Inclusive Single-Spin Asymmetries and Nucleon Structure in Electron Scattering

Andrei Afanasev

The George Washington University

Washington, DC, USA

INT Workshop ***Parity-Violation and other Electroweak Physics at JLab 12 GeV and Beyond***

29 June 2022

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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 for non-elementary targets
  - – SSA for electron DIS
    - Implications for TMD and electroweak studies
  - – Summary and outlook

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 box 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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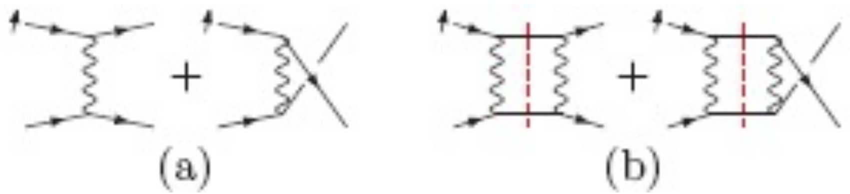
Normal Beam Asymmetry in Moller Scattering

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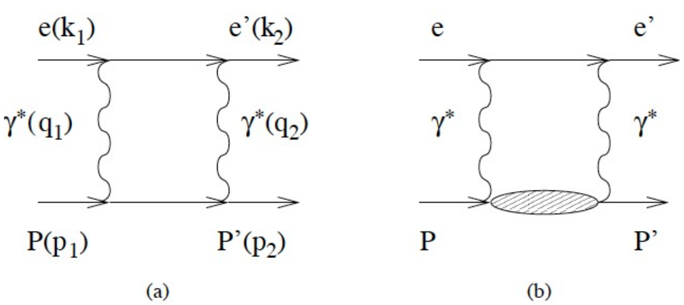
Single-Spin Target Asymmetry $\vec{s}_T \cdot \vec{k}_1 \times \vec{k}_2$

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

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



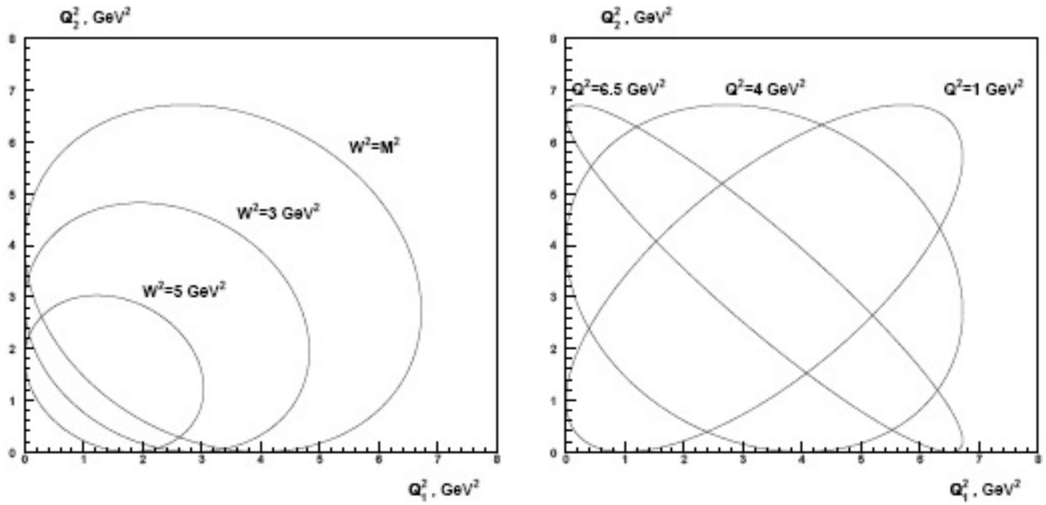


Figure 2. Integration region over Q_1^2 and Q_2^2 in Eq.(2) for elastic ($W^2 = M^2$) and inelastic contributions. The latter (left) is given for Q^2=4 GeV^2 and two values of W^2, which is an integration variable in this case. The elastic case is shown on the right as a function of external Q^2. The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

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Quark-level calculations for elastic ep

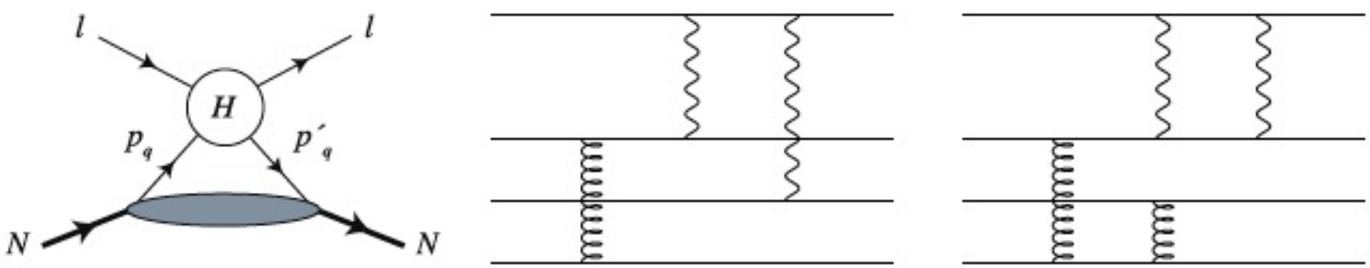
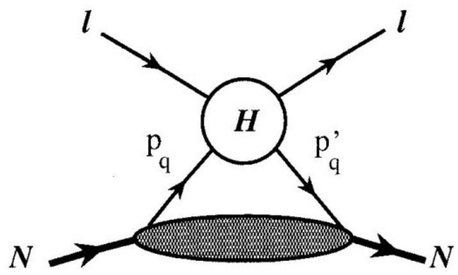


Fig. 2.11. *Left:* TPE diagram in the GPD-based approach to *eN* scattering at high Q^2 [47,48]. Both photons interact with the same quark, while the others are spectators. *Right:* Sample TPE diagrams in the QCD factorization approach. For the leading order term the photons interact with different quarks, with a single gluon exchange. The interaction of two photons with the same quark is of subleading order in this approach, as it involves two gluons.

