Single Spin Asymmetries in Inclusive DIS and Multi-Parton Correlations in the Nucleon

(A. Metz, Temple University, Philadelphia)

1. Introduction

2. Two photons coupling to the same quark

3. Two photons coupling to different quarks
   in collaboration with: Pitonyak, Schäfer, Schlegel, Vogelsang, Zhou
   - Analytical results
   - Relation between $q\gamma q$-correlator and qgq-correlator (ETQS matrix element)
   - Numerical results and discussion

4. Summary

Preliminaries

- DIS: $\ell(k) + N(P) \to \ell'(k') + X$

- Single spin asymmetry (SSA) can exist due to correlation

$$\varepsilon_{\mu\nu\rho\sigma} S^\mu P^\nu k^\rho k'^\sigma \sim \vec{S} \cdot (\vec{k} \times \vec{k}')$$

  - kinematics similar to, e.g., $p + p \to h + X$
  - S spin vector of nucleon, or initial/final state lepton

- Definition of transverse SSA:

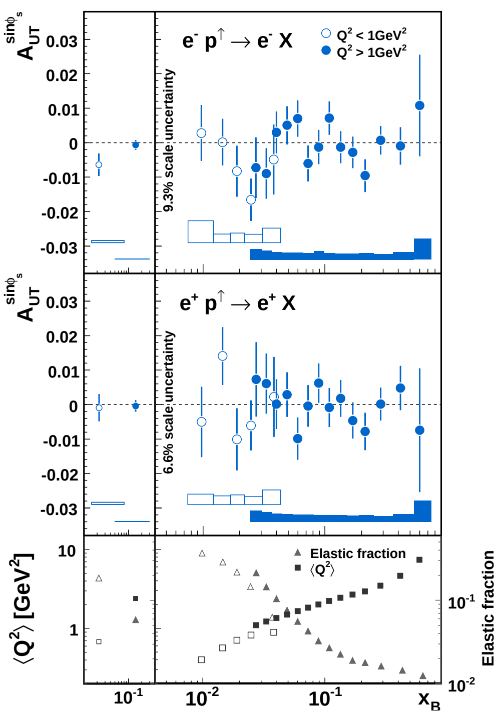
$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

- $A_{UT} = 0$ for one-photon exchange (Christ, Lee, 1966)
  - consider multi-photon exchange
  - $A_{UT} \sim \alpha_{em}$ (small)

Data

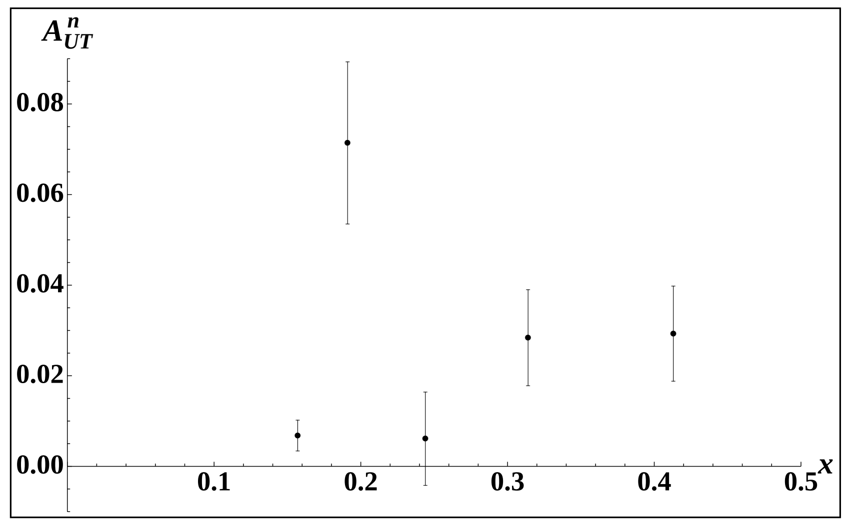
- Early data: CEA (1968), SLAC (1969)
  - not in DIS region, $A_{UT}^p = 0$ within uncertainties
- Recent data:

A_{UT}^p (HERMES, 2009)



$A_{UT}^p = 0$ within uncertainties (10^{-3})

A_{UT}^n (JLab Hall A, preliminary)
(Joseph Katich, Ph.D. thesis, 2011)



