Single Spin Asymmetries in Inclusive DIS and the ETQS Matrix Element

(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
   - Numerical results and discussion
4. Summary

Preliminaries

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

- 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., $p + p \rightarrow h + X$
  - S spin vector of nucleon, or initial/final state lepton

- Definition of transverse SSA:

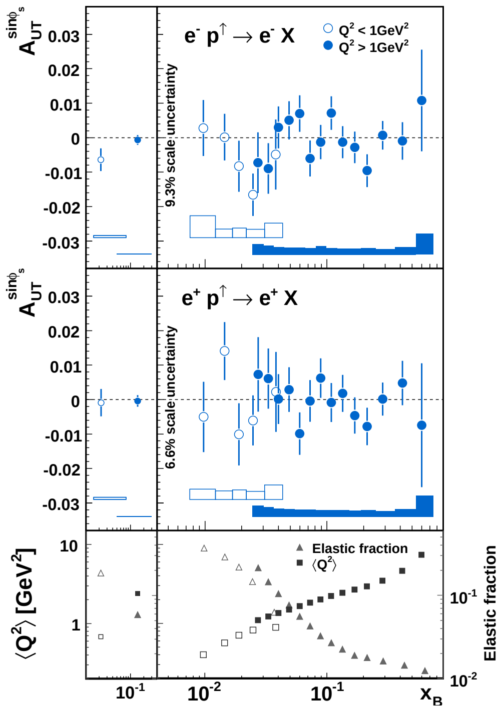
$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

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

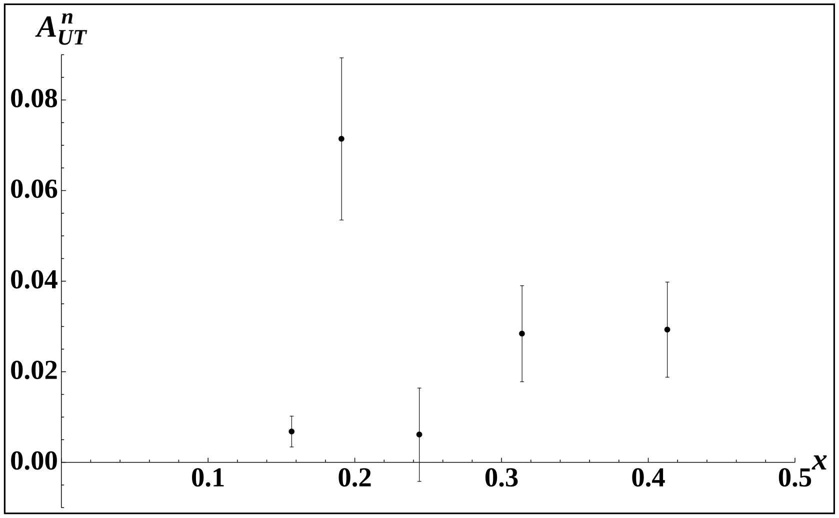
Data

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

A^p_{UT} (HERMES, 2009)



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



$A^n_{UT} \neq 0$

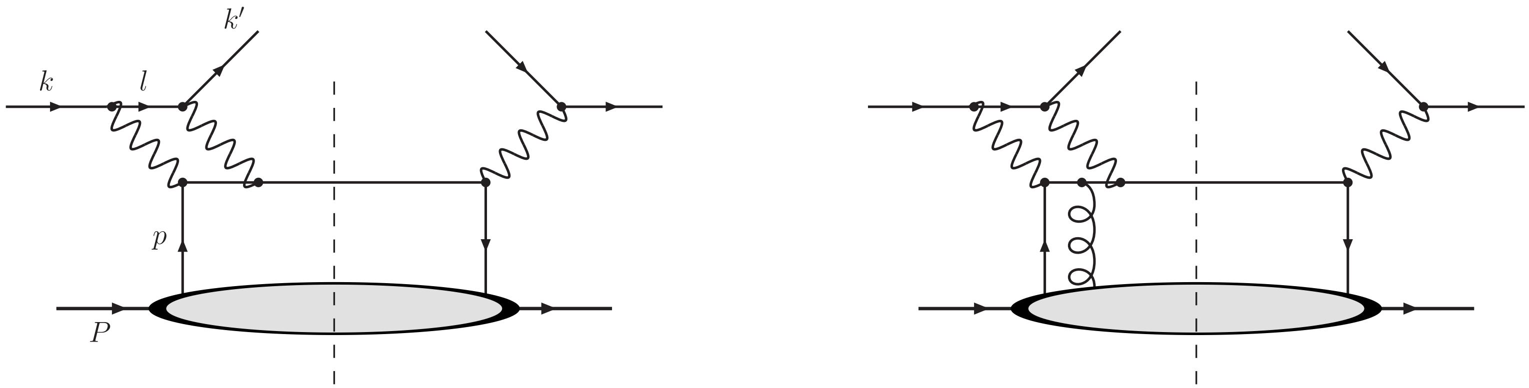
$A^p_{UT} = 0$ within uncertainties (10^{-3})

