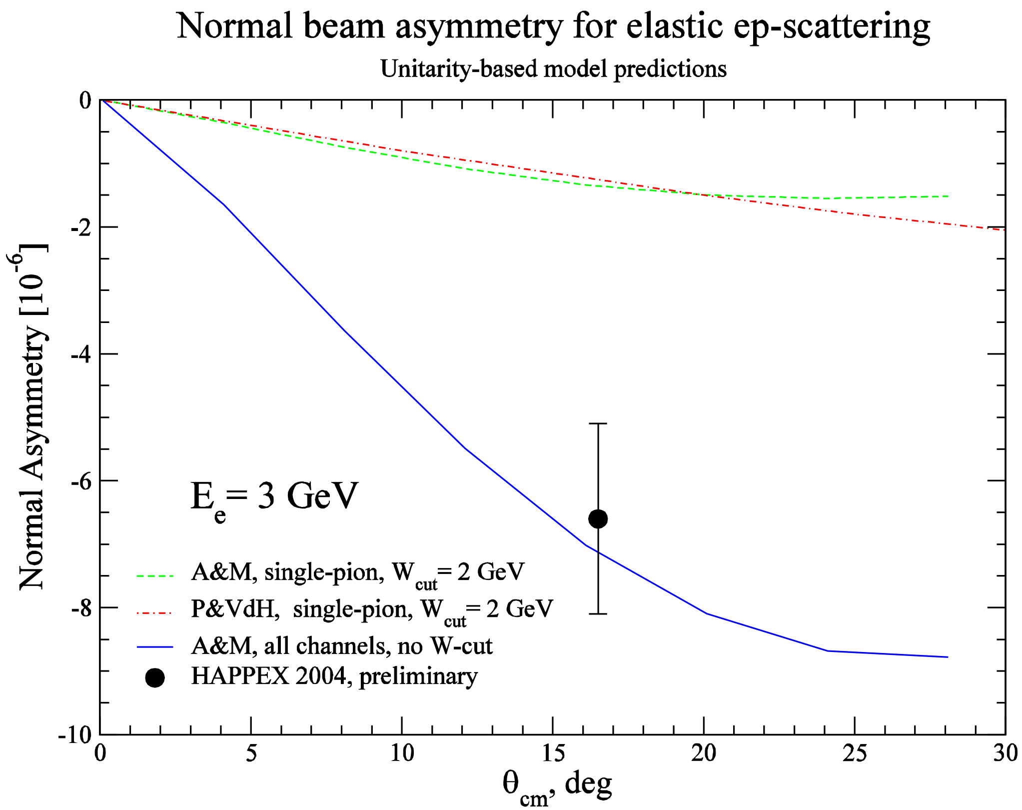
Total photoabsorption cross section
Proton target



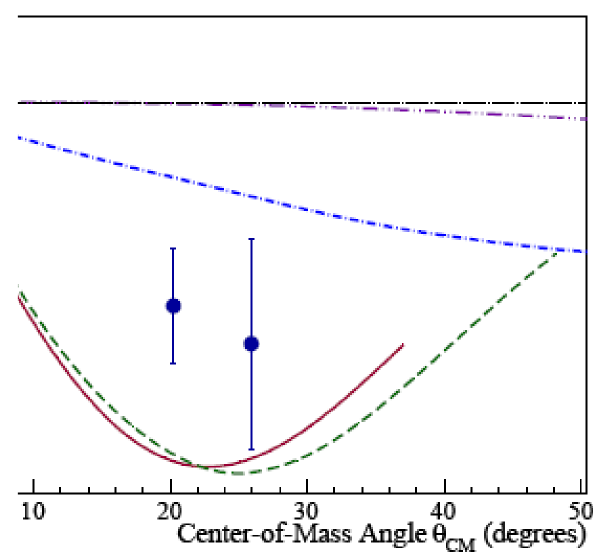
ɔ$_{\gamma p}$ from N. Bianchi at al.,
ıys.Rev.C54 (1996)1688
ɘsonance region) and
ock&Halzen,
Phys.Rev. D70 (2004) 091901

