Elastic Lepton-Proton Scattering and Higher-Order QED Effects

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Plan of talk

Radiative corrections for charged lepton scattering

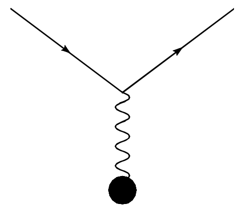
- Model-independent and model-dependent; soft and hard photons

Two-photon exchange effects

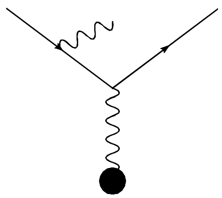
- Soft-photon exchange approximation and IR regularization
- Novel effects in muon scattering
- Single-spin asymmetries from two-photon exchange

Summary

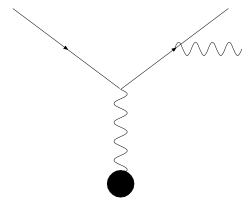
Basics of QED radiative corrections



(First) Born approximation

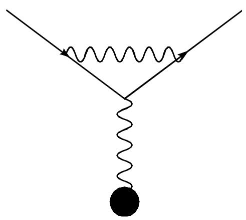


Initial-state radiation



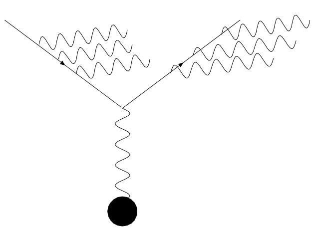
Final-state radiation

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



Vertex correction => cancels divergent terms; Schwinger (1949)
Assumed $Q^2/m_e^2 >> 1$

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



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

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

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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 <u>electron structure functions</u> based on Drell-Yan representation; currently widely used at e^+e^- colliders
  - Applied for polarized electron-proton scattering by AA et al, JETP 98, 403 (2004).

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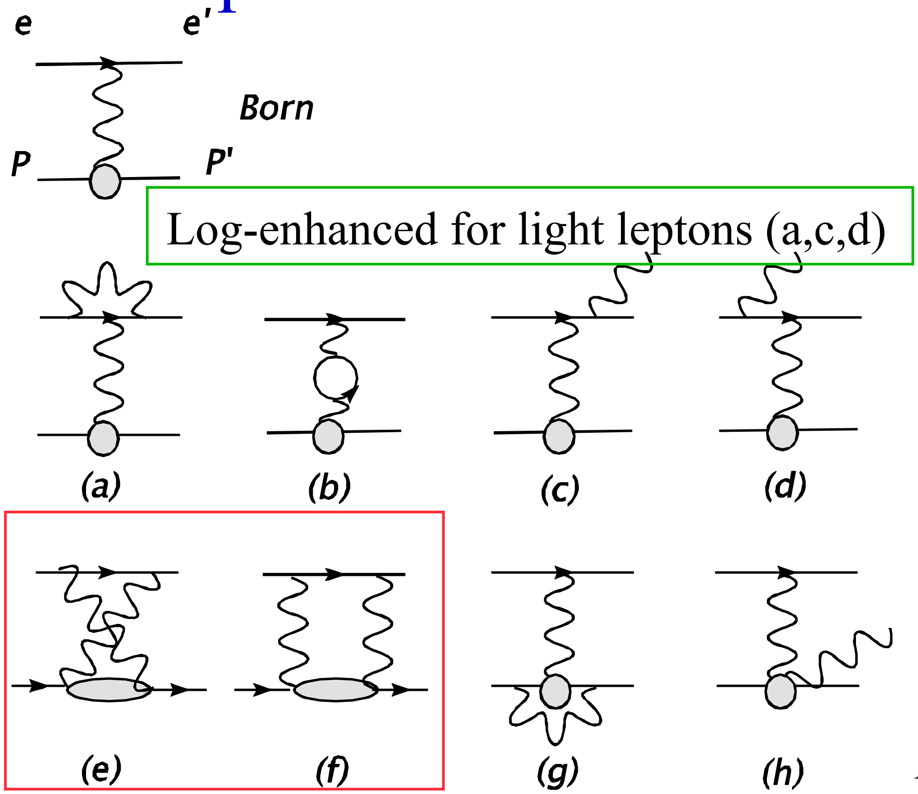
Complete radiative correction in $O(\alpha_{em})$



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

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Bremsstrahlung for Relativistic vs Nonrelativistic Lepton Scattering

- Accelerated charge always radiates, but the magnitude of the effect depends on kinematics
- See Bjorken&Drell (Vol.1, Ch.8):
  - For large $Q^2 >> m_e^2$ the rad.correction is enhanced by a large logarithm, $\log(Q^2/m_e^2) \sim 15$ for GeV^2 momentum transfers
  - For small $Q^2 << m_e^2$, rad.correction suppressed by Q^2/m_e^2
  - For intermediate $Q^2 \sim m_e^2$, neither enhancement nor suppression, rad correction of the order $2\alpha/\pi$
- Implications for COMPASS @CERN: rad. corrections reduce for $\log(Q^2/m_\mu^2) \sim 3$ by about a factor of 5 compared to electrons (*good news!*) and become comparable in magnitude to two-photon effects (*bad news!*)

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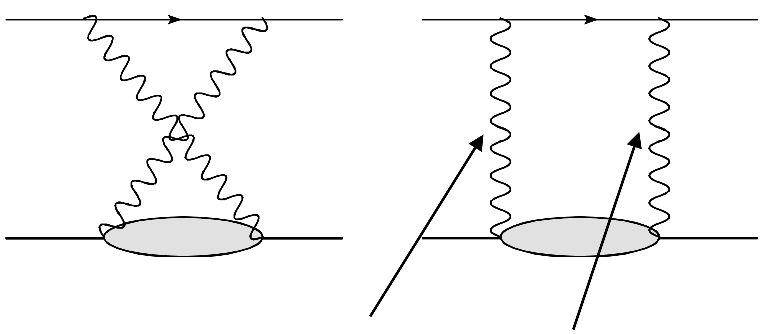
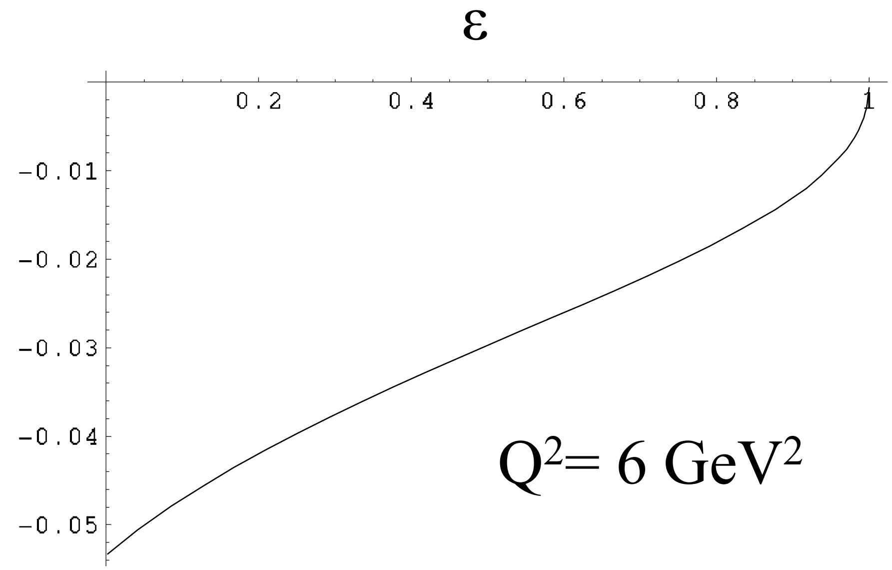
Separating *soft* 2-photon exchange

