Single Spin Asymmetries in Inclusive DIS and in Hadronic Collisions

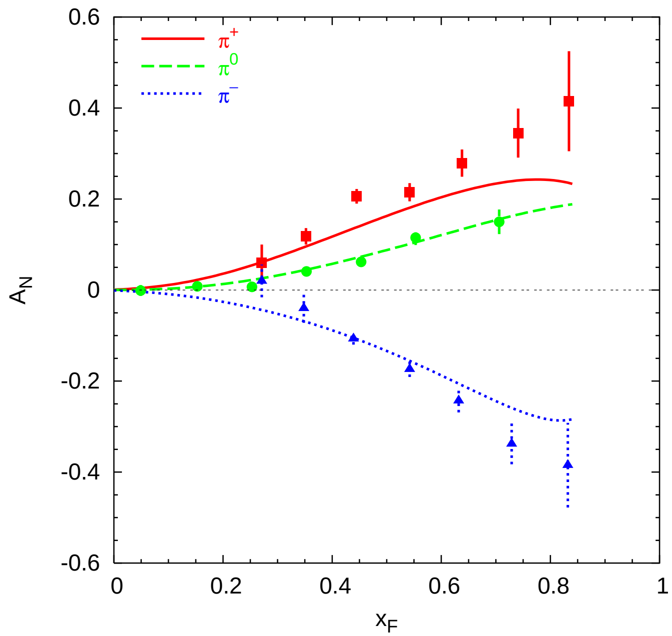
(A. Metz, Temple University, Philadelphia)

1. Introduction
   - SSAs in hadronic collisions
   - SSA in semi-inclusive DIS: Sivers effect
   - Sign mismatch puzzle
2. SSAs in inclusive DIS: Two photons coupling to the same quark
3. SSAs in inclusive DIS: 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

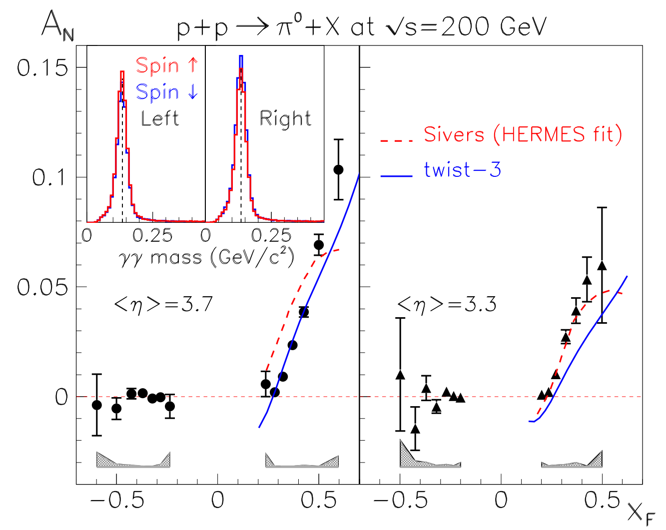
$\rightarrow$ see also talks by Scimemi, Krisch, Barish, Igo, Prok, Kunne, etc.

Transverse SSAs in $p^{\uparrow} p \to h\, X$

$$A_N = A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \qquad\qquad x_F = \frac{2P_{hL}}{\sqrt{s}}$$



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



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

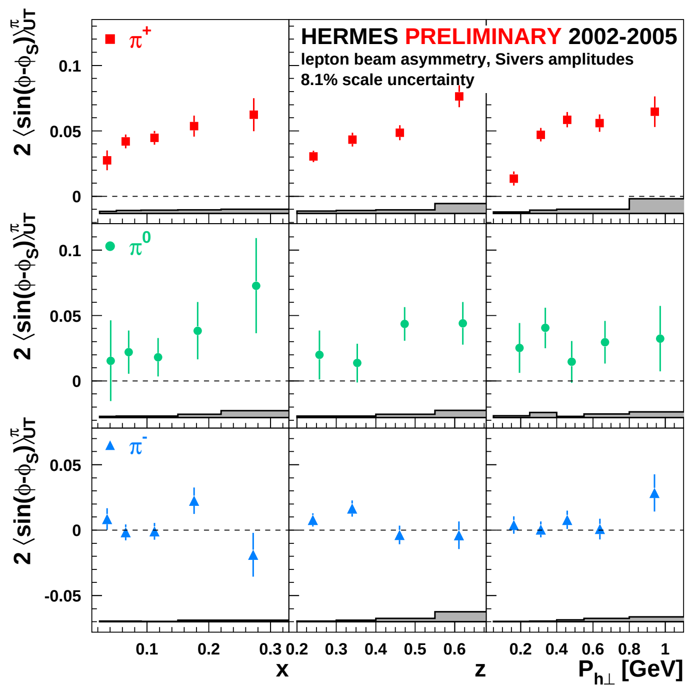
- Many more data available by now
- Understanding of these interesting effects in QCD still a challenge
- Considered to be related to collinear twist-3 qgq-correlators (?)
  (Efremov, Teryaev, 1984 / Qiu, Sterman, 1991 / etc.)