Predictions vs experiment for Mott asymmetry

Use fit to experimental data on $\sigma_{\gamma p}$ (dotted lines include only one-pion+nucleon intermediate states)

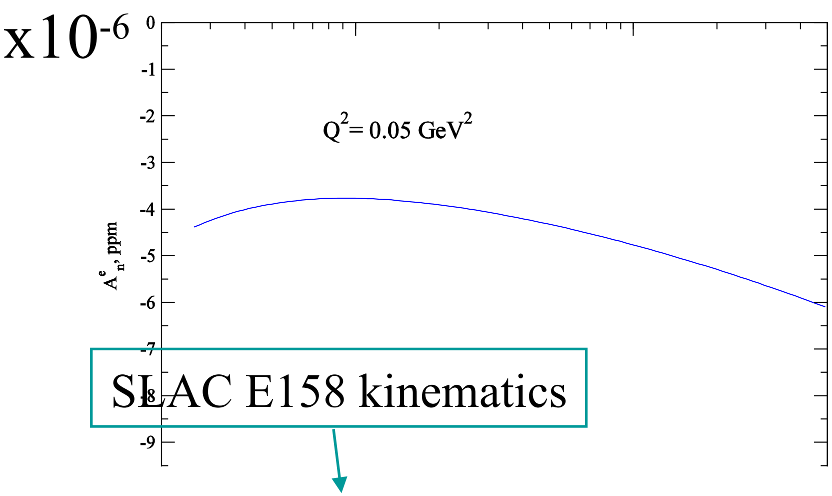


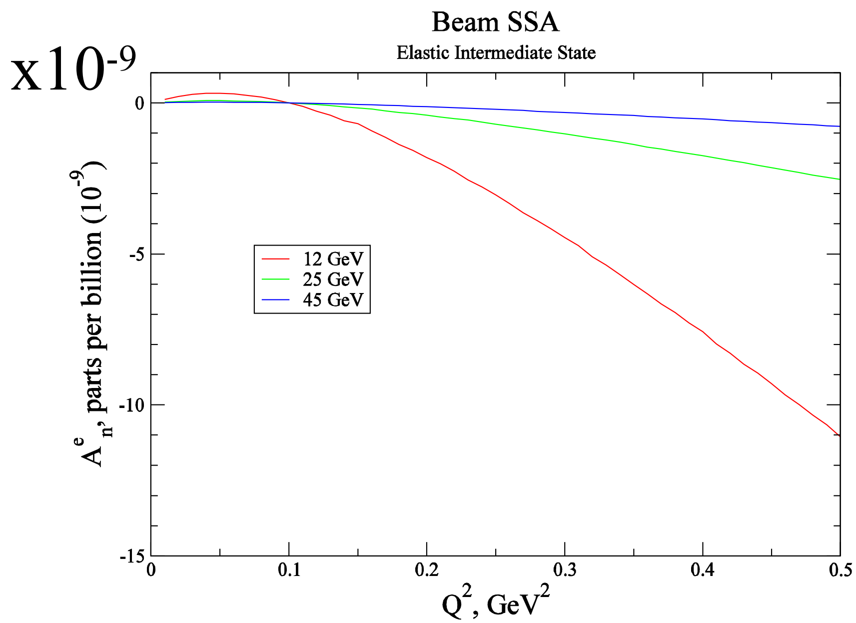
0 arXiv 0705.1525[nucl-ex]