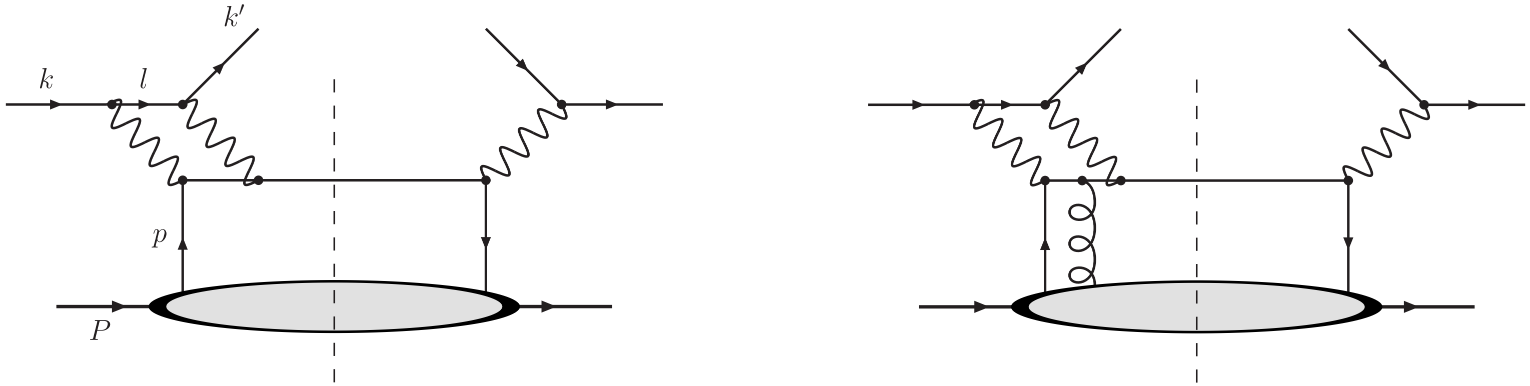
$A_{UT}^n \neq 0$

  - can one (qualitatively) understand these data ?

Photons coupling to the same quark

(Metz, Schlegel, Goeke, 2006)

- Feynman diagrams



- Polarized initial state lepton

$$k'^0 \frac{d\sigma^{\ell}_{pol}}{d^3\vec{k}'} = \frac{4\alpha^3_{em}}{Q^8}\, m_\ell\, x y^2\, \varepsilon^{S_\ell P k k'} \sum_q e_q^3\, x f_1^q(x)$$

  - essential element: imaginary part of lepton-quark box-graph (Barut, Fronsdal, 1960)
  - general behavior of SSA:

$$A^{\ell}_{UT} \sim \alpha_{em} \frac{m_\ell}{Q} \quad \longrightarrow \quad \text{small}$$

- Polarized target

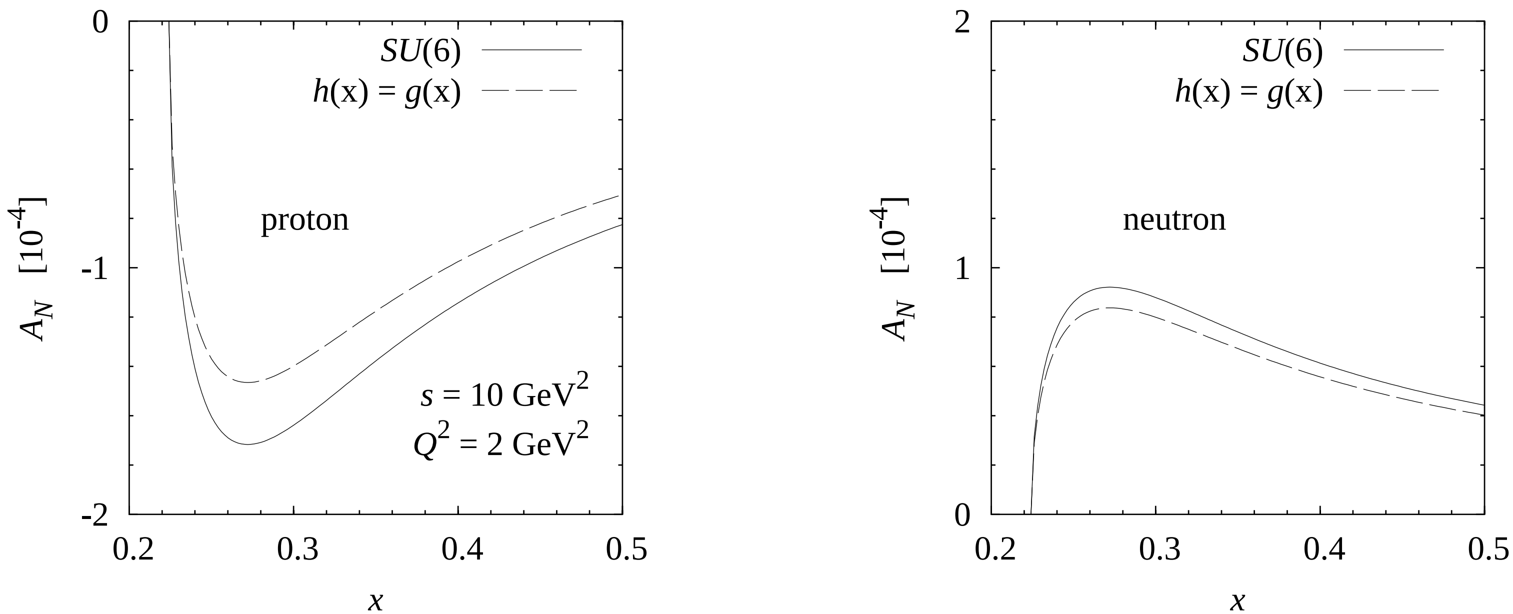
$$k'^0 \frac{d\sigma^N_{pol}}{d^3\vec{k}'} = \frac{4\alpha^3_{em}}{Q^8} M\, x^2 y(1-y)\, \varepsilon^{S_N P k k'} \sum_q e_q^3 \times \Bigg[\bigg(x g_T^q(x) - g_{1T}^{(1)q}(x) - \frac{m_q}{M} h_1^q(x) \bigg) \bigg(\ln \frac{Q^2}{\lambda^2} + H_1(y) \bigg) + \frac{m_q}{M} h_1^q(x) H_2(y) \Bigg]$$