Transverse SSA in semi-inclusive DIS: Sivers effect

- Process: $\ell\, N \to \ell'\, h\, X$
- Cross section (18 structure functions), Sivers asymmetry

$$d\sigma \sim \sin(\phi_h - \phi_S)\, F_{UT,T}^{\sin(\phi_h - \phi_S)} + \ldots$$

- Sample data



- Many more data available by now (HERMES, COMPASS, JLab)
- Effect may be described by transverse momentum dependent parton distribution (TMD) $\to$ Sivers function

Sivers function

- Forward quark distributions

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ip\cdot z}\, \langle P;S|\, \bar{\psi}^q(0)\,\gamma^+\,\mathcal{W}_{PDF}\,\psi^q(z)\,|P;S\rangle \Big|_{z^+=z_T=0} = f_1^q(x=p^+/P^+)$$

- TMDs

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\,\frac{d^2\vec{z}_T}{(2\pi)^2}\, e^{ip\cdot z}\, \langle P;S|\, \bar{\psi}^q(0)\,\gamma^+\,\mathcal{W}_{TMD}\,\psi^q(z)\,|P;S\rangle \Big|_{z^+=0}$$

$$= f_1^q(x,\vec{p}_T^{\,2}) - \frac{\vec{S}_T\cdot(\hat{P}\times\vec{p}_T)}{M}\, f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})$$

  - partonic nucleon structure beyond collinear approximation
    $\rightarrow$ 3-D structure in $(x,\vec{p}_T)$-space
  - Sivers function $f_{1T}^{\perp}$ describes strength of spin-orbit correlation (Sivers, 1989)
  - spin/azimuthal asymmetry on the level of parton distribution
    $\rightarrow$ spin/azimuthal asymmetry in observables (e.g., Sivers SSA observed by HERMES, COMPASS, and JLab in semi-inclusive DIS)

3-parton correlator and sign mismatch

- Quark-gluon-quark correlator

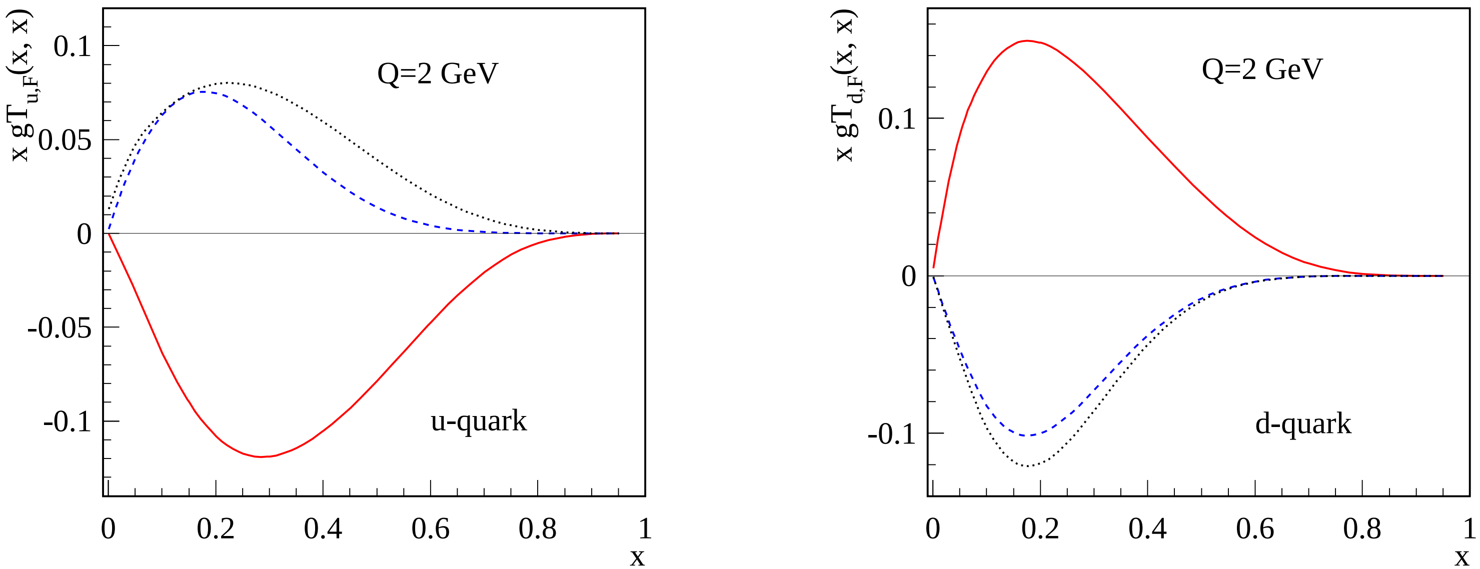
$$\int \frac{d\xi^- d\zeta^-}{4\pi}\, e^{ixP^+\xi^-} \langle P,S|\bar{\psi}^q(0)\,\gamma^+\, F^{+i}_{QCD}(\zeta)\,\psi^q(\xi)|P,S\rangle = -\varepsilon_T^{ij} S_T^j\, T_F^q(x,x)$$