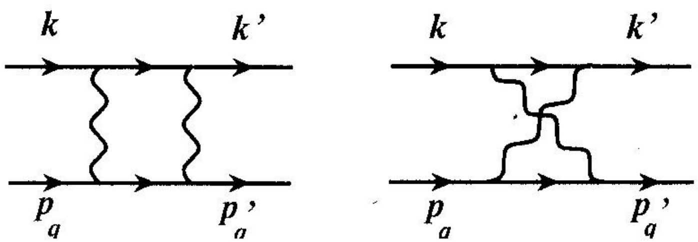
- Kivel, Vanderhaeghen
  - SCET, JHEP 1304 (2013) 029
- pQCD calculations, Phys.Rev.Lett. 103 (2009) 092004
  - Two photons couple to separate quarks, need one less hard gluon to transfer a large momentum to a nucleon – important to recover Low's theorem and electric charge in low-energy Compton scattering
- See Afanasev, Blunden, Hassell, Raue, Prog. Part. Nucl. Phys. 95, 245 (2017).

Elastic: 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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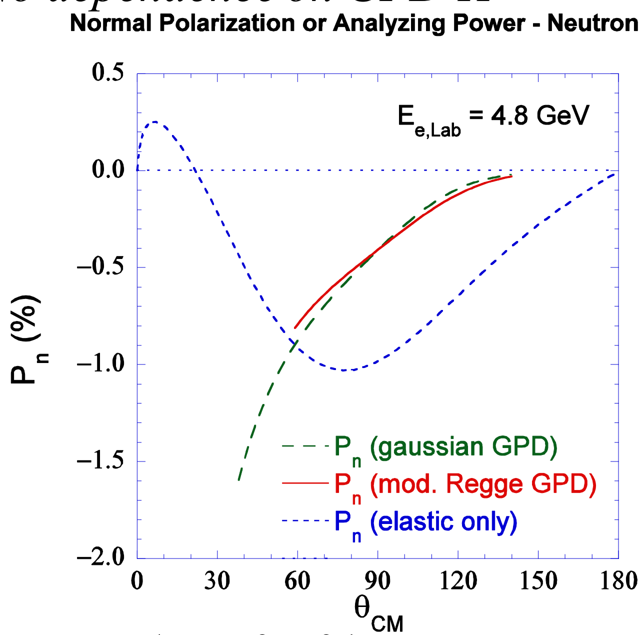
Quark+Nucleon Contributions to Target Asymmetry

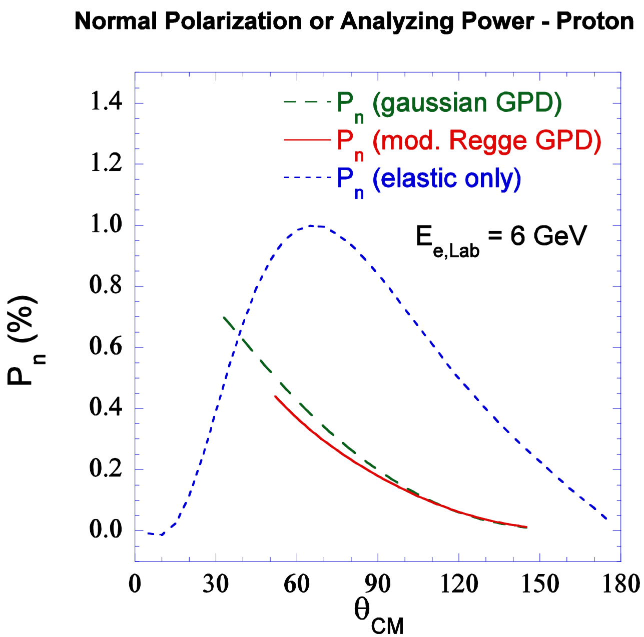
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetryof elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

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

Only minor role of quark mass

No dependence on GPD $\widetilde{H}$





JLAB E05-015

(Inclusive scattering on normally polarized ^{3}He in Hall A)

Elastic ep->ep
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

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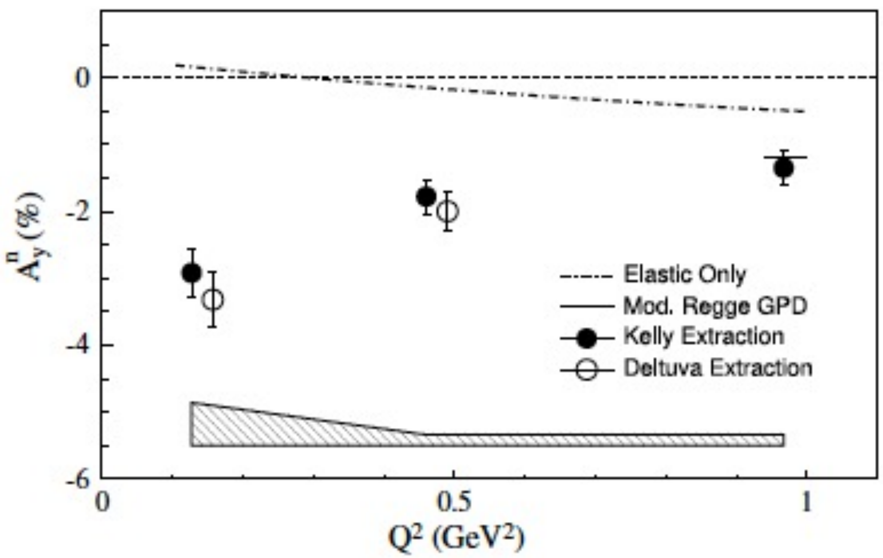