  - contributions: (1) collinear twist-3; (2) transv. quark momentum; (3) quark mass
  - calculation is em. gauge invariant, but uncancelled IR-divergence: λ is photon mass
  - transversity contribution first published by Afanasev, Strikman, Weiss, 2007
    $\longrightarrow$ they use transversity projector containing m_q
    $\longrightarrow$ calculation becomes identical to that for lepton SSA
    $\longrightarrow$ transversity result IR-finite
  - inclusion of quark-gluon-quark correlator can cure problem (work in progress)

$$x g_T(x) - g_{1T}^{(1)}(x) - \frac{m_q}{M} h_1(x) = x \tilde{g}_T(x) \qquad \text{(EOM-relation)}$$

$\longrightarrow$ final result $\sim x\tilde{g}_T$, plus quark mass term $\longrightarrow$ small ?

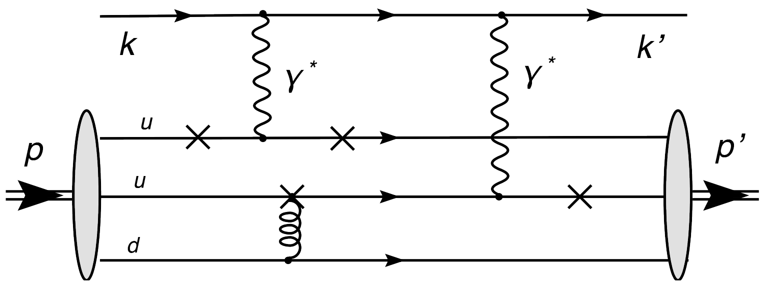
- Estimate of transversity contribution for A_{UT}^{N} (Afanasev, Strikman, Weiss, 2007)



  - they use constituent quark mass $m_q = M/3$
  - asymmetries very small
  - proton: compatible with data
  - neutron: not compatible with data; also sign opposite to data

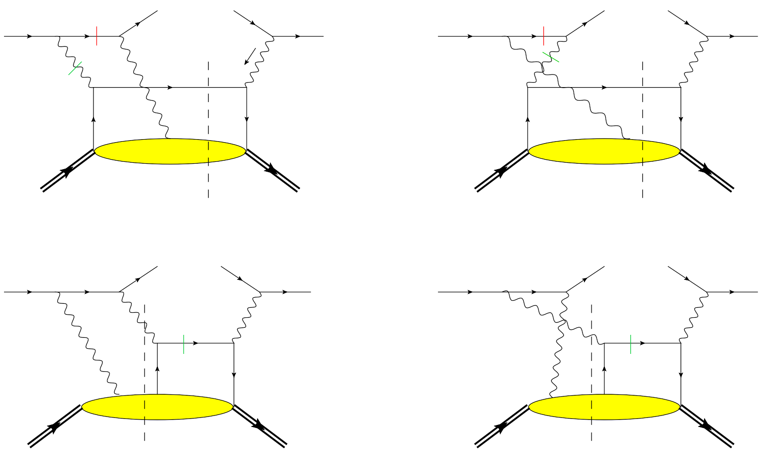
Photons coupling to different quarks

- Elastic scattering at large Q^2



  - 2 photons coupling to different quarks dominate in $1/Q$ expansion (Borisyuk, Kobushkin, 2008 / Kivel, Vanderhaeghen, 2009)

- Deep-inelastic scattering at large Q^2



  - express through $q\gamma q$ correlator
  - soft photon pole contribution
  - soft fermion pole contribution vanishes (see also Koike, Vogelsang, Yuan, 2007)
  - leads to $A_{UT} \sim 1/Q$
  - may dominate, in particular at larger x

3-parton correlators

- Quark-gluon-quark correlator

$$\int \frac{d\xi^- d\zeta^-}{4\pi}\, e^{ixP^+\xi^-} \langle P,S|\bar{\psi}^q(0)\,\gamma^+\, F_{QCD}^{+i}(\zeta)\,\psi^q(\xi)|P,S\rangle = -\varepsilon_T^{ij} S_T^j\, T_F^q(x,x)$$

  – first used by Efremov, Teryaev, 1984 / Qiu, Sterman, 1991 in order to explain SSAs $\longrightarrow$ ETQS matrix element

  – relation to Sivers function (Boer, Mulders Pijlman, 2003)

$$g\, T_F(x,x) = -\int d^2\vec{k}_T\, \frac{\vec{k}_T^{\,2}}{M}\, f_{1T}^{\perp}(x,\vec{k}_T^{\,2})\Big|_{SIDIS}$$

  – T_F depends on definition of covariant derivative, and on sign of g;
  T_F has mass dimension;
  in literature different definitions for same symbol T_F

- Quark-photon-quark correlator

$$\int \frac{d\xi^- d\zeta^-}{2(2\pi)^2}\, e^{ixP^+\xi^-} \langle P,S|\bar{\psi}^q(0)\,\gamma^+\, eF_{QED}^{+i}(\zeta)\,\psi^q(\xi)|P,S\rangle = -M\varepsilon_T^{ij} S_T^j\, F_{FT}^q(x,x)$$

