Normal Spin Asymmetry in Elastic Electron Scattering

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MITP Workshop *Precision Tests with Neutral-Current Coherent Interactions with Nuclei*

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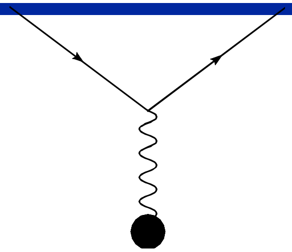
Plan of talk

- **Single-spin asymmetries**
  - **Introduction**
  - **Optical theorem approach in ep-scattering via two-photon exchange**
  - **Novel features of a single-spin asymmetry**
  - **Comparison with experiment on a nucleon and nuclei**
- **Summary and outlook**

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

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

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

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

$$(P_y = 0)$$

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

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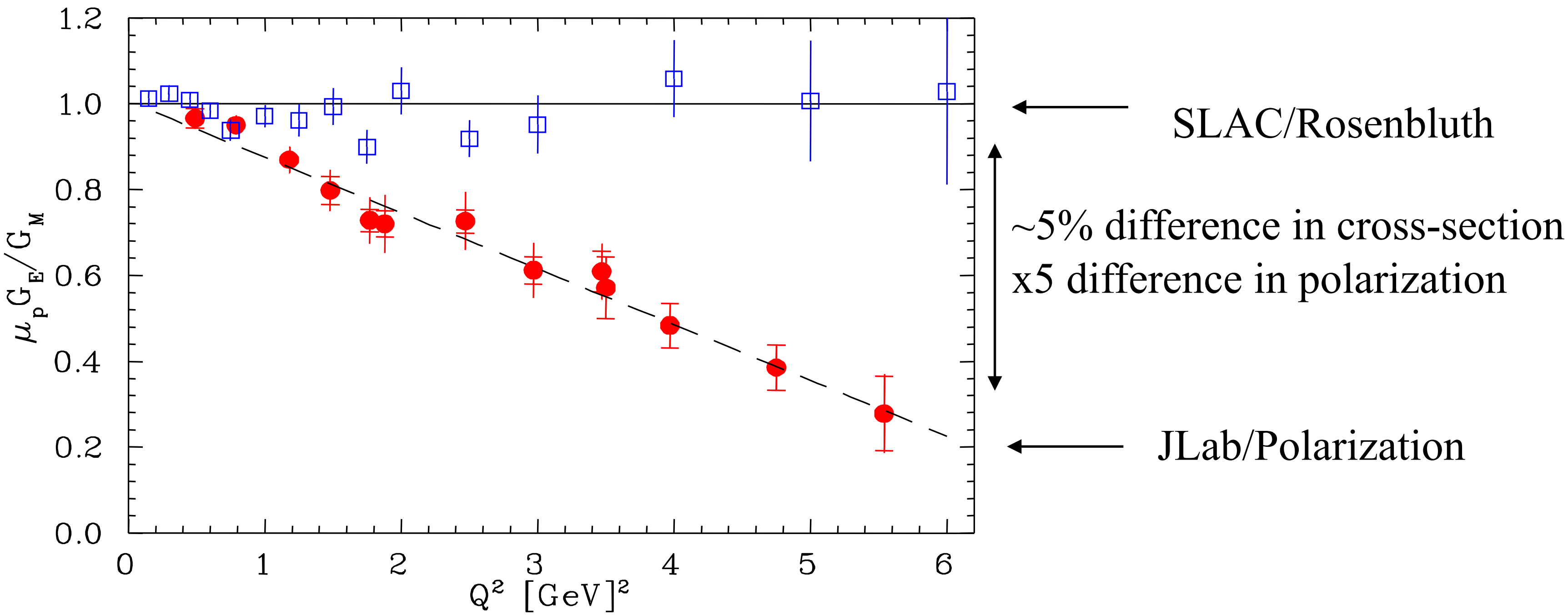
Ge/Gm Puzzle



- **Both early SLAC and 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

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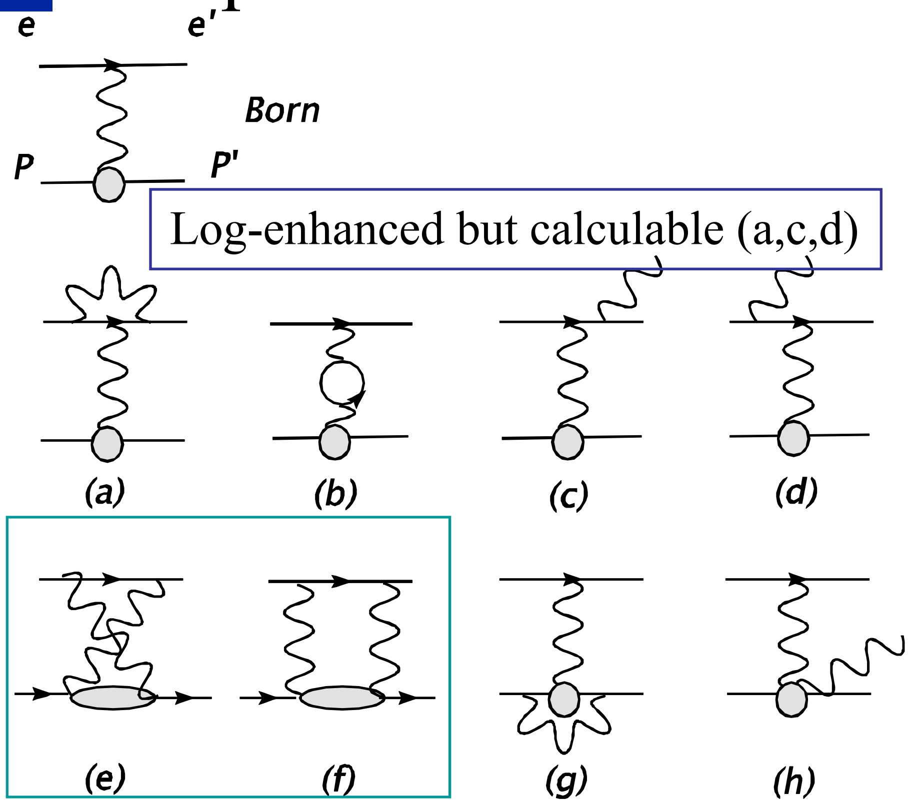
Complete radiative correction in $O(\alpha_{em})$