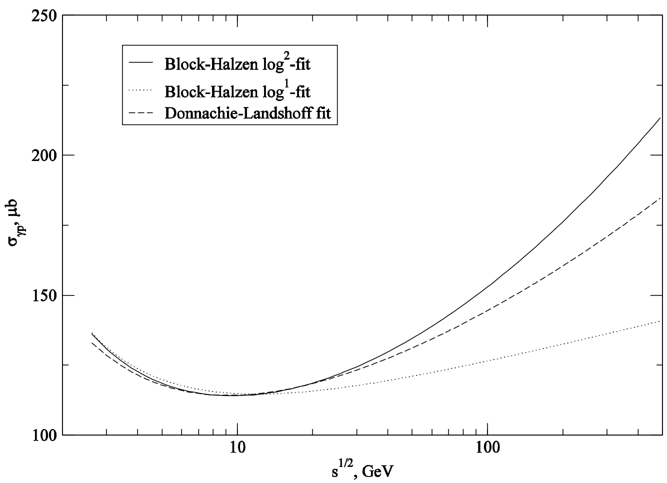


Estimated normal beam asymmetry for Qweak: **-5ppm**

Predict no suppression for Mott asymmetry with energy at fixed Q^2

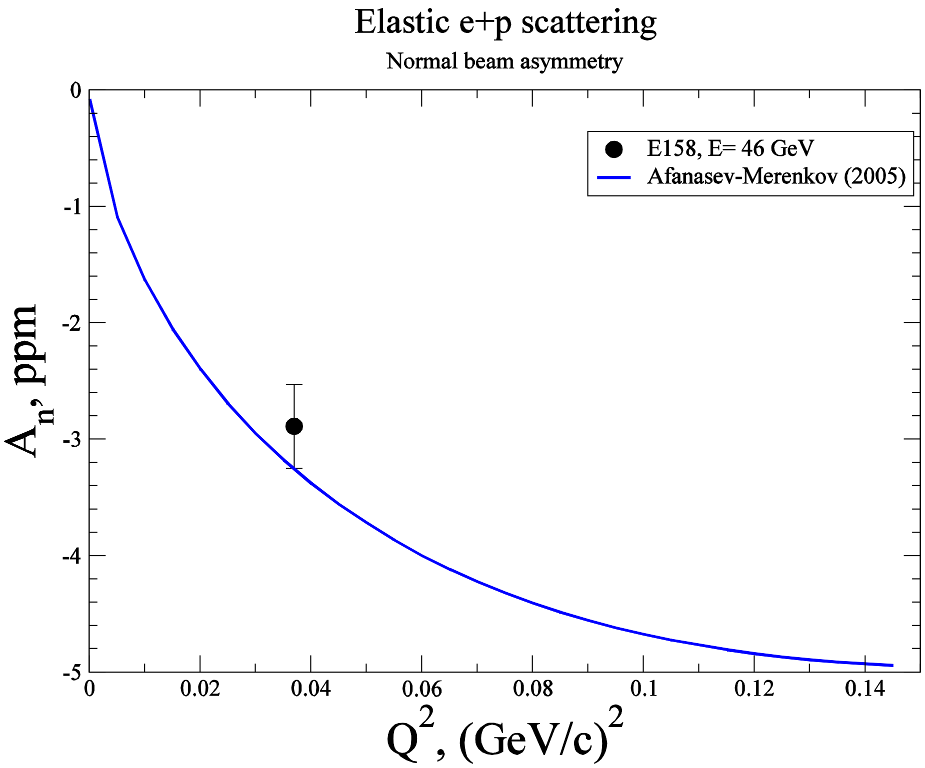






- At 45 GeV predict beam asymmetry parts-per-million (diffraction) vs. parts-per billion (Coulomb distortion)

Comparison with E158 data



- **SLAC E158: 46 GeV beam on fixed-target protons**

An=-2.89±0.36(stat)±0.17(syst) ppm

(K. Kumar, private communication)