- can one (qualitatively) understand these data ?

Photons coupling to the same quark

(Metz, Schlegel, Goeke, 2006 / Afanasev, Strikman, Weiss, 2007)

- Feynman diagrams



- Polarized initial state lepton

$$k'^0 \frac{d\sigma_{pol}}{d^3\vec{k}'} = \frac{4\alpha_{em}^3}{Q^8}\, m_\ell\, x y^2\, \varepsilon^{SPkk'} \sum_q e_q^3\, x f_1^q(x)$$

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

  – general behavior of SSA:

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

- Polarized target

$$k'^0 \frac{d\sigma_{pol}}{d^3\vec{k}'} = \frac{4\alpha_{em}^3}{Q^8} M\, x^2 y(1-y)\, \varepsilon^{SPkk'} \sum_q e_q^3$$

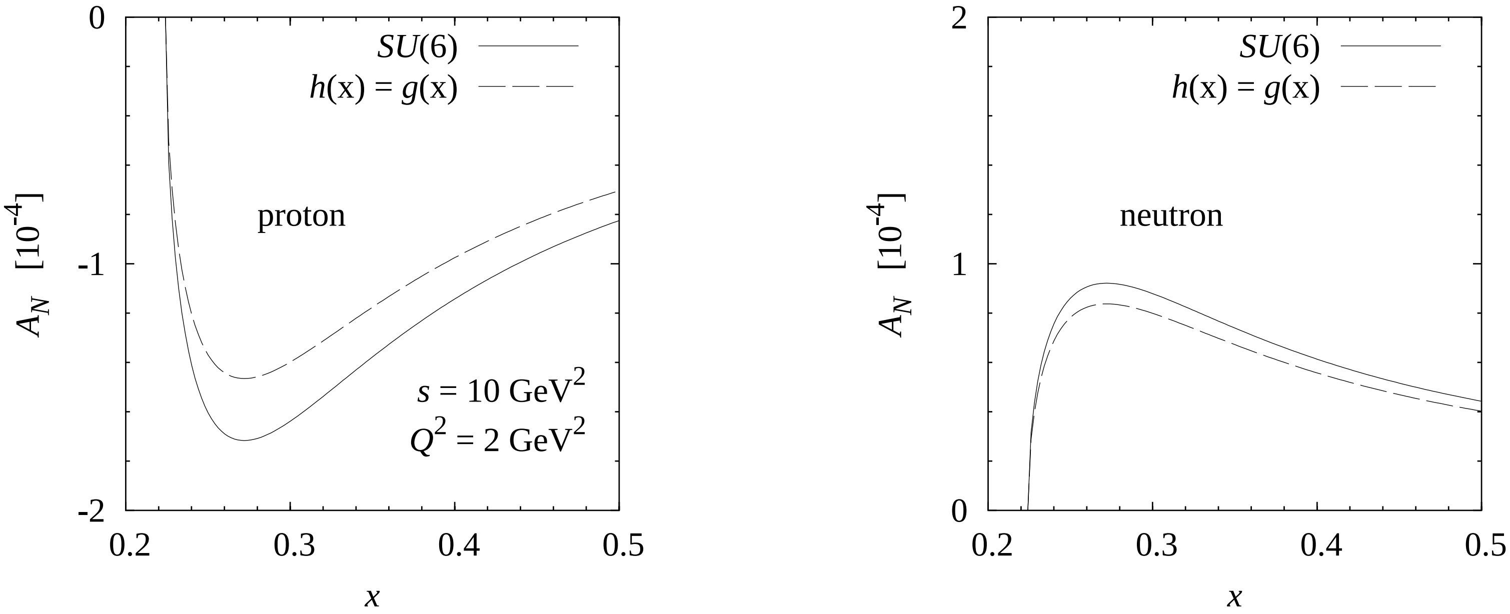
$$\times \left[\left(x g_T^q(x) - g_{1T}^{(1)q}(x) - \frac{m_q}{M} h_1^q(x) \right) \left(\ln \frac{Q^2}{\lambda^2} + H_1(y) \right) + \frac{m_q}{M} h_1^q(x) H_2(y) \right]$$