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

•For review, see AA, Blunden, Hasell, Raue, Prog.Part.Nucl.Phys. 95, 245 (2017)

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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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Beam Single-Spin Asymmetry: Early Calculations

Sir Nevill Mott
Nobel Prize (1977)

- *Spin-orbit interaction of electron scattering off a Coulomb field*

  N.F. Mott, Proc. Roy. Soc. London, Set. A 124, 425 (1929); ibid. 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)

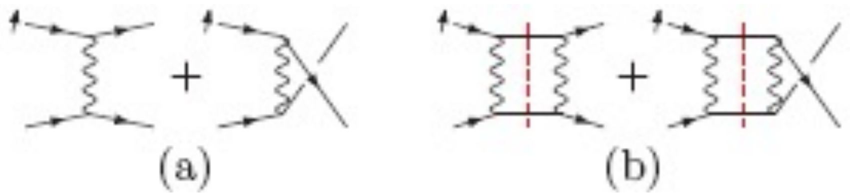
$$A_n \propto \frac{\alpha \cdot m_e \cdot \theta^3}{E}, \; for\; \theta << 1$$

$$(small-angle\; scattering)$$

- *Extended to quark-quark scattering SSA in pQCD*: Kane, Pumplin, Repko, Phys.Rev.Lett. 41, 1689 (1978)

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

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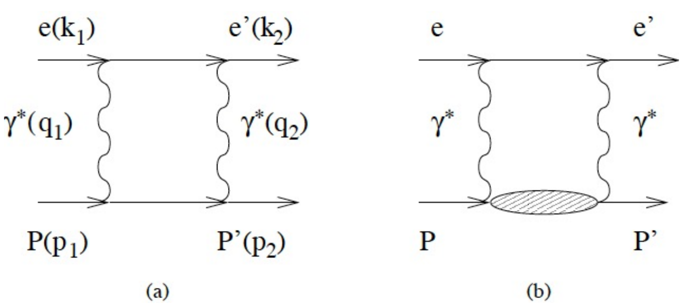
Single-Spin Target Asymmetry $\vec{s}_T \cdot \vec{k}_1 \times \vec{k}_2$

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

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



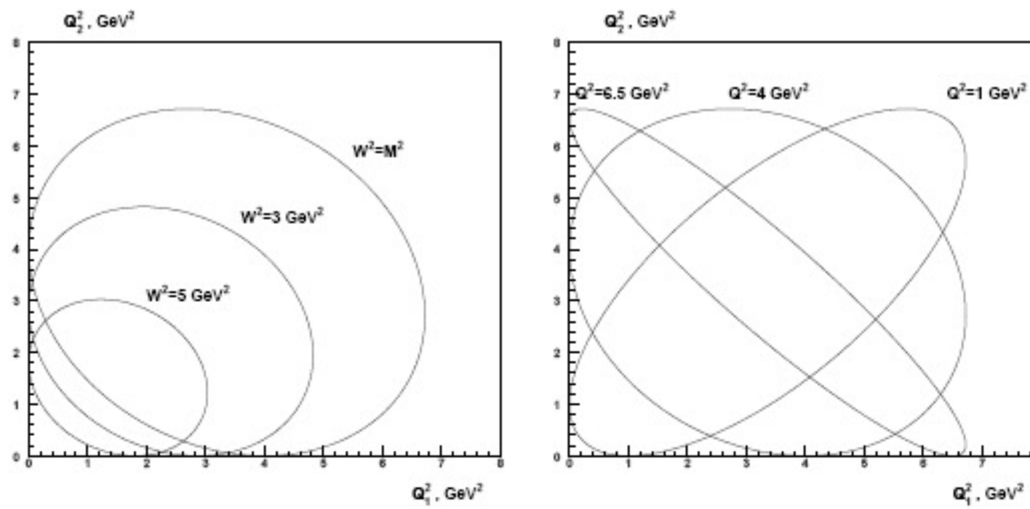


Figure 2. Integration region over Q_1^2 and Q_2^2 in Eq.(2) for elastic ($W^2 = M^2$) and inelastic contributions. The latter (left) is given for Q^2=4 GeV^2 and two values of W^2, which is an integration variable in this case. The elastic case is shown on the right as a function of external Q^2. The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

Sherman function on nuclei

- Theoretical approach by Sherman Phys. Rev. 103, 1601 (1956)

- Mott polarimetry is based on comparing measured analyzing power with theoretical asymmetry: Gay, Dunning, Rev. Sci. Instrum. 63, 1635 (1992); Price, Poelker, Sinclair et al., In: Proc. Protvino 1998, High Energy Spin Physics Symposium, p.554;Tioukine, Aulenbacher and Riehn, Rev. Sci. Instrum. 82, 033303 (2011)