- **Theory (AA, Merenkov):**

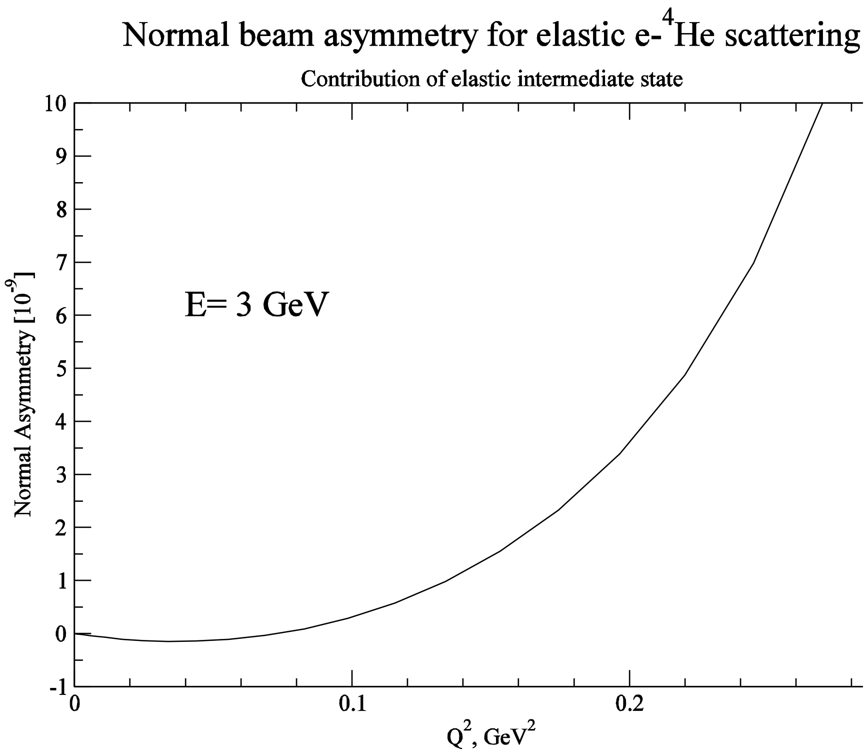
  An=-3.2ppm

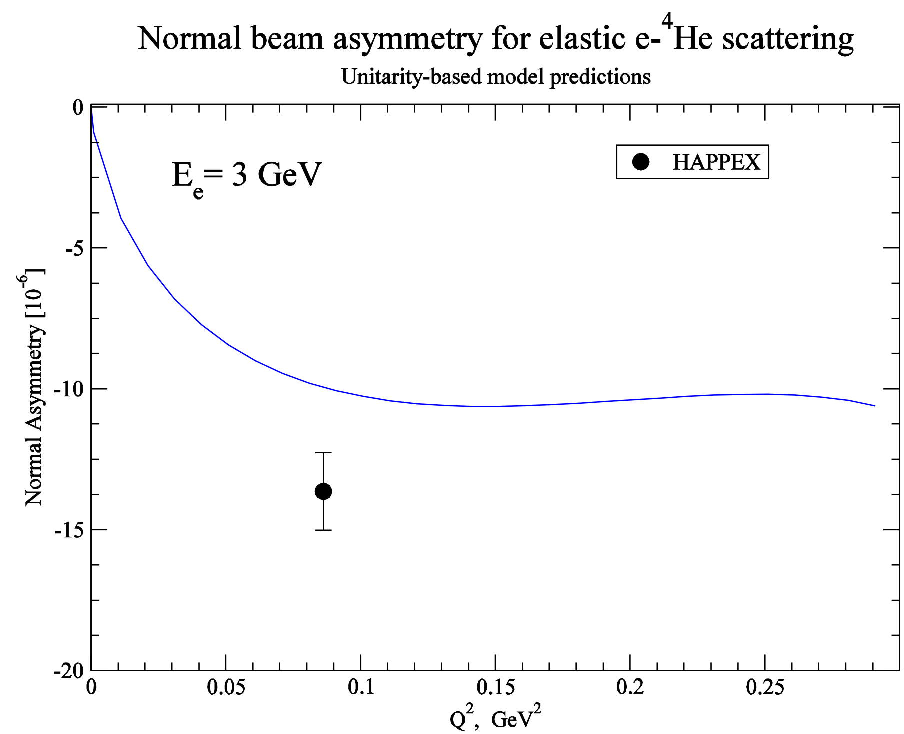
Need to include QED radiative correction