  - 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)

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

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

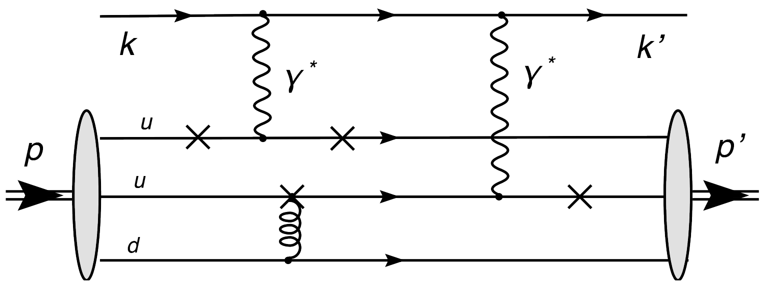
- Estimate of transversity contribution for A_{UT} (Afanasev, Strikman, Weiss, 2007)



  - 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

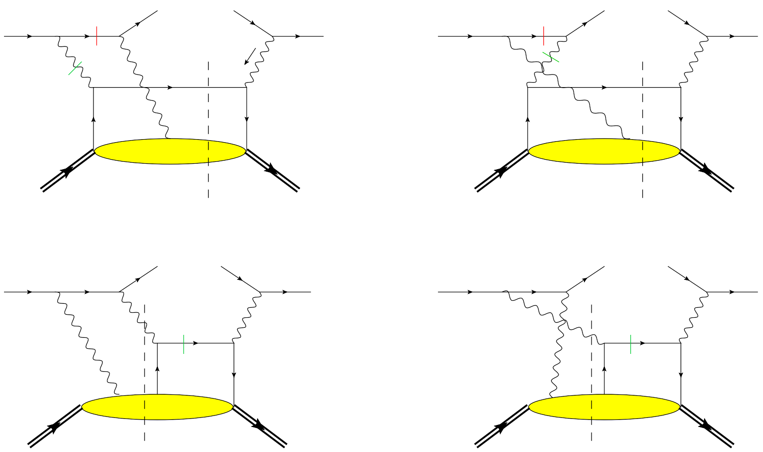
Photons coupling to different quarks

- 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

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

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

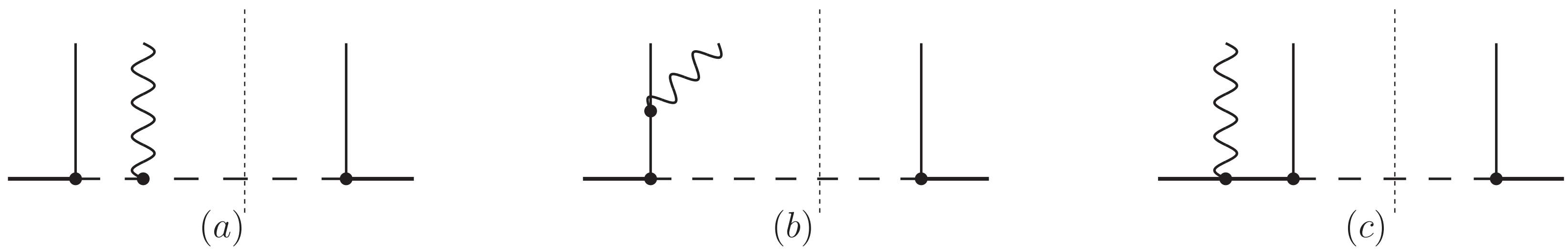
  - calculation in Feynman gauge and in light-cone gauge
  - can be compared to $qq' \to q'q$ channel calculation in Kouvaris, Qiu, Vogelsang, Yuan (2006) $\longrightarrow$ full agreement
  - derivative term dominates at large x: $\quad F_{FT} \sim \ldots (1-x)^{\tilde{\beta}}$