Data from JLAB E05-015 is in agreement with partonic picture.
(Inclusive scattering on normally polarized ^{3}He in Hall A)

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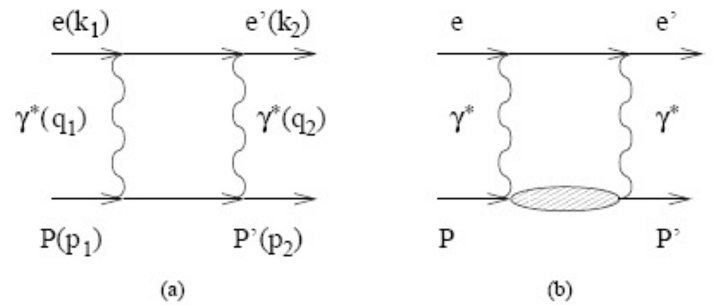
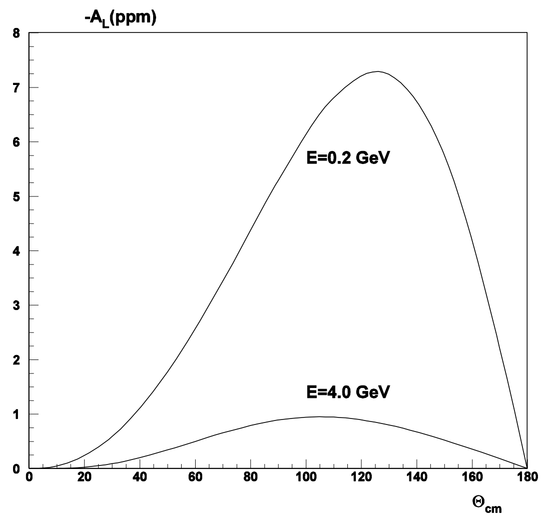
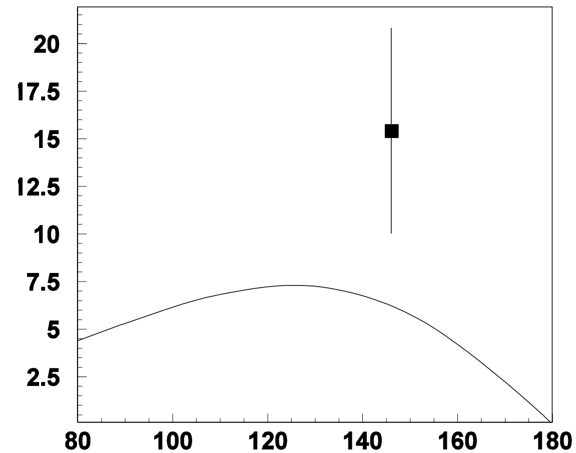
Proton Mott Asymmetry at Higher Energies

AA, Akushevich, Merenkov, hep-ph/0208260



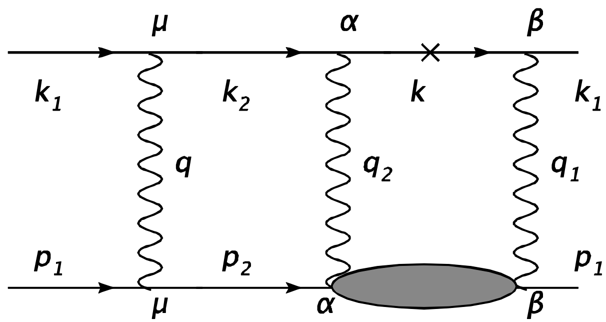
Transverse beam SSA, units are parts per million





- **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**

Beam Normal Asymmetry from Inelastic Intermediate States (hep-ph/0407167; *PL B599 (2004)48*)



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

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

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

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

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

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

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

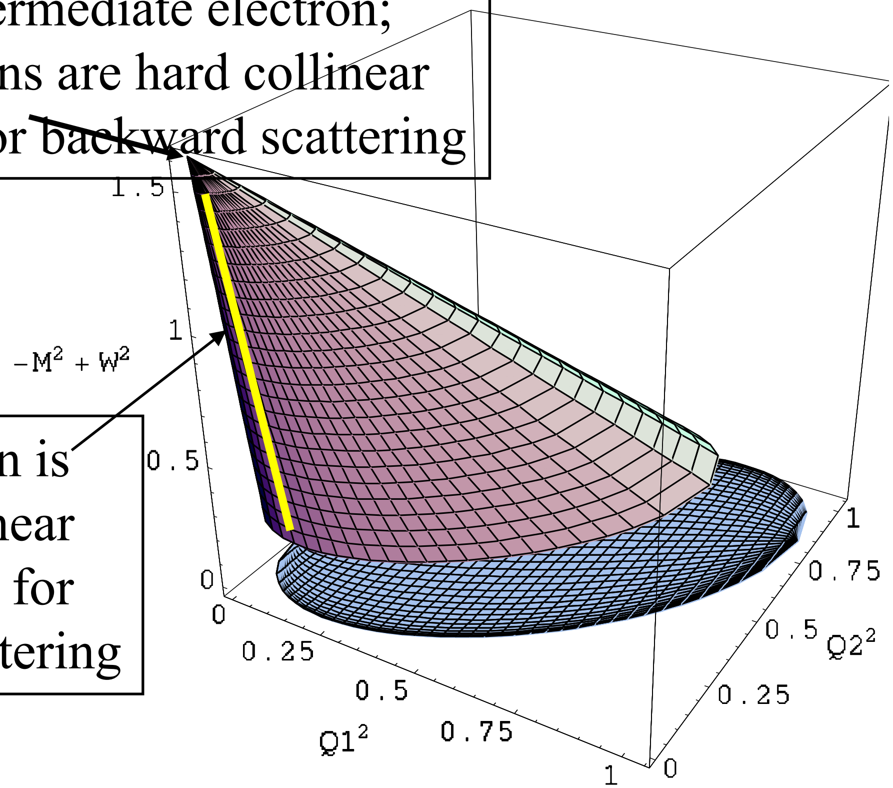
Also calculations by Vanderhaeghen, Pasquini (2004); Gorchtein, hep-ph/0505022; Borisyuk, Kobushkin, Phys. Rev. C 73 (2006) 045210; confirm ***quasi-real photon exchange***