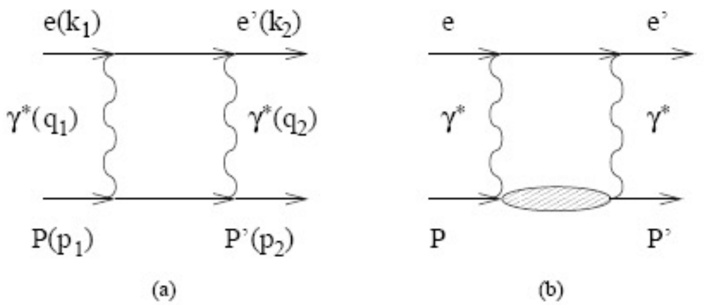
Extended to high energies (100-1000MeV) in

- Cooper and Horowitz, PRC 72, 034602 (2005)
- Jakubassa-Amundsen and Barday, 2012 J. Phys. G: Nucl. Part. Phys. 39 025102

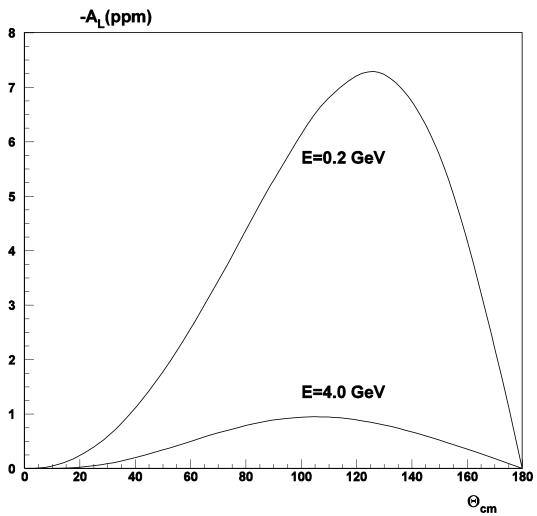
The approaches to calculating Sherman functions on nuclei involve solving Dirac equation in Coulomb field (see Jakubassa-Amundsen's talk)

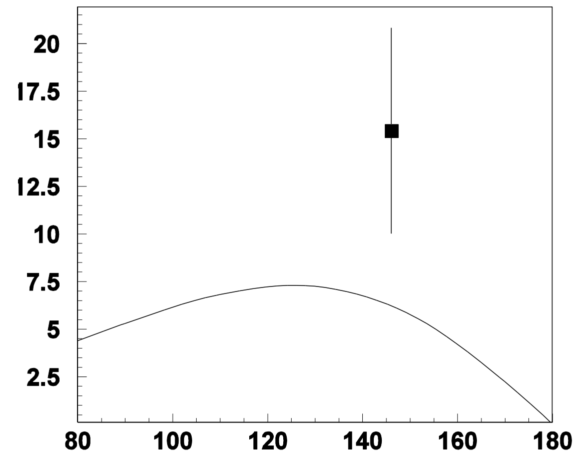
Proton Mott Asymmetry at Higher Energies

AA, Akushevich, Merenkov, hep-ph/0208260



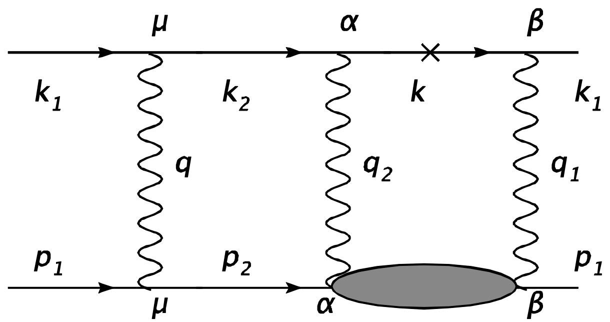
Transverse beam SSA, units are parts per million





- **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**

Beam Normal Asymmetry from Inelastic Intermediate States (hep-ph/0407167)



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

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

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

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

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

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

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

Novel feature of the normal beam asymmetry: After m_e is factored out, the remaining expression is singular when virtuality of photons reach zero in the loop integral! The expressions are regular for the target SSA, since the photon's virtualities are at hadronic mass scale

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

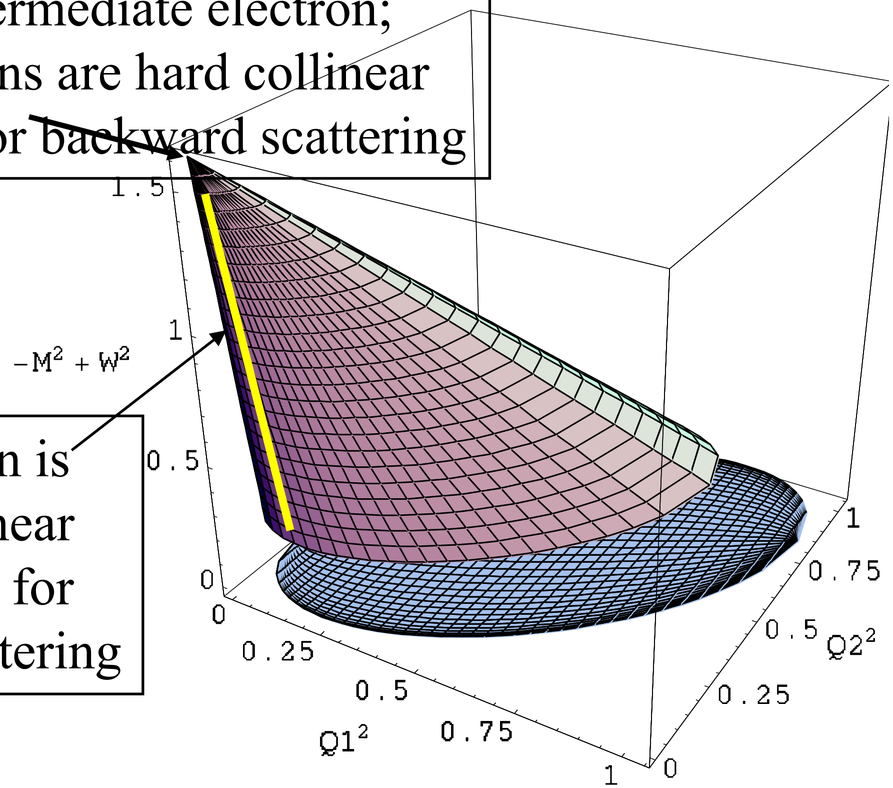
Also calculations by Vanderhaeghen, Pasquini (2004); Gorchtein, hep-ph/0505022; Borisyuk, Kobushkin, Phys. Rev. C 73 (2006) 045210; confirm ***quasi-real photon exchange***