- Asymmetry

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

Relation between F_{FT} and T_F

- Focus on region of larger x (neglect antiquarks, gluons)
- Consider $F^q_{FT}(x, x)$ 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^q_{FT} and T^q_F (determined by charge of diquark)

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

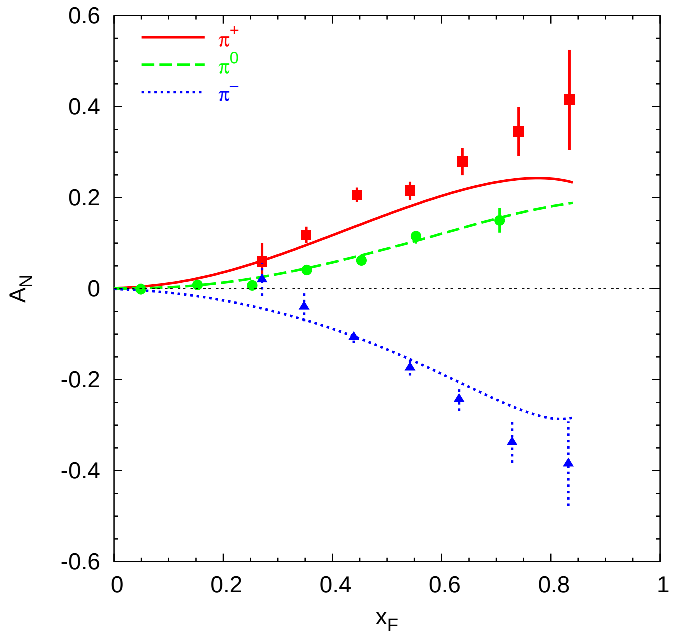
$$F^{u/n}_{FT} = \frac{\alpha_{em}}{3\pi C_F \alpha_s M}\,(g\,T^{d/p}_F) \qquad F^{d/n}_{FT} = -\frac{\alpha_{em}}{6\pi C_F \alpha_s M}\,(g\,T^{u/p}_F)$$

