

Two-Photon Exchange Corrections for SIDIS

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SIDIS: partonic cross sections

$$\nu = (qP)/M$$

$$Q^2 = (k - k')^2$$

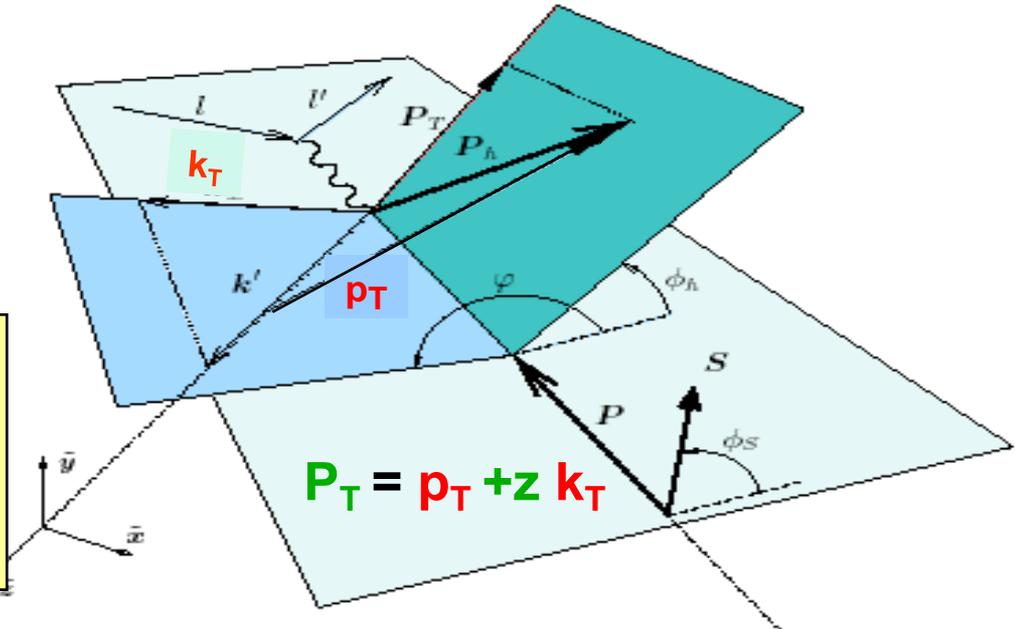
$$y = (qP)/(kP)$$

$$x = Q^2/2(qP)$$

$$z = (qP_h)/(qP)$$

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

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

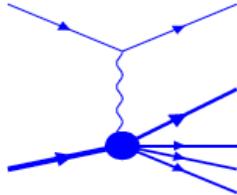
$$F_{XY}^h(P_T) \propto \sum e_q^2 H \times f^q(x, k_T, ..) \otimes D^{q \rightarrow h}(z, p_T, ..)$$

beam polarization

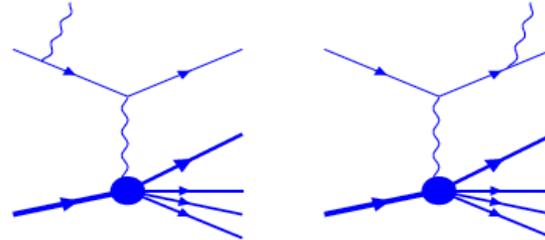
target polarization

Radiative corrections in SIDIS

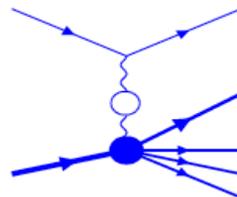
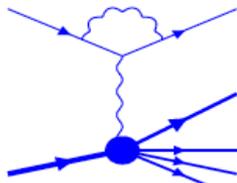
The Born cross section



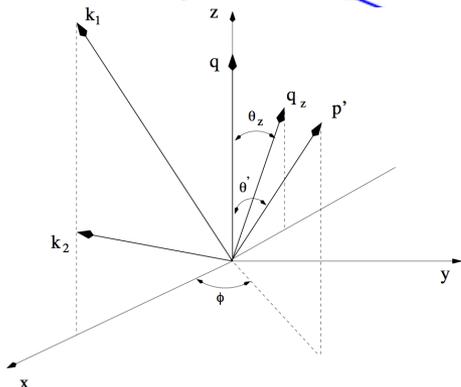
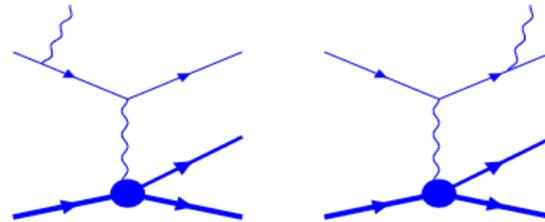
Emission of a radiated photon (semi-inclusive processes)