  - ETQS matrix element (Efremov, Teryaev, 1984 / Qiu, Sterman, 1991)
  - vanishing gluon momentum $\longrightarrow$ soft gluon pole matrix element
  - relation to Sivers function (Boer, Mulders, Pijlman, 2003)

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

  - 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

- Sign mismatch (Kang, Qiu, Vogelsang, Yuan, 2011)
  - T_F can be extracted from different sources (direct extraction vs Sivers input)



  - striking sign mismatch !
  - resolution ?

SSAs in inclusive DIS: Preliminaries

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

- Kinematical variables

$$Q^2 = -(k-k')^2 \qquad x = \frac{Q^2}{2P\cdot(k-k')} \qquad y = \frac{P\cdot(k-k')}{P\cdot k} = \frac{Q^2}{xS}$$

- Single spin asymmetry can exist due to correlation

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

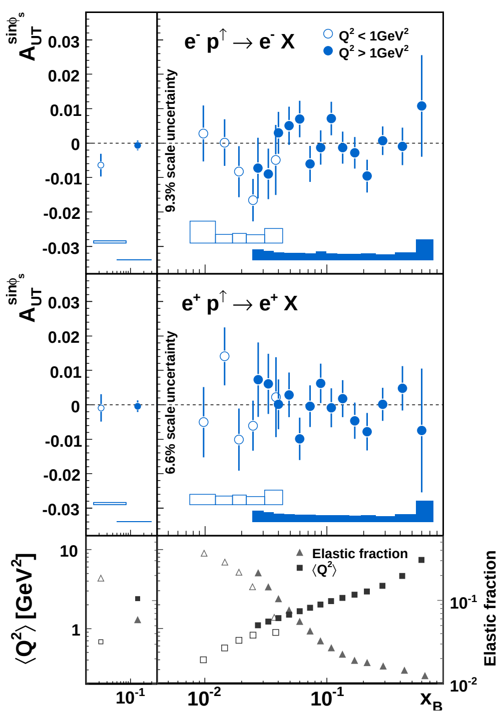
  - kinematics similar to, e.g., $p + p \to h + X$
  - S spin vector of nucleon, or initial/final state lepton

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

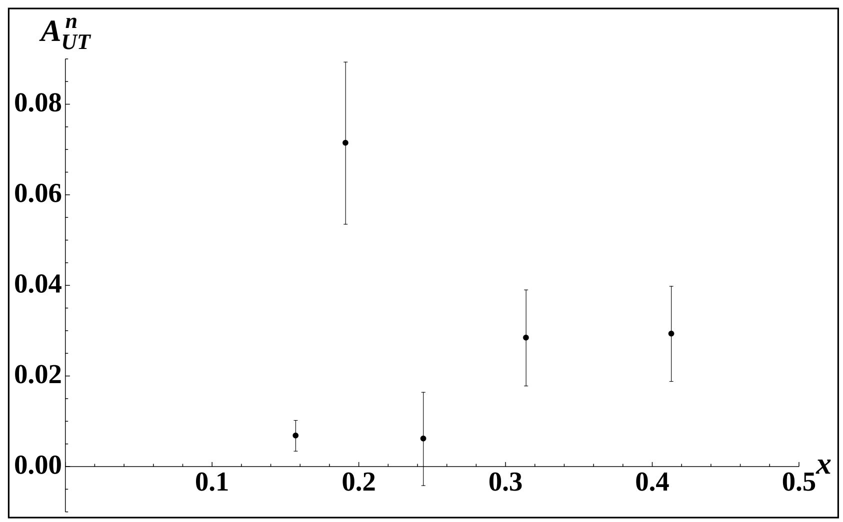
Data

- 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)