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

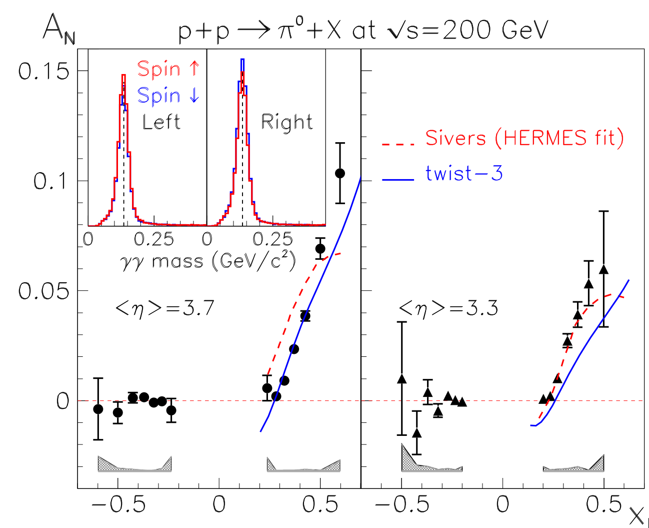
Input for T_F

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

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



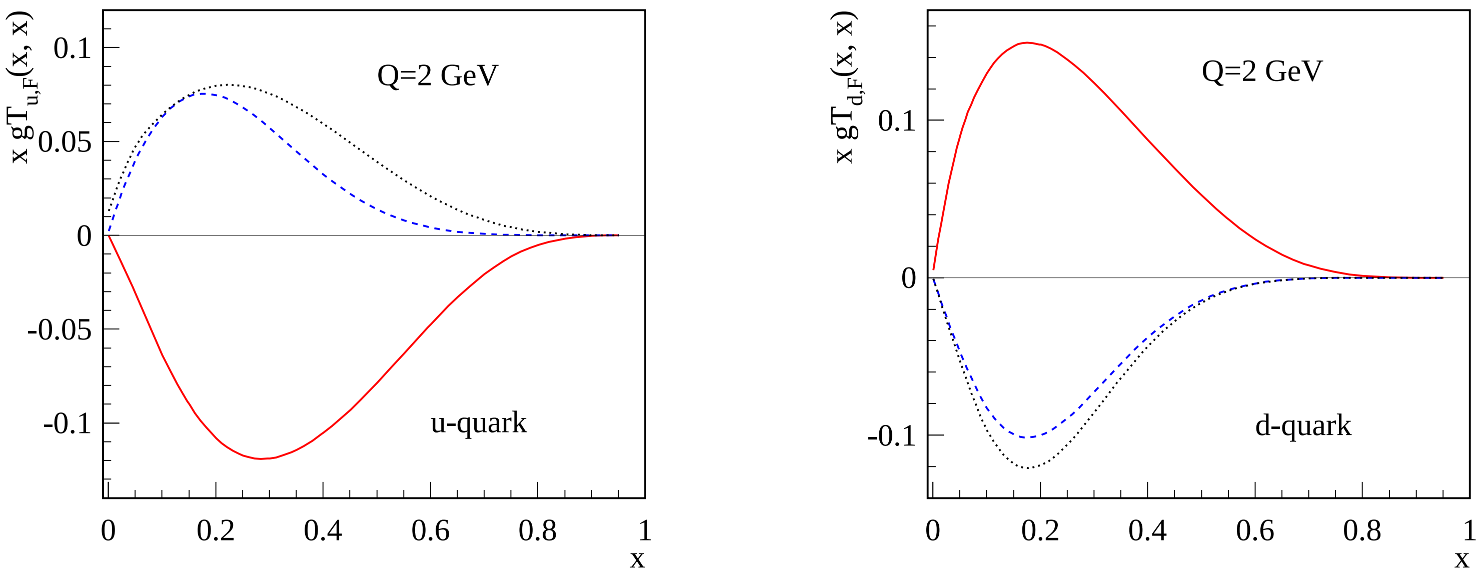
FermiLab, E704, 1990 $\sqrt{s} = 20\,\mathrm{GeV}$



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 (Kang, Qiu, Vogelsang, Yuan, 2011)

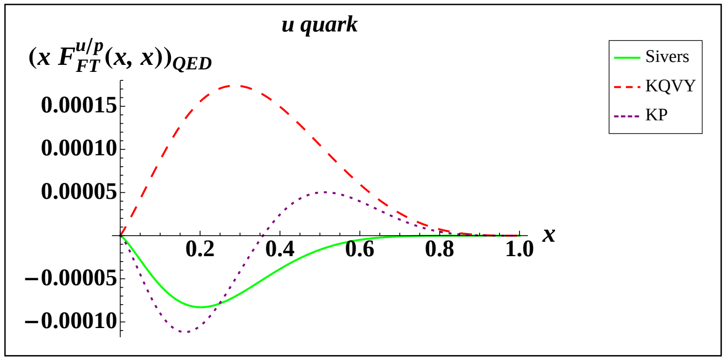


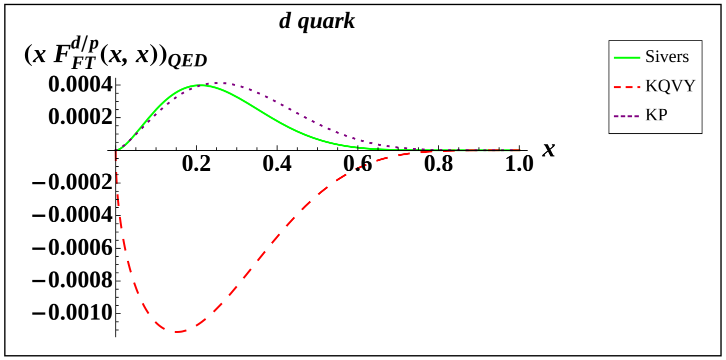
$\longrightarrow$ resolution ?