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

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

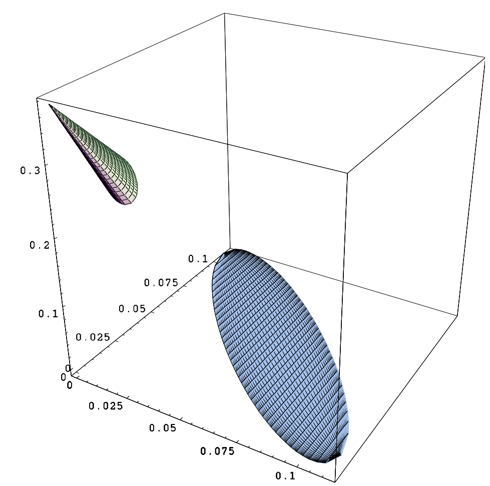
- 2-dimensional integration (Q_1^2, Q_2^2) for the elastic intermediate state
- 3-dimensional integration (Q_1^2, Q_2^2,W^2) for inelastic excitations

\`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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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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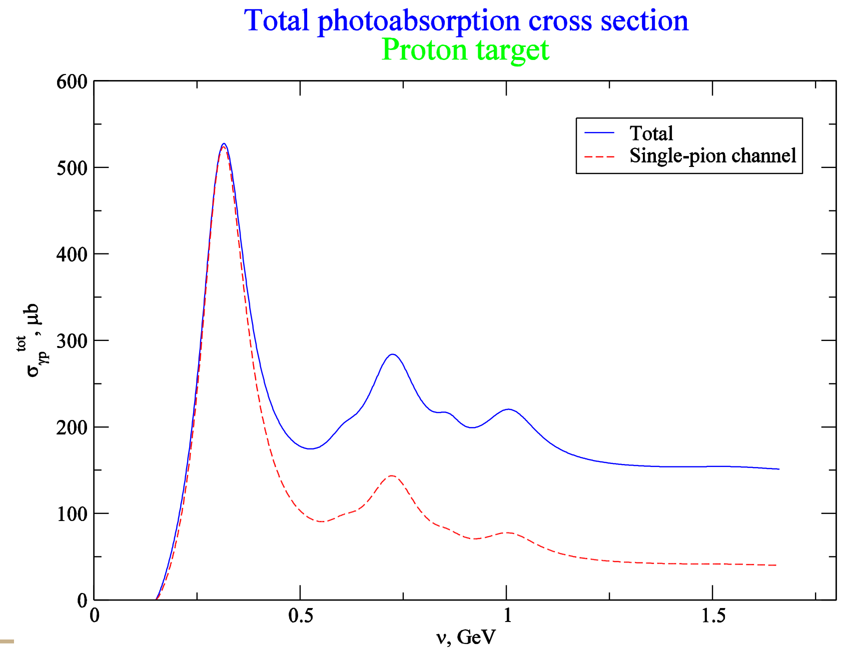
Input parameters

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

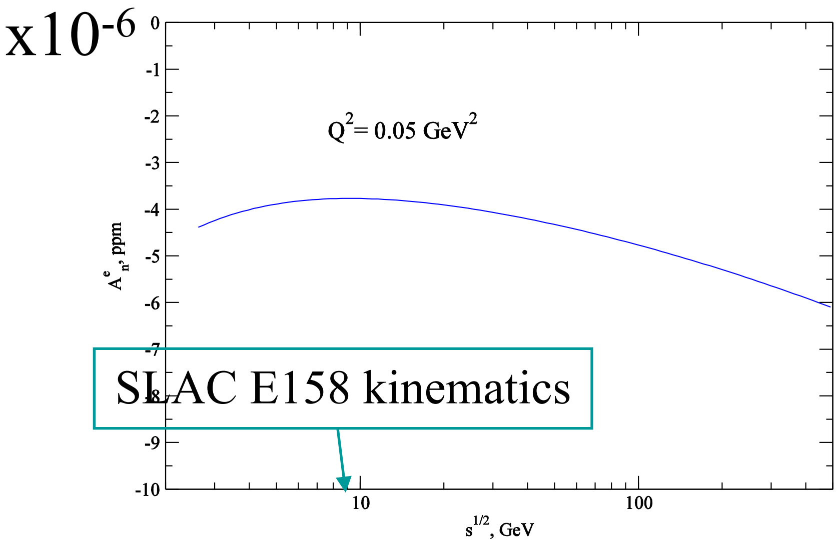
$$A_n \propto \frac{1}{E_e^2} \int_{\nu_{th}}^{E_e} d\nu \cdot \nu \sigma_{\gamma p}^{tot}(\nu; q_{1,2}^2 \approx 0)$$

