Single-Spin Asymmetries in Elastic Electron-Hadron Scattering

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The George Washington University

Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV

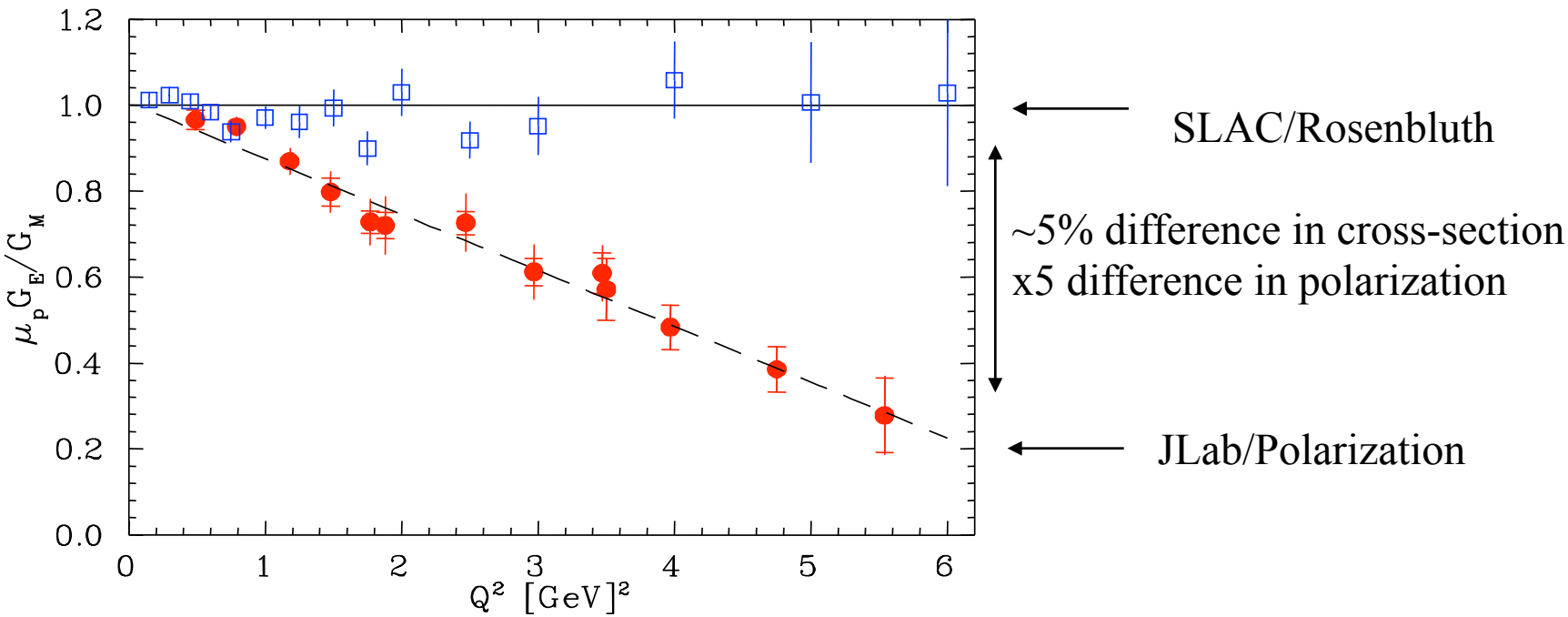
March 14-16, 2013

MIT, Cambridge, Massachusetts

Plan of talk

- Elastic electron-proton scattering beyond the leading order in QED
- Models for two-photon exchange
- Single-spin asymmetries
  - Inelastic intermediate state in ep-scattering via two-photon exchange
  - Novel features of a single-spin asymmetry
  - Comparison with experiment
- Summary

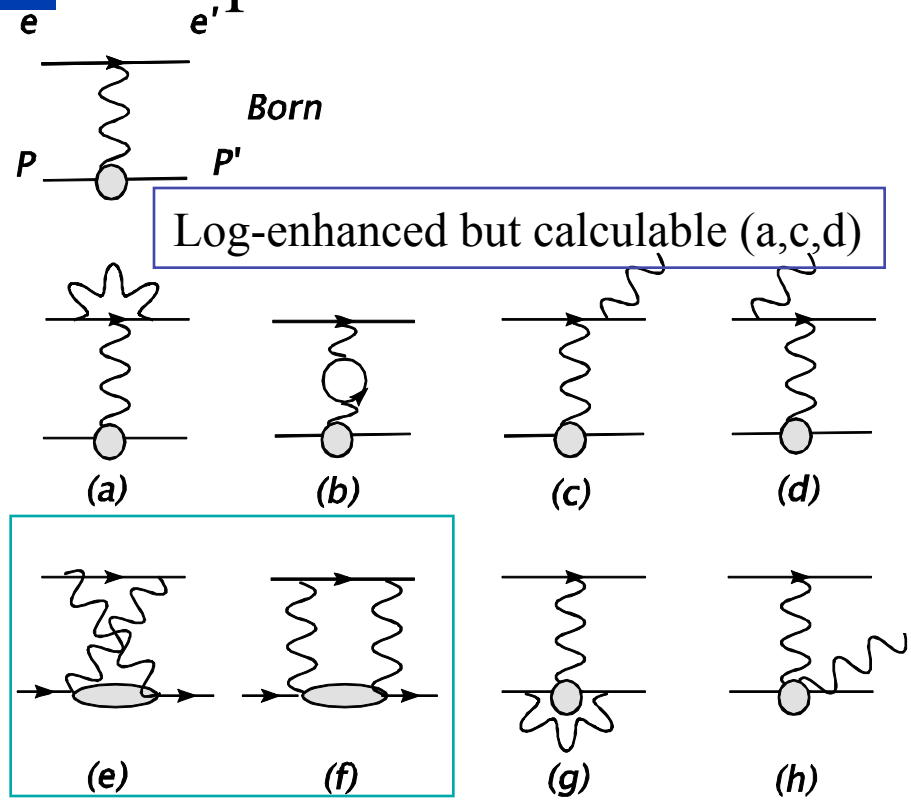
Do the techniques agree?



