Semi-analytic vs. Monte-Carlo Approaches for QED Corrections to SIDIS

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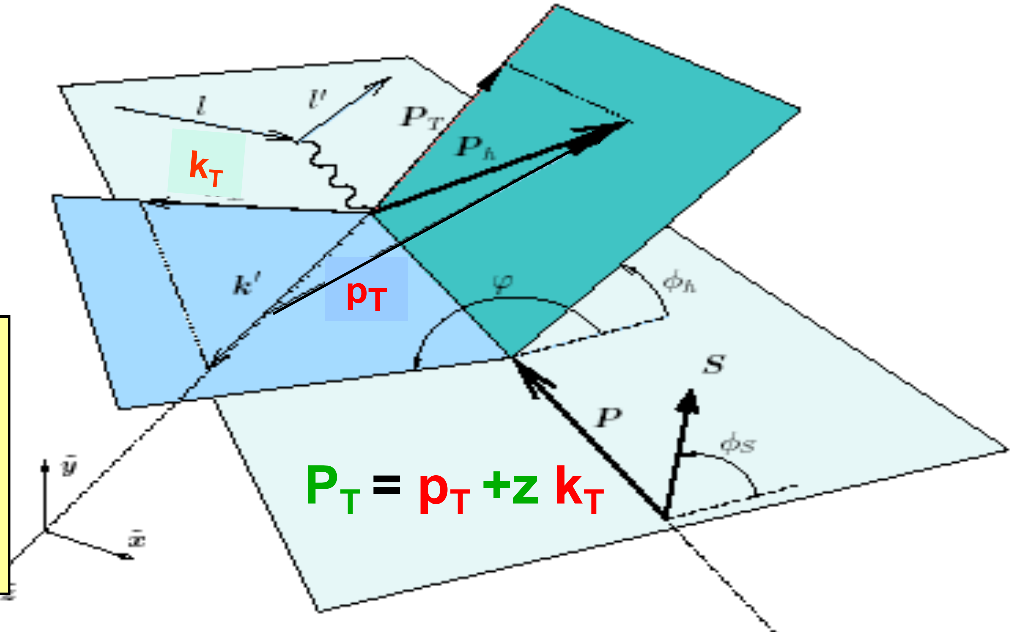
SIDIS: partonic cross sections

$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

$$\sigma = \sigma_0(1 + c_1(y)A_{UU}^{\cos\phi} + \cdots + c_6(y)A_{UT}^{\sin\phi_S} + c_7(y)A_{UT}^{\sin(\phi-\phi_S)})$$



Azimuthal moments in hadron production in SIDIS provide access to different structure functions and underlying transverse momentum dependent distribution and fragmentation functions.

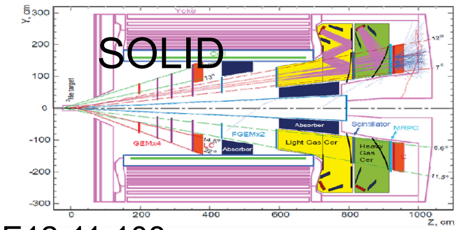
$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(\vec{k}_T + \vec{p}_T - \vec{P}_T/z)$$

Ji,Ma,Yuan Phys.Rev.D71:034005,2005

$$F_{XY}^h(P_T) \propto \sum e_q^2 H \times f^q(x, k_T, ..) \otimes D^{q\to h}(z, p_T, ..)$$

beam polarization   target polarization

A_{UT} studies at JLab



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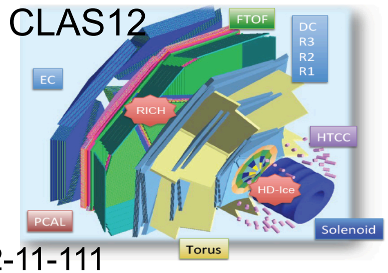

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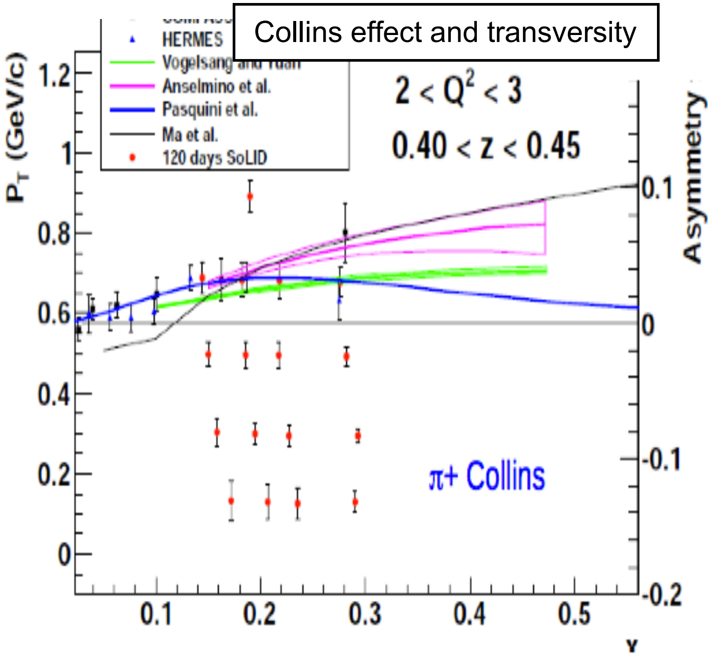
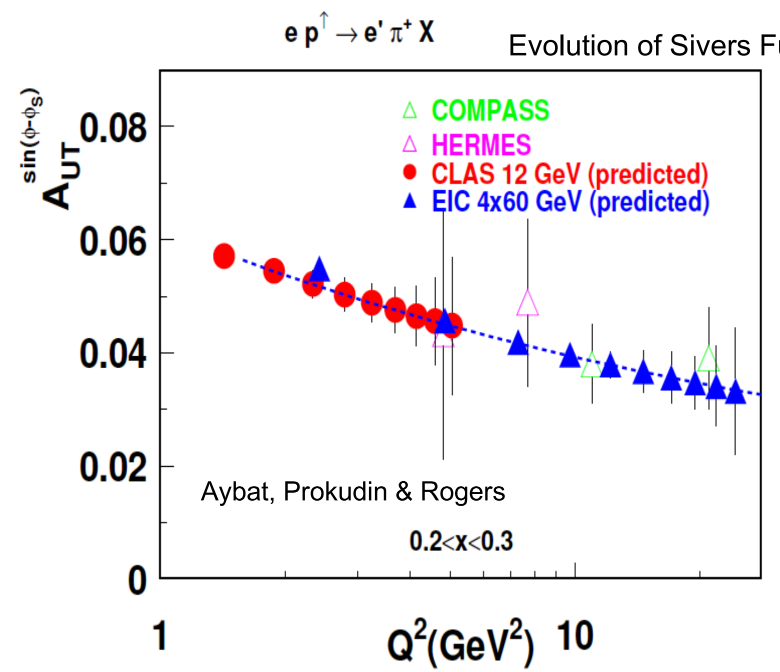
EIC²
EIC Center at Jefferson Lab

Collins effect and transversity



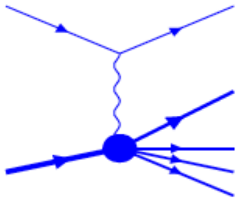
Evolution of Sivers Function



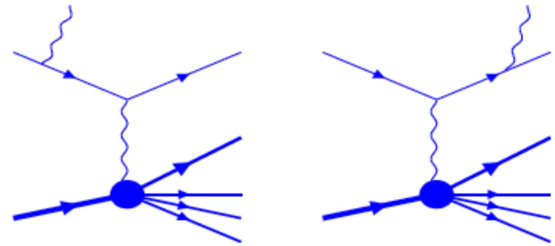
Precision 4-d mapping of transverse target SSAs using SoLID, CLAS12, EIC will require detailed understanding of RC azimuthal modulations