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





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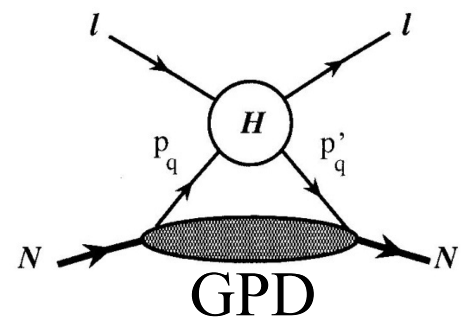
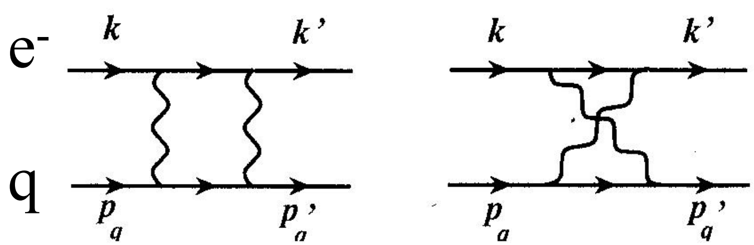
Lepton mass is not essential for TPE calculation in ultra-relativistic case; Two-photon effect below 1% for lower energies and $Q^2 < 0.1 GeV^2$

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

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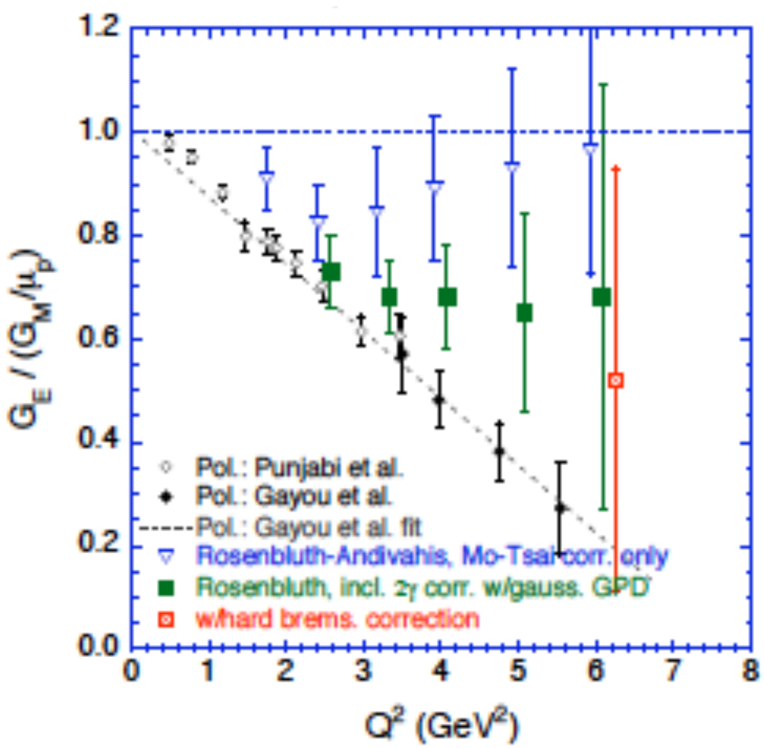
Updated Ge/Gm plot

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 114 (2015) 6, 062003
  - OLYMPUS (coming 2015)

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Hard Bremsstrahlung

- Need to include radiative lepton tensor in a complete form:

AA et al, **Phys.Rev. D64 (2001) 113009; PLB 514, 269 (2001*):*** terms ~ k emitted photon momentum) usually neglected in rad.correction calculations, but can lead to ~1% effect for Rosenbluth slope at high Q^2

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

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

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

additional terms, about 1% effect

common soft-photon approximation (Mo&Tsai;Maximon&Tjon)

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Coulomb and Two-Photon Corrections

- Coulomb correction calculations are well justified at lower energies and Q2
- Hard two-photon exchange (TPE) contributions cannot be calculated with the same level of precision as the other contributions.
- Two-photon exchange is independent on the lepton mass in an ultra-relativistic case.
- Issue: For energies ~ mass TPE amplitude is described by 6 independent generalized form factors; but experimental data on TPE are for ultrarelativistic electrons, hence independent info on 3 other form factors will be missing.
- Theoretical models show the trend that TPE has a smaller effect at lower Q^2 . The reason is that "hard" TPE amplitudes do not have a $1/Q^2$ Coulomb singularity, as opposed to the Born amplitude.

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Lepton Mass Effects

- Standard approximations keep the lepton mass in the logarithms but neglect it in power terms. May be justified in the ultrarelativistic case and Q^2>>(lepton mass)^2
- Most of analysis codes use exact mass dependence for hard brem, but use above approximations for the "soft" part of brem correction
- Revised approach is required that will NOT result in new theoretical uncertainties
- New rad.correction codes no longer use peaking approximation (justified for relatively small lepton masses)
- Formalism and Monte-Carlo generators can be adapted for this analysis (ELRADGEN; MASCARAD, etc;

  more on www.jlab.org/RC); HAPRAD for SIDIS of muons

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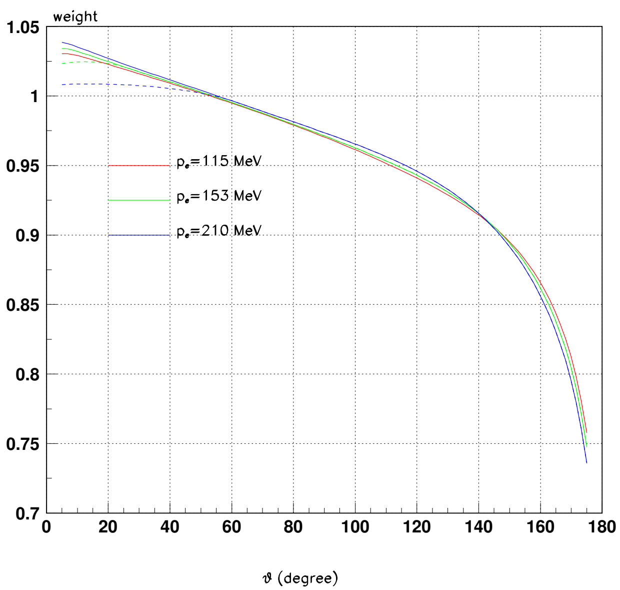
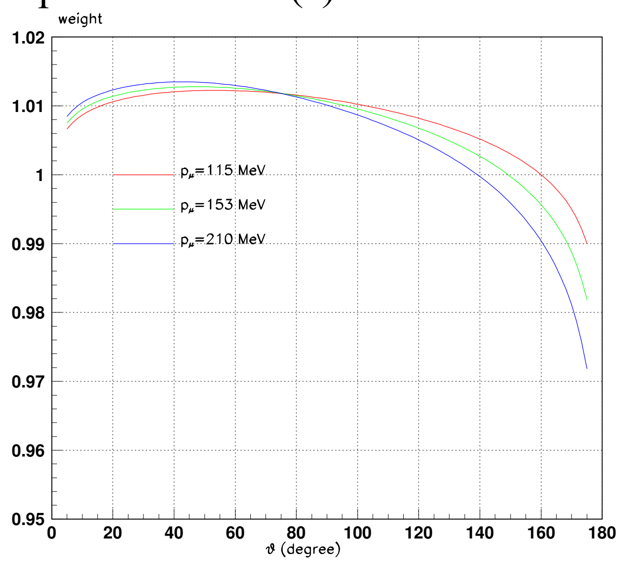
ELRADGEN Results for 100MeV-beams

MUSE: Proposed experiment at PSI to measure proton charge radius in elastic scattering of muons, arXiv:1303.2160

- Ilyichev (Minsk) and AA: updated ELRADGEN Monte Carlo (Afanasev et al., Czech. J. Phys. 53 (2003) B449; Akushevich et al., Comput. Phys. Commun. 183 (2012) 1448) to include (a) mass effects and (b) two-photon effects (c) hard brem included





Left: Radiative correction for elastic electron-proton scattering as a function of lab scattering angle in MUSE kinematics. Dashed lines show the effect of a kinematic cut. Right: Same result but for the scattering of muons.