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

Next talk by Ilyichev

Measuring cross sections and asymmetries

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

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

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

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

Simple approximation used to extract Collins and Sivers effects $A_C(A_S)$ will be affected ($Y \rightarrow$ 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

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

Correction to SSA

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

Correction to DSA

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

Generate fake DSA moments (cos)

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

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)

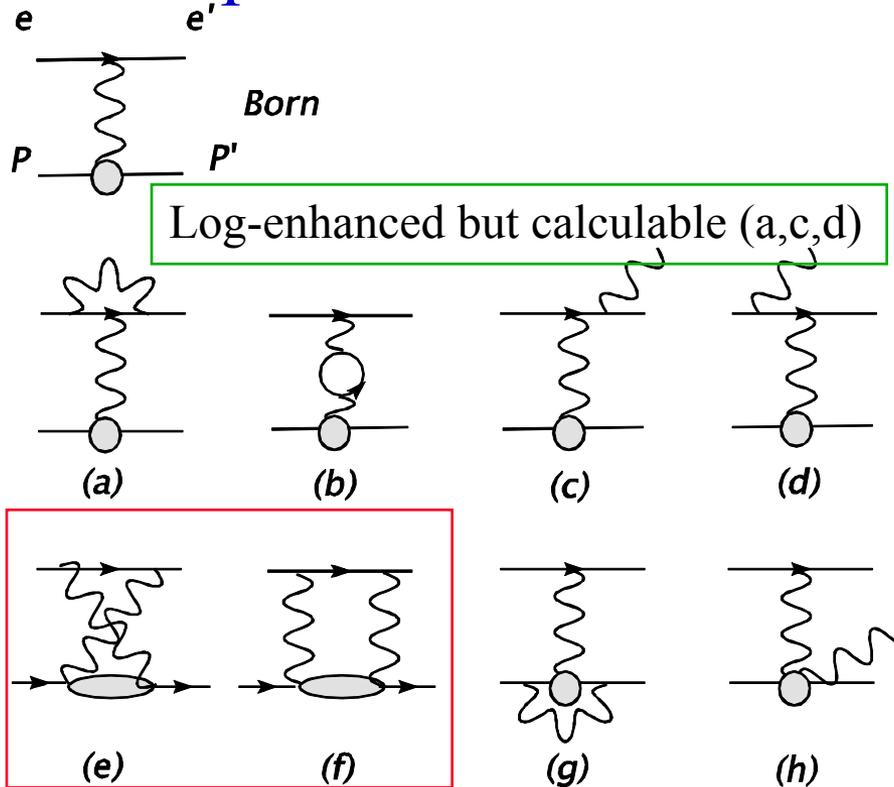
Two-Photon Exchange

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

Complete radiative correction in NLO



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

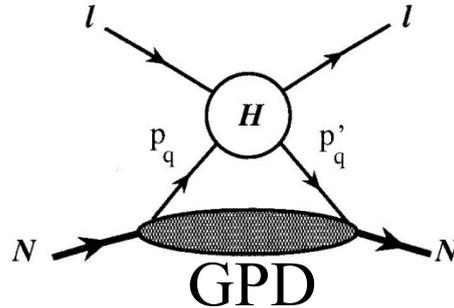
What was missing in the calculation?

- 2-photon exchange contributions for non-soft intermediate photons
 - Can estimate based on a text-book example from *Berestetsky, Lifshitz, Pitaevsky: Quantum Electrodynamics* (original results by Gorshkov&Lipatov'68)
 - Double-log asymptotics of electron-quark backward scattering

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

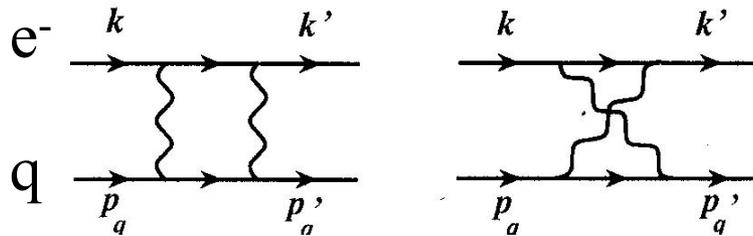
- Negative sign for backward ep-scattering; zero for forward scattering → Can (at least partially) mimic the electric form factor contribution to the Rosenbluth cross section
- Numerically ~3-4% (for SLAC kinematics and $m_q \sim 300$ MeV)
- **Motivates a more detailed calculation of 2-photon exchange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

$$A_{eq \rightarrow eq}^{2\gamma} = \frac{e_q^2}{t} \frac{\alpha_{em}}{2\pi} (V_\mu^e \otimes V_\mu^q \times f_V + A_\mu^e \otimes A_\mu^q \times f_A),$$

$$V_\mu^{e,q} = \bar{u}_{e,q} \gamma_\mu u_{e,q}, \quad A_\mu^{e,q} = \bar{u}_{e,q} \gamma_\mu \gamma_5 u_{e,q}$$