Radiative corrections in SIDIS

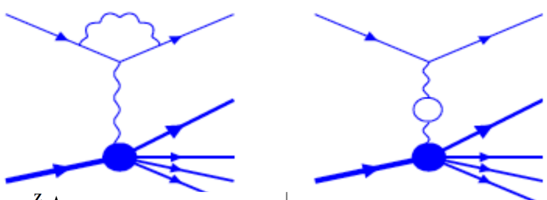
The Born cross section



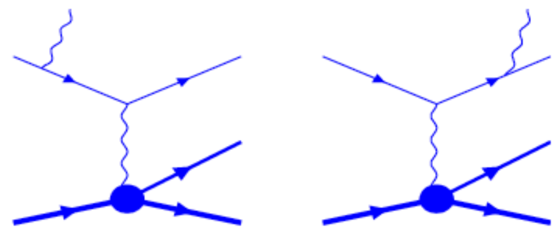
Emission of a radiated photon (semi-inclusive processes)

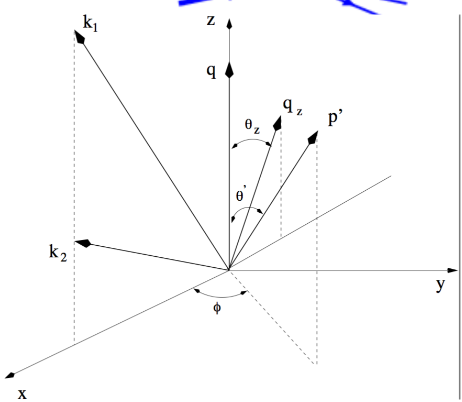


Loop diagrams



Emission of a radiated photon (exclusive processes)



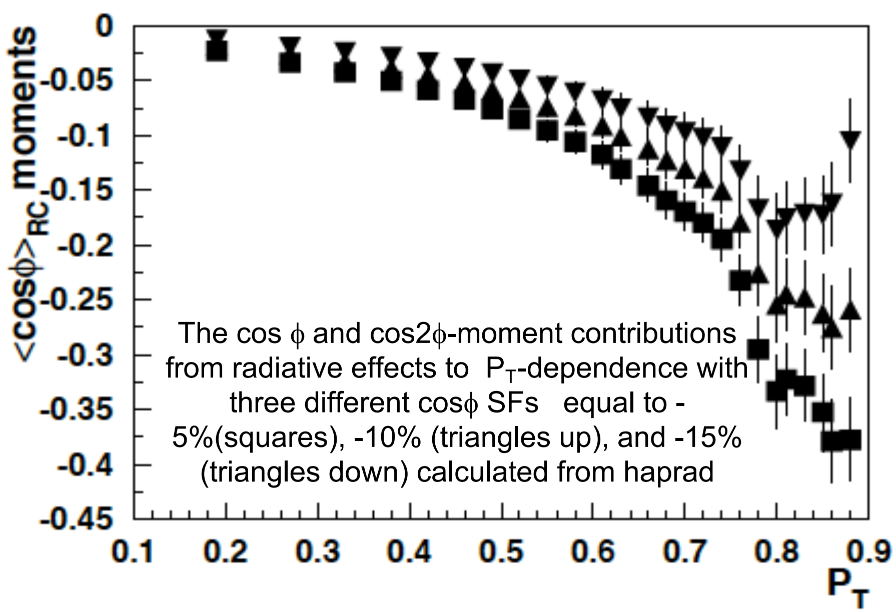


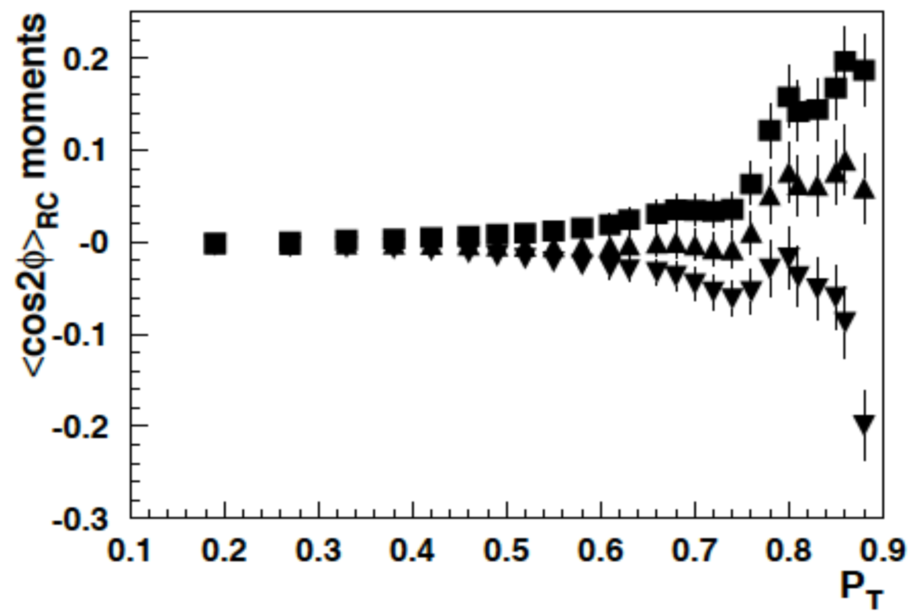
The real polar angle of virtual photon is changing due to radiation of the real photon, introducing azimuthal dependence, coupling to ϕ-dependence of the x-section Akushevich, Ilyichev, Osipenko, PL B672 (2009) 35

Radiative corrections in SIDIS

- Two basic contributions to RC in SIDIS needs to be separately calculated: the contribution from continuous spectrum (i.e., analog of inelastic radiative tail in DIS RC) and exclusive radiative tail (i.e., analog of elastic radiative tail in DIS or radiative tail from elastic peak).

P_T-dependence of the RC factor for the semi-inclusive π+ electroproduction for lepton beam energy 12 GeV:,





Radiative corrections may be very significant at small M_X and large P_T

Measuring cross sections and asymmetries

Due to radiative corrections, coupling of shifted γ^* angle with ϕ-dependent x-section

$$\sigma_{Rad}^{ehX}(x,y,z,P_{hT},\phi,\phi_S) \to$$
$$\sigma_0^{ehX}(x,y,z,P_{hT},\phi_h,\phi_S) \times R(x,y,z,P_{hT},\phi_h) + R_A(x,y,z,P_{hT},\phi_h,\phi_S)$$

Even neglecting the virtual photon angle with polarization vector, radiative effects can contribute to all moments, in particular transverse asymmetries

$$Y_{\phi,\phi_S} \sim \quad +S_T\Big[\sin(\phi_h-\phi_S)\big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\big)$$
$$+\varepsilon \sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

Simple approximation used to extract Collins and Sivers effects A_C(A_S) will be affected (Y →normalized yield)

$$A(\phi_h,\phi_S) = \frac{1}{P}\frac{Y_{\phi_h,\phi_S} - Y_{\phi_h,\phi_S+\pi}}{Y_{\phi_h,\phi_S} + Y_{\phi_h,\phi_S+\pi}} \approx A_C \sin(\phi_h+\phi_S) + A_S \sin(\phi_h-\phi_S), \quad ($$

Extracting the moments with rad corrections

Moments mix in experimental azimuthal distributions

Simplest rad. correction $$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$$

Correction to normalization

$$\sigma_0(1+\alpha\cos\phi_h)R_0(1+r\cos\phi_h) \to \sigma_0 R_0(1+\alpha r/2)$$

Correction to SSA

$$\sigma_0(1+sS_T\sin\phi_S)R_0(1+r\cos\phi_h) \to \sigma_0 R_0(1+sr/2S_T\sin(\phi_h-\phi_S)+sr/2S_T\sin(\phi_h+\phi_S))$$

Correction to DSA

$$\sigma_0(1+g\lambda\Lambda+f\lambda\Lambda\cos\phi_h)R_0(1+r\cos\phi_h) \to \sigma_0 R_0(1+(g+fr/2)\lambda\Lambda)$$

Generate fake DSA moments (cos)

$$\sigma_0(1+g\lambda\Lambda)R_0(1+r\cos\phi_h) \to \sigma_0 R_0 gr\cos\phi_h$$

Simultaneous extraction of all moments is important also because of correlations!