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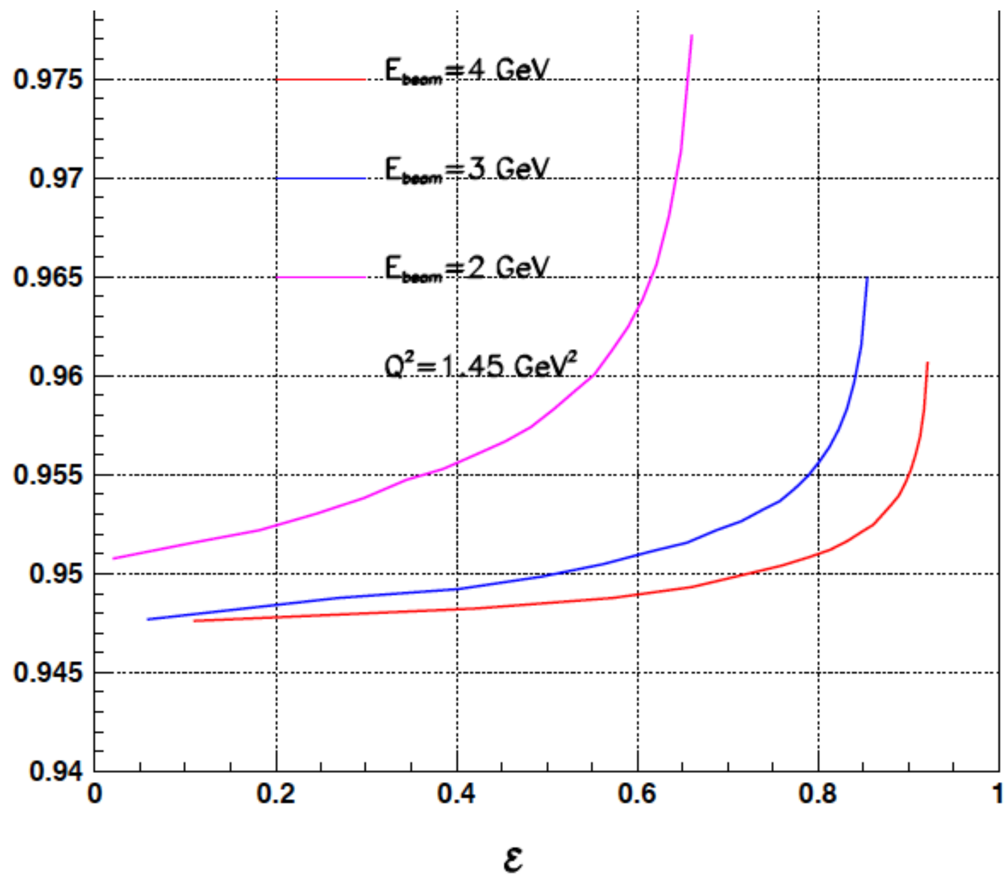
C-odd Effects in ELRADGEN

- Order-α corrections due to (a) two-photon exchange and (b) lepton-hadron brem interference for opposite-sign leptons are also opposite in sign
  - ELRADGEN included TPE (soft photons only) and brem interference), predicted charge asymmetry in JLAB CLAS kinematics (electrons)

$R=\sigma(e^-)/\sigma(e^+)$



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Helicity amplitudes for μp elastic scattering

- Total of 6 amplitudes:
  - 3 helicity-conserving, 3 helicity flip
  - Helicity-flip amplitudes neglected in ultra-relativistic $E_\mu >> m_\mu$
  - Exception: single-spin beam asymmetries caused by interference of helicity-conserving and helicity-flip
- For muon scattering at ~100 MeV ultra-relativistic approximation no longer applies
- Model-independent analysis of two-photon exchange requires to fit amplitudes

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Elastic contribution to TPE

- TPE for elastic mu-p scattering calculated by Tomalak&Vanderhaeghen, PRD 90 (2014) 013006; included only elastic intermediate state described by form factors

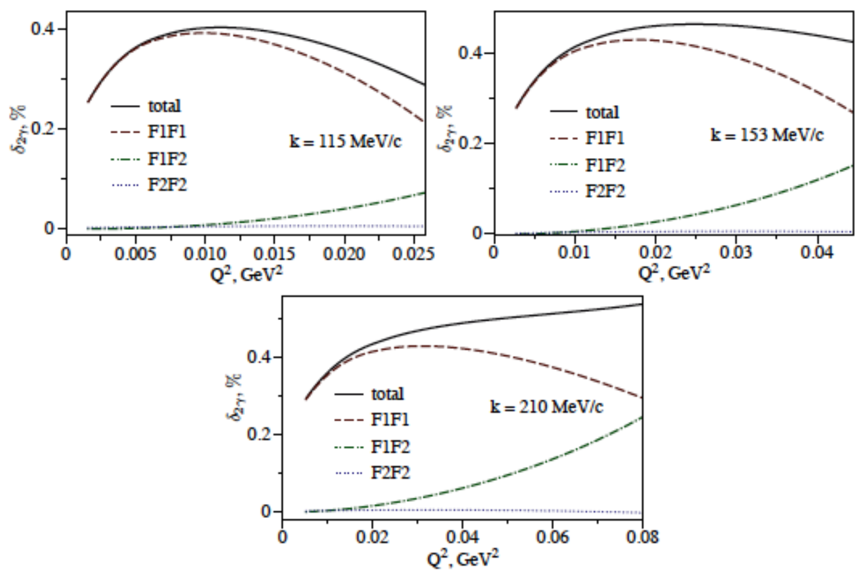

FIG. 4: TPE correction to the unpolarized elastic $\mu^- p$ cross section for three different muon beam momenta. The total correction is shown by the black solid curves, the contribution from the F1F1 structure of photon-proton-proton vertices is shown by the red dashed curves, the contribution from the F1F2 structure by the green dashed-dotted curves, and the contribution from the F2F2 structure by the blue dotted curves.