Diaconescu , Ramsey-Musolf (2004): power expansion for low energies, no logs

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

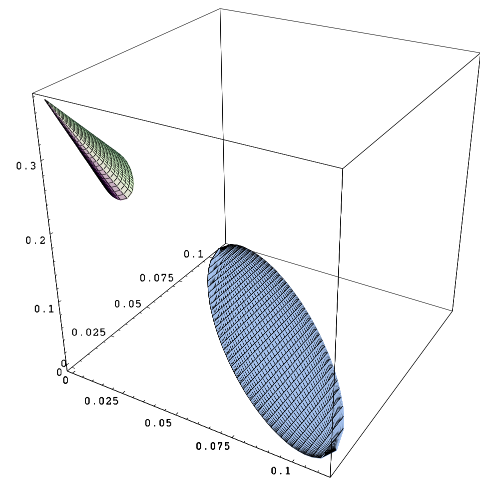
- 2-dimensional integration (Q_1^2, Q_2^2) for the elastic intermediate state
- 3-dimensional integration (Q_1^2, Q_2^2, W^2) for inelastic excitations

\`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



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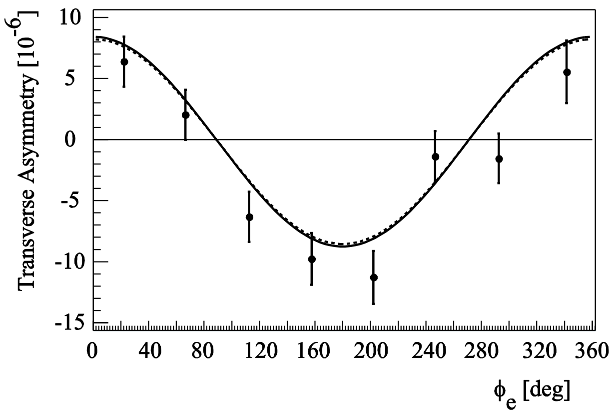
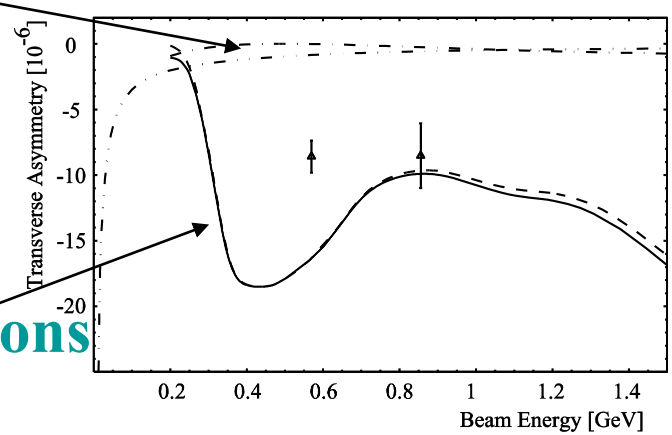
MAMI data on Mott Asymmetry

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

Surprising result: Dominance of inelastic intermediate excitations



Elastic intermediate state



Inelastic excitations dominate

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

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

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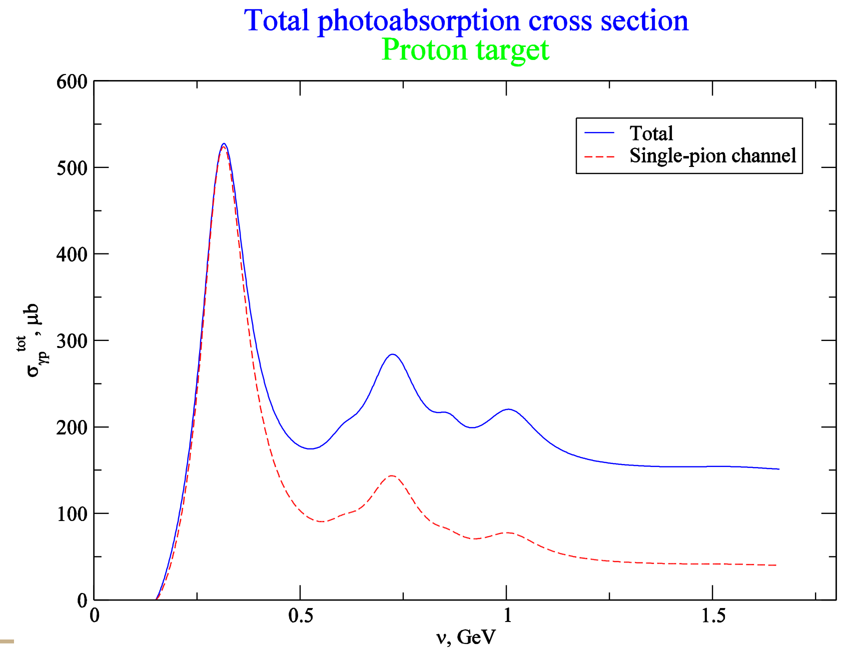
Input parameters