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

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

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

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

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;

c.f. Khriplovich'74, derived for TPE for charge asymmetry in e+e- annihilation

Quark-level calculations for elastic ep

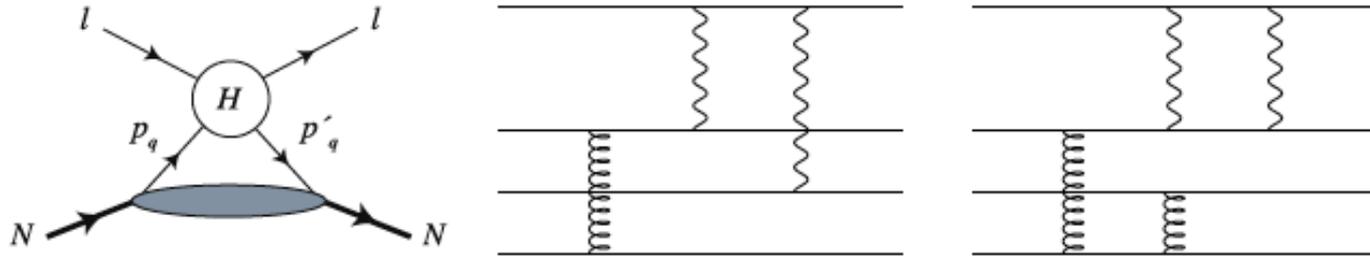


Fig. 2.11. *Left:* TPE diagram in the GPD-based approach to eN scattering at high Q^2 [47,48]. Both photons interact with the same quark, while the others are spectators. *Right:* Sample TPE diagrams in the QCD factorization approach. For the leading order term the photons interact with different quarks, 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
- See Afanasev, Blunden, Hassell, Raue, Prog. Part. Nucl. Phys. 95, 245 (2017).

Quark-Parton Calculations (cont)

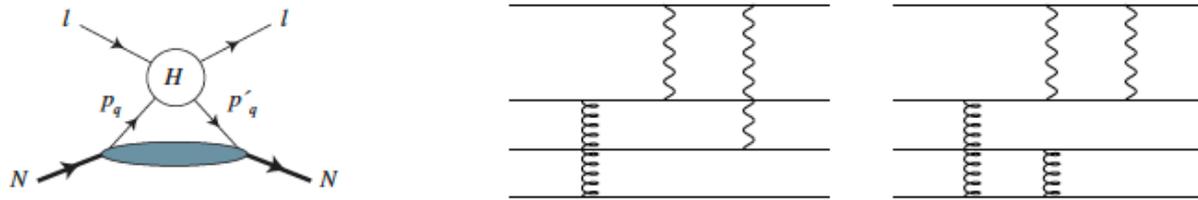


Figure 2.11: *Left*: TPE diagram in the GPD-based approach to eN scattering at high Q^2 [47, 48]. Both photons interact with the same quark, while the others are spectators. *Right*: Sample TPE diagrams in the QCD factorization approach. For the leading order term the photons interact with different 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. Figures taken from Ref. [49].