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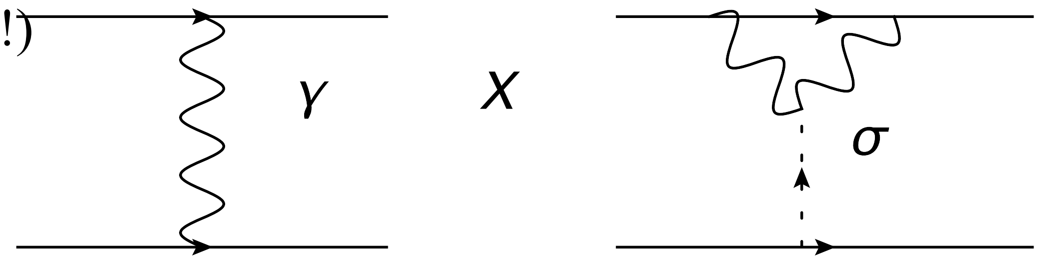
Helicity-Flip in TPE; estimate of inelastic contribution

- 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!)



$$\delta_{\sigma}^{2\gamma} = -\alpha \frac{4\sqrt{\tau(1+\tau)(1-\varepsilon^2)}\, m_{\mu} M_N F_{\sigma\mu\mu} f_{\sigma NN} G_{Ep}}{(\tau G_{Mp}^2 + \varepsilon G_{Ep}^2)(Q^2 + m_{\sigma}^2)}$$

- No information on $F_{\sigma\mu\mu}$ is available. Need model estimates.

From sigma-pole contribution to nucleon polarizability, we estimate for Q^2=0.01 GeV^2 $\delta_{\sigma}^{2\gamma}$ is about 10^{-4}, lepton helicity-flip is important, scales as $\sqrt{\tau}$, $\tau = Q^2 / 4M_N^2$

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Can be studied directly in the ratio of μ+ and μ- cross sections

Conclusions

MUSE:

- 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
- 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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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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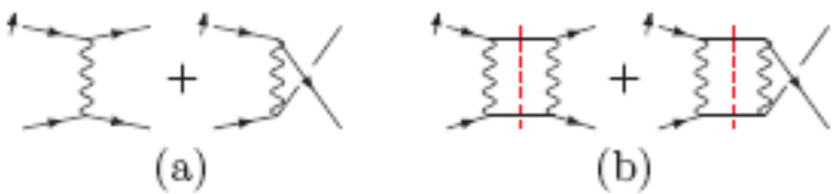
Normal Beam Asymmetry in Moller Scattering

- 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

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

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

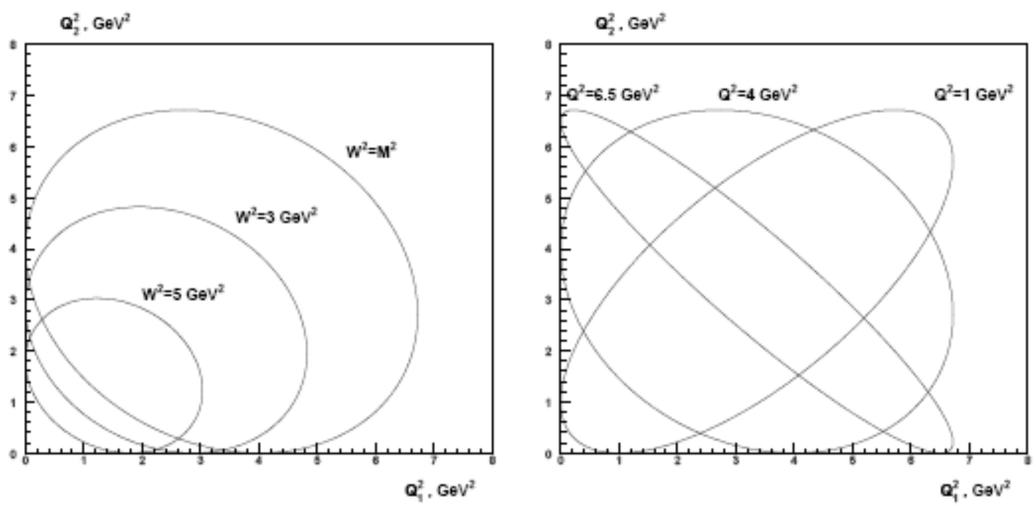


Figure 2. Integration region over Q_1^2 and Q_2^2 in Eq.(2) for elastic ($W^2 = M^2$) and inelastic contributions. The latter (left) is given for Q^2=4 GeV^2 and two values of W^2, which is an integration variable in this case. The elastic case is shown on the right as a function of external Q^2. The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

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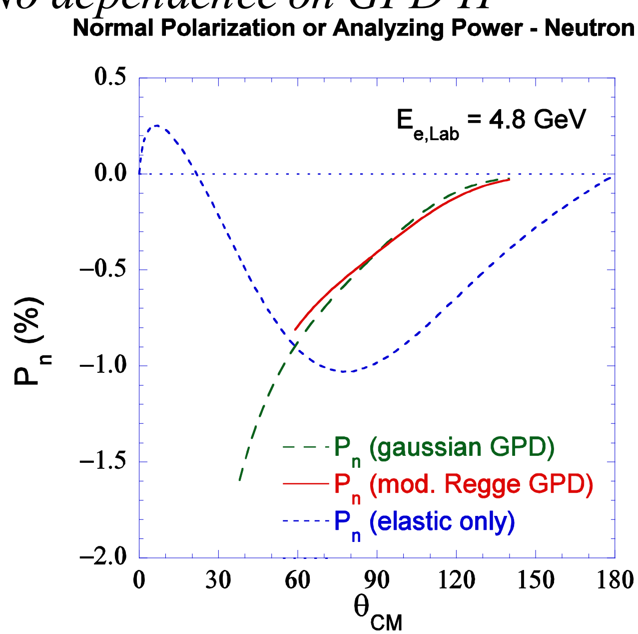
Quark+Nucleon Contributions to Target Asymmetry

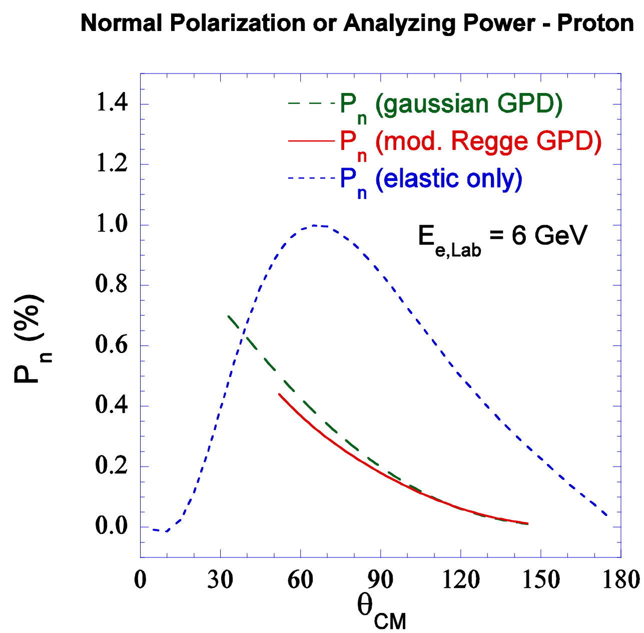
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetry of elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