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

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



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

Phys.Rev. D70 (2004) 091901

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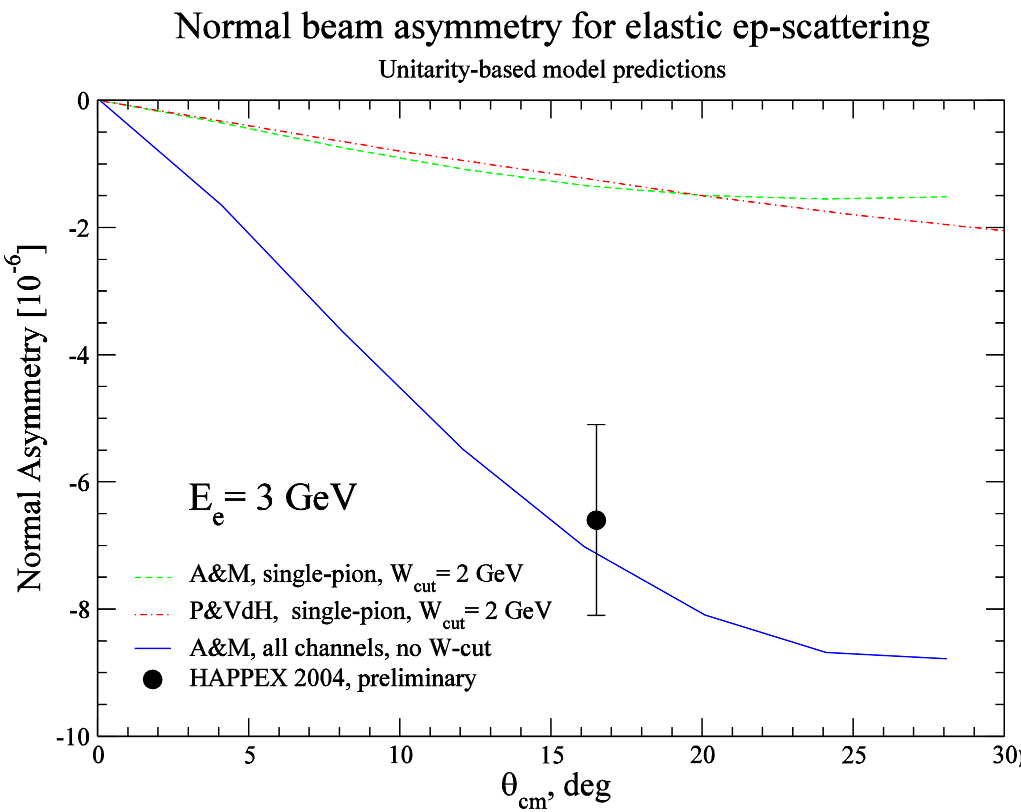
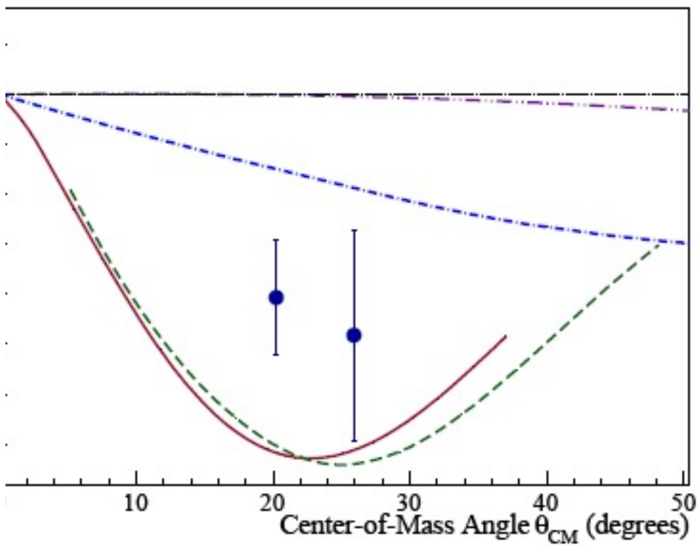
Predictions vs experiment for Mott asymmetry