$A^n_{UT} \neq 0$

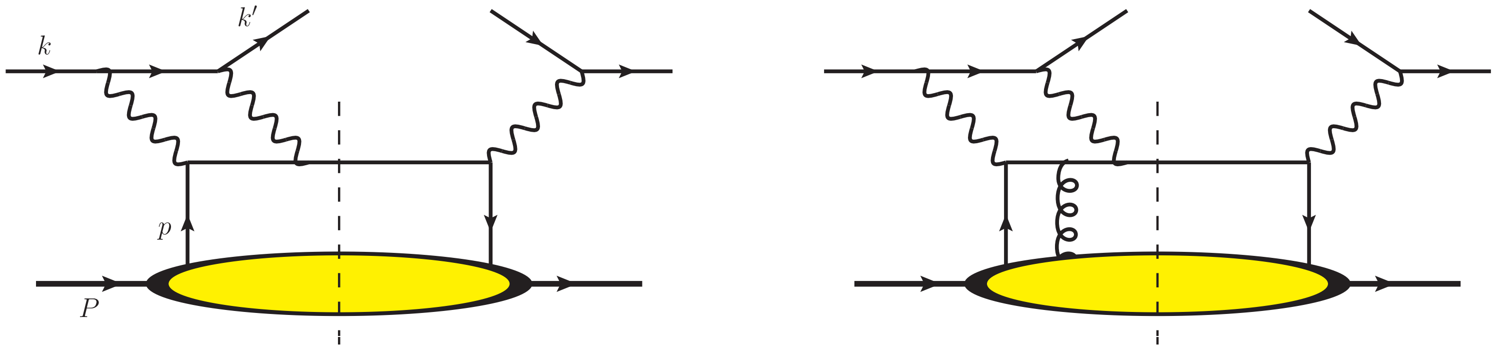
$A^p_{UT} = 0$ within uncertainties (10^{-3})

- can one (qualitatively) understand these data ?
- can one learn something beyond inclusive DIS ?

Photons coupling to the same quark

(Metz, Schlegel, Goeke, 2006)

- Feynman diagrams



- Polarized initial state lepton

$$k'^0 \frac{d\sigma^{\ell}_{pol}}{d^3\vec{k}'} = \frac{4\alpha^3_{em}}{Q^8}\, m_\ell \, x y^2 \, \varepsilon^{S_\ell P k k'} \sum_q e^3_q \, x f^q_1(x)$$

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

  – general behavior of SSA:

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

- Polarized target

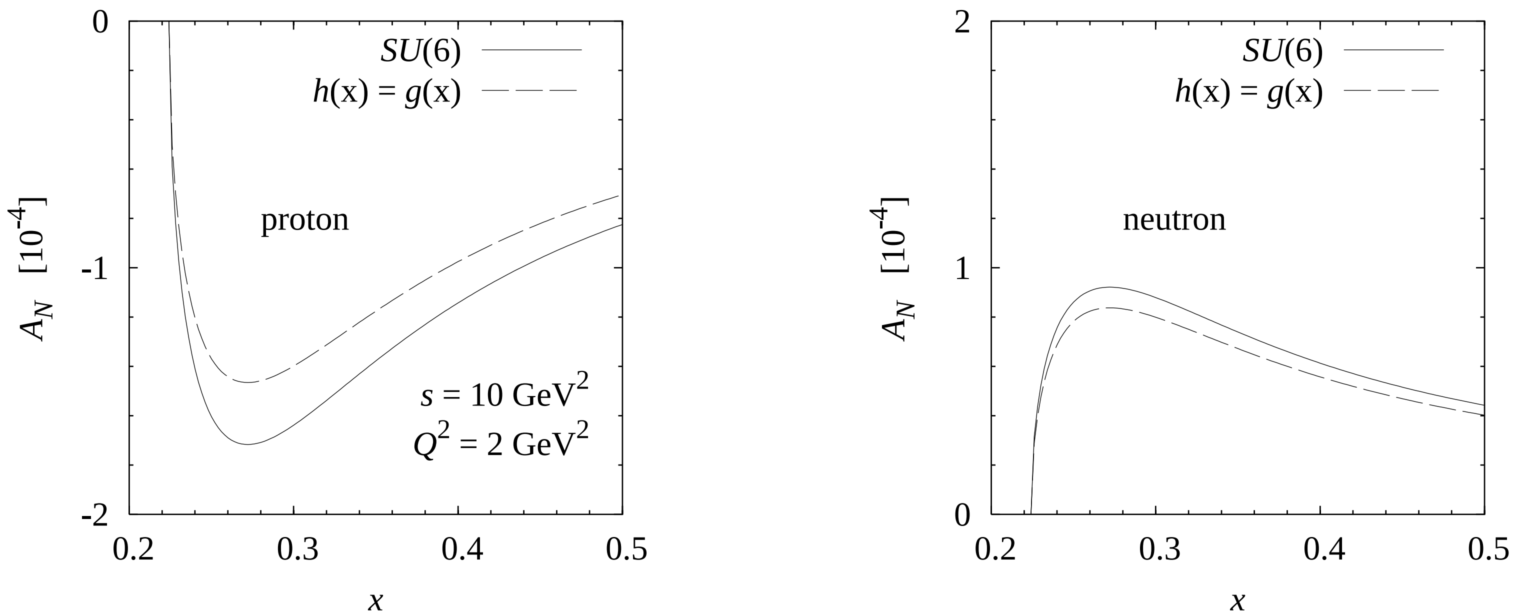
$$k'^0 \frac{d\sigma^N_{pol}}{d^3\vec{k}'} = \frac{4\alpha^3_{em}}{Q^8} M\, x^2 y(1-y)\, \varepsilon^{S_N P k k'} \sum_q e_q^3$$
$$\times \Bigg[\Bigg(x g_T^q(x) - g_{1T}^{(1)q}(x) - \frac{m_q}{M} h_1^q(x)\Bigg)\Bigg(\ln\frac{Q^2}{\lambda^2} + H_1(y)\Bigg)$$
$$+ \frac{m_q}{M} h_1^q(x) H_2(y)\Bigg]$$