Analytical results

- Unpolarized cross section

$$k'^0 \frac{d\sigma_{unp}}{d^3\vec{k}'} = \frac{2\alpha_{em}^2\, y}{Q^4}\, \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \sum_q e_q^2\, x f_1^q(x)$$

- Polarized cross section

$$k'^0 \frac{d\sigma_{pol}^N}{d^3\vec{k}'} = \frac{8\pi\alpha_{em}^2\, xy^2\, M}{Q^8}\, \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \left(2 + \frac{\hat{u}}{\hat{t}}\right) \varepsilon^{S_N P k k'} \sum_q e_q^2\, x \tilde{F}_{FT}^q(x,x)$$

$$\text{with} \quad \tilde{F}_{FT}(x,x) = F_{FT}(x,x) - x\frac{d}{dx}F_{FT}(x,x)$$

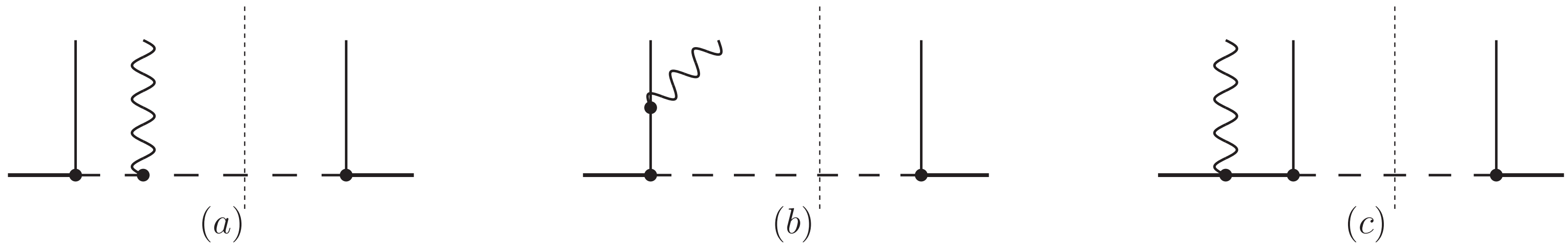
  - calculation in Feynman gauge and in light-cone gauge
  - can be compared to $qq' \longrightarrow q'q$ channel calculation in Kouvaris, Qiu, Vogelsang, Yuan (2006) $\longrightarrow$ full agreement
  - derivative term dominates at large x: $F_{FT} \sim \ldots (1-x)^{\tilde{\beta}}$

- Asymmetry

$$A_{UT}^N = -\frac{2\pi M}{Q}\, \frac{2-y}{\sqrt{1-y}}\, \frac{\sum_q e_q^2\, x \tilde{F}_{FT}^q(x,x)}{\sum_q e_q^2\, x f_1^q(x)}$$

Relation between F_{FT} and T_F

- Focus on region of larger x (neglect antiquarks, gluons)
- Consider $F_{FT}^q(x,x)$ in diquark model



  - diagram (b) vanishes (see also Kang, Qiu, Zhang, 2010); diagram (c) vanishes
  - no assumption about type of diquark and nucleon-quark-diquark vertex
  - one can relate QED correlator F_{FT} to QCD correlator T_F

- Quantitative relation between F_{FT}^q and T_F^q (determined by charge of diquark)

$$F_{FT}^{u/p} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M}\,(g\,T_F^{u/p}) \qquad F_{FT}^{d/p} = -\frac{2\,\alpha_{em}}{3\pi C_F \alpha_s M}\,(g\,T_F^{d/p})$$

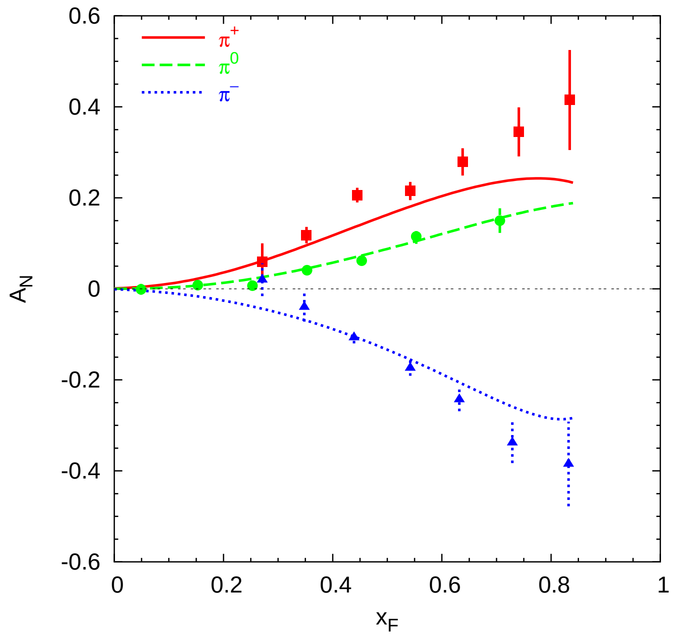
$$F_{FT}^{u/n} = \frac{\alpha_{em}}{3\pi C_F \alpha_s M}\,(g\,T_F^{d/p}) \qquad F_{FT}^{d/n} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M}\,(g\,T_F^{u/p})$$