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

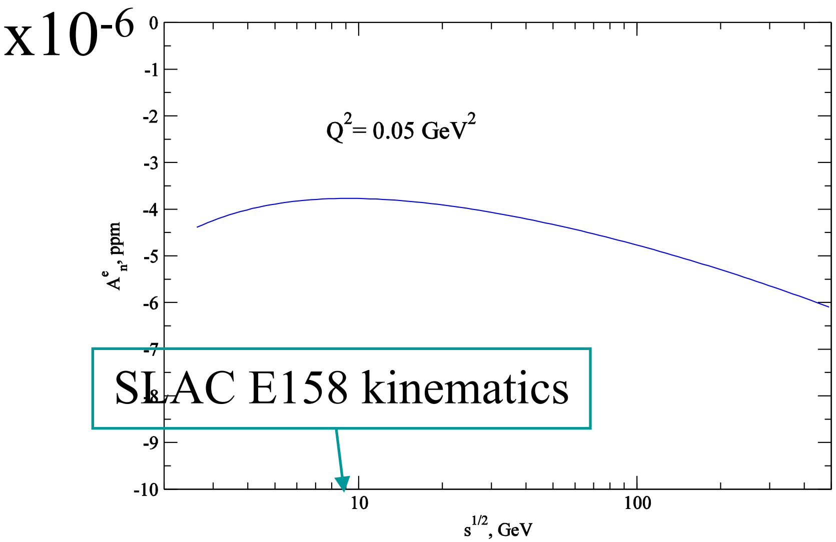
G0 data Phys.Rev.Lett.99:092301,2007

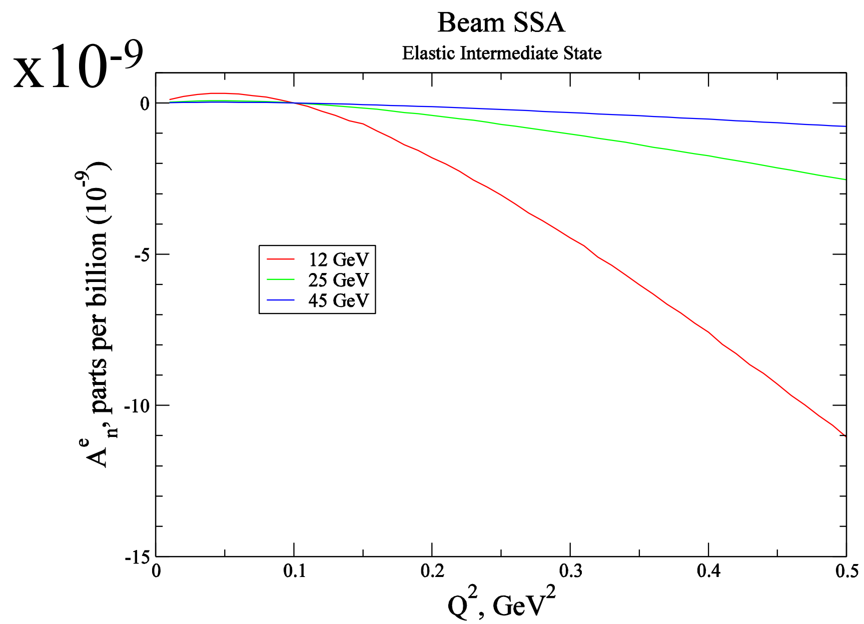


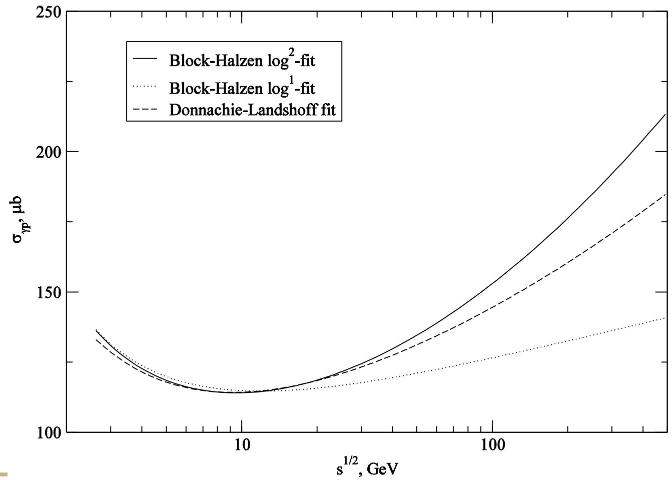


HAPPEX

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

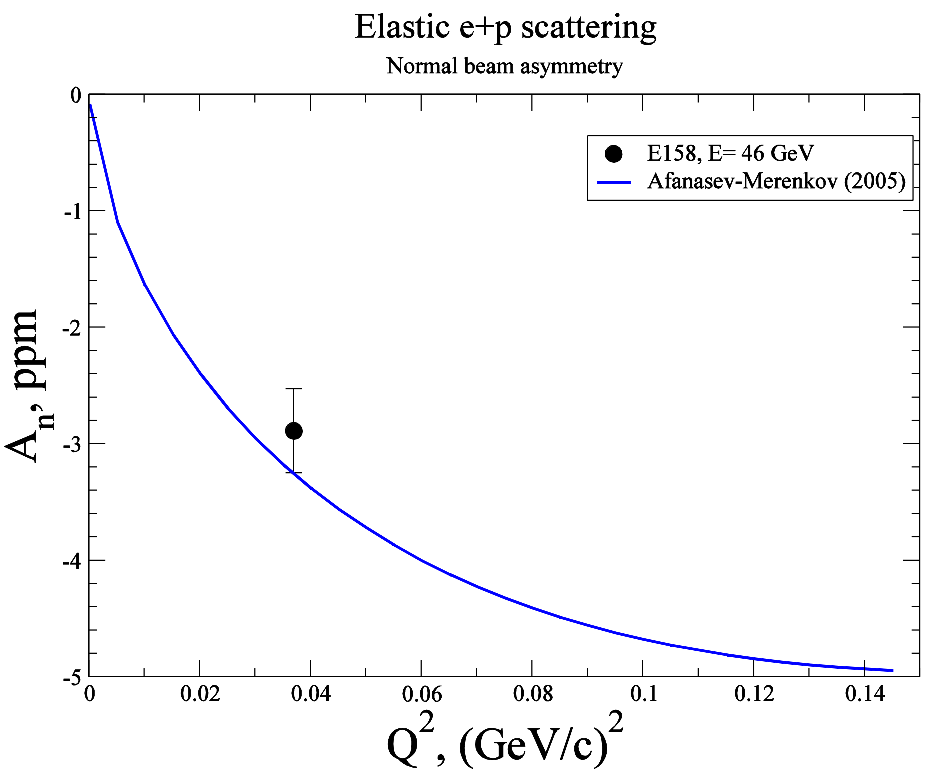






- At 45 GeV predict beam asymmetry parts-per-million (diffraction) vs. parts-per billion (Coulomb distortion)