  - 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
    $\rightarrow$ they use transversity projector containing m_q
    $\rightarrow$ calculation becomes identical to that for lepton SSA
    $\rightarrow$ transversity result IR-finite
  - inclusion of quark-gluon-quark correlator

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

$\rightarrow$ IR-divergence cancels (work in progress)

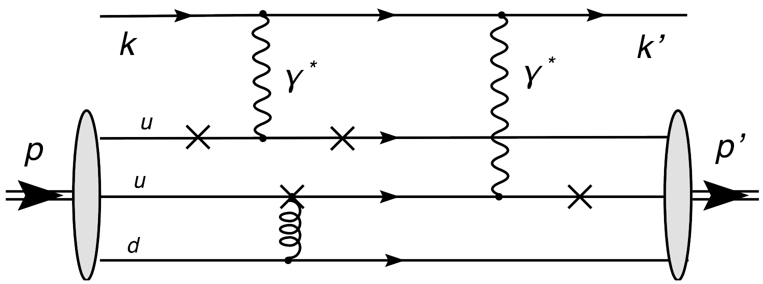
- Estimate of transversity contribution for A_{UT}^{N} (Afanasev, Strikman, Weiss, 2007)



  - 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

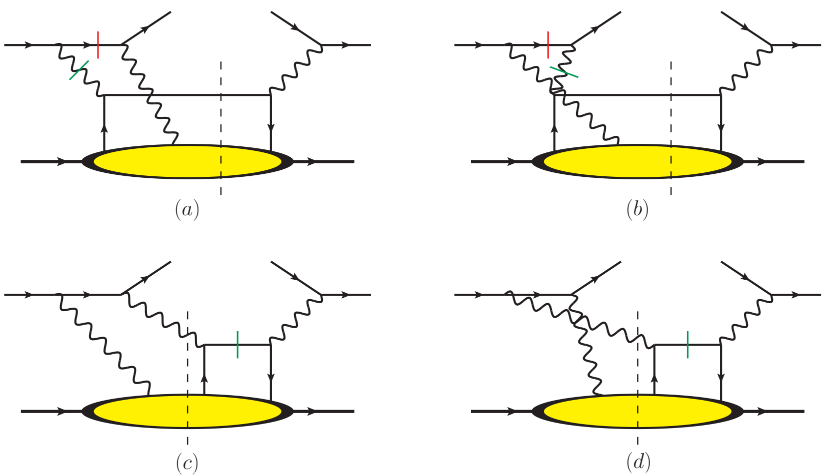
Photons coupling to different quarks

- 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

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 (collinear twist-3 factorization)

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

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

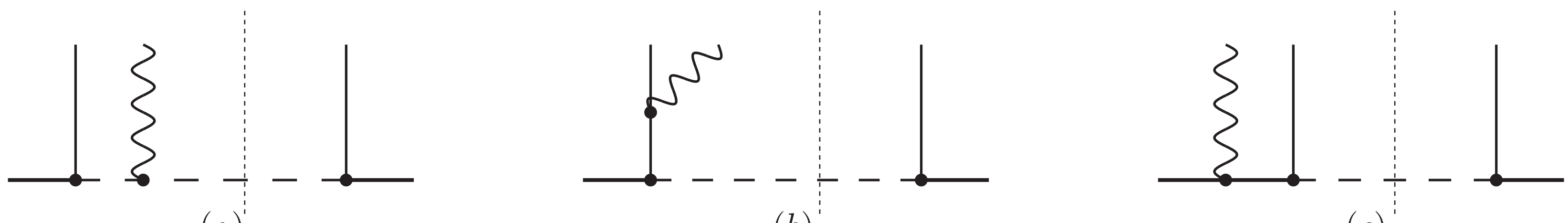
  - calculation in Feynman gauge and in light-cone gauge
  - can be compared to $qq' \to q'q$ channel calculation in Kouvaris, Qiu, Vogelsang, Yuan (2006) $\to$ full agreement
  - derivative term dominates at large x: $\quad F_{FT} \sim \ldots (1-x)^{\tilde{\beta}}$