  - exactly same relations in general light-front 3-quark model
    (acknowledge discussion with Lorcé and Pasquini)

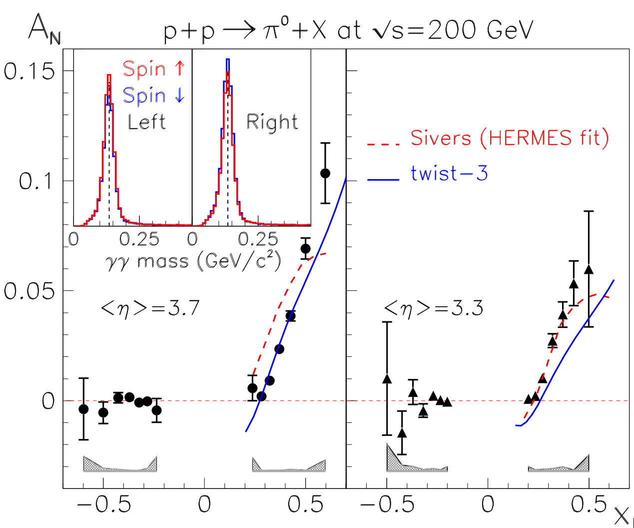
Input for T_F

- T_F from HERMES and COMPASS data on $\ell N^{\uparrow} \to \ell' h X$
  - extraction of $f_{1T}^{\perp}$ by Anselmino et al. (2008)
  - use relation between $f_{1T}^{\perp}$ and T_F
  - same general conclusions for other extractions

- T_F from FNAL and RHIC data on $p^{\uparrow} p \to h X$
  - sample data



FermiLab, E704, 1990 $\sqrt{s} = 20\,\mathrm{GeV}$



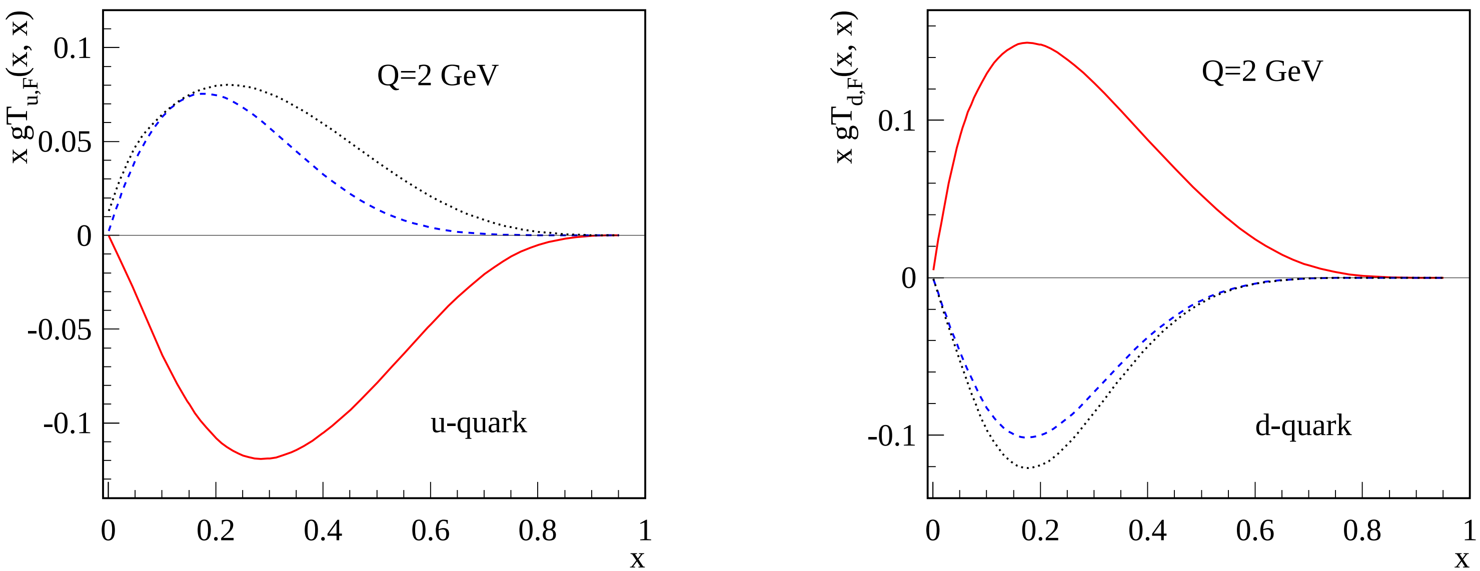
RHIC, STAR, 2008 $\sqrt{s} = 200\,\mathrm{GeV}$

  - extraction by Kouvaris, Qiu, Vogelsang, Yuan (2006) (FIT I: no antiquarks)

– ansatz for each flavor: $T_F(x,x) = N\,x^{\alpha}\,(1-x)^{\beta}\,f_1(x)$

– in order to describe large x_F behavior one needs: $\beta < 1$
$\longrightarrow$ A_N diverges for $x_F \to 1$ due to derivative term