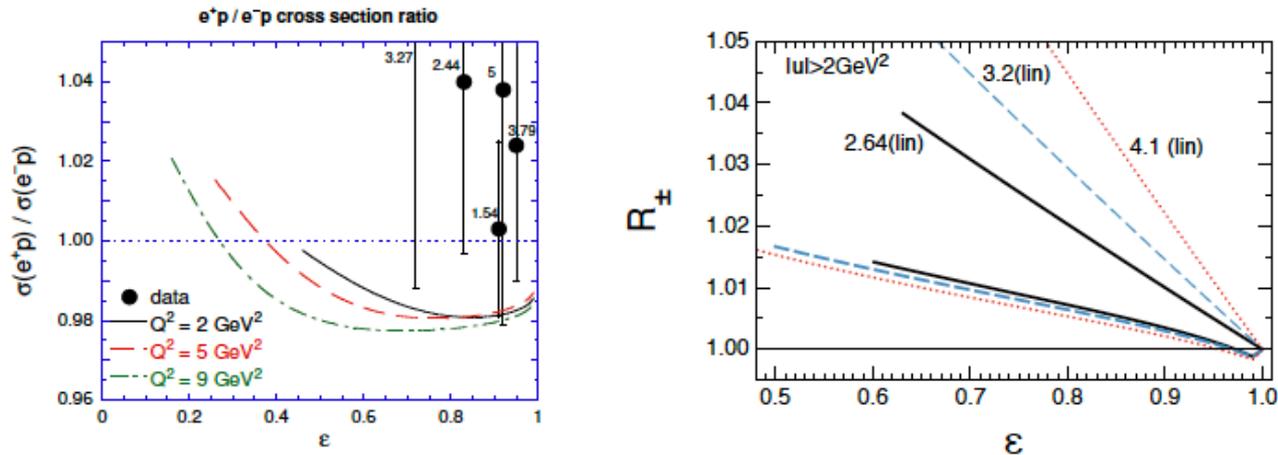
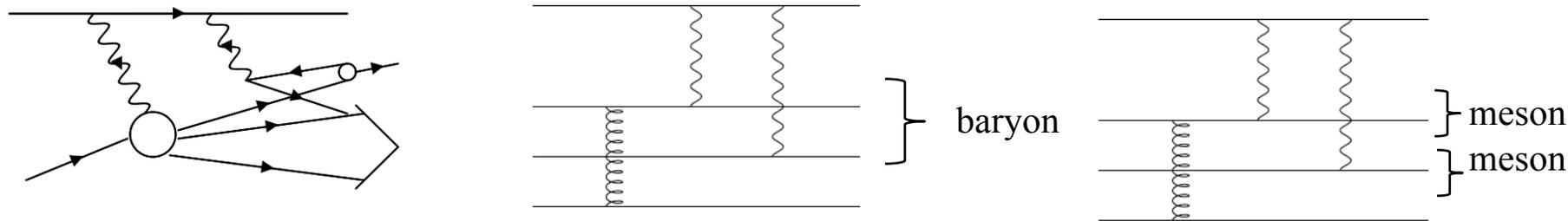


Figure 2.12: *Left*: Ratio of e^+p/e^-p elastic cross sections, taken from Ref. [48]. The GPD calculations for the TPE correction are for three fixed Q^2 values of 2, 5, and 9 GeV^2 , for the kinematical range where $-u$ is above M^2 . Also shown are early SLAC data [66], with Q^2 above 1.5 GeV^2 . The numbers near the data give Q^2 for that point in GeV^2 . *Right*: Ratio of e^+p/e^-p at high Q^2 calculated in the QCD factorization approach [65]. Also shown for comparison are the results (labelled *lin*) from the phenomenological fits of Ref. [67]. Figure taken from Ref. [65].

Two-Photon Fragmentation for SIDIS

- 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 - q bar 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

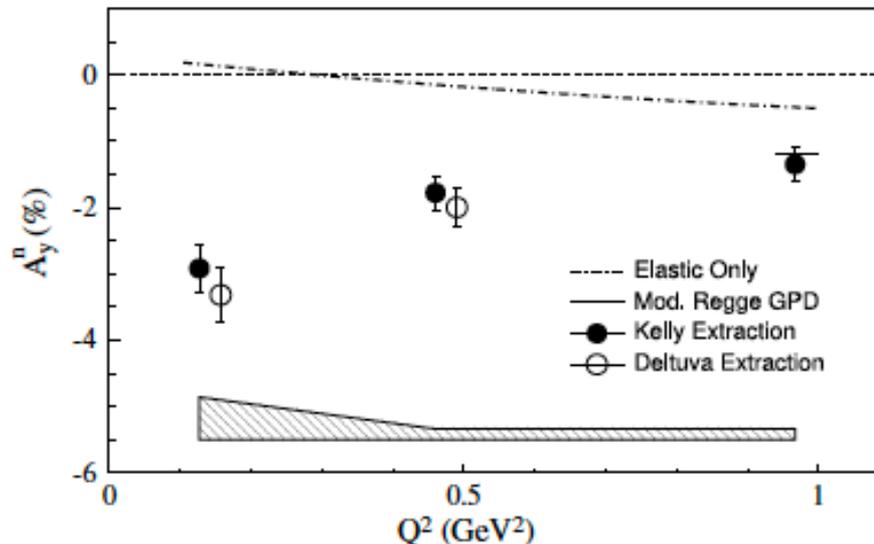
Elastic ep->ep

Quark+Nucleon Contributions to Target Asymmetry

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

$$A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}} \frac{1}{\sigma_R} \left[G_E \text{Im}(A) - \sqrt{\frac{1+\varepsilon}{2\varepsilon}} G_M \text{Im}(B) \right] \quad \text{Only minor role of quark mass}$$