- 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 light-front quark model
    (acknowledge discussion with Lorcé and Pasquini)

Input for T_F

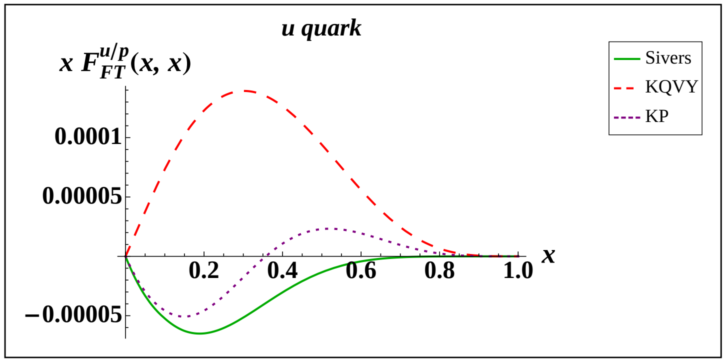
- T_F from HERMES and COMPASS data on $\ell N^{\uparrow} \to \ell' h X$
  - extraction of $f_{1T}^{\perp}$ by Anselmino et al. (2008)
  - use relation between $f_{1T}^{\perp}$ and T_F
  - same general conclusions for other extractions

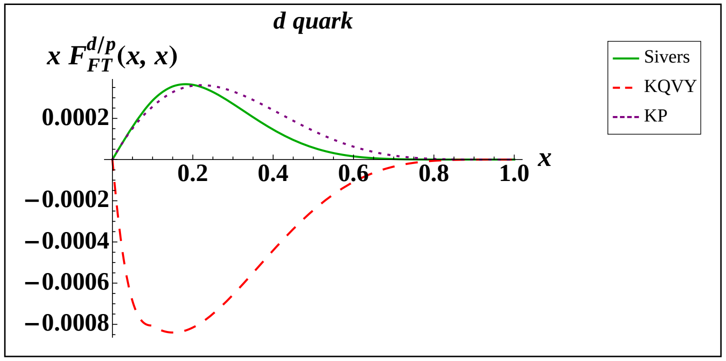
- T_F from FNAL and RHIC data on $p^{\uparrow} p \to h X$ and $\bar{p}^{\uparrow} p \to h X$
  - extraction by Kouvaris, Qiu, Vogelsang, Yuan (2006) (FIT I: no antiquarks)

- 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 p_T) in $f_{1T}^{\perp}$

Numerical results for F_{FT}

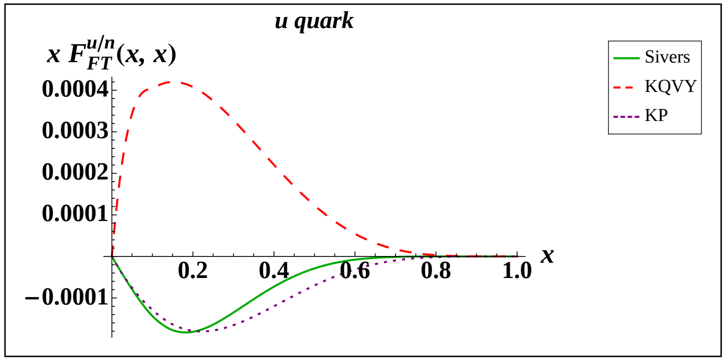
- Proton

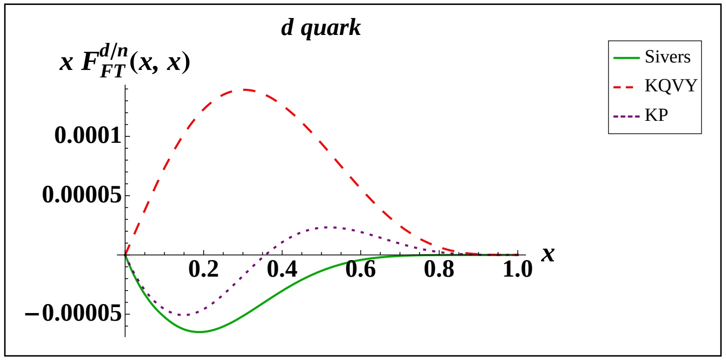




  – side-remark: large N_c analysis predicts: $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$ (Pobylitsa, 2003)