- **Good agreement justifies application of this approach to the real part of two-boson exchange (Gorchtein's talk on γZ box)**

Mott Asymmetry on Nuclei

- Important systematic correction for parity-violation experiments (~-10ppm for HAPPEX on ^{4}He, ~-5ppm for PREX on Pb,), *see AA arXiv:0711.3065 [hep-ph]* ; also Gorchtein, Horowitz, Phys.Rev.C77:044606,2008
- Coulomb distortion: only10^{-10} effect (Cooper&Horowitz, Phys.Rev.C72:034602,2005)



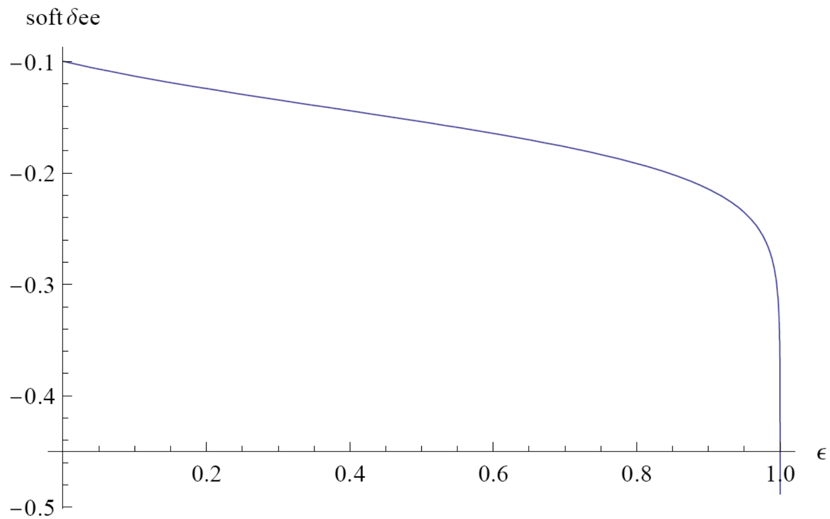


Five orders of magnitude enhancement in HAPPEX kinematics due to excitation of inelastic intermediate states in 2γ-exchange (AA, Merenkov; use Compton data from Erevan)

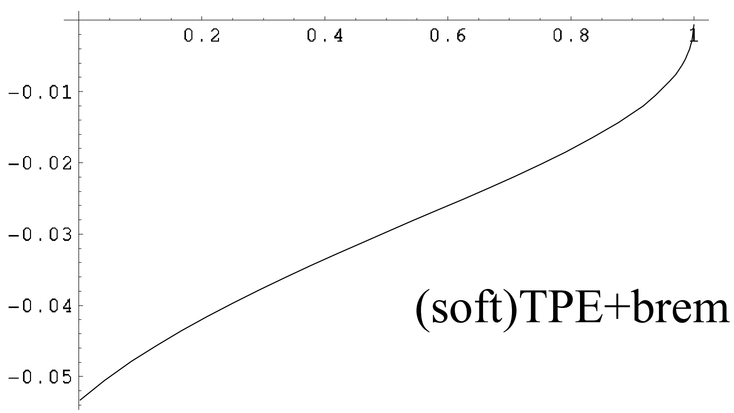
RC for Elastic ep-scattering at EIC

- **Large beam energy, fixed Q2 => need high epsilon~1 to maintain reasonable count rates (keep in mind luminosity 10^{34} e-N/cm^2/s)**
  - **E.g., for Q2=6GeV^2, value of 1-ε is in the 10^{-4}-10^{-5} range**
  - **Consider behavior of rad.correction at large epsilon**