- **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 $O(\alpha_{em})$



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

Single-Spin Asymmetries in Elastic Scattering

Parity-conserving

- **Observed spin-momentum correlation of the type:**

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

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

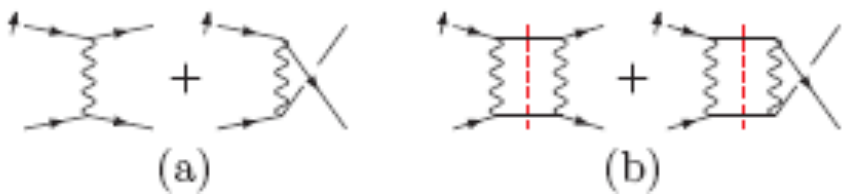
- **For elastic scattering asymmetries are due to *absorptive part* of 2-photon exchange amplitude**

Parity-Violating

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

Normal Beam Asymmetry in Moller Scattering

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



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

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

An(exp)=7.04±0.25(stat) ppm

An(theory)=6.91±0.04 ppm

Single-Spin Target Asymmetry $\vec{s}_T \cdot \vec{k}_1 \times \vec{k}_2$

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

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

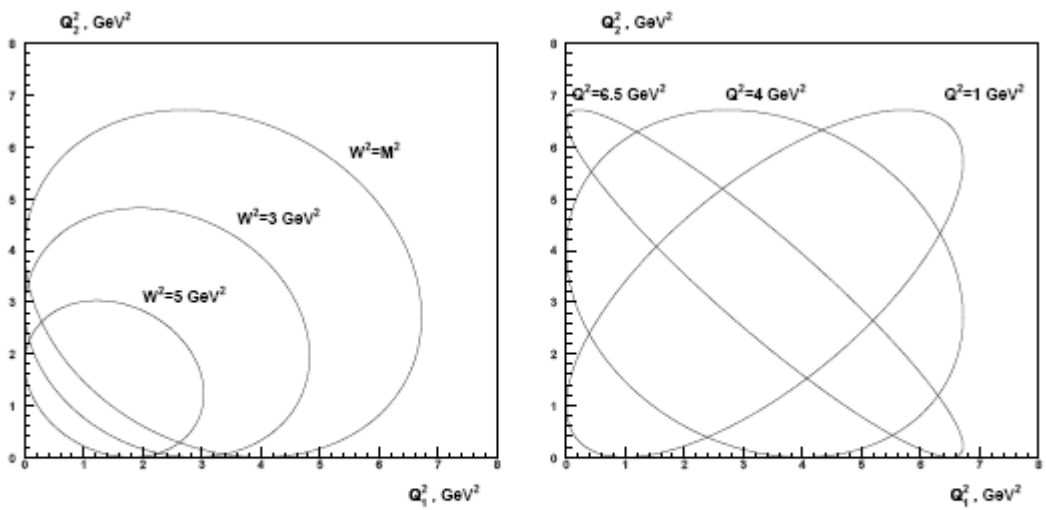
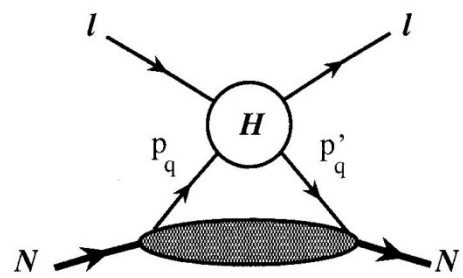
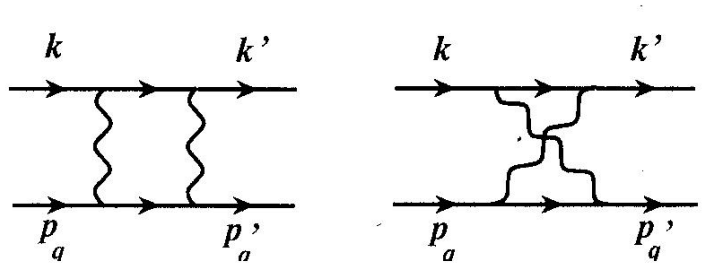


Figure 2. Integration region over Q_1^2 and Q_2^2 in Eq.(2) for elastic ($W^2 = M^2$) and inelastic contributions. The latter (left) is given for Q^2=4 GeV^2 and two values of W^2, which is an integration variable in this case. The elastic case is shown on the right as a function of external Q^2. The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

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

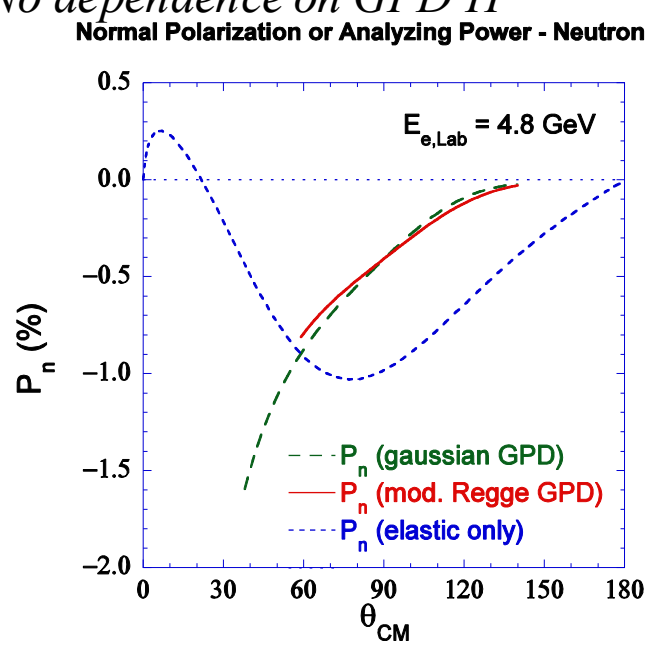
Quark+Nucleon Contributions to Target Asymmetry