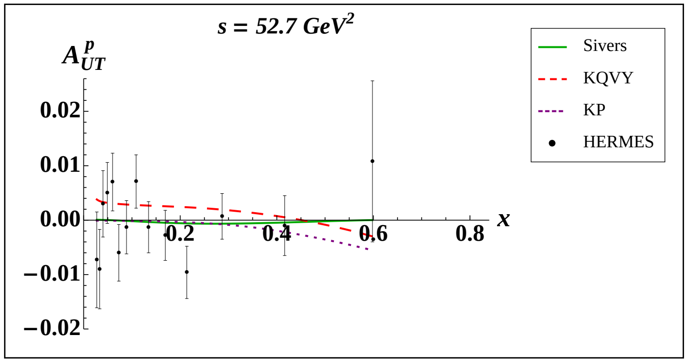
- Neutron

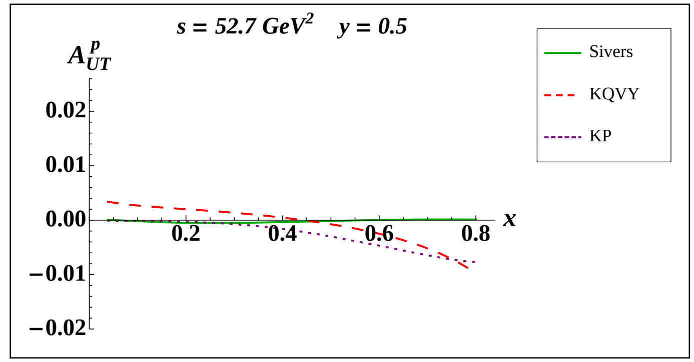




Numerical results for asymmetries

- Proton

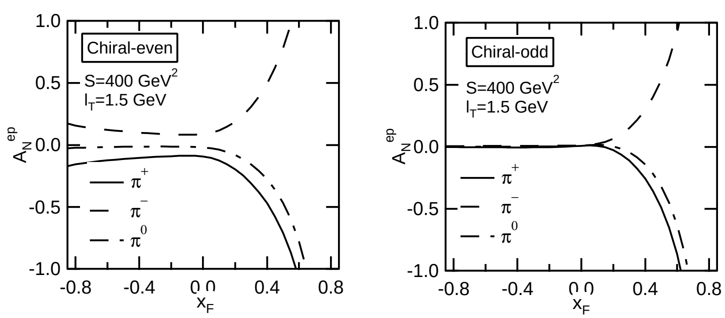


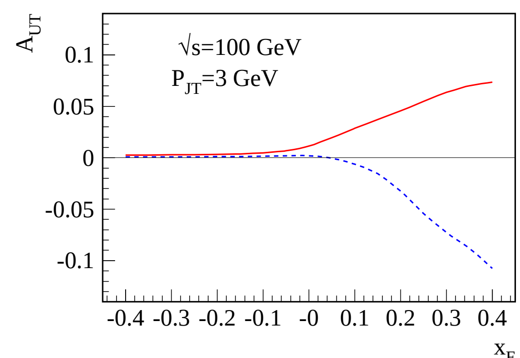


  - Sivers function input in perfect agreement with data
  - KQVY seems somewhat too large at large x; even diverges for $x \to 1$

    $\longrightarrow$ similar observation for other processes

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

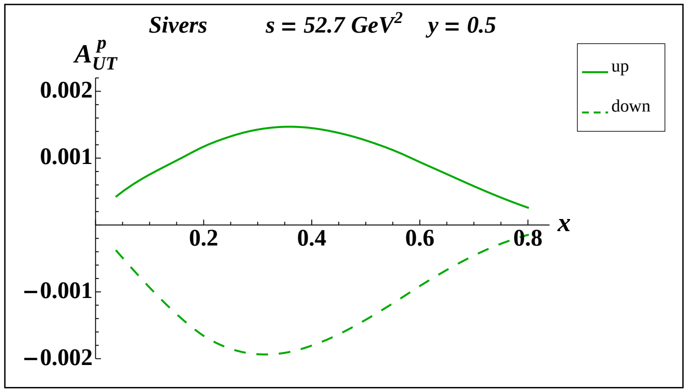


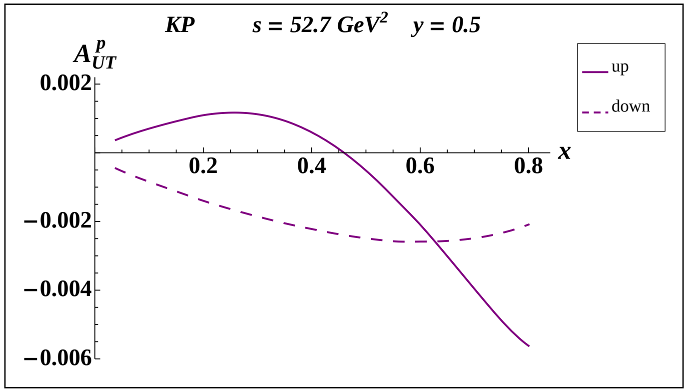


$\longrightarrow$ side-remark: data on $\ell p^\uparrow \to hX$ from HERMES, COMPASS would be useful !