Requirements for consistent RC corrections in SIDIS

- Preliminary studies show that RC can strongly depend on models for SFs
  - RC are particularly sensitive to P_T model choice.
  - Rad corrections to polarized structure functions are important

$$\Delta A = \frac{\sigma_0^p + \sigma_{RC}^p}{\sigma_0^u + \sigma_{RC}^u} - \frac{\sigma_0^p}{\sigma_0^u} = \frac{\sigma_{RC}^p \sigma_0^u - \sigma_{RC}^u \sigma_0^p}{\sigma_0^u(\sigma_0^u + \sigma_{RC}^u)}$$

- We need the full set of SFs as continuous functions of all four variables in all kinematical regions for RC calculation in and beyond the region of an experiment on SIDIS measurements
  - The RC procedure of experimental data should involve an iteration procedure in which the fits of SFs of interest are re-estimated at each step of this iteration procedure.
  - Use experimental data or theoretical models to construct the models in the regions of softer processes, resonance region, and exclusive scattering
- Need all constructed models provide correct asymptotic behavior when we go to the kinematical bounds (Regge limit, QCD limit)

Comparison with other RC approaches

	Our Approach	Mo & Tsai	Radgen-Hermes	Polrad2.0/Sirad	Haprad 2.0
Applicability to SIDIS	Yes	No (only unpolarized DIS)	Questionable	Yes, no exclusive radiative tail	Yes, only unpolarized SIDIS
Method of calculation	Exact	Containes hidden approximations	Simulation	Exact RC, naïve QPM for SIDIS	Exact
Applicability to polarization asymmetries	Yes	No	Yes	Yes	No
Applicability to azimuthal asymmetries	Yes	No	No	No	Yes
SIDIS SF implementation	Yes, using iteration procedure of extraction of SF	No	As in Pepsi/Pythia	In QPM	Unpolarized only

Proposed framework will the first consistent approach to address the RC for Spin-Azimuthal asymmetries in polarized SIDIS

Relevance of RC for future SIDIS studies

- The potential impact on the lab

➔RC framework crucial for precision studies of TMDs

- The likelihood you will achieve your goals

90%

•The prospects for attracting future funding (post LDRD)

➔High

- The strategic value of your project to the lab

➔High (important for the JLab12 and EIC physics programs)

- The level of innovation in science and/or technology you propose

➔High (never done before)

SIDIS RC: our expectations

- For the unpolarized cross section RC strongly depends on all 5 kinematic variables:
  - x and Q^2-dependences are similar to what we have in DIS
  - RC goes down with increasing z, e.g., RC factor can change from 1.05 to 0.85 between z=0.2 and 0.8 for the same x and Q^2. The z-dependence of RC is generated by decreasing the phase space of radiated photon with increasing z.
  - p_t-dependence is strong: RC can increase by a factor of 2 or more for very high p_t. Both semi-inclusive and exclusive RC have large RC for large p_t.
  - RC to ϕ-dependence can be large. RC generate new ϕ-dependence and therefore new observables like $< cos(3\phi) >$ that are exactly zero at born level.
  - RC from exclusive radiative tail has its own dependence and can give high contribution especially as small M_x^2 (e.g., 0.95 and 1.4 without and with exclusive radiative tail for M_x^2=1.5 GeV^2 or 1.05 and 1.3 for M_x^2=3.0 GeV^2) and for high p_t.
- Radiative correction in polarized case are largely unknown. From our experience in DIS, we expect similar patterns of RCs and larger size of polarized RC. The effect strongly depends on the structure functions. The strong model dependence can be partly addressed withing the RC iteration procedure of experimental data.

RC procedure of experimental data in SIDIS

The possible (successful) strategy of RC could be developed using our experience in the modeling for DIS. The RC procedure of experimental data should involve an iteration procedure in which the fits of SFs of interest are re-estimated at each step of this iteration procedure.

- *The fit of SFs are constructed to have the model in the region covered by the experiment*
- *Use experimental data or theoretical models to construct the models in the regions of softer processes, resonance region, and exclusive scattering*
- *Check that the constructed models provide correct asymptotic behavior when we go to the kinematical bounds (Regge limit, QCD limit)*
- *Joint all the models to have continuous function of all four variables in all kinematical regions necessary for RC calculation*
- *Implement this scheme in a computer code and define the iteration procedure*
- *If several SFs are measured in an experiment, implement the procedure of their separation in data and model each of them.*
- *If other SFs are necessary (e.g., unpolarized SFs when spin asymmetries are measured), construct the models for them as well.*
- *Pay specific attention to exclusive SFs, because the radiative tail from exclusive peak is important (or even dominate) in certain kinematical regions.*
- *Pay specific attention to* p_T *dependence because RC is too sensitive for* p_T *model choice.*

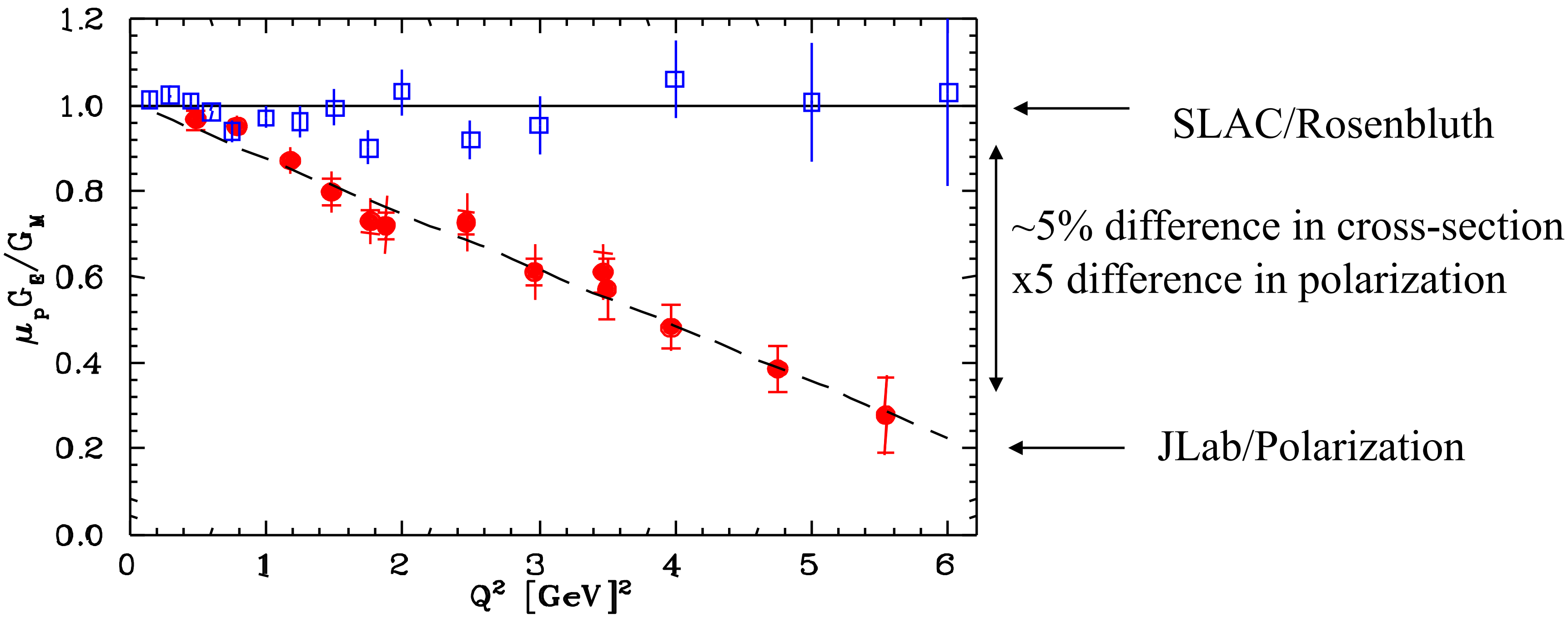
Two-Photon Exchange

Two-photon exchange effects in elastic ep-scattering

Two-photon exchange effects in inclusive DIS

Two-photon exchange effects in exclusive and semi-inclusive electroproduction of pions