- T_F from combined fit of data on $\ell N^{\uparrow} \to \ell' h X$ and $p^{\uparrow} p \to h X$ (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 $f_{1T}^{\perp}$

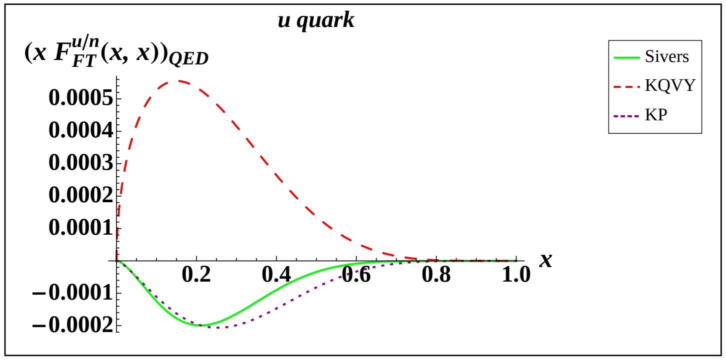
Numerical results for F_{FT}

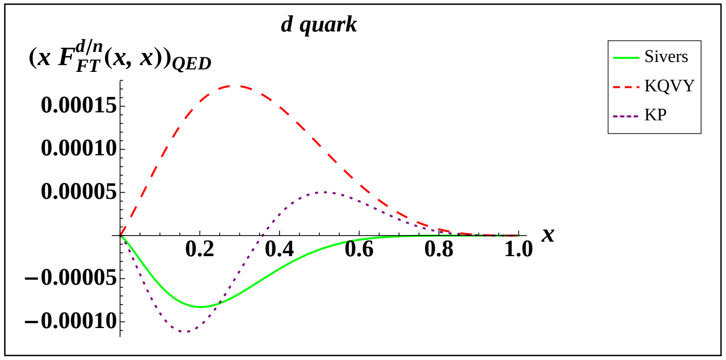
- Proton





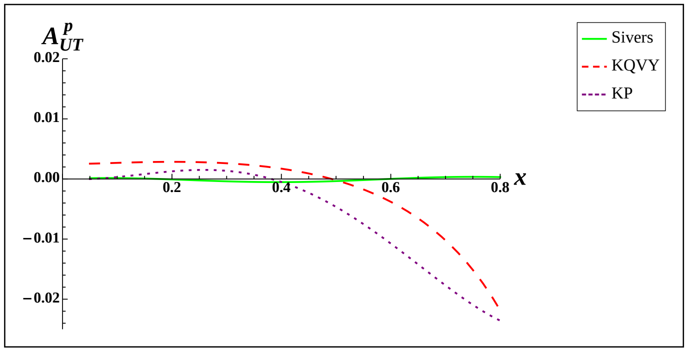
- Neutron

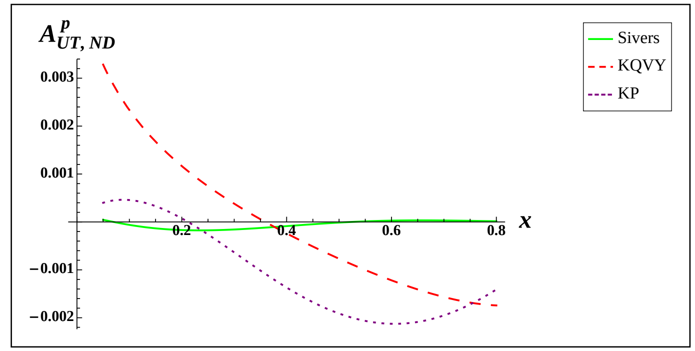




Numerical results for asymmetries

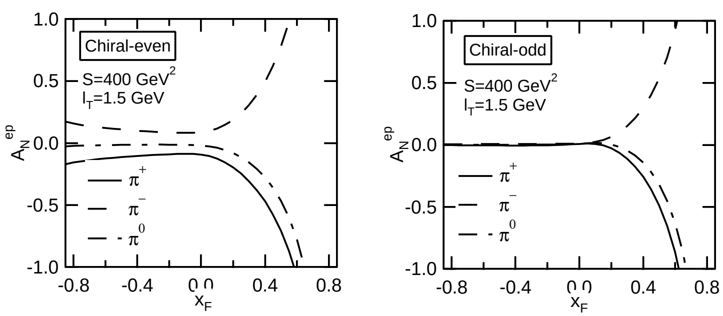
- Proton: $\langle Q^2 \rangle = 2.4\,\text{GeV}^2 \qquad \langle y \rangle = 0.5$