No dependence on GPD \tilde{H}



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

Two-Photon Exchange in inclusive DIS

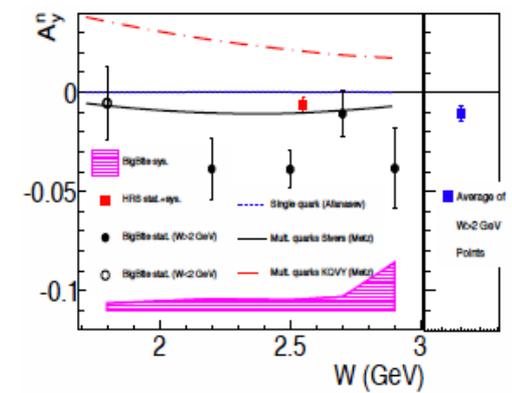
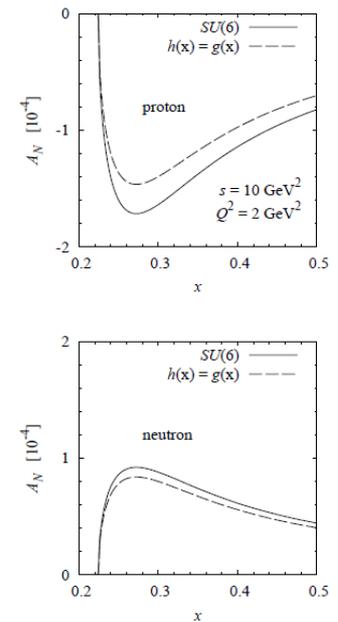
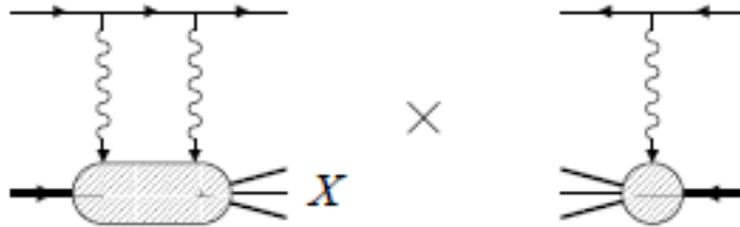


FIG. 3. Neutron asymmetry results (color online). **Left panel:** Solid black data points are DIS data ($W > 2$ GeV) from the BigBite spectrometer; open circle has $W = 1.72$ GeV. BigBite data points show statistical uncertainties with systematic uncertainties indicated by the lower solid band. The square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

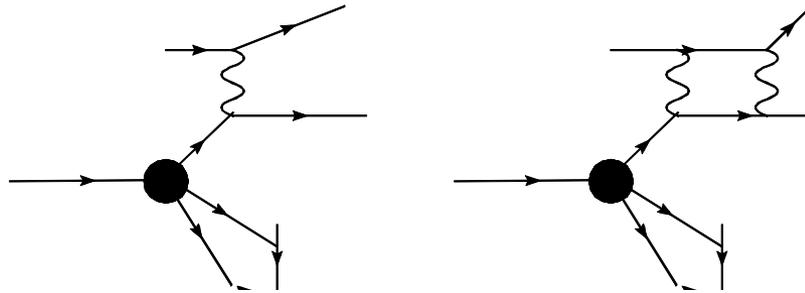
Theory: Afanasev, Strikman, Weiss, *Phys.Rev.D77:014028,2008*

- Asymmetry due to 2γ -exchange $\sim 1/137$ suppression
- Additional suppression due to transversity parton density \Rightarrow predict asymmetry at $\sim 10^{-4}$ level
- EM gauge invariance is crucial for cancellation of collinear divergence in theory predictions
- Hadronic non-perturbative $\sim 1\%$ vs partonic 10^{-4} : Major disagreement**

Prediction consistent with HERMES measurements who set upper limits $\sim (0.6-0.9) \times 10^{-3}$: *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).