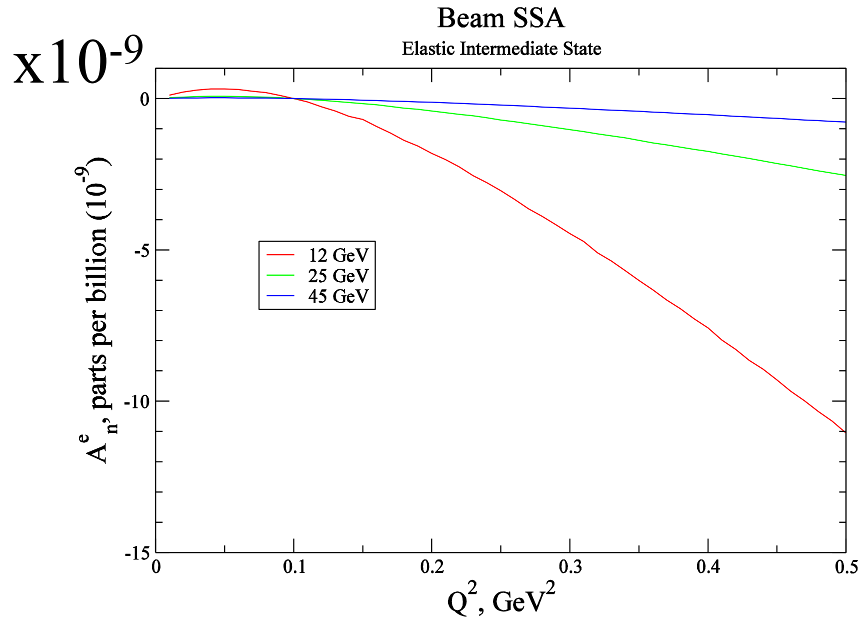


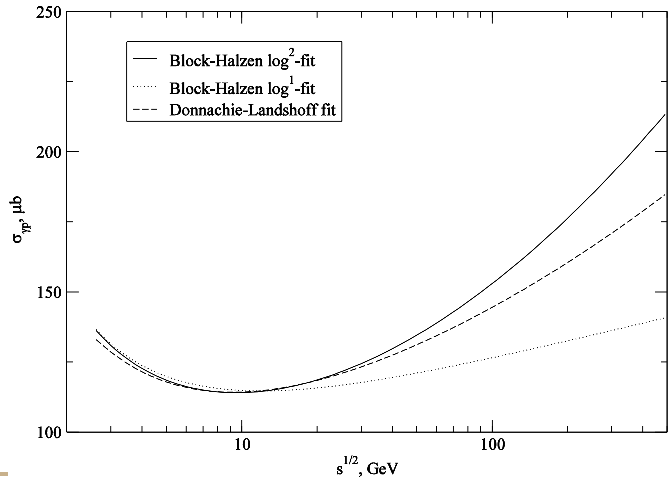
$\sigma_{\gamma p}$ from N. Bianchi at al., Phys.Rev.C54 (1996)1688 (resonance region) and Block&Halzen,

Phys.Rev. D70 (2004) 091901

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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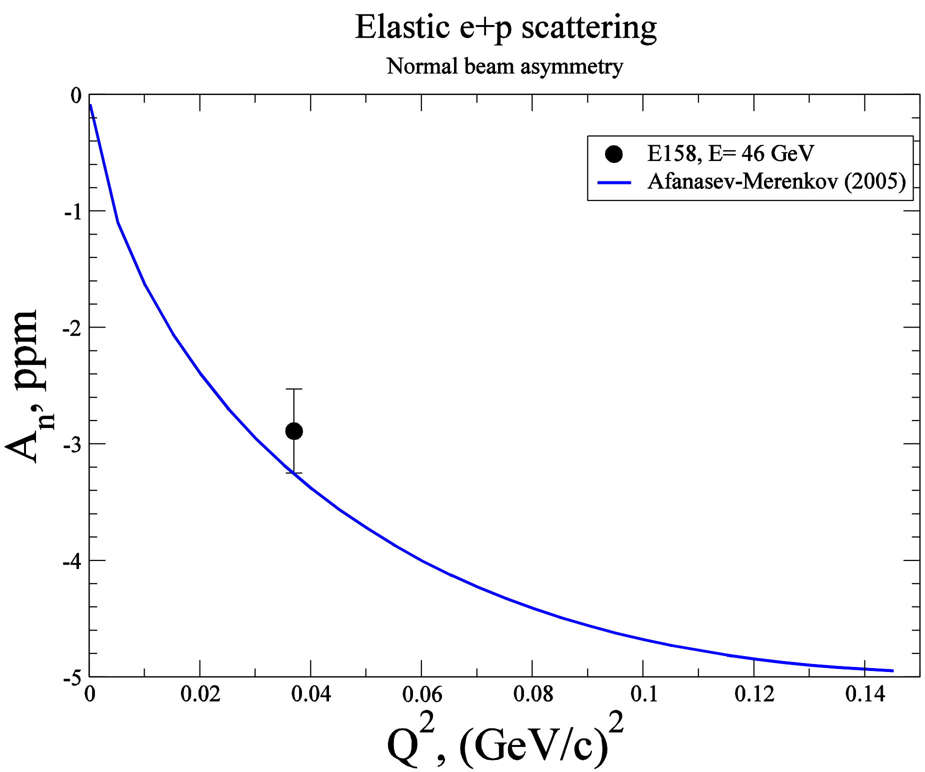
Comparison with E158 data



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

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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.