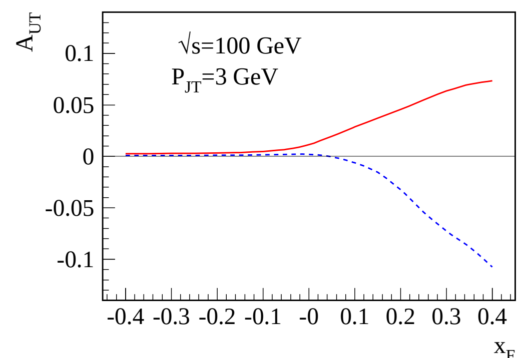




  - Sivers function input in perfect agreement with data
  - KQVY apparently too large at large x; even diverges for $x \to 1$
    $\longrightarrow$ similar observation for $\ell p^\uparrow \to hX$ and $\ell p^\uparrow \to jetX$

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

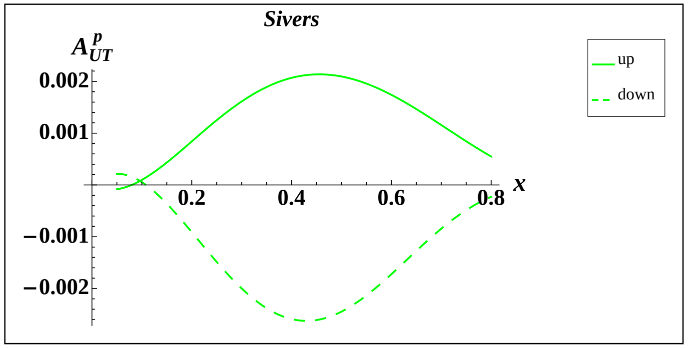


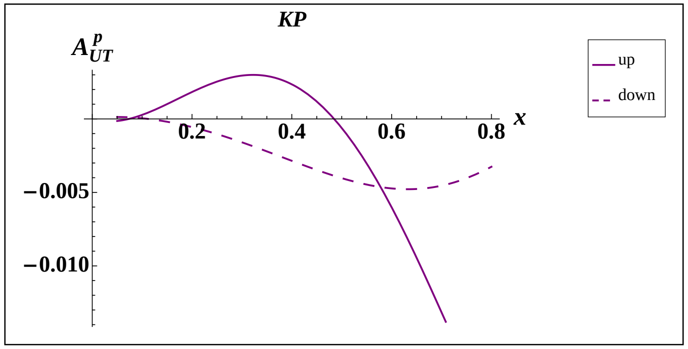


$\longrightarrow$ side-remark: data on $\ell p^\uparrow \to hX$ from HERMES, COMPASS would be useful !