Beam SSA: 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:

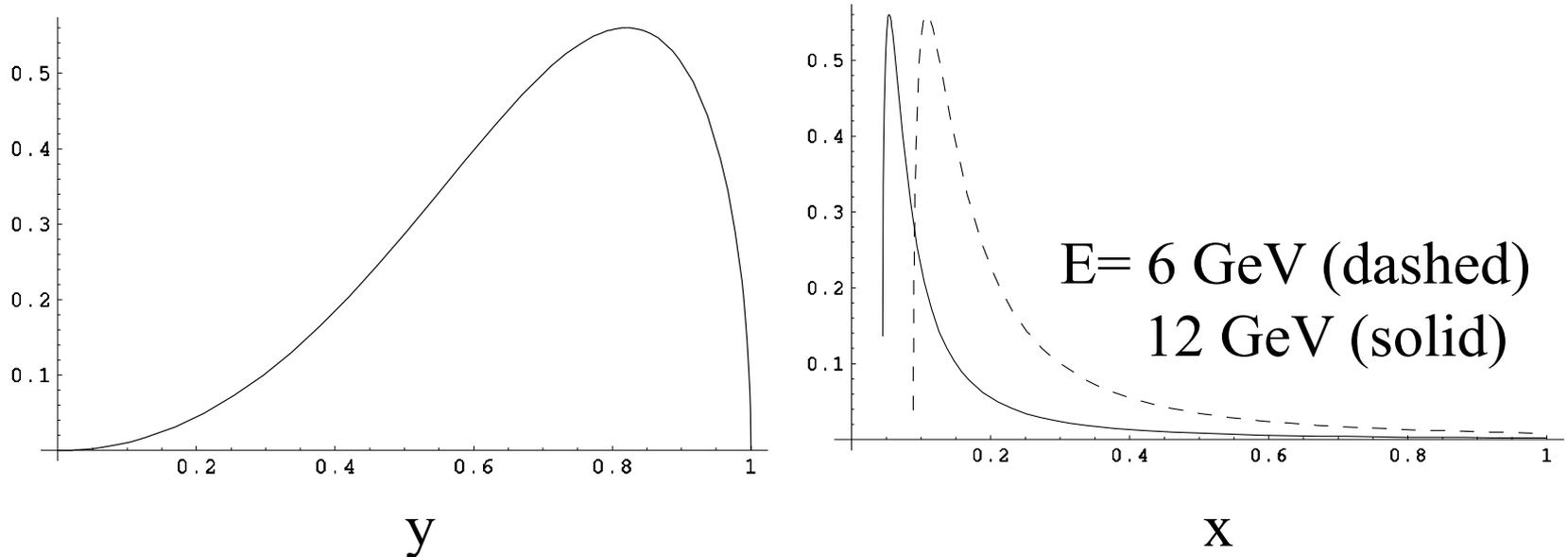
$$A_n^{Beam} = \frac{\alpha y^2 \sqrt{1-y^2}}{1+(1-y)^2} \frac{m_e}{Q} \sum_q (e_q)^3$$

- Measured at JLAB PVDIS (upper limit in ~ 50 ppm is set – limit of sensitivity)
- See also Marc Schlegel et al (+talk tomorrow)

Magnitude of Beam SSA in Inclusive DIS

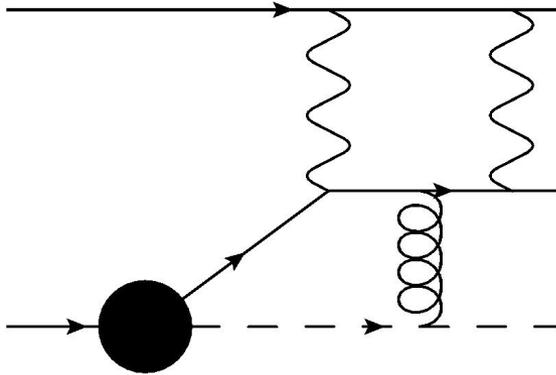
$$Q^2 = 1 \text{ GeV}^2$$

Beam Asymmetry, ppm

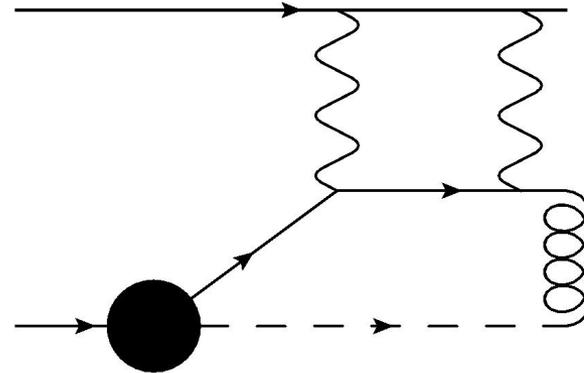


The leading-twist calculation predicts the effect around $\frac{1}{2}$ ppm
Regge-limit (optical theorem): 10-100ppm: AA PRB 599 (2004) 48
May be observed in next-generation PVDIS experiments