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 (Gorchtein et al and γZ box calculations for small-angle scattering)**

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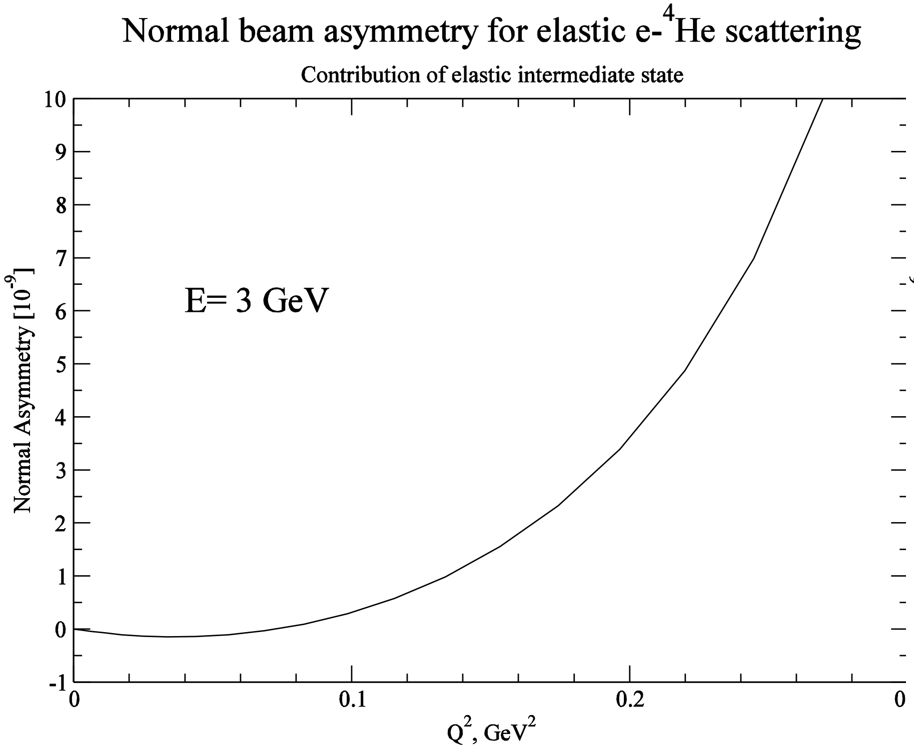
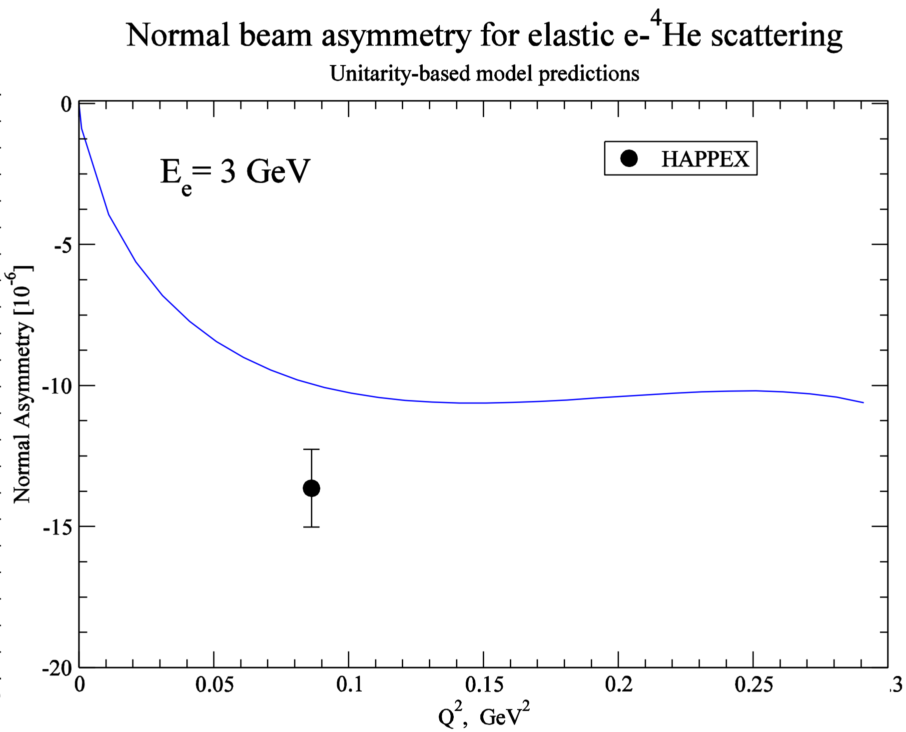
Mott Asymmetry on Nuclei

- 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)

JLAB Experiments: HAPPEX, PREX

- Abrahamyan et al. New Measurements of the Transverse Beam Asymmetry for Elastic Electron Scattering from Selected Nuclei, PRL 109, 192501 (2012)

TABLE I. Kinematic values for the various targets.