– sign mismatch (striking spin crisis !) (Kang, Qiu, Vogelsang, Yuan, 2011)

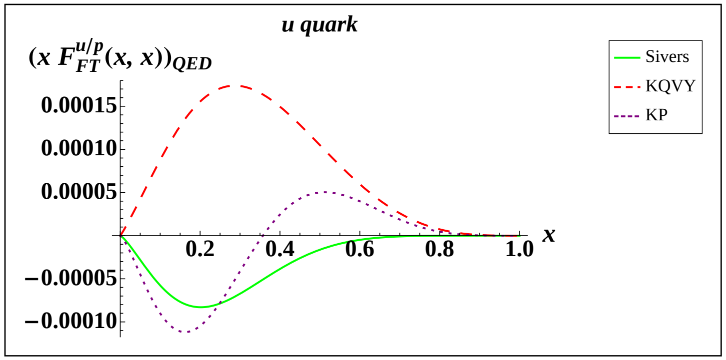


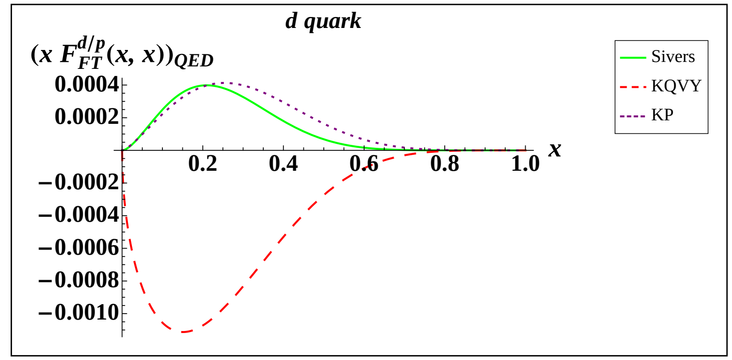
$\longrightarrow$ resolution ?

- T_F from combined fit of data on $\ell N^{\uparrow} \to \ell' h X$ and $p^{\uparrow} p \to hX$
(Kang, Prokudin, 2012)
  – use relation between $f_{1T}^{\perp}$ and T_F
  – do not include FNAL data
  – allow for node in x (and k_T) in $f_{1T}^{\perp}$

Numerical results for F_{FT}

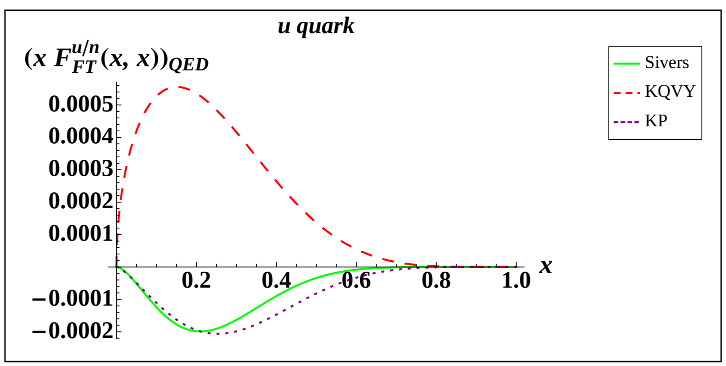
- Proton

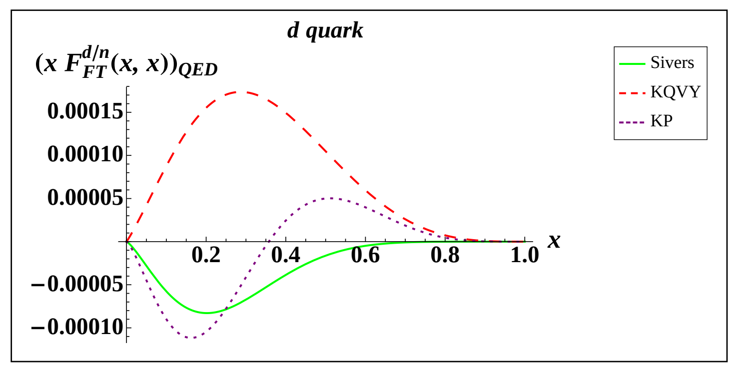




  – side-remark: large N_c analysis predicts: $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$ (Pobylitsa, 2003)