QED+diquark model



(a)



(b)

TPE may be treated in a model-dependent way via Brosky-Yuan-Schmidt's diquark model for SIDIS

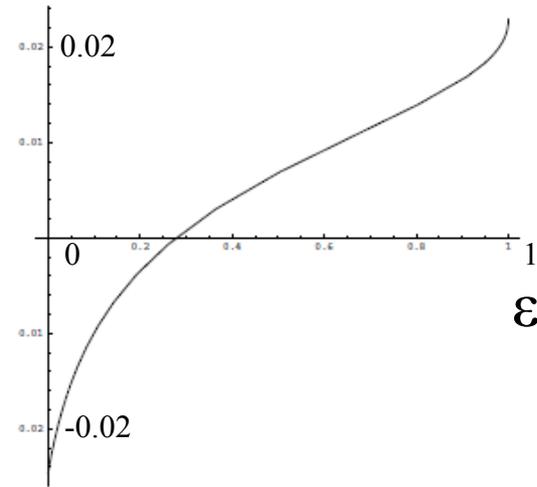
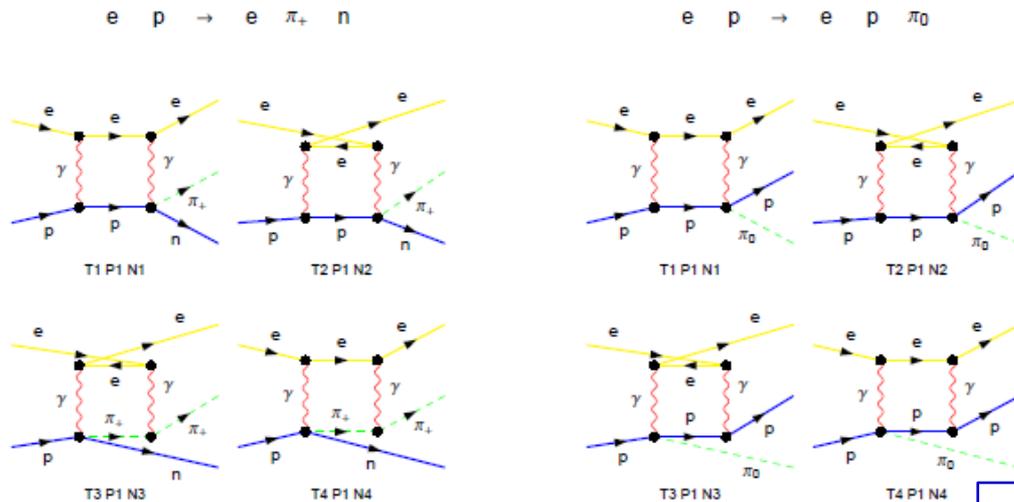
(a) can be treated in a soft-photon approximation

(b) can NOT

Exact two-loop calculation ongoing with Aleksejevs

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, PV functions



Calculated ϵ -dependence of TPE correction.
 $Q^2=6 \text{ GeV}^2$, $W=3.2 \text{ GeV}$, $E_e=5.5 \text{ GeV}$.
 Shows $\pm 2\%$ variation with ϵ .