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

Only minor role of quark mass

No dependence on GPD $\widetilde{H}$

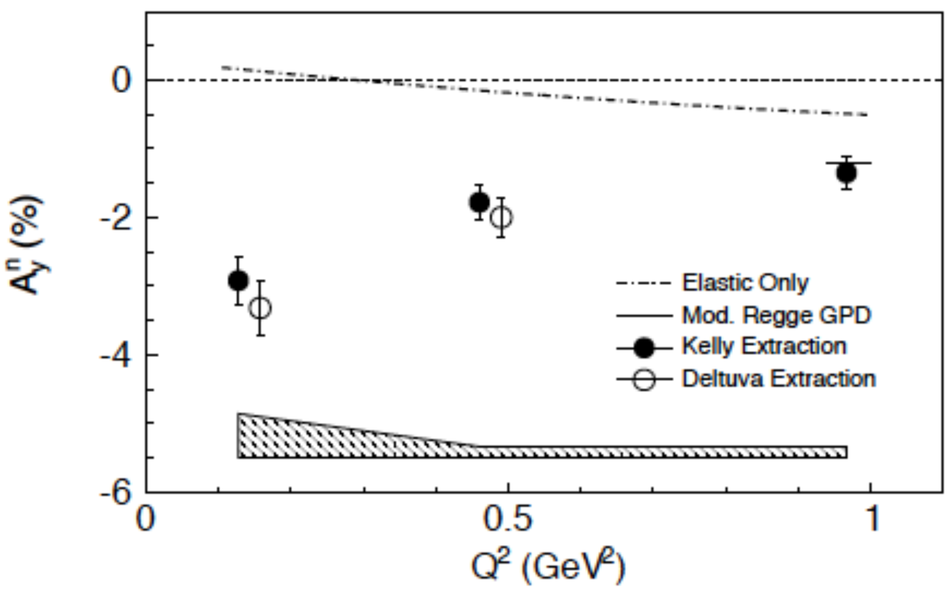




Data coming from JLAB E05-015
(Inclusive scattering on normally polarized ^{3}He in Hall A)

Single-spin Asymmetries at JLAB

- Polarized target (He3) JLAB E-05-015 (arXiv:1502.02636)
- Recoil polarimetry (proton)



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Single-Spin Asymmetry in Elastic Scattering
Early Calculations

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

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

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

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)

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

$$(small - angle\ scattering)$$

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

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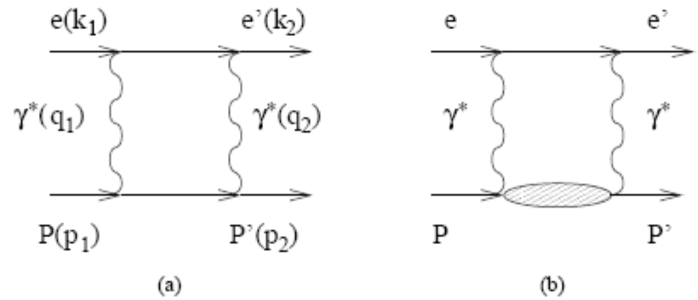
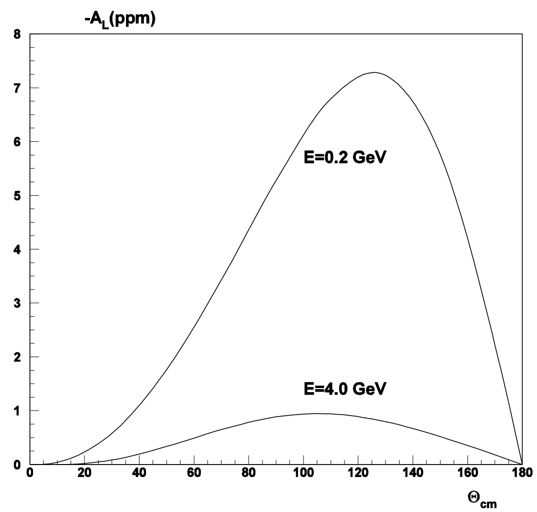
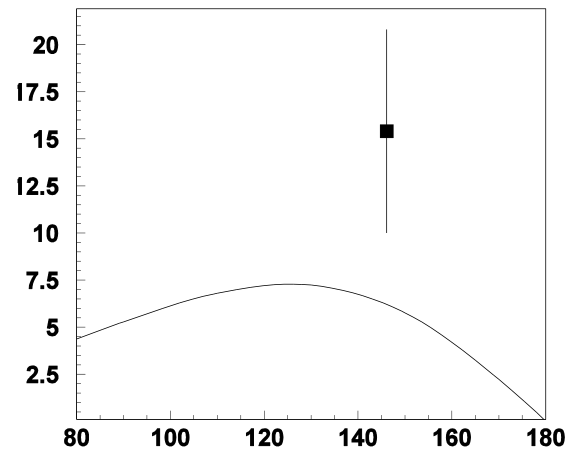
Proton Mott Asymmetry at Higher Energies

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

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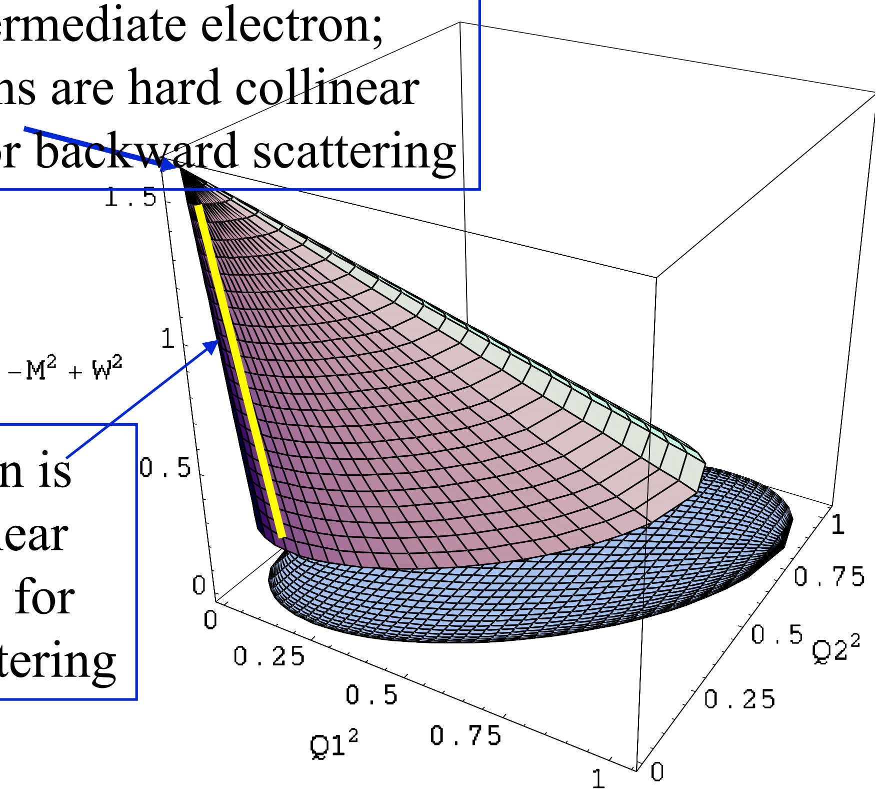
Phase Space Contributing to the absorptive part of 2γ-exchange amplitude

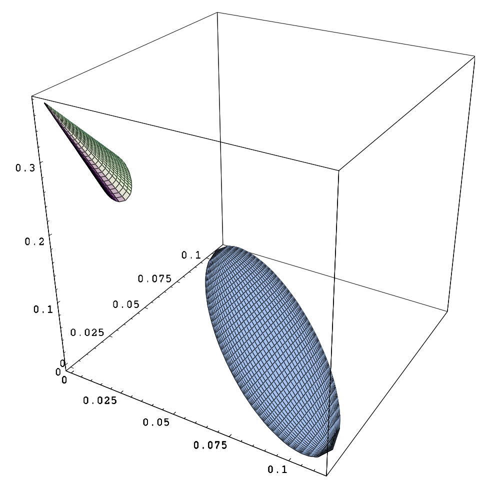
- 2-dimensional integration (Q_1^2, Q_2^2) for the elastic intermediate state
- 3-dimensional integration (Q_1^2, Q_2^2,W^2) for inelastic excitations