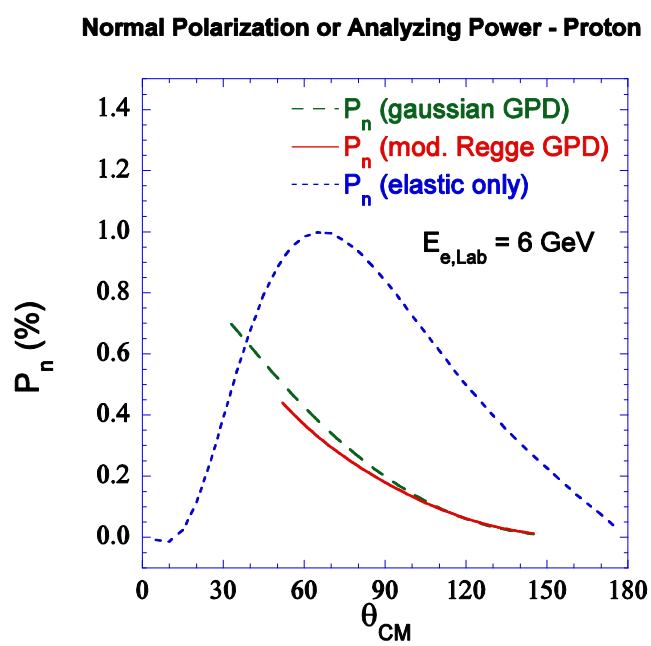
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetry of elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

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

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)

Single-Spin Asymmetry in Elastic Scattering
Early Calculations

- ***Spin-orbit interaction of electron moving in a Coulomb field***

Need in spin-flip and spin-nonflip +phase difference

N.F. Mott, Proc. Roy. Soc. London, Set. A 135, 429 (1932);

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

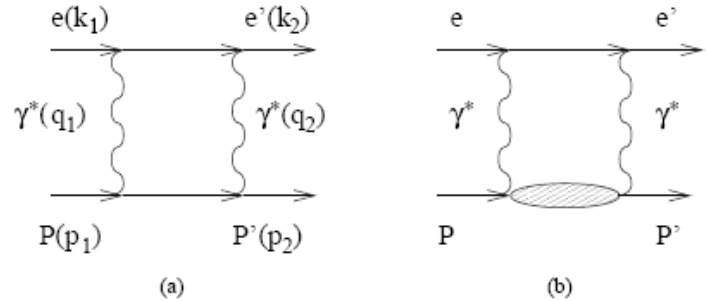
- ***Interference of one-photon and two-photon exchange Feynman diagrams in electron-muon scattering:*** **Barut, Fronsdal, Phys.Rev.120, 1871 (1960)**
- ***Extended to quark-quark scattering SSA in pQCD*: Kane, Pumplin, Repko, Phys.Rev.Lett. 41, 1689 (1978)**

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

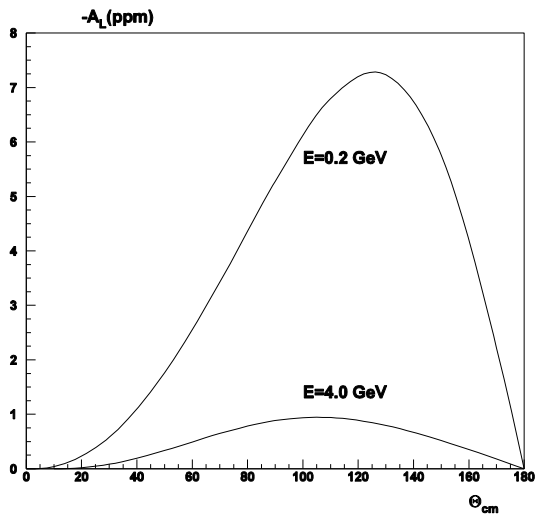
$$(small - angle\ scattering)$$

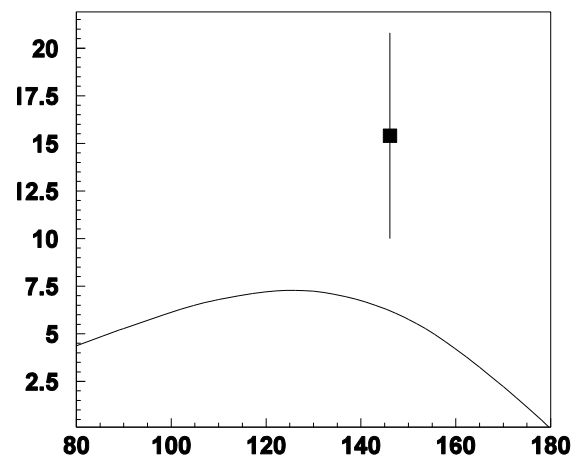
Proton Mott Asymmetry at Higher Energies

AA, Akushevich, Merenkov, hep-ph/0208260



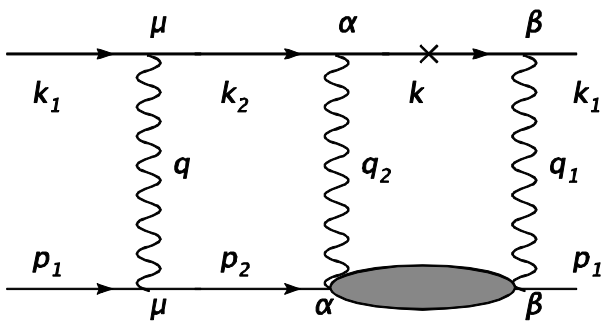
Transverse beam SSA, units are parts per million





- 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
- Also calculated by Diaconescu&Ramsey-Musolf (2004); used low-momentum expansion, questionable in SAMPLE kinematics