$$\sigma_{\exp} = \sigma_{Born}(1+\delta)$$



Q^2=6 GeV^2



Rad.Corrections Changes very rapidly at high epsilon

For 1-ε~10^{-4}-10^{-5} , RC(brem)=-39% to -44%; RC(TPE)~10^{-4}

Observable in large-epsilon limit

- **Observables in terms of 2g-exchange form factors**

$$\sigma_R = |G'_M|^2 + \frac{\varepsilon}{\tau}|G'_E| + \sqrt{\frac{(1+\tau)(1-\varepsilon^2)}{\tau}} G_M \,\mathrm{Re}(G'_A) + O(\alpha^2)$$

$$P_n\sigma_R = A_n\sigma_R = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\left[\mathrm{Im}(G_E{}'^* G_M{}') + \sqrt{\frac{(1+\tau)(1-\varepsilon)}{\tau(1+\varepsilon)}} G_E \,\mathrm{Im}(G_A{}') + O(\alpha^2)\right]$$

$$P_s\sigma_R = A_s\sigma_R = -P_e\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\left[\mathrm{Re}(G_E{}'^* G_M{}') + \sqrt{\frac{(1+\tau)(1+\varepsilon)}{\tau(1-\varepsilon)}} G_E \,\mathrm{Re}(G_A{}') + O(\alpha^2)\right]$$

$$P_l\sigma_R = A_l\sigma_R = P_e\left[\sqrt{1-\varepsilon^2}\,|G_M{}'|^2 + 2\sqrt{\frac{1+\tau}{\tau}} G_M \,\mathrm{Re}(G_A{}') + O(\alpha^2)\right]$$

- **Factors of $\sqrt{1-\varepsilon}$ are common; they have an infinite slope when ε→1**

- **Studies of elastic ep-scattering at EIC may be possible at forward scattering angles**
  - **2gamma correction is suppressed, but may be rapidly variable with epsilon**
  - **Standard RC is enhanced; also varies rapidly with epsilon**

Summary: SSA in Elastic ep-Scattering

- **Collinear photon exchange present in (light particle) beam SSA**
- **Models violating EM gauge invariance encounter collinear divergence for target SSA**
- **VCS amplitude in *beam asymmetry* is enhanced in different kinematic regions compared to *target asymmetry***
- ***Beam asymmetry unsuppressed in forward angles, important systematic effect for PREX, Q_{weak}***
- **Strong-interaction dynamics for Mott asymmetry in small-angle ep-scattering above the resonance region is *soft diffraction***
  - ***For the diffractive mechanism A_n is a) not suppressed with beam energy and b) does not grow with Z (~A/Z)***
  - ***Confirmed experimentally (SLAC E158) → first observation of diffractive component in elastic electron-hadron scattering***

Two-photon exchange for electron-nucleon scattering

- **Model calculations of 2γ-exchange radiative corrections bring into agreement the results of polarization transfer and Rosenbluth techniques for Gep measurements**
- **Full treatment of brem corrections removes ~25% of R/P discrepancy in addition to 2γ → Important to compute conventional corrections accurately**
- **Experimental tests of two-photon exchange**
  - **C-violation in electron vs positron elastic scattering (JLab E04-116, E-07-005)**
  - **Measurement of nonlinearity of Rosenbluth plot (JLab E05-017)**
  - **Search for deviation of angular dependence of polarization and/or asymmetries from Born behavior at fixed Q^2 (JLab E04-019)**
  - **Elastic single-spin asymmetry or induced polarization (JLab E05-015)**
    - **Extended to inelastic (e,e') in E-07-013**
  - **2γ normal beam asymmetry measurements parallel to parity-violating experiments (HAPPEX, G0, PREX)**

Objectives: a) Testing precision of the electromagnetic probe

b) Double-virtual VCS studies

Implications for EIC

- ***Elastic ep-scattering studies may be possible with EIC***
- ***Limited to forward region: covers previously unexplored high-epsilon region***
- ***QED corrections essential; detailed feasibility studies needed***