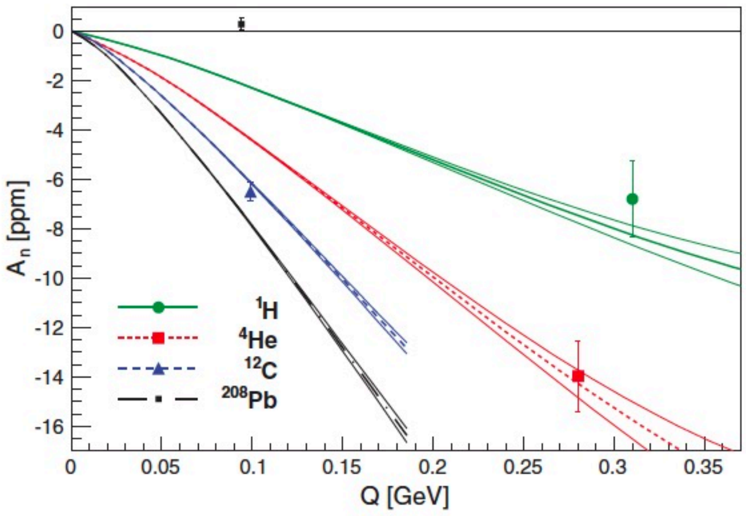
Target	H	^{4}He	^{12}C	^{208}Pb
θ	6°	6°	5°	5°
Q^2(GeV^2)	0.0989	0.0773	0.009 84	0.008 81
E_b(GeV)	3.026	2.750	1.063	1.063
$\langle\cos\phi\rangle$	0.968	0.967	0.963	0.967

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

JLAB Experiments: CREX

- 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

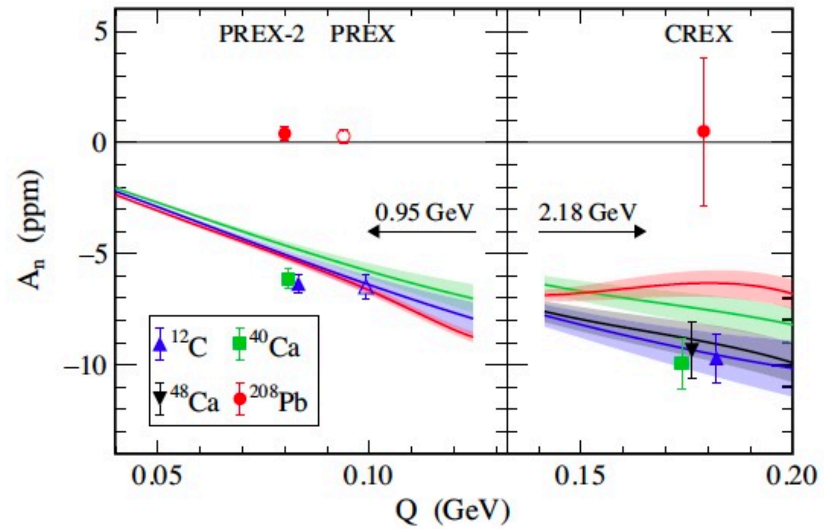


FIG. 2. A_n measurements from PREX-2, PREX (open circle and triangle, previously published [20]), and CREX at beam energies of 0.95 GeV, 1.06 GeV, and 2.18 GeV, respectively. The solid lines show theoretical calculations from [26] at 0.95 GeV and 2.18 GeV together with their respective one sigma uncertainty 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"**

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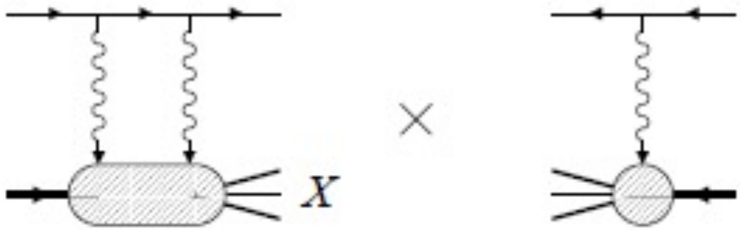
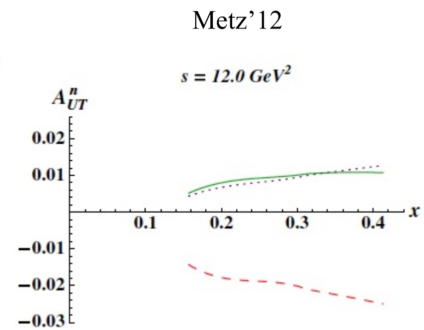
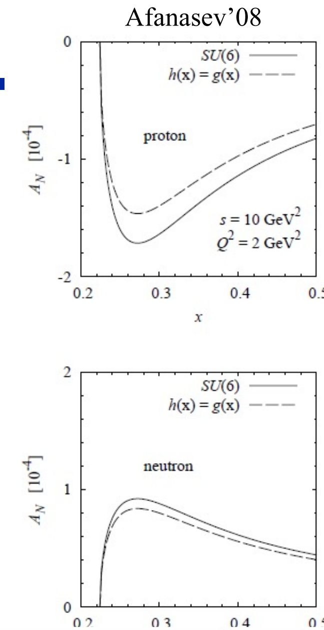
Gorchtein's talk

Two-Photon Exchange in inclusive DIS







- Theory: Afanasev, Strikman, Weiss, Phys.Rev.D77:014028,2008
  - Asymmetry due to 2γ-exchange ~1/137 suppression
  - Additonal suppression due to transversity parton density => predict asymmetry at ~10^{-4} level
  - EM gauge invariance is crucial for cancellation of collinear divergence in theory predictions
  - Hadronic non-perturbative ~1% vs partonic 10^{-4}: Major disagreement
- Prediction consistent with HERMES measurements who set upper limits ~$(0.6\text{-}0.9)\times10^{-3}$: Phys.Lett.B682:351-354,2010
- In contradiction to JLAB observation of per-cent asymmetry Katich et al. Phys. Rev. Lett. 113, 022502 (2014).
- Work by Metz PRD **86, 094039 (2012) – relation to TMD, +1% or -2%**
- **TPE-induced SSA at per cent level may have jeopardize JLAB and EIC programs on TMD studies (measured in SIDIS)**