Beam Normal Asymmetry from Inelastic Intermediate States



$$A_n^{e,P} = -\frac{\alpha Q^2}{\pi^2 D(s,Q^2)} \mathrm{Im} \int \frac{d^3k}{2k_0} \cdot \frac{L_{\mu\alpha\beta} H_{\mu\alpha\beta}}{Q_1^2 Q_2^2}$$

$$L_{\mu\alpha\beta} = \frac{1}{4} Tr(\hat{k}_2 + m_e)\gamma_\mu(\hat{k}_1 + m_e)(1 - \gamma_5 \hat{\xi}_e)\gamma_\beta(\hat{k} + m_e)\gamma_\alpha$$

$$H_{\mu\alpha\beta} = \frac{1}{4} Tr(\hat{p}_2 + M)\Gamma_\mu(\hat{p}_1 + M)(1 - \gamma_5 \hat{\xi}_p)T_{\beta\alpha}$$

$$\hat{a} \equiv a_\mu \gamma_\mu$$

$$L_{\mu\alpha\beta} q_\mu = L_{\mu\alpha\beta} q_{2\alpha} = L_{\mu\alpha\beta} q_{1\beta} = H_{\mu\alpha\beta} q_\mu = H_{\mu\alpha\beta} q_{2\alpha} = H_{\mu\alpha\beta} q_{1\beta} = 0$$

Gauge invariance essential in cancellation of infra-red singularity for target asymmetry

$$L_{\mu\alpha\beta} H_{\mu\alpha\beta} \to 0 \quad if \quad Q_1^2 \; and/or \; Q_2^2 \to 0$$

Feature of the normal beam asymmetry: After m_e is factored out, the remaining expression is singular when virtuality of the photons reach zero in the loop integral! But why are the expressions regular for the target SSA?! Answer: small virtuality is due to small electron mass

$$L_{\mu\alpha\beta} H_{\mu\alpha\beta} \to m_e \cdot const \quad if \quad Q_1^2 \; and/or \; Q_2^2 \to 0 \Rightarrow A \sim m_e \log^2 \frac{Q^2}{m_e^2}, m_e \log \frac{Q^2}{m_e^2}$$

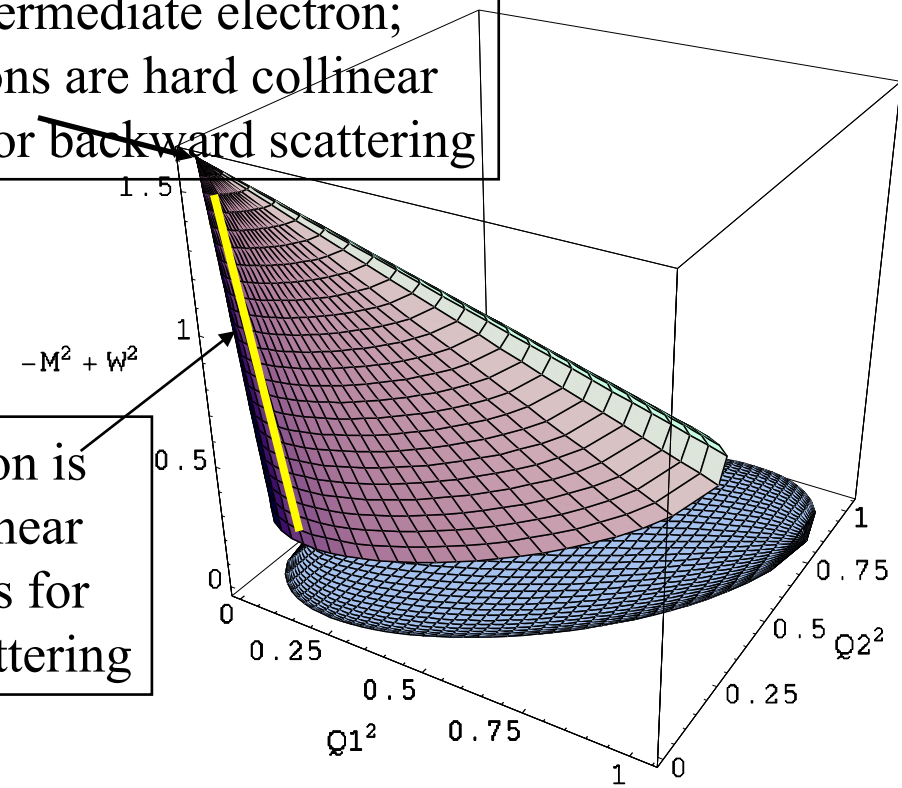
AA, Merenkov, hep-ph/0407167: Models violating EM gauge invariance encounter collinear divergence for target SSA

Also calculations by Vanderhaeghen, Pasquini (2004); Gorchtein (2004); Kobushkin (2005) confirm ***quasi-real photon exchange*** enhancement

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

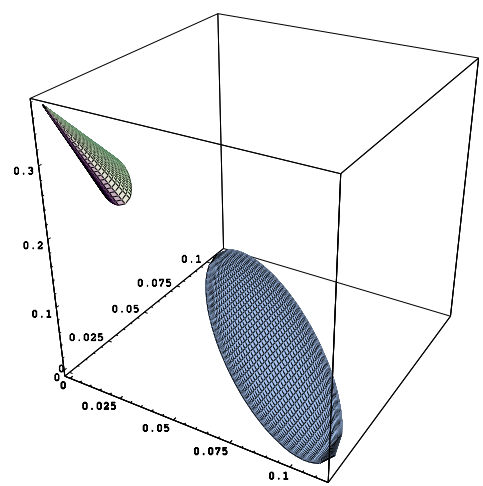
- 2-dimensional integration (Q_1^2, Q_2^2) for the elastic intermediate state
- 3-dimensional integration (Q_1^2, Q_2^2,W^2) for inelastic excitations