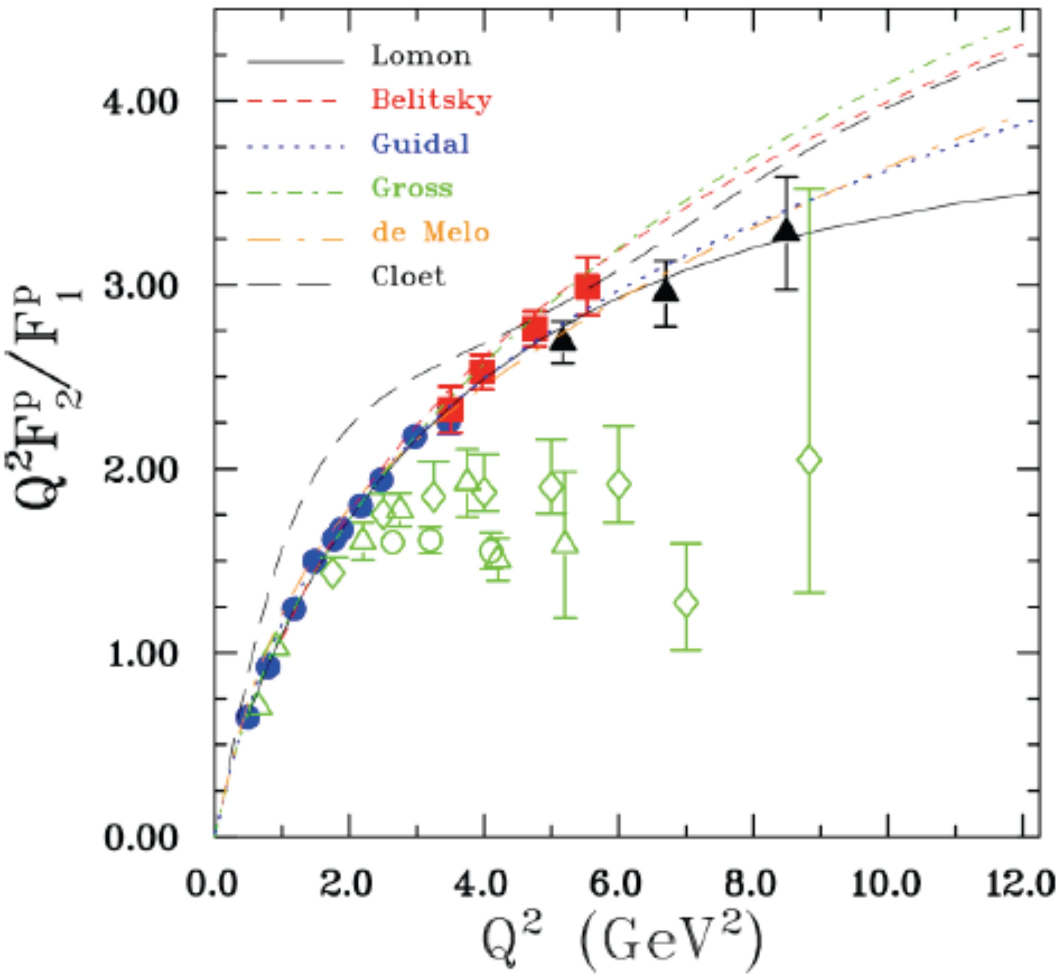
Do the techniques agree?



- **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)**

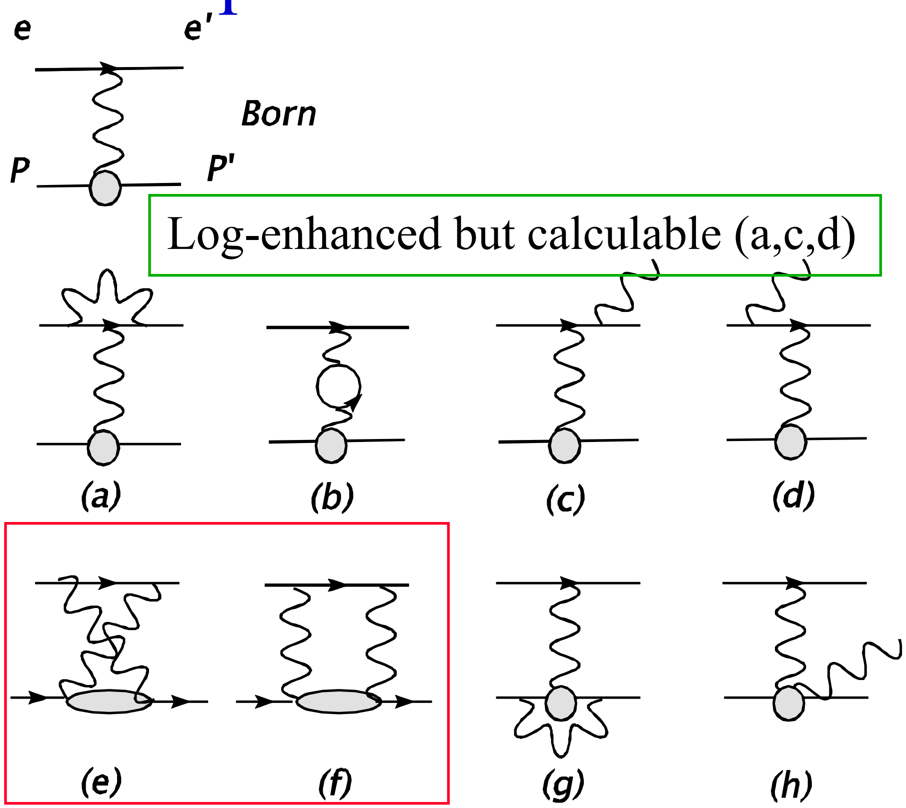
Radiative corrections, in particular, a short-range part of 2-photon exchange is a likely origin of the discrepancy

Proton Form Factors: Experiment vs Theory



- **Theory curves:**
- Lomon 2002, 2006 (VMD)
- Belitsky 2003 (pQCD scaling)
- Guidal 2005 (GPD)
- Gross, Ramalho, Pena 2008 (covariant spectator model)
- de Melo 2009 (Bethe-Salpeter Amplitude)
- Cloet 2009 (Dyson-Schwinger/Faddeev/quark-diquark)

Complete radiative correction in O(α_{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

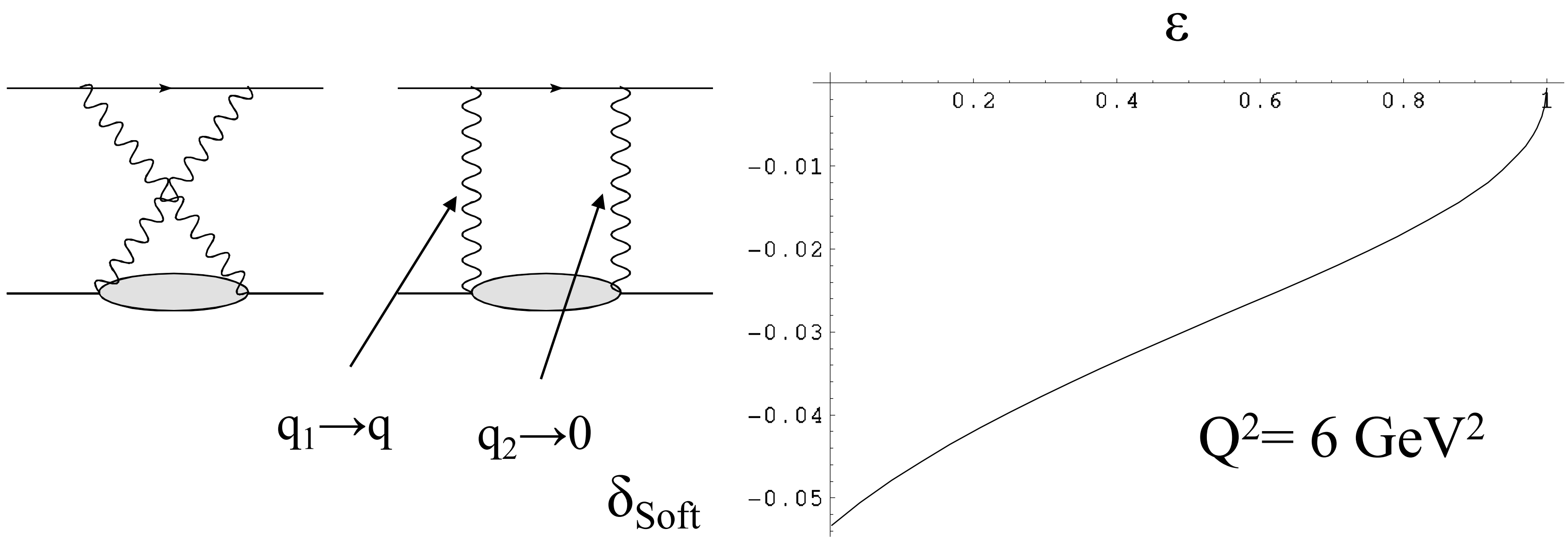
Model calculations:

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

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

Separating *soft* 2-photon exchange

- Tsai; Maximon & Tjon ($k \to 0$); similar to Coulomb corrections at low Q^2
- Grammer &Yennie prescription PRD 8, 4332 (1973) (also applied in QCD calculations)
- Shown is the resulting (soft) QED correction to cross section
- **Already included in experimental data analysis**
- NB: Corresponding effect to polarization transfer and/or asymmetry is zero



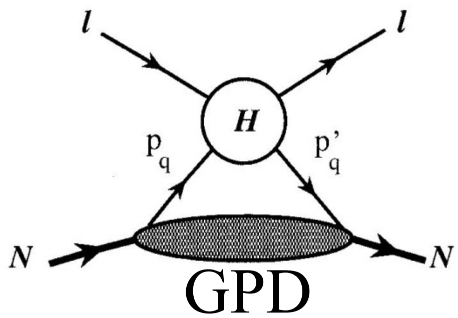
What is missing in the calculation?

- 2-photon exchange contributions for non-soft intermediate photons
  - Can estimate based on a text-book example from *Berestetsky, Lifshitz, Pitaevsky: Quantum Electrodynamics*
  - Double-log asymptotics of electron-quark backward scattering

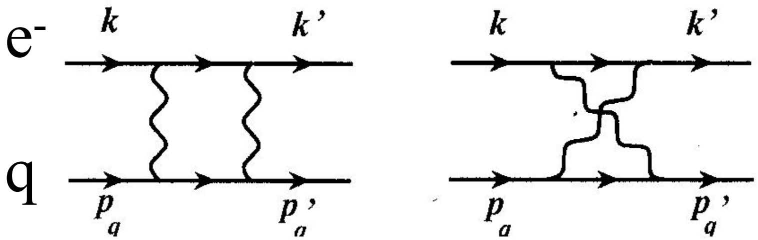
$$\delta = -\frac{e_q e}{8\pi^3} \log^2 \frac{s}{m_q^2}$$

  - Negative sign for backward ep-scattering; zero for forward scattering → Can (at least partially) mimic the electric form factor contribution to the Rosenbluth cross section
  - Numerically ~3-4% (for SLAC kinematics and m_q~300 MeV)
  - **Motivates a more detailed calculation of 2-photon exchange at quark level**

"GPD-based approach"



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

Note also: "QCD factorization" approach (Kivel, Vanderhaeghen, PRL 103:092004,2009) uses pQCD for VCS amplitude calculation

Short-range effects; on-mass-shell quark (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

Two-photon probe directly interacts with a (massless) quark
Emission/reabsorption of the quark is described by GPDs

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

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

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

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

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

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

Note the additional effective (axial-vector)^2 interaction; absence of mass terms;
The amplitude has a non-zero imaginary part for scattering on a free quark

`Hard' contributions to generalized form factors

GPD integrals

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

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

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

Two-photon-exchange form factors from GPDs

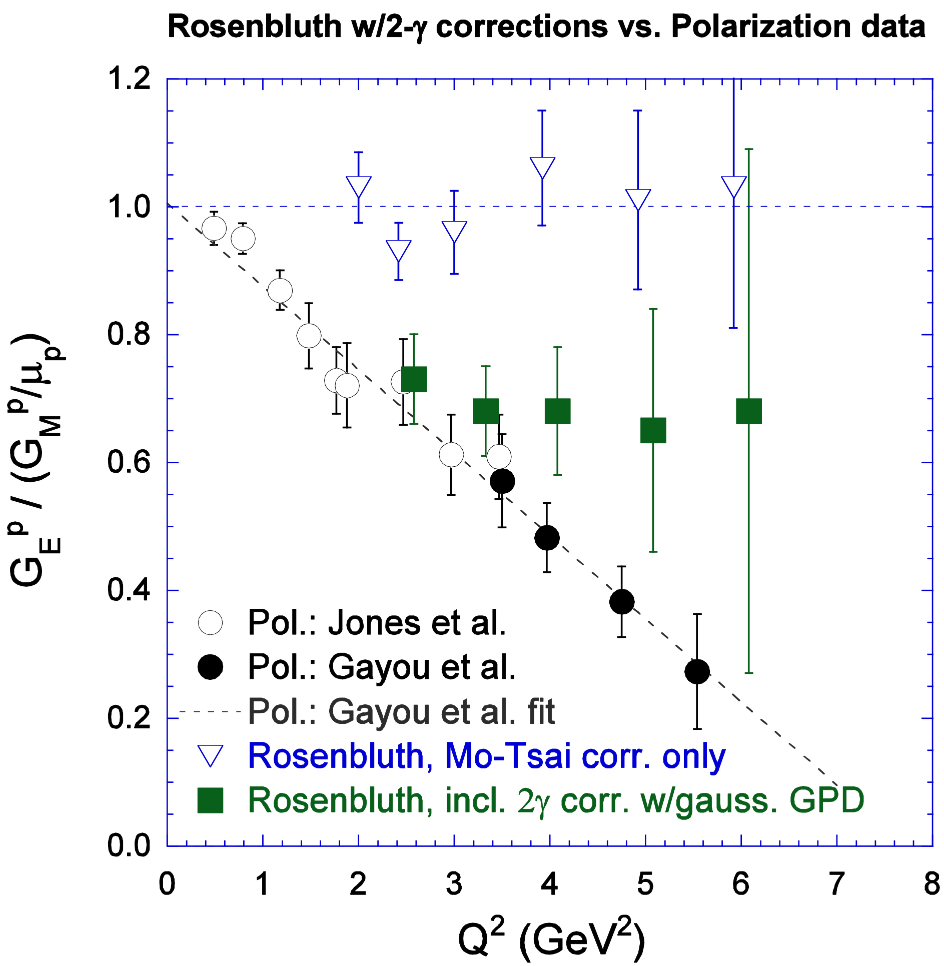
$$\delta\tilde{G}_M^{hard} = C$$

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

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

Updated Ge/Gm plot

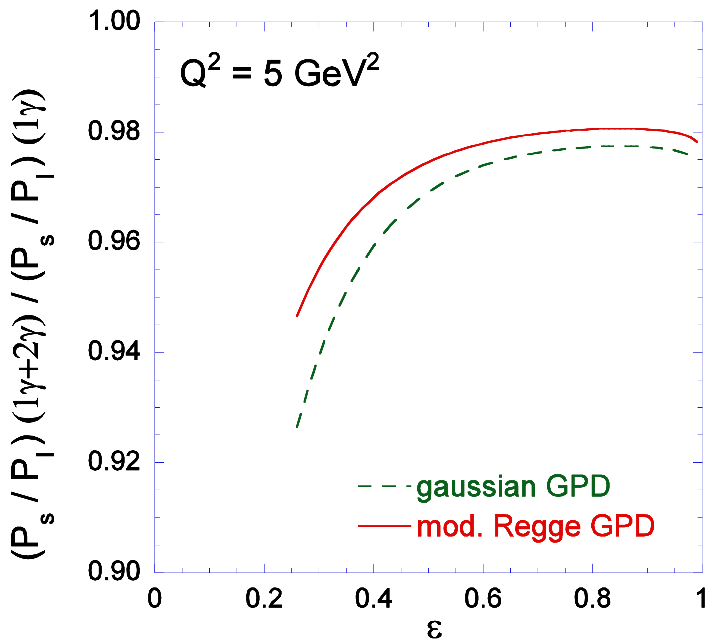
AA, Brodsky, Carlson, Chen, Vanderhaeghen,
Phys.Rev.Lett.93:122301, 2004; Phys.Rev.D72:013008, 2005