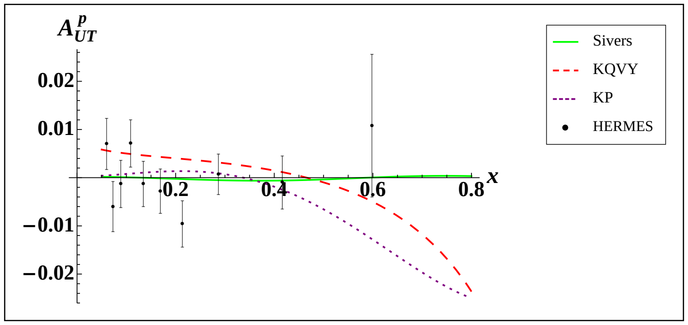
- Neutron

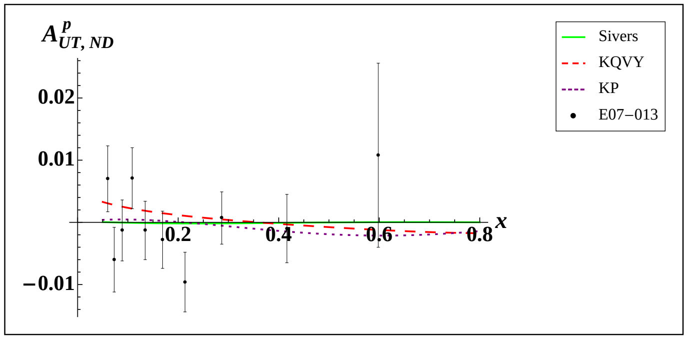




Numerical results for asymmetries

- Proton: $\langle Q^2 \rangle = 2.4\,\mathrm{GeV}^2 \qquad \langle y \rangle = 0.5$

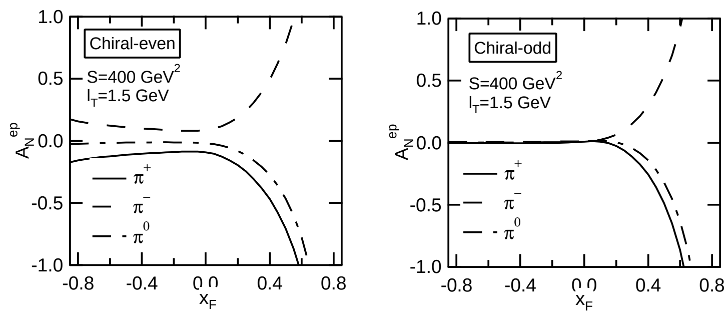


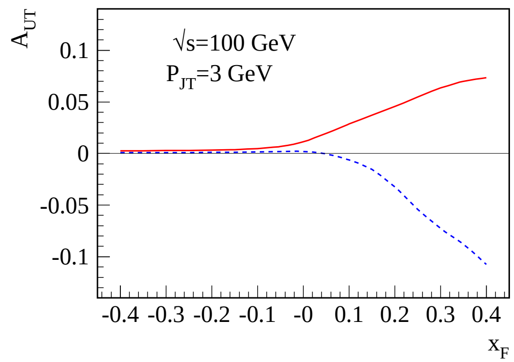


– Sivers function input in perfect agreement with data

– KQVY seems too large at large x; even diverges for $x \longrightarrow 1$
$\longrightarrow$ similar observation for $\ell p^\uparrow \longrightarrow hX$ and $\ell p^\uparrow \longrightarrow jetX$

$\ell p^\uparrow \longrightarrow \pi X$ (Koike, 2002) $\qquad$ $\ell p^\uparrow \longrightarrow jetX$ (Kang, Metz, Qiu, Zhou, 2011)

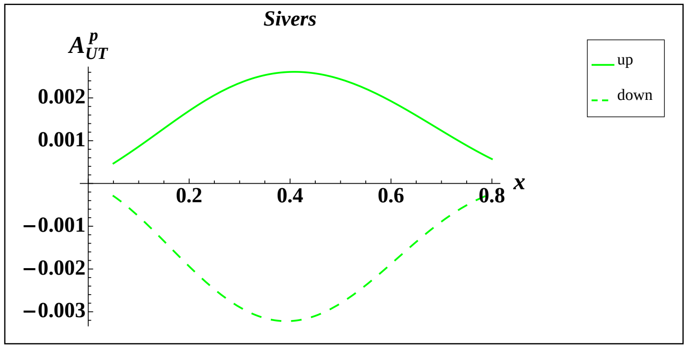


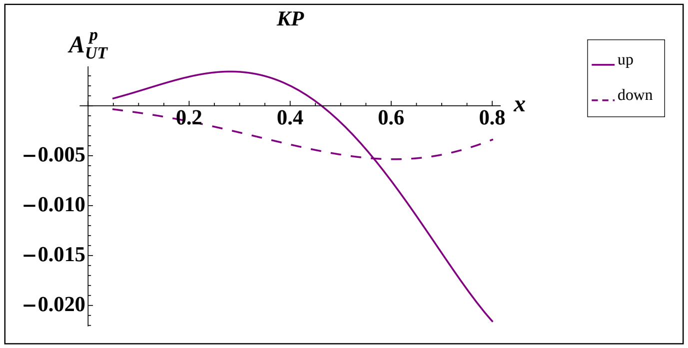


$\longrightarrow$ side-remark: data on $\ell p^\uparrow \longrightarrow hX$ from HERMES, COMPASS would be useful !