`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

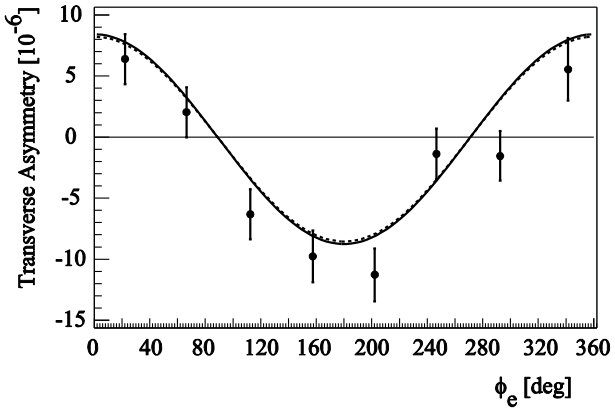


MAMI data on Mott Asymmetry

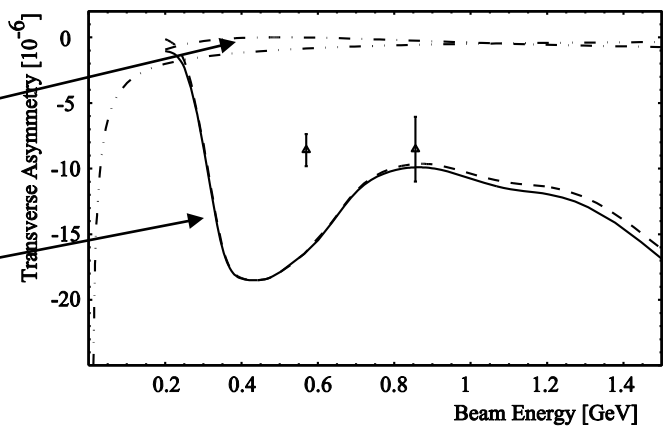
- F. Maas et al., [MAMI A4 Collab.] Phys.Rev.Lett.94:082001, 2005
- Pasquini, Vanderhaeghen: Phys.Rev.C70:045206,2004

Used single-pion electroproduction amplitudes from MAID to

Surprising result: Dominance of inelastic intermediate excitations



Elastic intermediate state



Inelastic excitations Dominate

However, it doesn't make it into TPE for Rosenbluth

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:

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

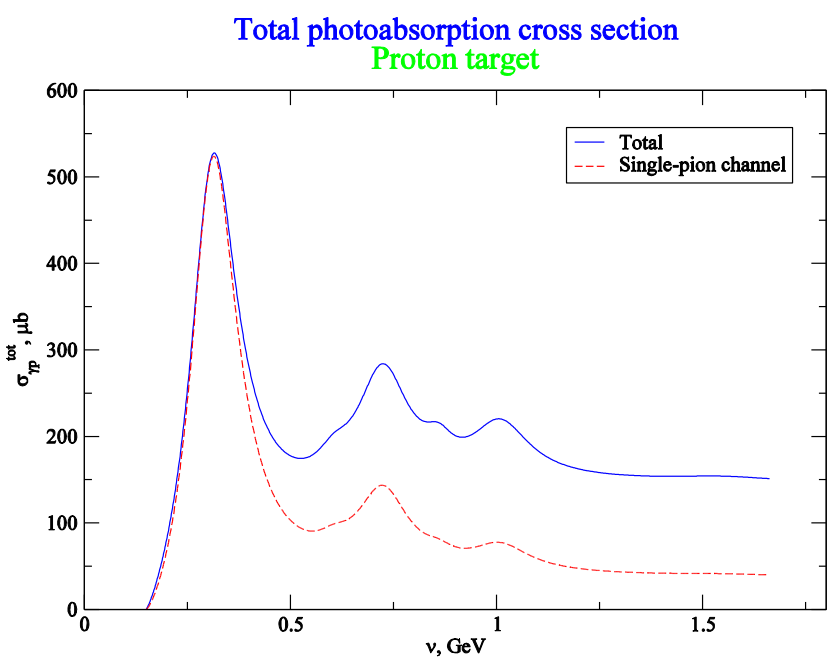
Compare with asymmetry caused by Coulomb distortion at small θ =>
may differ by orders of magnitude depending on scattering kinematics

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

Input parameters

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

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



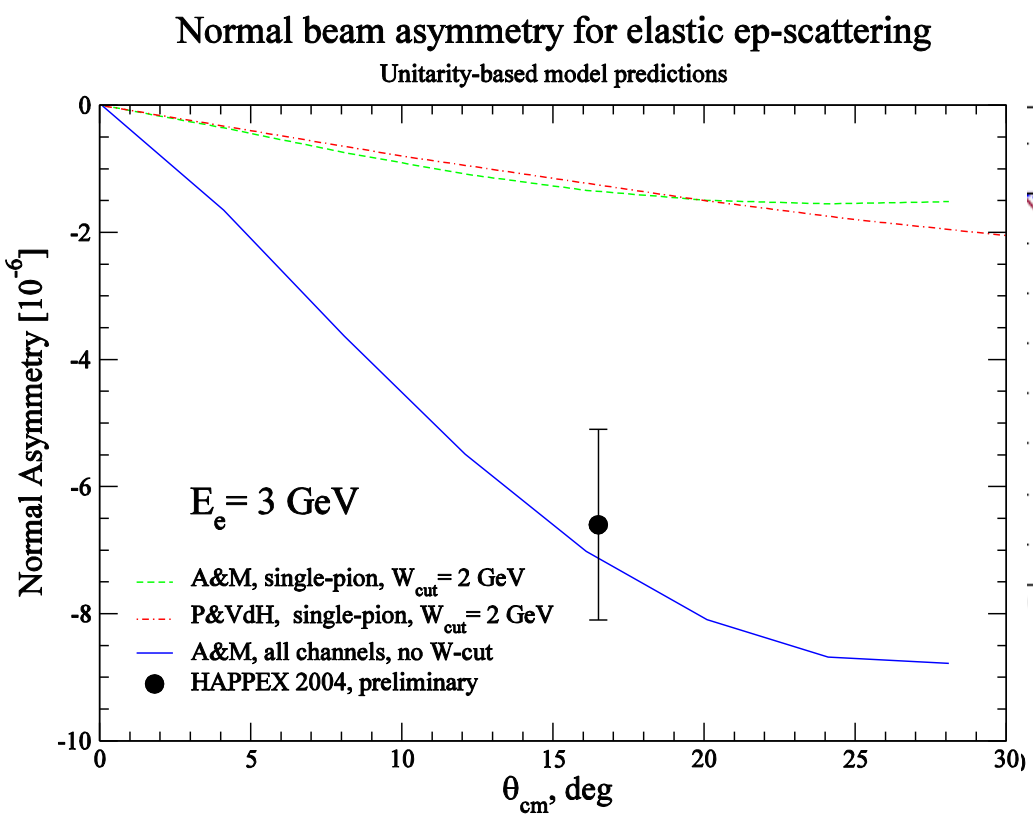
The integral is energy-weighed, higher energies enhanced