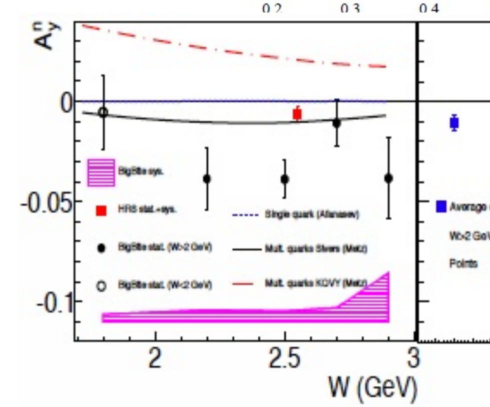


FIG. 3. Neutron asymmetry results (color online). **Left panel:** Solid black data points are DIS data ($W > 2$ GeV) from the BigBite spectrometer; open circle has $W = 1.72$ GeV. BigBite data points show statistical uncertainties with systematic uncertainties indicated by the lower solid band. The square point is the LHRS data with combined statistical and systematic uncertainties. The dotted curve near zero (positive) is the calculation by A. Afanasev *et al.* [11], The solid and dot-dashed curves are calculations by A. Metz *et al.* [12] (multiplied by −1). **Right panel:** The average measured asymmetry for the DIS data with combined systematic and statistical uncertainties.

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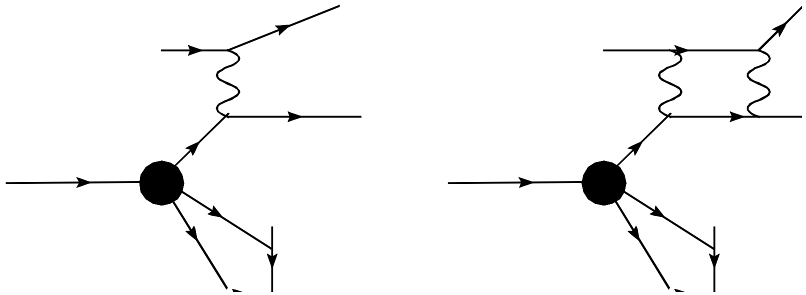
Beam SSA: Partonic-Level Calculation



- Interference of 1-photon and 2-photon exchange is responsible for the beam single-spin normal asymmetry
- Adapting Barut & Fronsdal, Phys.Rev. **120** (1960) 1891,

we get at the leading twist:

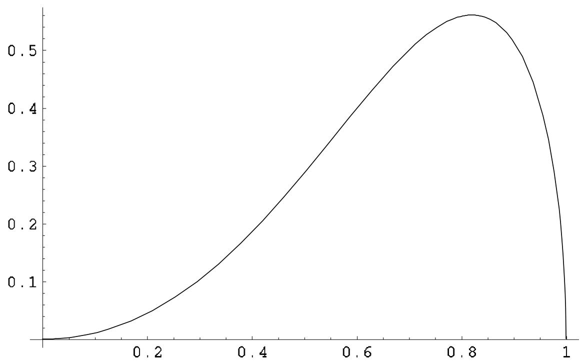
$$A_n^{Beam} = \frac{\alpha\, y^2 \sqrt{1-y^2}}{1+(1-y)^2} \frac{m_e}{Q} \sum_q (e_q)^3$$

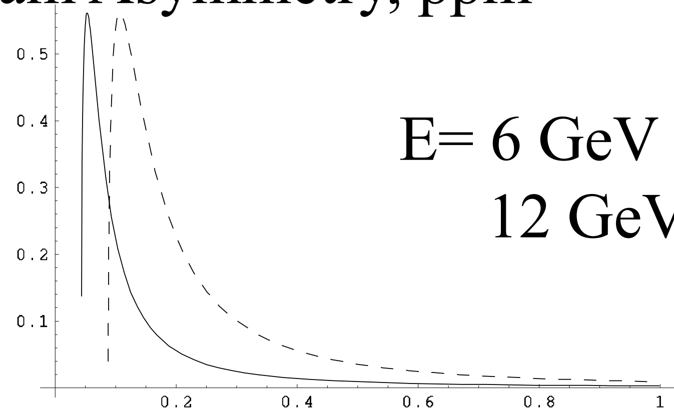
- Measured at JLAB PVDIS (upper limit in ~20ppm is set – limit of sensitivity) – also see M. Nycz's talk today – PAC50 proposal
- But putting the parton off-mass shell results in logarithmic enhancements
- Marc Schlegel and Andreas Metz suggested (model-dependent) relations of beam and target SSA to TMDs

Leading-twist Beam SSA in Inclusive DIS

Q^2= 1 GeV^2

Beam Asymmetry, ppm





E= 6 GeV (dashed)
12 GeV (solid)

y x

The leading-twist calculation predicts the effect around ½ ppm

Regge-limit (optical theorem): 10-100ppm: AA PRB 599 (2004) 48

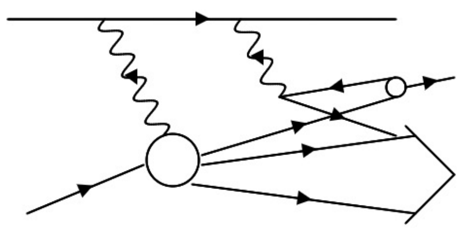
PVDIS at JLAB *Phys. Rev.* C 91 (2015) ~20ppm, large uncertainty

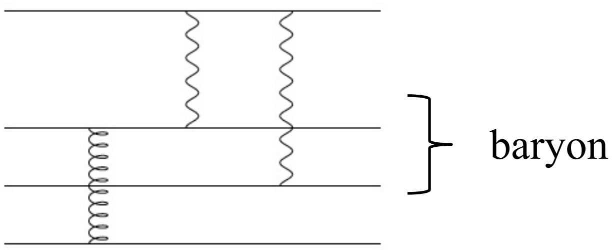
Large-log enhancements leads to the estimates