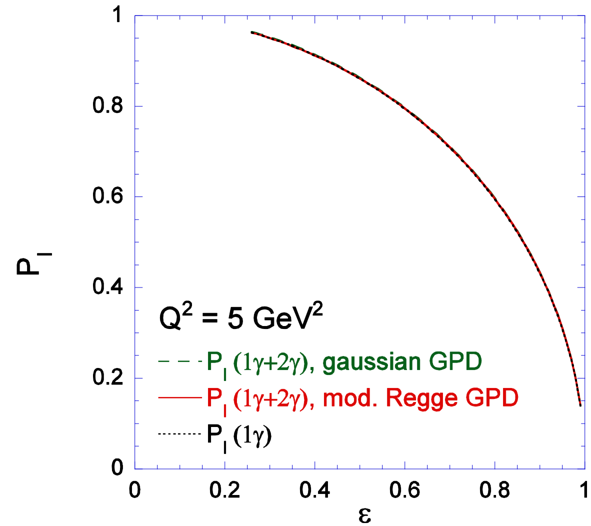
Polarization transfer

- Also corrected by two-photon exchange, but with little impact on G_{ep}/G_{mp} extracted ratio

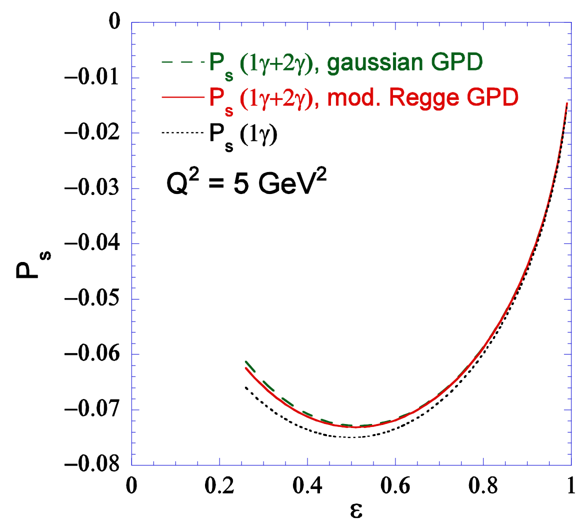
2-γ corrections to polarization ratio - proton



Longitudinal polarization - proton



Sideways polarization - proton



Quark-level calculations for elastic ep

- 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

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

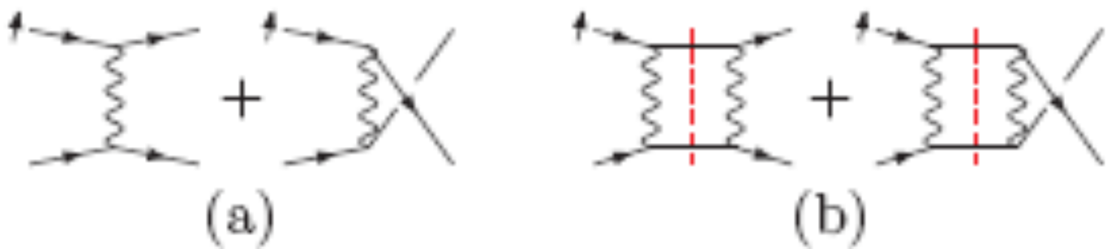
- For elastic scattering asymmetries are due to *absorptive part* of 2-photon exchange amplitude

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

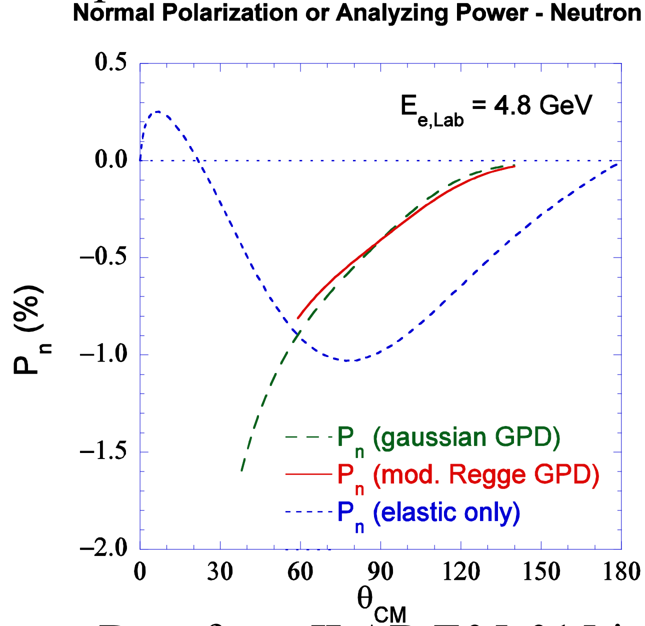
Quark+Nucleon Contributions to Target Asymmetry

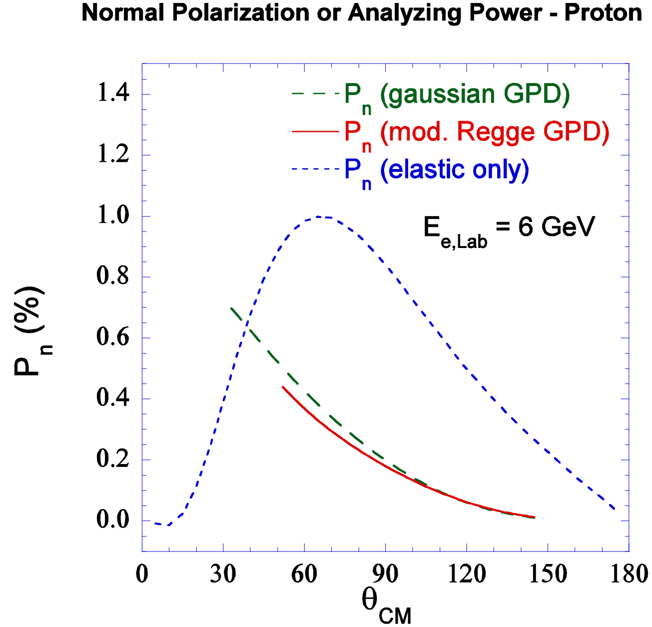
- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetryof elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

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

Only minor role of quark mass

No dependence on GPD $\widetilde{H}$

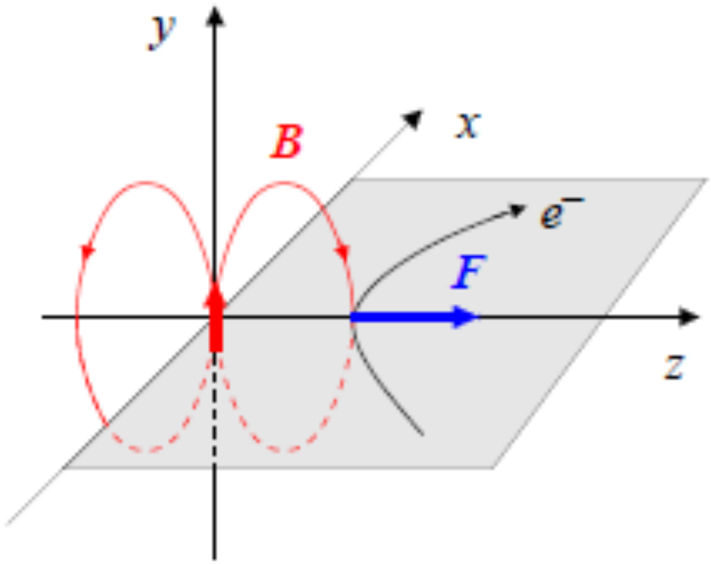




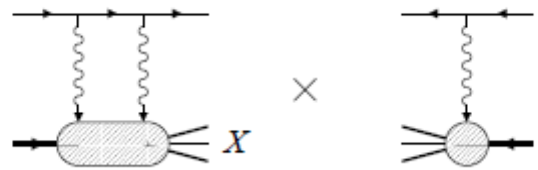
Data from JLAB E05-015 is in agreement with partonic picture.
(Inclusive scattering on normally polarized ^{3}He in Hall A)

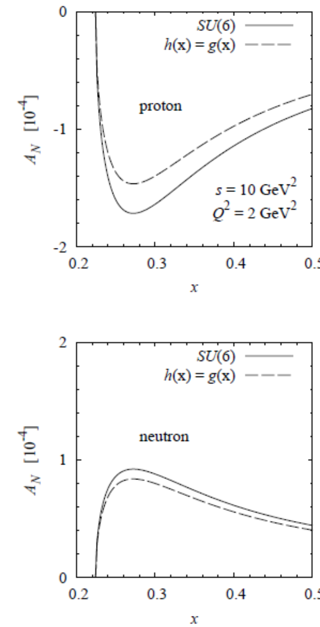
Parity-Conserving Single-Spin Asymmetry

- Classical analogue: a Lorentz force **F** acting on charge moving in the magnetic field **B** of a dipole



Two-Photon Exchange in inclusive DIS





- <u>Theory</u>: Afanasev, Strikman, Weiss, **Phys.Rev.D77:014028,2008**
  - Asymmetry due to 2γ-exchange ~1/137 suppression
  - Addional 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}
- Prediction consistent with HERMES measurements who set upper limits ~(0.6-0.9)x10^{-3} : **Phys.Lett.B682:351-354,2010**
- **In contradiction to JLAB observation of per-cent asymmetry**
  J. Katich et al. Phys. Rev. Lett. **113,** 022502 (2014).