$\sigma_{\gamma p}$ from N. Bianchi at al., Phys.Rev.C54 (1996)1688 (resonance region) and Block&Halzen, Phys.Rev. D70 (2004) 091901

-A_n serves as an ideal tool to sum over a variety of intermediate states

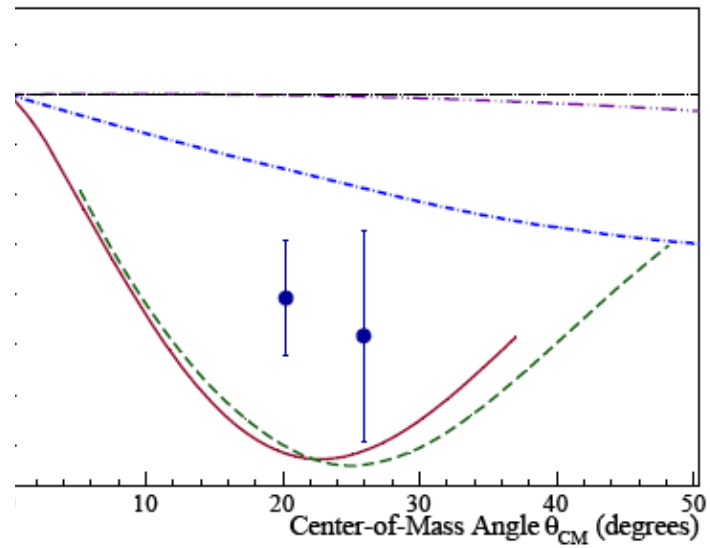
Predictions vs experiment for Mott asymmetry

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



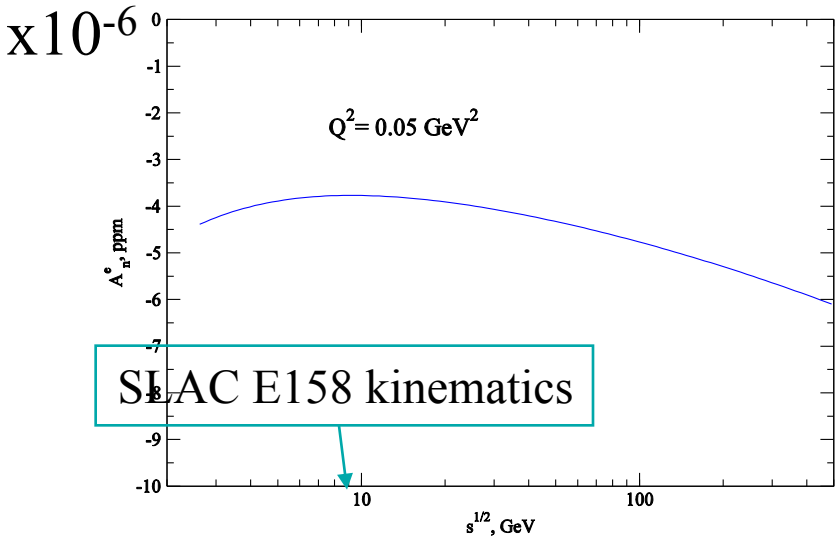
HAPPEX

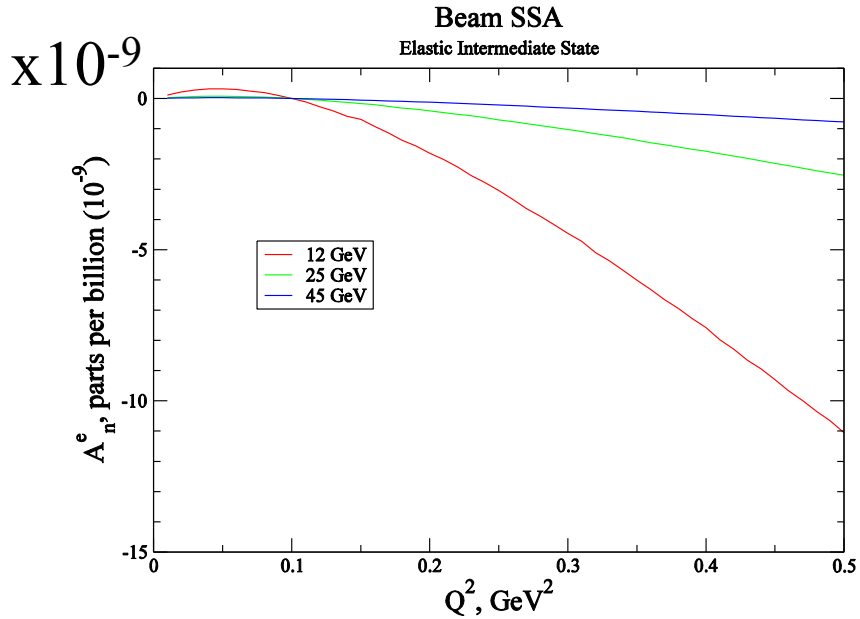
G0 arXiv 0705.1525[nucl-ex]