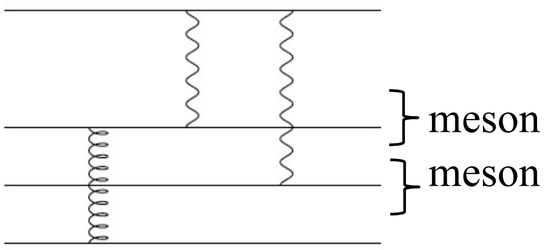
A_n~0.5ppm (leading twist) ➡ 0.5ppm $\log(Q^2/m_e^2)$~8ppm

Novel Two-Photon Scattering Channels for DIS

- Extending Kivel-Vanderhaeghen mechanism to SIDIS
  - Emission of an additional photon that converts into quark-antiquark pair leads do an additional mechanism for fragmentation
  - Produced hadron may be kinematically isolated (similar to higher-twist Berger's mechanism)

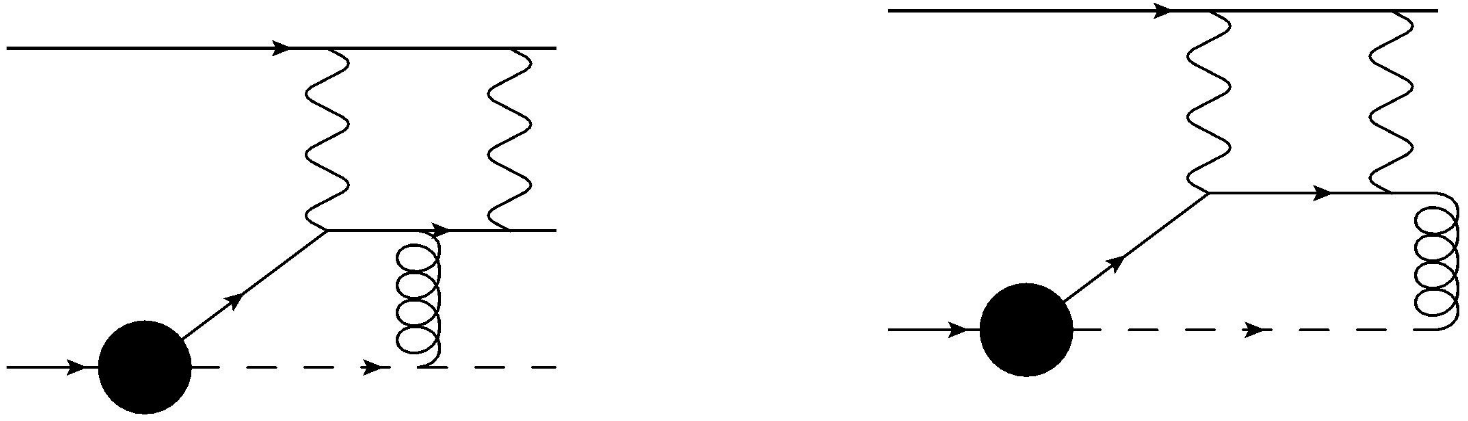






(a) one of the photons generates a q-qbar pair to form a final-state meson
(b) two-photon exchange facilitates baryon production from current fragmentation
(c) two-photon mechanism for production of fast meson pairs

QED+diquark model

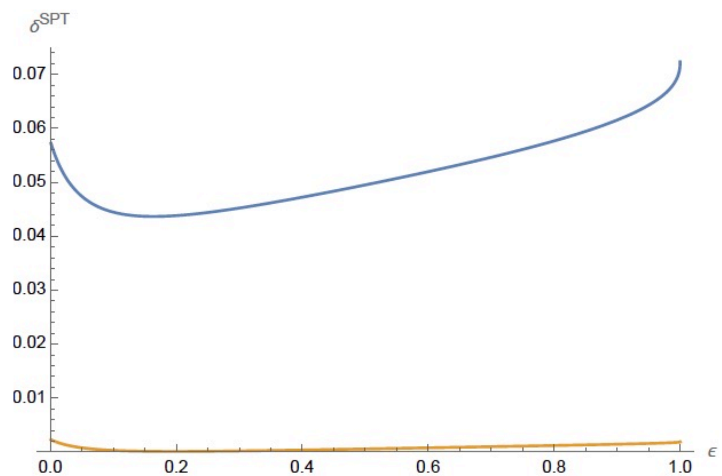


(a) (b)

- TPE may be treated in a model-dependent way via Brodsky-Yuan-Schmidt's diquark model for SIDIS
- Two-loop calculation ongoing with Stinson Lee (GWU grad student)

Soft Two-Photon Exchange in a diquark model

- *Soft* 2γ-exchange is an overall modulation of the entire rate by a common factor that depends on all kinematic variables (including an azimuthal angle) Example: $\sin(2\phi)$ modulation appears in addition to $\sin(\phi)$ beam polarization –dependent rate, but it cancels in beam SSA.
- *Hard* 2γ-exchange will alter all spin asymmetries and generate additional T-odd spin effects (that would not cancel with ϕ-integration); mix spin-independent and spin-dependent TMDs



- Additional ϵ-dependence of cross section due to 2γ corrections to σ_T
- Implications for L/T separation at a few per cent level
- 5% for cross section, but zero SSA
  - SSA measurements do not address all TPE effects

Figure: soft-photon effects in a diquark model (blue: up-quarks, orange: down-quarks); Q2=6 GeV^2, E=10.5 GeV, W=3.5 GeV, $p_\perp$=0

Summary: SSA in 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*
- JLAB data on target SSA exceeds parton model predictions by orders of magnitude
- Two-photon exchange opens new scattering mechanisms in DIS
- TPE is a major background for C-odd P-even electroweak effects
- Enhancement of beam SSA in electron DIS due to proton structure and strong-interaction dynamics may result in ~10ppm asymmetries, an order of magnitude larger than leading-twist partonic predictions (~1ppm)