`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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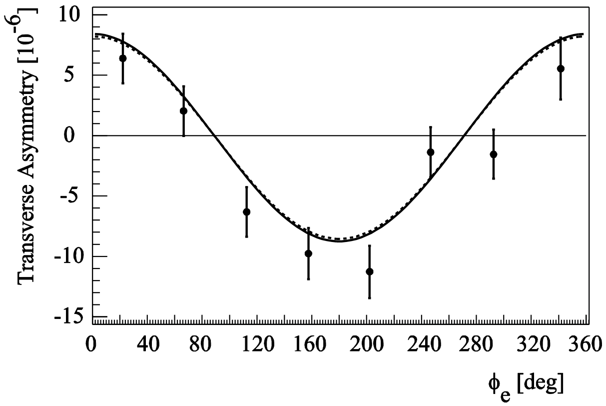
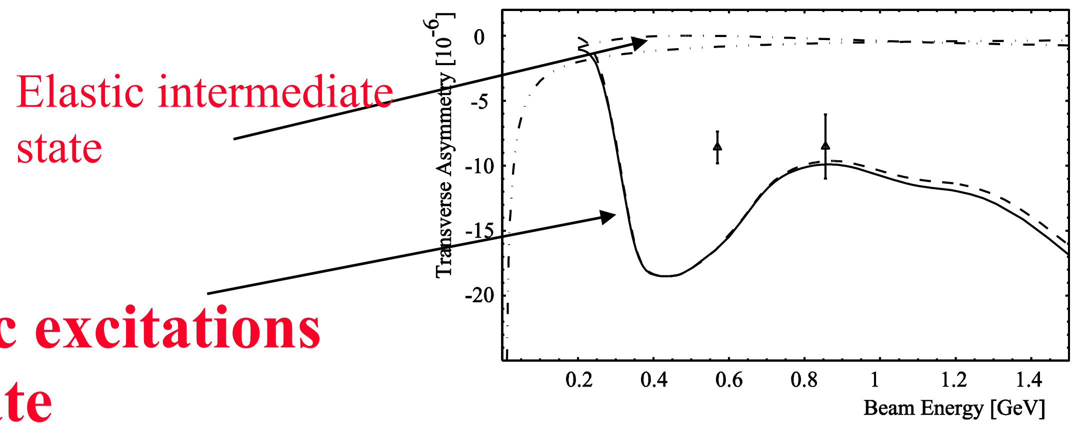
MAMI data on Mott Asymmetry

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

Used single-pion electroproduction amplitudes from MAID to

Surprising result: Dominance of inelastic intermediate excitations





Inelastic excitations Dominate

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

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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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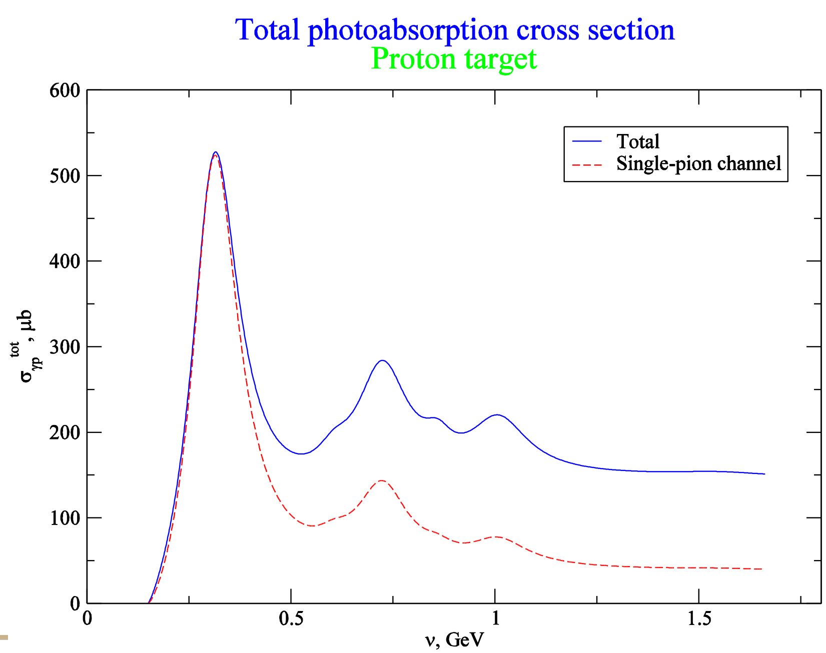
Input parameters

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

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



<u>The integral is energy-weighed, higher energies enhanced</u>

$\sigma_{\gamma p}$ 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

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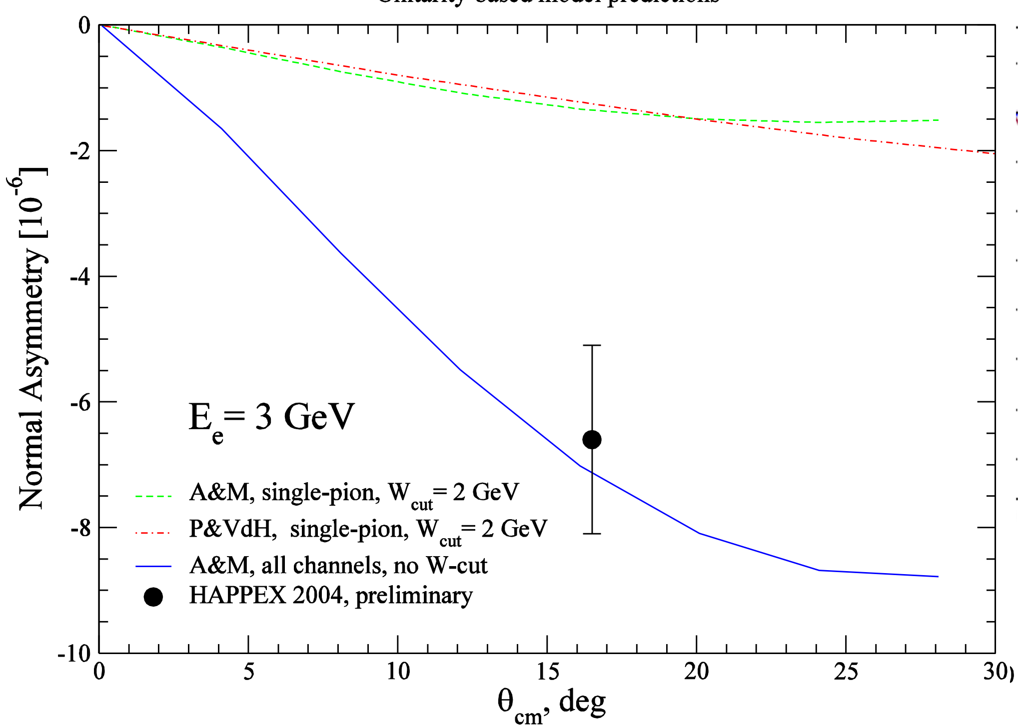
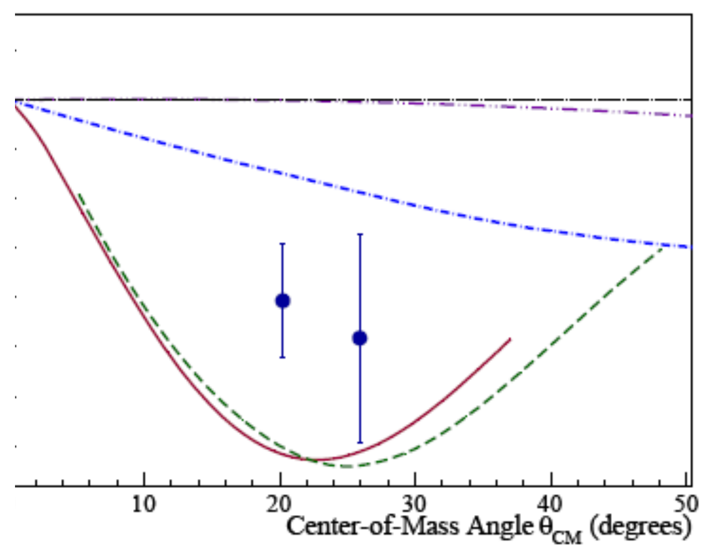
Predictions vs experiment for Mott asymmetry