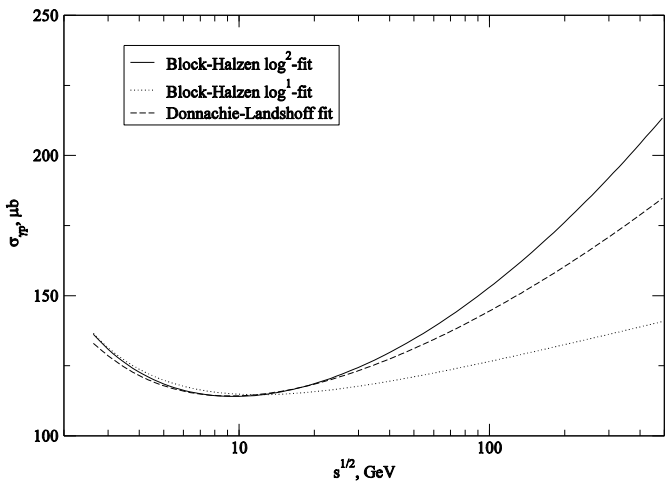


Estimated normal beam asymmetry for Qweak: **-5ppm**

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

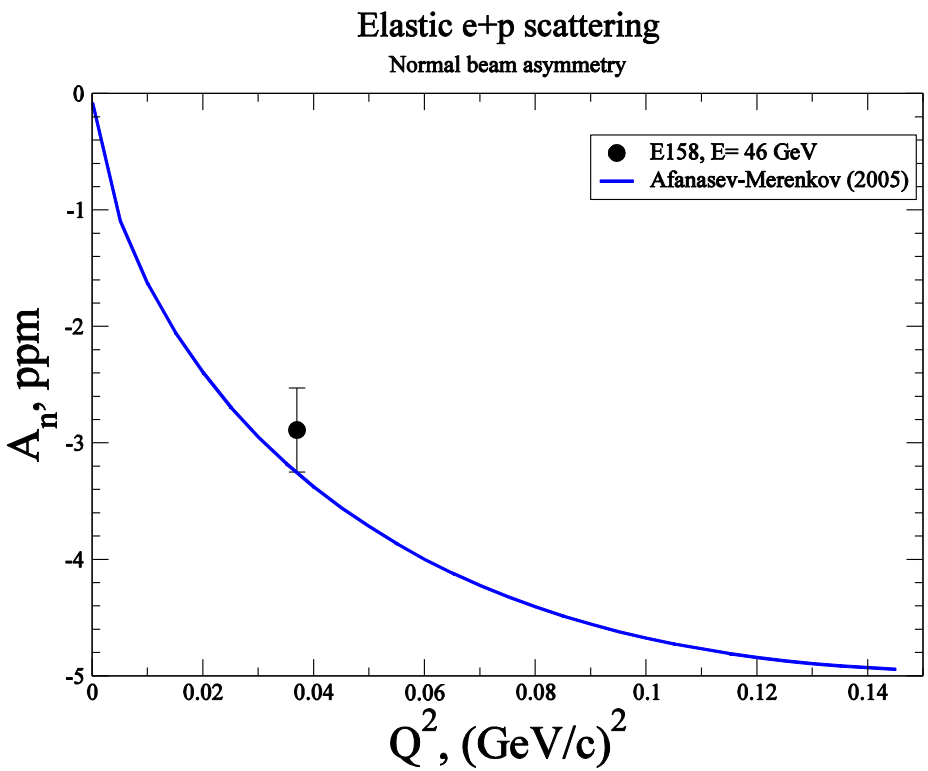






- At 45 GeV predict beam asymmetry parts-per-million (diffraction) vs. parts-per billion (Coulomb distortion)

Comparison with E158 data



- **SLAC E158:**

An=-2.89±0.36(stat)±0.17(syst) ppm

(K. Kumar, private communication)