– KP seems somewhat too large at large x; does not diverge for $x \to 1$
$\longrightarrow$ node in x not preferred

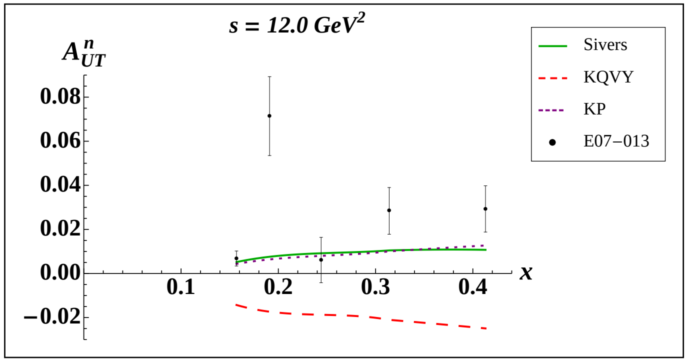
– individual flavor contributions

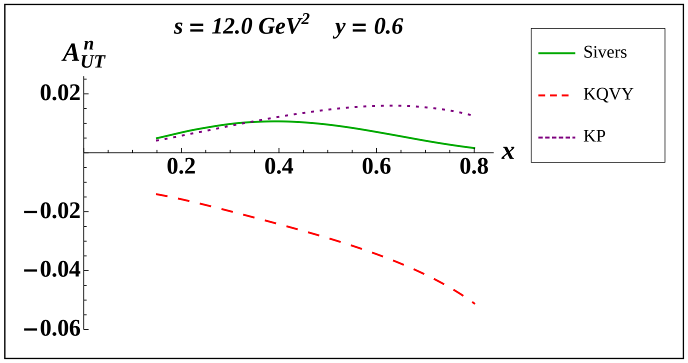




$\longrightarrow$ Sivers: individual contributions small, plus cancellation
$\longrightarrow$ KP: due to node in $f_{1T}^{\perp u/p}$ no cancellation at larger x

- Neutron



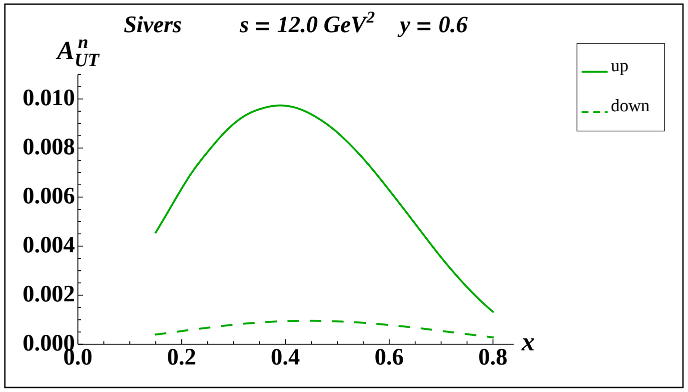


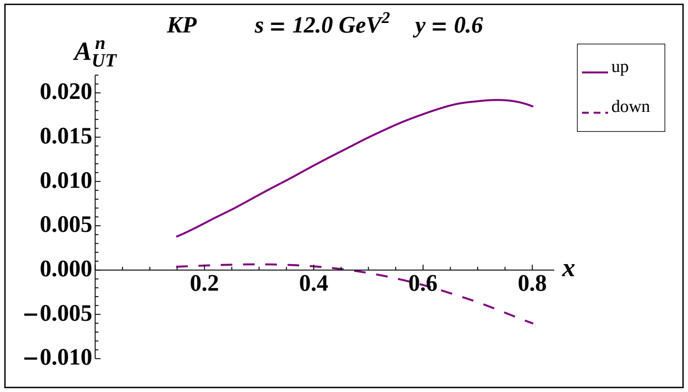
– Sivers function input in reasonable agreement with preliminary data
(sign, order of magnitude)
$\longrightarrow$ wrong sign if f_{1T} had node in p_T
$\longrightarrow$ this finding agrees with recent work by Kang, Prokudin, 2012

– 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_{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 observed in various hard scattering processes
- Focus on inclusive DIS — 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 p_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) generated by re-scattering of active partons; c.f. reversed sign of $f_{1T}^{\perp}$ between semi-inclusive DIS and Drell-Yan (Collins, 2002)