– KP apparently 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



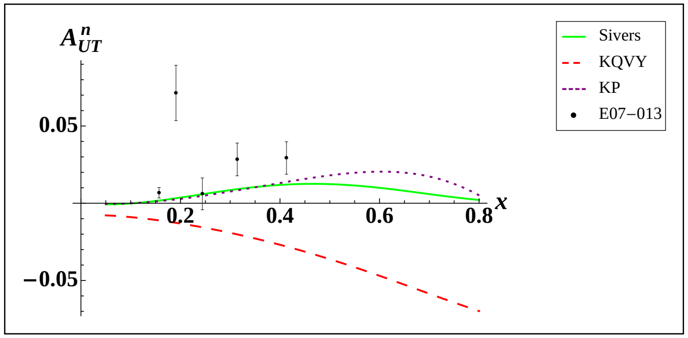


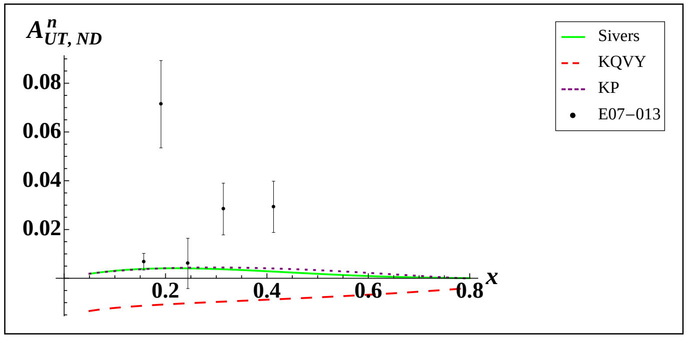
$\longrightarrow$ Sivers: individual contributions small, plus cancellation

$\longrightarrow$ KP: due to node in Sivers function no cancellation at larger x

– Note: discussion about proton does not depend on sign of A_{UT}

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





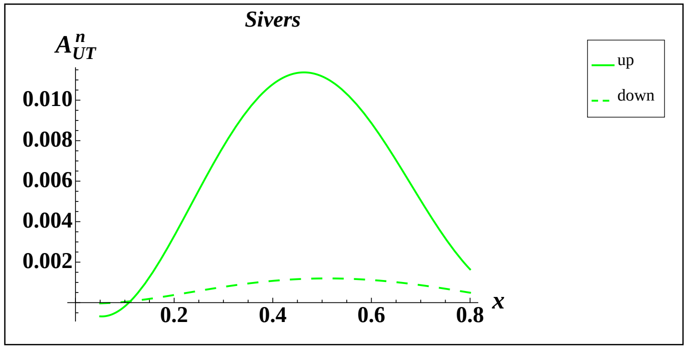
  – Sivers function input in reasonable agreement with preliminary data (sign, order of magnitude)
  $\longrightarrow$ wrong sign if f_{1T} had node in k_T
  $\longrightarrow$ this finding agrees with recent work by Kang, Prokudin, 2012

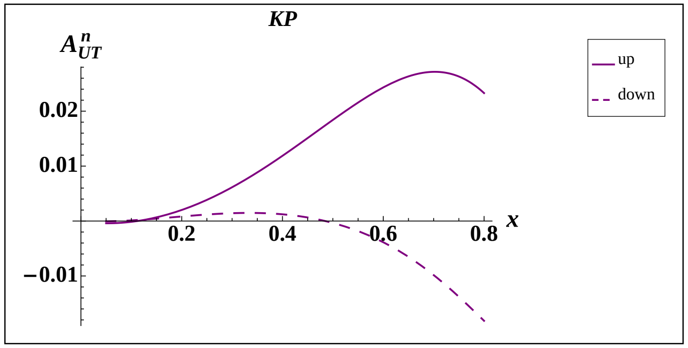
  – data may change somewhat; sign and order of magnitude not affected (J.P. Chen, private communication)

  – KQVY has the wrong sign
  $\longrightarrow$ indication that SSAs in $p^\uparrow p \longrightarrow hX$ not primarily caused by Sivers effect
  $\longrightarrow$ sign mismatch boils down to puzzle about origin of SSAs in $p^\uparrow p \longrightarrow hX$
  $\longrightarrow$ Collins effect, etc. ?
  $\longrightarrow$ effects are too nice and too large to be left unexplained
  $\longrightarrow$ crucial new insight might come from $p^\uparrow p \longrightarrow jetX$

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

– individual flavor contributions





$\longrightarrow$ A_{UT}^n 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}
  - F_{FT} can be related to T_F and $f_{1T}^\perp$ (model-dependent)
  - 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 (ultimate test expected from measurement of Sivers SSA in Drell-Yan)