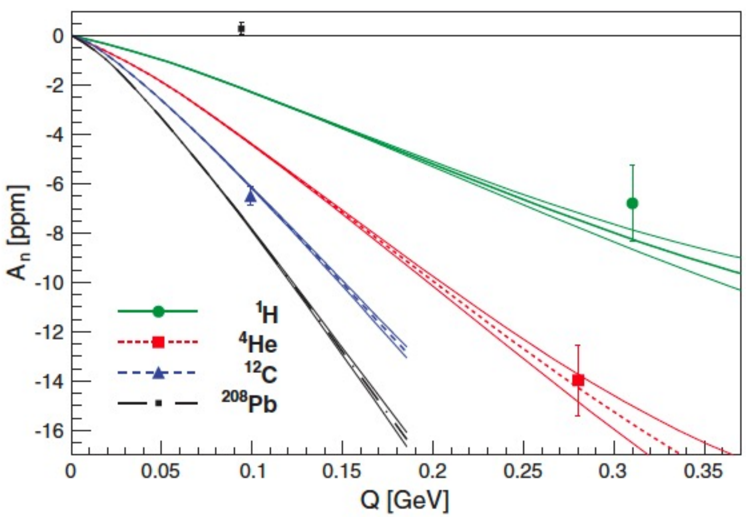
Target	H	^{4}He	^{12}C	^{208}Pb
θ	6°	6°	5°	5°
Q^2(GeV^2)	0.0989	0.0773	0.009 84	0.008 81
E_b(GeV)	3.026	2.750	1.063	1.063
$\langle\cos\phi\rangle$	0.968	0.967	0.963	0.967

TABLE III. The measured A_n and derived $\hat{A}_n$ values [Eq. (2)] for the four nuclei along with the corresponding total uncertainties A/Z and Q.

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

$$A_n = \hat{A}_n \frac{QA}{Z},$$

The formula captures dependence of the asymmetry on A and Z, and power dependence on Q



Agreement for all lighter nuclei except ^{208}Pb

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JLAB Experiments: CREX data

- Adhikari et al (PREX and CREX Collab), New Measurements of the Beam-Normal Single Spin Asymmetry in Elastic Electron Scattering over a Range of Spin-0 Nuclei, PRL **128**, 142501 (2022)

TABLE I. A_n measurement kinematics.

E_{beam} (GeV)	Target	$\langle\theta_{lab}\rangle$ (deg)	$\langle Q^2\rangle$ (GeV^2)	$\langle\cos\phi\rangle$
0.95	^{12}C	4.87	0.0066	0.967
0.95	^{40}Ca	4.81	0.0065	0.964
0.95	^{208}Pb	4.69	0.0062	0.966
2.18	^{12}C	4.77	0.033	0.969
2.18	^{40}Ca	4.55	0.030	0.970
2.18	^{48}Ca	4.53	0.030	0.970
2.18	^{208}Pb	4.60	0.031	0.969

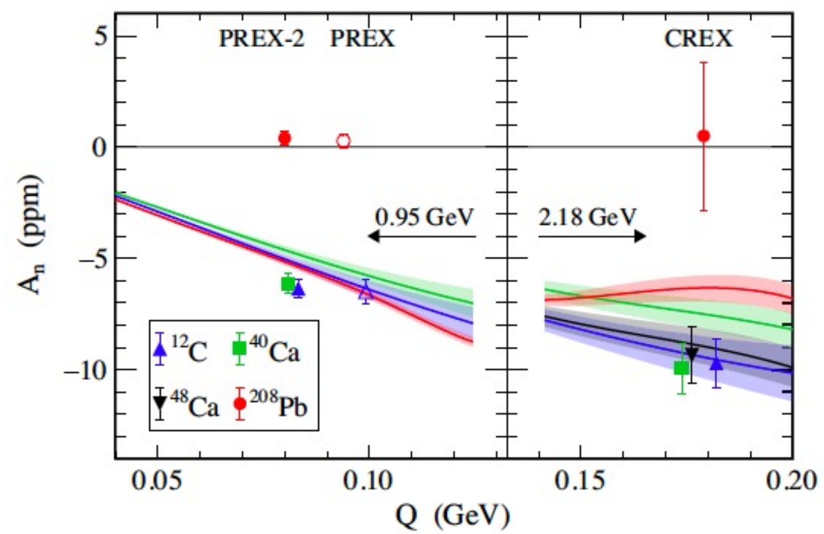

FIG. 2. A_n measurements from PREX-2, PREX (open circle and triangle, previously published [20]), and CREX at beam energies of 0.95 GeV, 1.06 GeV, and 2.18 GeV, respectively. The solid lines show theoretical calculations from [26] at 0.95 GeV and 2.18 GeV together with their respective one sigma uncertainty bands. The color of each band represents the calculation for the same color data point. Overlapping points are offset slightly in Q to make them visible.

Recently Coulomb distortion and inelastic excitations were considered in a unified approach: Koshchii, Gorchtein, Roca-Maza, Spiesberger C 103, 064316 (2021) but

^{208}Pb Asymmetry remains an unsolved mystery or **"PREX Puzzle"**

See Anselm Esser's talk on Mainz data

Inclusive Electroproduction of Pions (Singles)

- 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->πX)~ $A_{LT'}$(ep->e' πN)*m_e/E'/sin(θ_e)
      - Use MAMI data $A_{LT'}$(ep->e' πN)~7%, from Bartsch et al Phys.Rev.Lett.88:142001,2002 => An(ep->πX)~250ppm
    - See C.E. Carlson et al.

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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 is unsuppressed with energy in forward angles, follows the magnitude of total photoproduction cross section*
- 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)*
- *Good agreement for scattering on nuclei* ***except ^{208}Pb***
  - ***^{208}Pb remains unresolved and requires detailed studies***

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