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



G0 arXiv 0705.1525[nucl-ex]



HAPPEX

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

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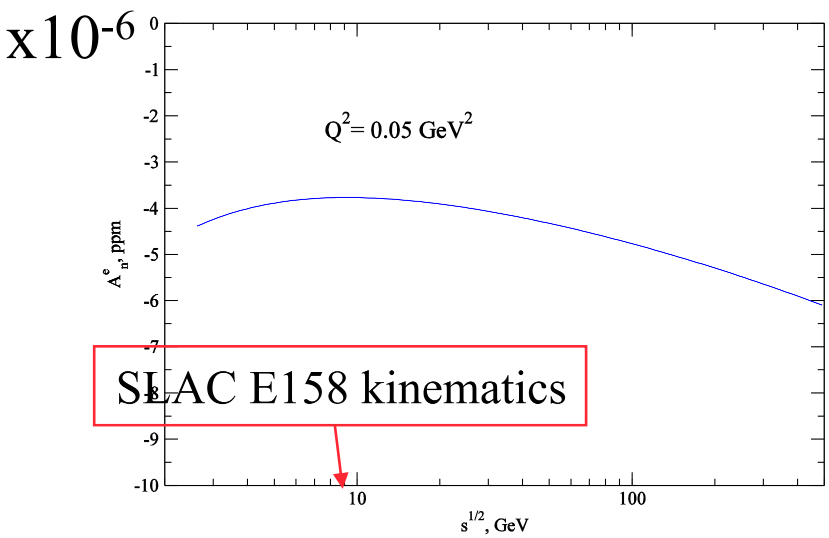
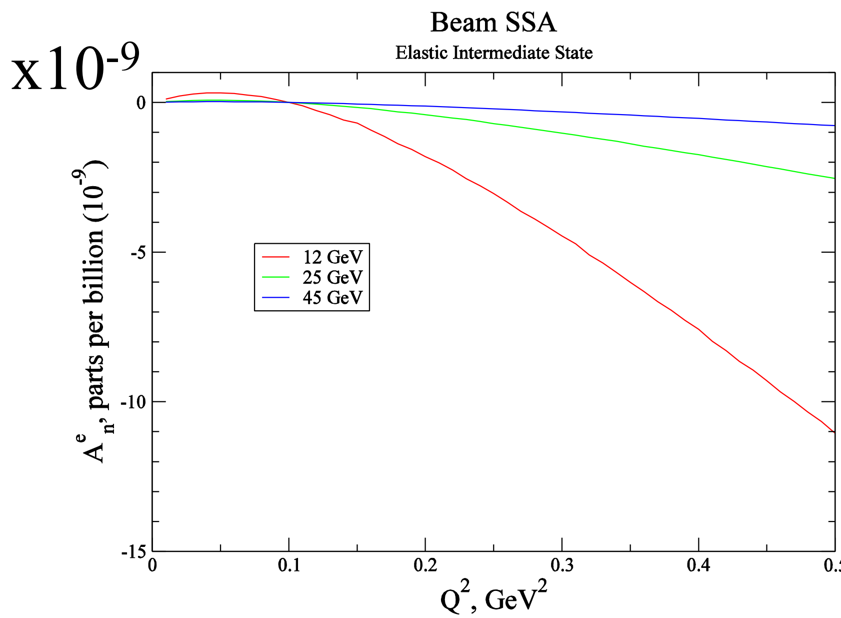
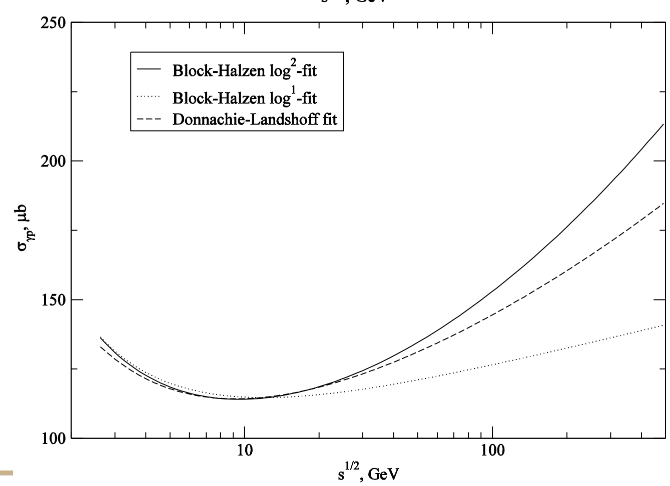
Predict no suppression for Mott asymmetry with energy at fixed Q^2







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

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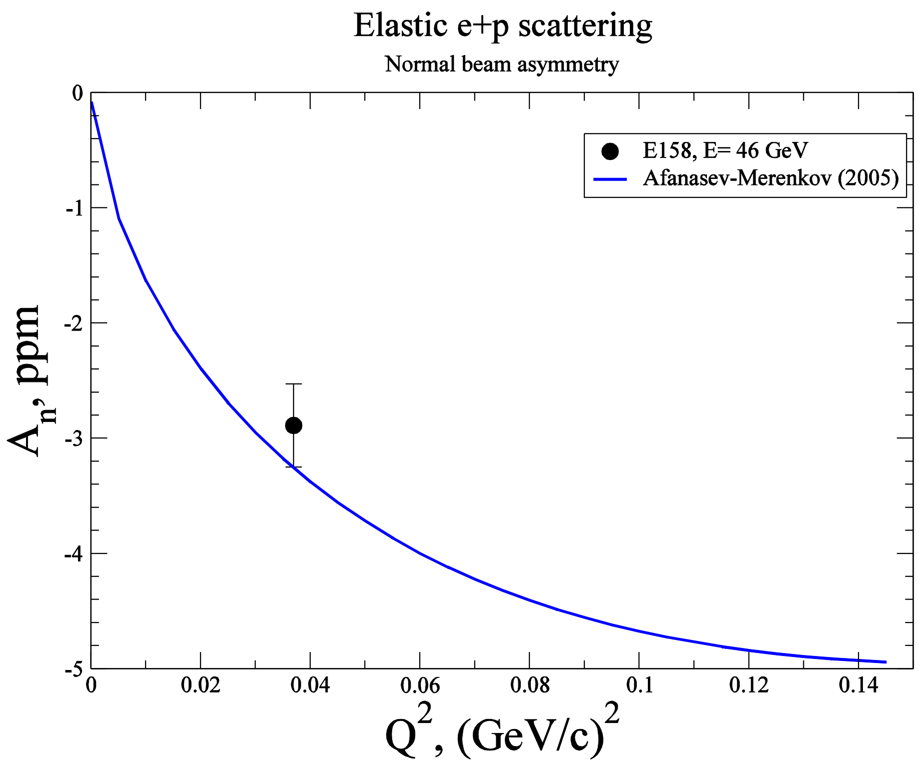
Comparison with E158 data