– KP seems too large at large x; does not diverge for $x \longrightarrow 1$
(caveat: use x-related value for Q rather than $\langle Q \rangle$)

– individual flavor contributions

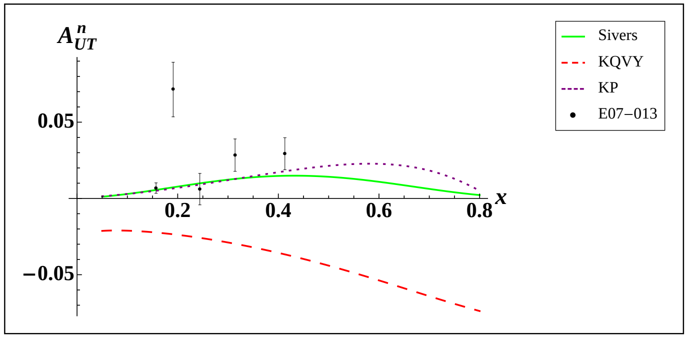


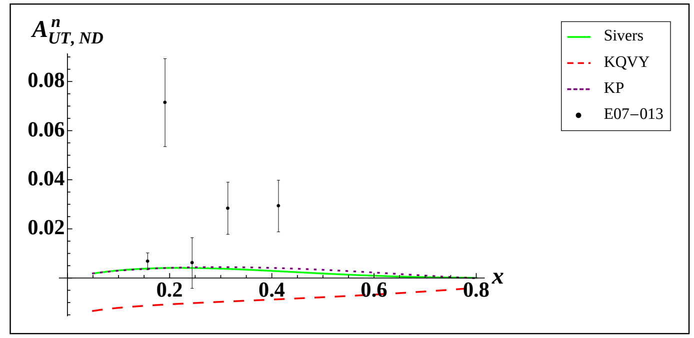


$\longrightarrow$ Sivers: individual contributions small, plus cancellation

$\longrightarrow$ KP: due to node in Sivers function no cancellation at larger x,
node in x not preferred

- Neutron: $\langle Q^2 \rangle = 2.1\,\mathrm{GeV}^2 \qquad \langle y \rangle = 0.66$





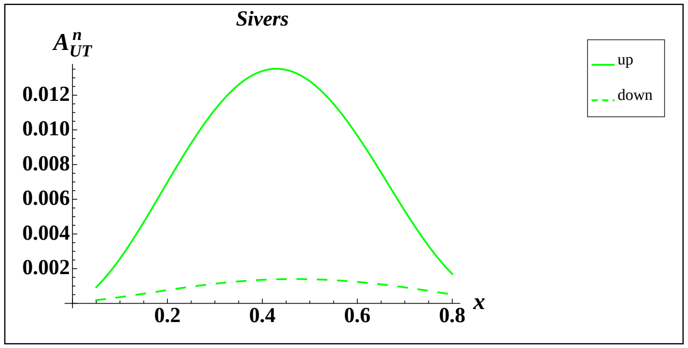
  – Sivers function input in reasonable agreement with preliminary data (sign, order of magnitude)
  $\longrightarrow$ wrong sign if f_{1T} had node in k_T
  $\longrightarrow$ this finding agrees with recent work by Kang, Prokudin, 2012

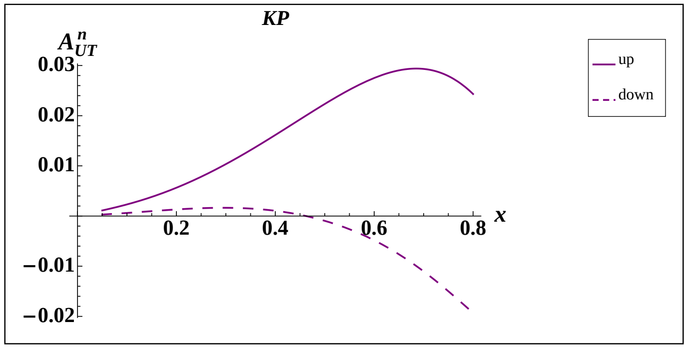
  – data may change somewhat; sign and order of magnitude not affected (J.P. Chen, private communication)

  – KQVY has the wrong sign
  $\longrightarrow$ indication that SSAs in $p^\uparrow p \to hX$ not primarily caused by Sivers effect
  $\longrightarrow$ sign mismatch boils down to puzzle about origin of SSAs in $p^\uparrow p \to hX$
  $\longrightarrow$ Collins effect, or something else ?
  $\longrightarrow$ effects are too nice and too large to be left unexplained

– KP in reasonable agreement with preliminary data
(sign, order of magnitude)

– individual flavor contributions





$\longrightarrow$ A^n_{UT} largely dominated by $f_{1T}^{\perp d/p}$

$\longrightarrow$ difference in $f_{1T}^{\perp u/p}$ between Sivers and KP only matters at rather large x

Summary

- Transverse SSAs in inclusive DIS can exist when going beyond one-photon exchange
- Nice recent data on target SSAs A_{UT}^{p} and A_{UT}^{n}
- Two photons coupling to same quark
  - complete result for lepton SSA A_{UT}^{ℓ}
  - result for target SSA incomplete (work in progress)
- Two photons coupling to different quarks
  - does not affect result for lepton SSA
  - may dominate target SSA
  - calculation in twist-3 collinear factorization
  - result depends on $q\gamma q$-correlator F_{FT}
  - in valence quark picture, F_{FT} can be related to T_F and $f_{1T}^{\perp}$
  - best description of data if T_F taken from SIDIS Sivers function
- Node of $f_{1T}^{\perp}$ in k_T would not work; also node in x not preferred
- Indication that SSAs in $p^{\uparrow}p \to hX$ not primarily caused by Sivers effect
- Indication that Sivers effect indeed due to rescattering of active partons through gauge boson exchange