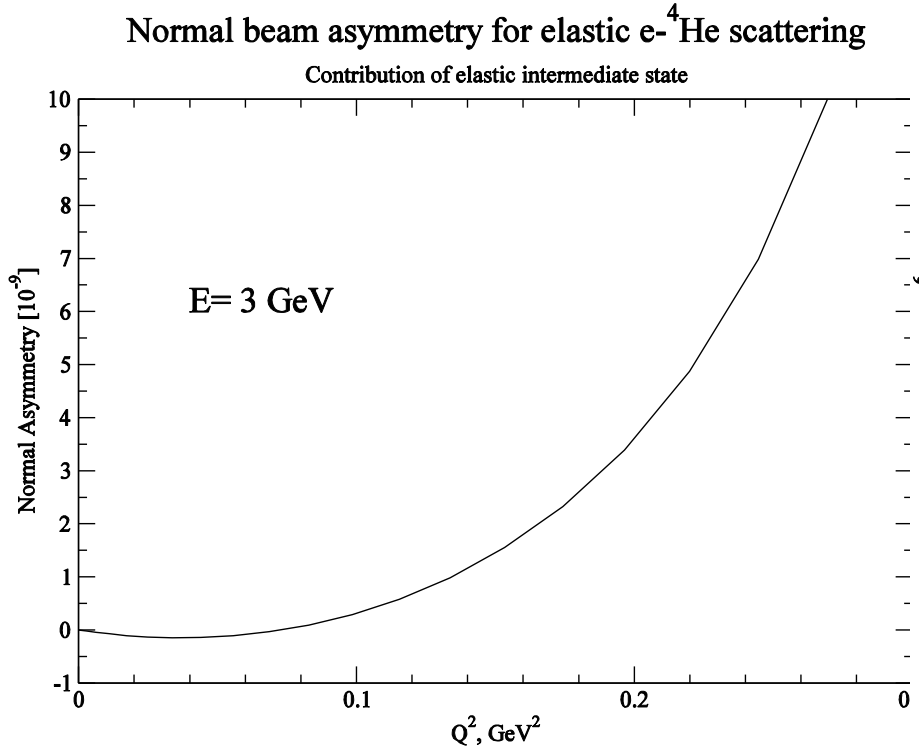
- **Theory (AA, Merenkov):**

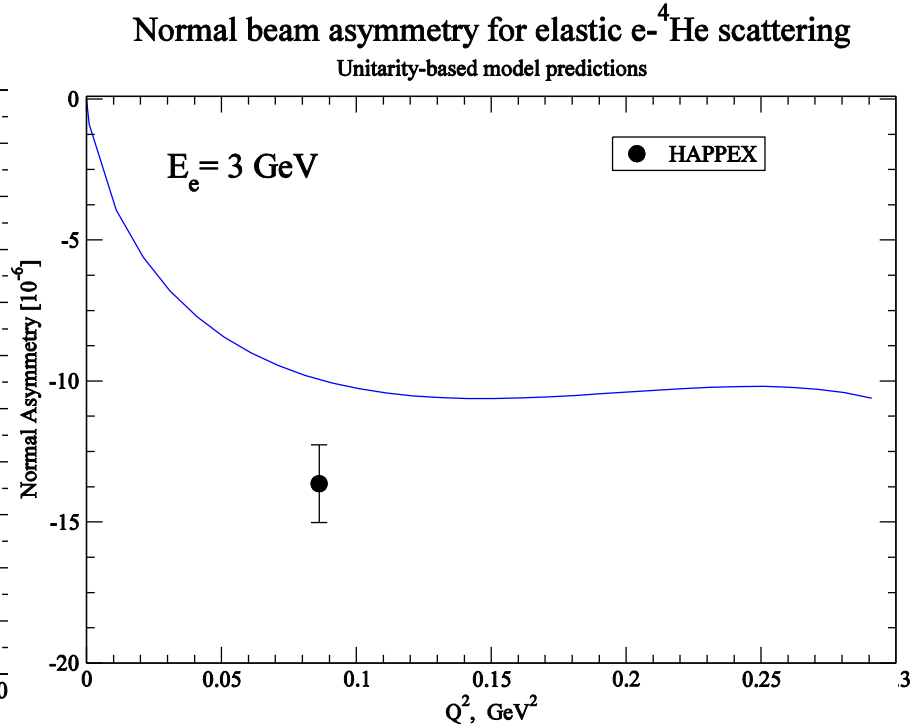
  An=-3.2ppm

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

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)

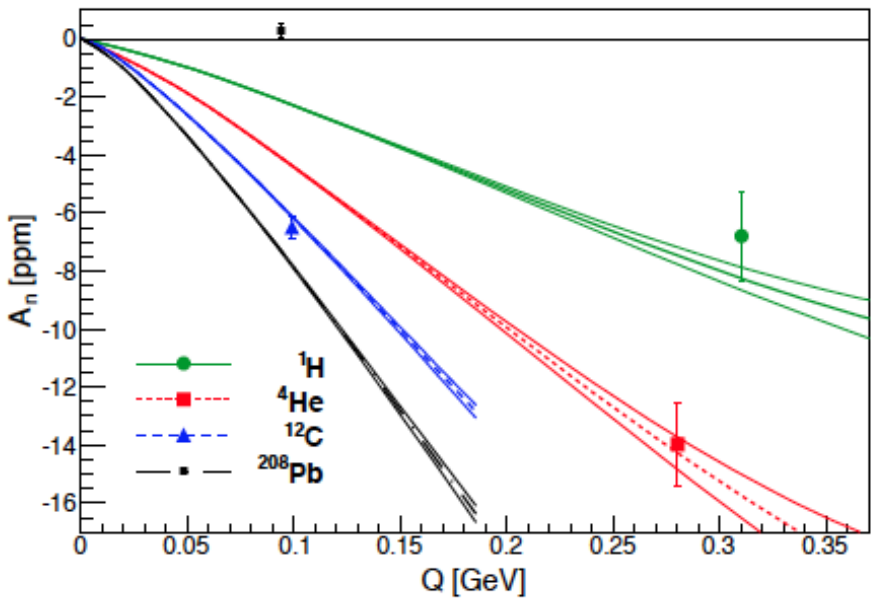




Five orders of magnitude enhancement in HAPPEX kinematics due to excitation of inelastic intermediate states in 2γ-exchange (AA, Merenkov; use Compton data from Erevan)

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,



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

Inclusive Electroproduction of Pions

- Reaction $p(e_{pol},\pi)X$
  - Parity-conserving spin-momentum correlation $\vec{s}_e \cdot \vec{k}_e \times \vec{k}_\pi$
  - Introduced in Donnelly, Raskin, Annals Phys. 169, 247 (1986)
    - Can be shown to be a) due to $R_{TL'}$ response function (=fifth structure function) and b) not to integrate to zero after integration over momenta of the scattered electron
  - This is **NOT** a two-photon exchange effect (but suppressed by an electron mass)
    - Order-of magnitude estimate: $An(ep\text{->}\pi X) \sim A_{LT'}(ep\text{->}e'\ \pi N)*m_e/E'/\sin(\theta_e)$
      - Use MAMI data $A_{LT'}(ep\text{->}e'\ \pi N)\sim 7\%$, from Bartsch et al Phys.Rev.Lett. 88:142001,2002 => $An(ep\text{->}\pi X)\sim 250ppm$
  - Physics probe of (strong) final-state interactions in electroproduction reactions
    - Why not simply measuring SF in $A(e_{pol},e\pi)X$ directly with longitudinal polarization? Because transverse SSA gives access to very low Q^2, may not available to spectrometers

Summary:
SSA in Elastic ep- and eA-Scattering

- VCS amplitude in *beam asymmetry* is enhanced in different kinematic regions compared to *target asymmetry* or corrections to *Rosenbluth cross section*
- *Physics probe of an absorptive part of a non-forward Compton amplitude*
- *Important systematic effect for PREX,* Q_{weak}
- Mott asymmetry in small-angle ep-scattering above the pion threshold is controlled by quasi-real photoproduction cross section with photon energy approximately matching beam energy – similarity with Weizsacker-Williams Approximation – collinear photon exchange
- *Due to excitation of inelastic intermediate states* A_n *is*

(a) not suppressed with beam energy and

(b) does not grow with Z (proportional to instead A/Z)

(c) At small angles $\sim\theta$ *(vs* θ^3 *for Coulomb distortion)*

- Confirmed experimentally for a wide range of beam energies

Outlook

- Beam and target SSA for elastic electron scattering probe imaginary part of virtual Compton amplitude.
  - Beam SSA: target helicity flip^2+nonflip^2
  - Target SSA: Im[target helicity flip*nonflip]
  - Ideal "4π detector" to probe electroproduction amplitudes for a variety of final states (π, 2π, etc)
- Beam SSA for nuclear targets in good agreement with theory except for a high-Z target 208Pb. Interesting nuclear physics effects beyond two-photon exchange
- Beam SSA in Reaction $A(e_{pol},\pi)X$ probes strong final-state interactions – due to "fifth stucture function"

  in A(e,e' π)X