- 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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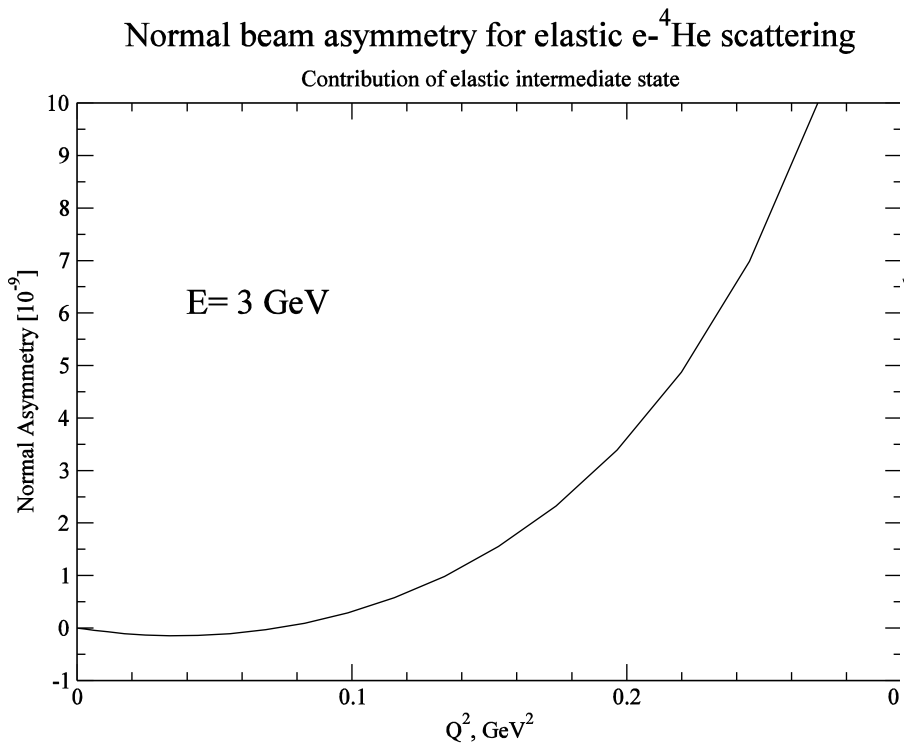
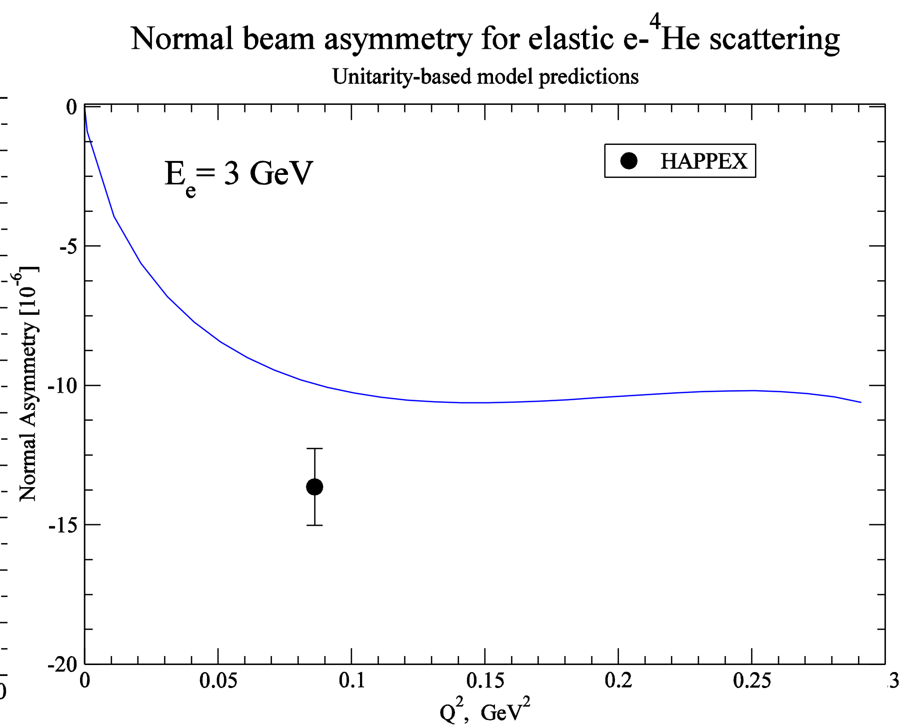
Mott Asymmetry on Nuclei

- 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)

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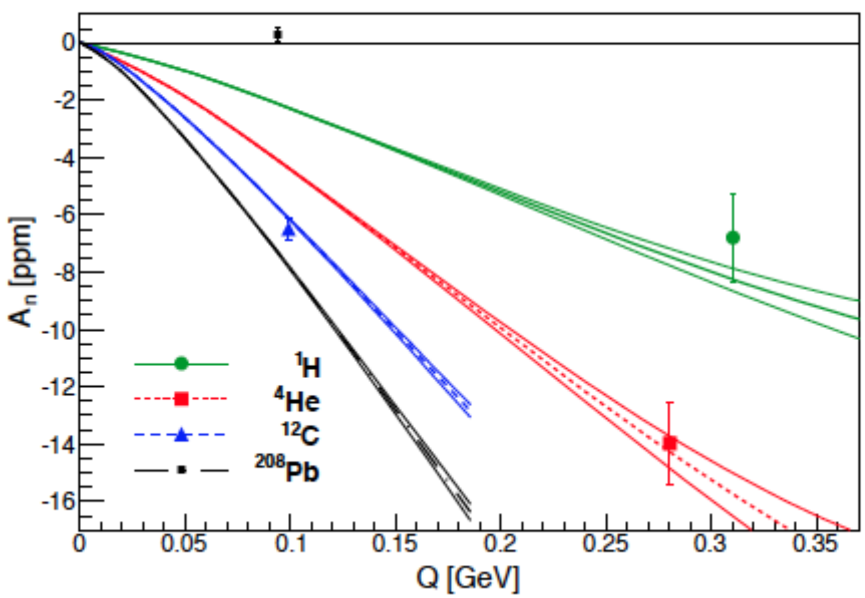
Transverse Beam Asymmetries on Nuclei (HAPPEX+PREX)

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



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

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Inclusive Electroproduction of Pions

$$\vec{s}_e \cdot \vec{k}_e \times \vec{k}_\pi$$

- Reaction p(e_{pol},π)X
  - Parity-conserving spin-momentum correlation
  - 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
  - Physics probe of (strong) final-state interactions in electroproduction reactions
    - Why not simply measuring SF in A(e_{pol},eπ)X directly with longitudinal polarization? Because transverse SSA gives access to very low Q^2, may not available to spectrometers

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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

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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},π)X probes strong final-state interactions – due to "fifth stucture function"

in A(e,e' π)X

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Physics Opportunities with High Intensity Beams

- High intensities allow measurements with high statistical accuracy
- QED corrections limit interpretation of electron scattering measurements in terms of one-photon exchange quantities (eg, form factors)
- Systematics from high-order QED can be studied by

(a) comparing electron and positron measurements (C-odd asymmetries) and

(b) studies of single-spin asymmetries (that are otherwise zero in first Born approximation)