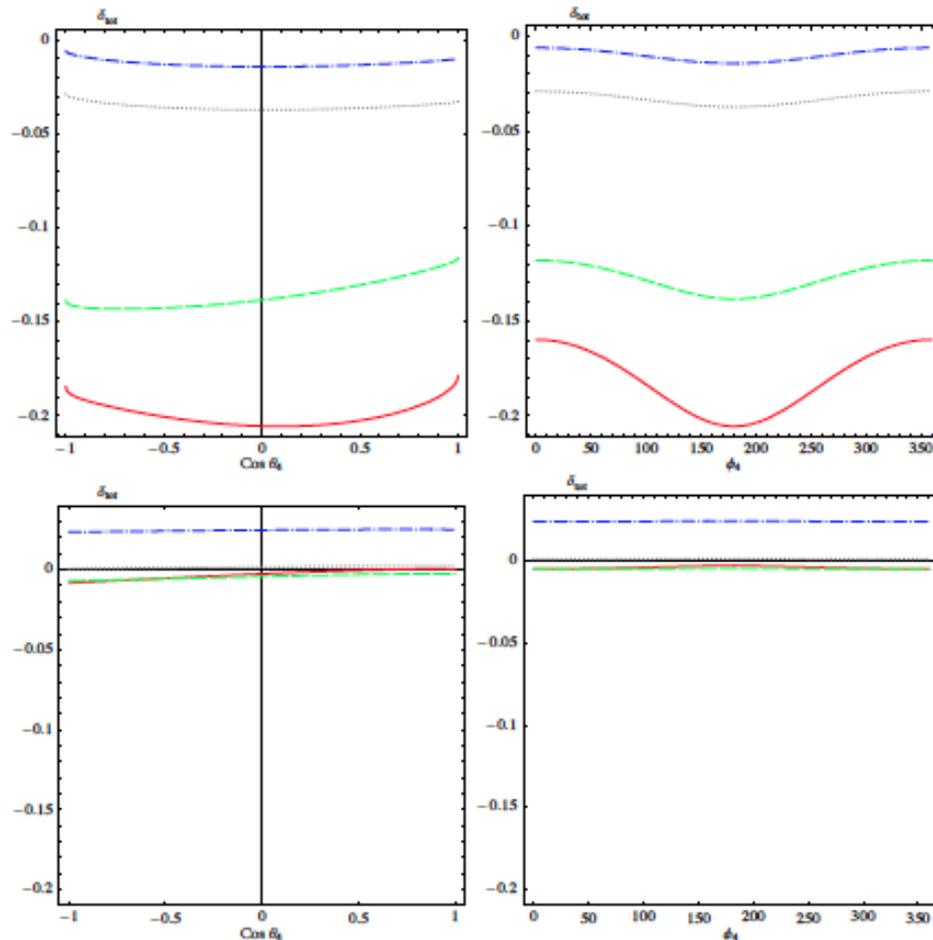
Results for Exclusive Pion Production

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



“Soft” two-photon corrections significantly affect angular dependences

Magnitude of the two-photon effects is similar to electron and muon scattering

Figure 3: π^0 electroproduction two-photon box correction angular dependencies for the high $Q^2 = 6.36 \text{ GeV}^2$ (top row) and low $Q^2 = 0.4 \text{ GeV}^2$ (bottom row) momentum transfers, $W = 1.232 \text{ GeV}$ and $E_{\text{lab}} = 5.75 \text{ GeV}$. Left column: dependence on $\cos \theta_4$ with $\phi_4 = 180^\circ$. Right column: dependence on ϕ_4 with $\theta_4 = 90^\circ$. Dot-dashed curve - SPT, dotted curve - SPT with α_T 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
 - SSA may come with large logs (beam) or not (target)
 - 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 on SSA indicate QED loop effects of the same order as SSA from strong interactions
- Experimentally can be, e.g, extracted from $\sin(2\phi)$ helicity asymmetries due to both QED loops and bremsstrahlung
- Or by comparing SIDIS with electron and positron beams: positron beams at JLAB would be highly useful: AA et al, Physics with Positron Beams at Jefferson Lab 12 GeV, arXiv:1906.09419

Strategy for SIDIS

- Model development of QED loop effects at partonic level
 - Soft/hard scale separation
- Integration with self-consistent covariant approaches to soft+hard radiation
- Inclusion into Monte-Carlo and/or semi-analytic approaches for SIDIS analysis
 - Next talk by Ilyichev: QED corrections due to hard radiated photons

QED for photons with high Orbital Angular Momentum: test ground for nucleon spin problem and SIDIS

- "Twisted" photons can pass to a composite system total angular momentum projected on beam direction $\Delta J_z > 1$
- Predicted in Afanasev, Carlson, Mukherjee, *Off-axis excitation of hydrogenlike atoms by twisted photons*, Phys. Rev. A **88**, 033841 (2013); Afanasev, Carlson, Mukherjee, *High-multipole excitations of hydrogen-like atoms by twisted photons near a phase singularity*, J. Opt. 18 (2016) 074013
- Verified experimentally in C.T. Schmiegelow et al., "*Transfer of optical orbital angular momentum to a bound electron*", Nature Comm. 7, 12998 (2016); A. Afanasev et al., "*Experimental verification of position-dependent angular-momentum selection rules for absorption of twisted light by a bound electron*," New J. Phys. 20, 023032 (2018).
- "Twisted" photons can produce $\Delta J_z = 2$ transition in $\gamma N \rightarrow \Delta (m_N = -\frac{1}{2} \rightarrow s_{\Delta; z} = \frac{3}{2})$ forbidden for plane waves, effect depends on impact parameter
 - ***Important: OAM effects are most pronounced for small impact parameters***