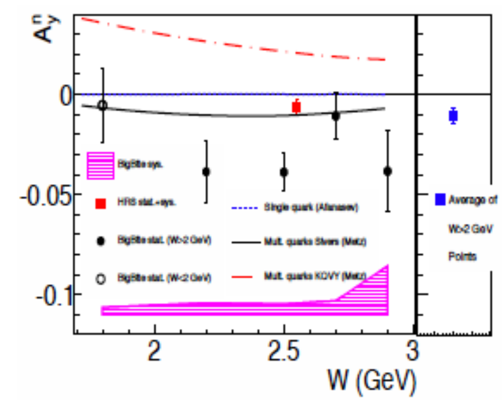


FIG. 3. Neutron asymmetry results (color online). **Left panel:** Solid black data points are DIS data ($W > 2$ GeV) from the BigBite spectrometer; open circle has $W = 1.72$ GeV. BigBite data points show statistical uncertainties with systematic uncertainties indicated by the lower solid band. The square 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.

Work by Andreas Metz and collaborators

- Important: Inclusive asymmetries from TPE, coupling to the same quark vs different quarks A. Metz, D. Pitonyak, A. Schafer, M. Schlegel, W. Vogelsang, J. Zhou, Phys.Rev. D**86** (2012) 114020
- SIDIS: Metz et al, Few Body Syst. **56** (2015) 331-336
- Emphasized sin(2φ) effect for SIDIS arising from two-photon exchange

Target asymmetry:

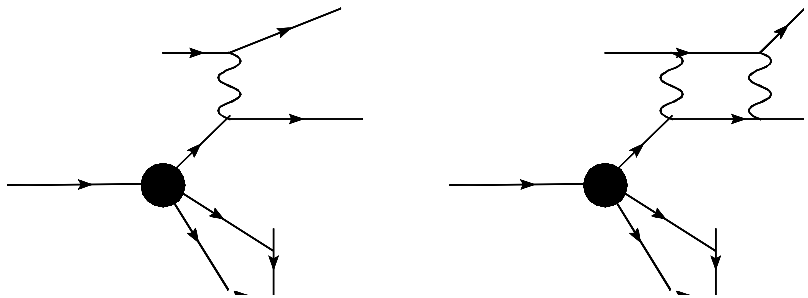
$$A_{LU}^{\sin(2\phi)} = \alpha \frac{y\left(1+\frac{2-y}{1-y}\ln y\right)}{1-y+\frac{1}{2}y^2}\sin(2\phi)\frac{\sum_q e_q^3 \mathscr{C}\left[\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{2Mm_\pi} h_1^{\perp q} H_1^{\perp q}\right]}{\sum_q e_q^2 \mathscr{C}\left[f_1^q D_1^q\right]}$$

$$A_{UT}(x_B, y, \phi_s) = \alpha \frac{x_B M}{2Q}\frac{y(1-y)\sqrt{1-y}}{1-y+\frac{1}{2}y^2}|\vec{S}_T|\sin(\phi_s)\left(\ln\frac{Q^2}{\lambda^2}+\text{finite}\right)\frac{\sum_q e_q^3 g_T^q(x_B)}{\sum_q e_q^2 f_1^q(x_B)}$$

Beam SSA

- Beam SSA in inclusive ep-scattering
- Due to absorptive part of two-photon amplitude
- Measured at JLAB PVDIS (only upper limit in ~50ppm is set)
  - Asymmetry suppressed by a factor of electron mass/energy
  - Predicted at fraction of ppm for leading-order partonic model
  - Theory also in Metz, Schlegel, Goeke (2006)

Partonic-Level Effect

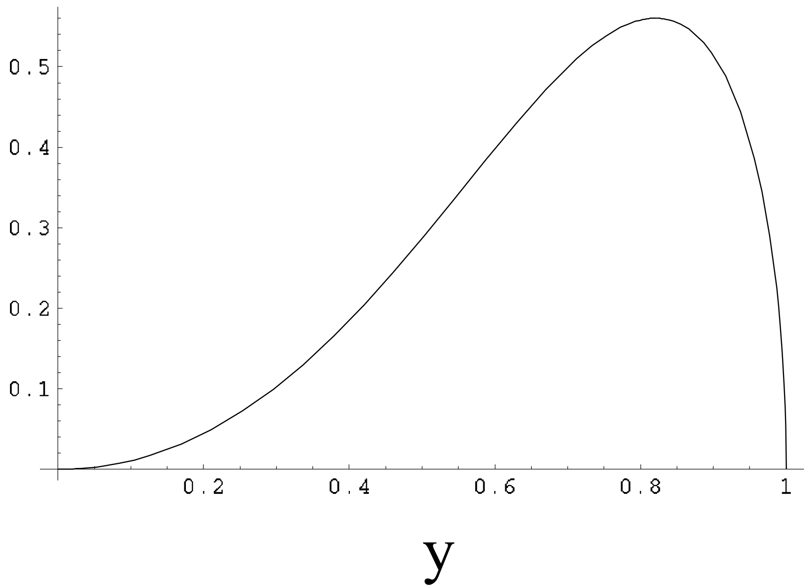


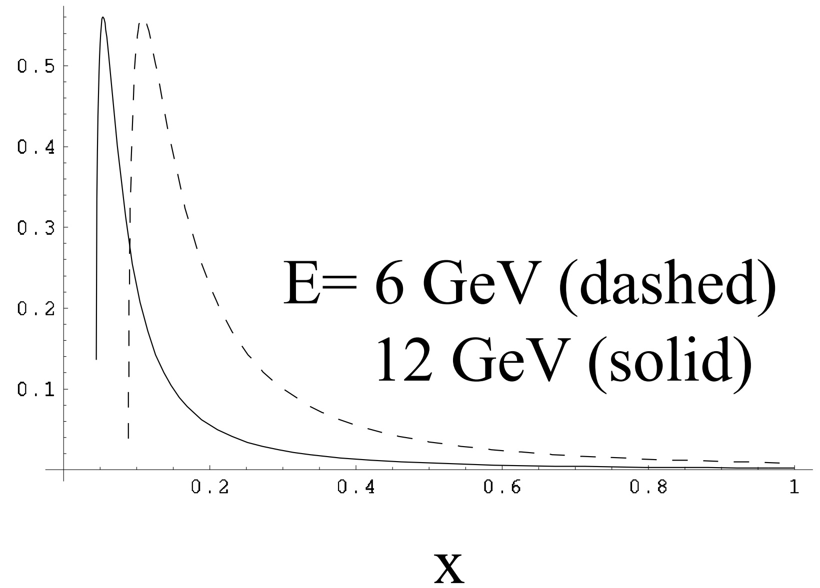
- Interference of 1-photon and 2-photon exchange is responsible for the beam single-spin normal asymmetry (SSNA)
- Adapting Barut & Fronsdal, Phys.Rev. **120** (1960) 1891, we get at the leading twist:

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

Magnitude of Beam SSA in Inclusive DIS
$Q^2 = 1\ GeV^2$

Beam Asymmetry, ppm





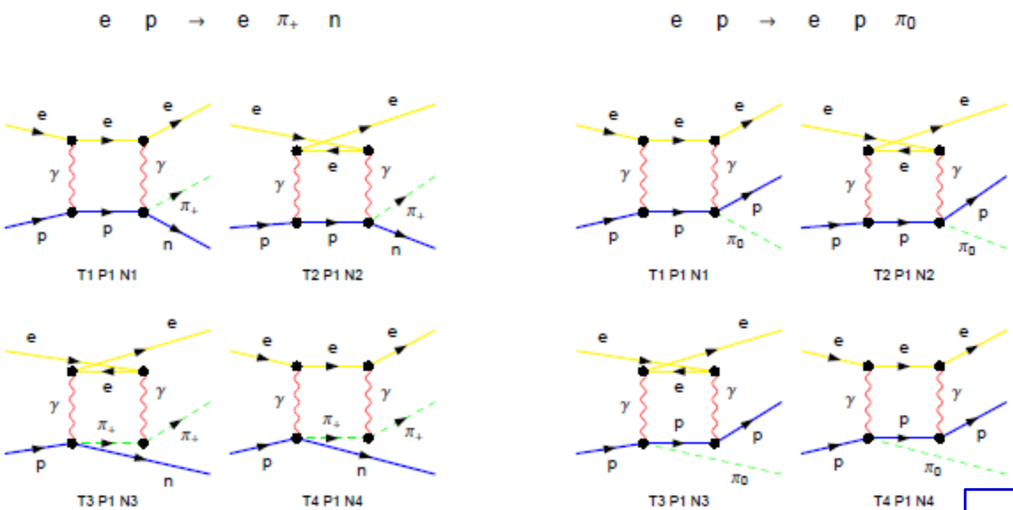
The leading-twist calculation predicts the effect around ½ ppm

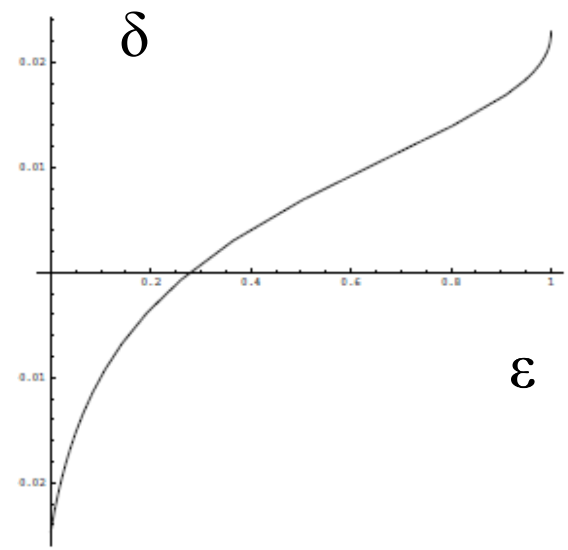
QED+non-perturbative QCD: 10-100ppm

May be observed in next-generation PVDIS experiments

Two-Photon Exchange in Exclusive Electroproduction of Pions

- Standard contributions considered, e.g., AA, Akushevich, Burkert, Joo, **Phys.Rev.D66:074004,2002** (Code EXCLURAD used for data analysis)
- *Additional contributions due to two-photon exchange*, calculated by AA, Aleksejevs, Barkanova, **Phys.Rev. D88: 053008, 2013** Calculated in soft-photon approximation





Calculated ε-dependence of TPE correction. Q^2=6 GeV^2, W=3.2 GeV, E_e=5.5 GeV . Shows ±2% variation with ε.

Results for Exclusive Pion Production Phys.Rev. D88 (2013) 053008

- Soft photon exchange
- Dependence on IR photon separation
- Obtained model-independent corrections, applicable to SIDIS
- Soft-photon contributions expressed in terms of Passarino-Veltman integrals
- Can be added to HAPRAD and studied for specific experimental conditions (AA, Barkanova, Aleksejevs; Akushevich, Ilychev, Avakian)
- Equally applicable to muon scattering (important for DVMP at COMPASS)

Angular dependence of "soft" corrections
Phys.Rev. D88 (2013) 053008

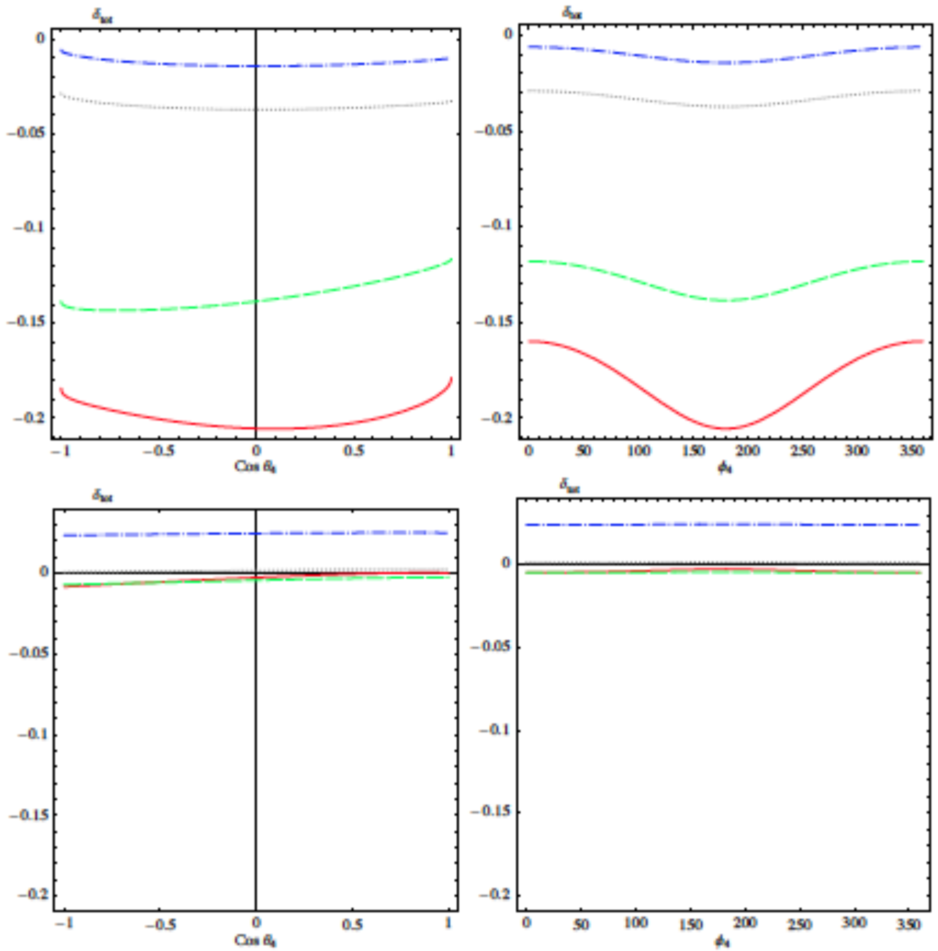


Figure 3: π^0 electroproduction two-photon box correction angular dependencies for the high $Q^2 = 6.36\,GeV^2$ (top row) and low $Q^2 = 0.4\,GeV^2$(bottom row) momentum transfers, $W = 1.232\,GeV$ and $E_{lab} = 5.75\,GeV$. Left column: dependence on $\cos\theta_4$ with $\phi_4 = 180°$. Right column: dependence on ϕ_4 with $\theta_4 = 90°$. Dot-dashed curve - SPT, dotted curve - SPT with $\alpha\pi$ subtracted, dashed curve - SPMT, solid curve - FM approach.

Summary on QED loops

- Two-photon exchange
  - "Soft" photon corrections essential for cross section measurements, do not change spin asymmetries, model-independent
  - "Hard" photon corrections, alter spin structure of the amplitude, generate single-spin asymmetries, alter double-spin asymmetries
  - Target SSA has no logarithmic enhancements (EM gauge invariance essential for collinear divergence cancellations)
  - Beam SSA (~10^{-5} effect at GeV energies) may be enhanced by hard collinear photon exchange
- SSA due to 2-photon exchange have distinctly different features from, eg. Collins and Sivers effects (would not integrate to zero wrt azimuthal angle) but need to be included in analysis
- *JLAB experiments onn SSA indicate QED loop effects of the same order as SSA from strong interactions*
- Experimentally can be, e.g, extracted from sin(2φ) helicity asymmetries due to both QED loops and bremsstrahlung