

# Transversity in Hard Exclusive Electroproduction of Pions

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## Outline:

- Pion electroproduction to leading-twist accuracy
- Pion pole, GPDs
- Transversity and a twist-3 contribution
- Results
- Transversity in vector-meson production?
- Summary

based on work done in collaboration with [S. Goloskokov, arXiv:0906.0460 \[hep-ph\]](#)

# The leading $\gamma^* p \rightarrow \pi^+ n$ amplitudes

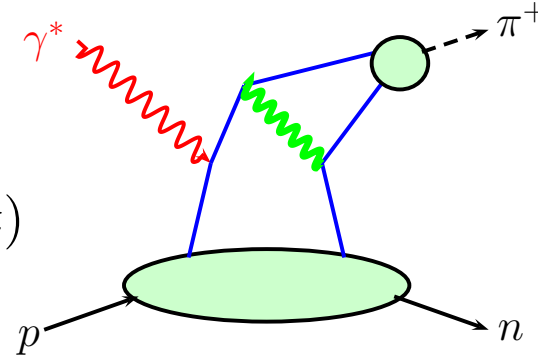
$$\mathcal{M}_{0+,0+}(\pi^+) = \sqrt{1-\xi^2} \frac{e_0}{Q} \left\{ \langle \tilde{H}^{(3)} \rangle - \frac{\xi^2}{1-\xi^2} \langle \tilde{E}_{n.p.}^{(3)} \rangle - \frac{2m\xi Q}{1-\xi^2} \frac{\rho_\pi}{t-m_\pi^2} \right\},$$

$$\mathcal{M}_{0-,0+}(\pi^+) = \frac{e_0}{Q} \frac{\sqrt{-t'}}{2m} \left\{ \xi \langle \tilde{E}_{n.p.}^{(3)} \rangle + 2mQ^2 \frac{\rho_\pi}{t-m_\pi^2} \right\},$$

$$t' = t - t_0, \quad \xi \simeq x_{Bj}/2, \quad F^{(3)} = F^u - F^d$$

convolution:

$$\langle F \rangle = \sum_\lambda \int_{-\xi}^1 dx \mathcal{H}_{0\lambda,0\lambda}(x, \xi, Q^2, t=0) F(x, \xi, t)$$



**GK:** subprocess amplitudes worked out in modified pert. approach:

LO pQCD + quark trans. momenta and Sudakov suppressions

for  $Q^2 \rightarrow \infty \implies$  lead. twist (collinear approximation) (Sterman et al)

# Double distributions

integral representation ( $i = u, d$  valence quarks)

$$\tilde{H}^i(\bar{x}, \xi, t) = \int_{-1}^1 d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(\beta + \xi\alpha - \bar{x}) \tilde{f}_i(\beta, \alpha, t)$$

$\tilde{f}_i$  double distributions Mueller *et al* (94), Radyushkin (99)

advantage - polynomiality automatically satisfied

useful ansatz with relation to PDFs (reduction formula respected)

$$\tilde{f}_i(\beta, \alpha, t) = \Delta q_i(\beta) \Theta(\beta) \exp[(\tilde{b}_i + \tilde{\alpha}'_i \ln(1/\beta))t] \frac{3}{4} \frac{[(1 - |\beta|)^2 - \alpha^2]}{(1 - |\beta|)}$$

$\tilde{\alpha}'_h = 0.45 \text{ GeV}^{-2}$      $\tilde{b}_h = 0$      $t$ -dependence of Regge residue

Regge intercept and residue at  $t = 0$  included in PDF

$\tilde{E}_{n.p.}$  analogously, forward limit parameterized as

$$\tilde{e}_u = -\tilde{e}_d = \tilde{N}_e \beta^{-0.48} (1 - \beta)^5$$

$$\tilde{\alpha}'_e = 0.25 \text{ GeV}^{-2} \quad \tilde{b}_e = 0$$

# The pion pole contribution

pion exchange (small  $-t$ , large  $Q^2$ )

$$\rho_\pi = \sqrt{2}g_{\pi NN}F_\pi(Q^2)F_{\pi NN}(t')$$

$$F_\pi = [1 + Q^2/(0.50\text{GeV}^2)]^{-1}$$

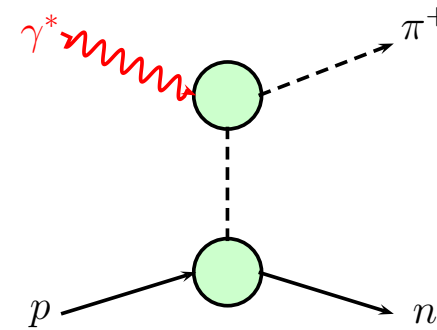
$$F_{\pi NN} = (\Lambda_N^2 - m_\pi^2)/(\Lambda_N^2 - t')$$

$\mathcal{M}_{0\pm,0+}^{\text{pole}}$  as before

$$\mathcal{M}_{0+, \pm\pm}^{\text{pole}} = \pm 2\sqrt{2}e_0\xi m\sqrt{-t'} \frac{\rho_\pi}{t - m_\pi^2},$$

$$\mathcal{M}_{0-, \pm\pm}^{\text{pole}} = \pm\sqrt{2}e_0t' \sqrt{1 - \xi^2} \frac{\rho_\pi}{t - m_\pi^2}.$$

transverse amplitudes very small



full pion FF needed and non-pole  $\tilde{E}$

see Goloskokov-K(09), Bechler-Mueller (09) (analysis of  $d\sigma/dt$  and  $A_{UT}^{\sin(\phi-\phi_s)}$  using coll. factorization.)

lead. twist accuracy: only pert. contr. to pion FF

(about 1/3 of exp. value measured in same reaction  $F_\pi - 2(08)$ )

fails with cross section by order of magnitude

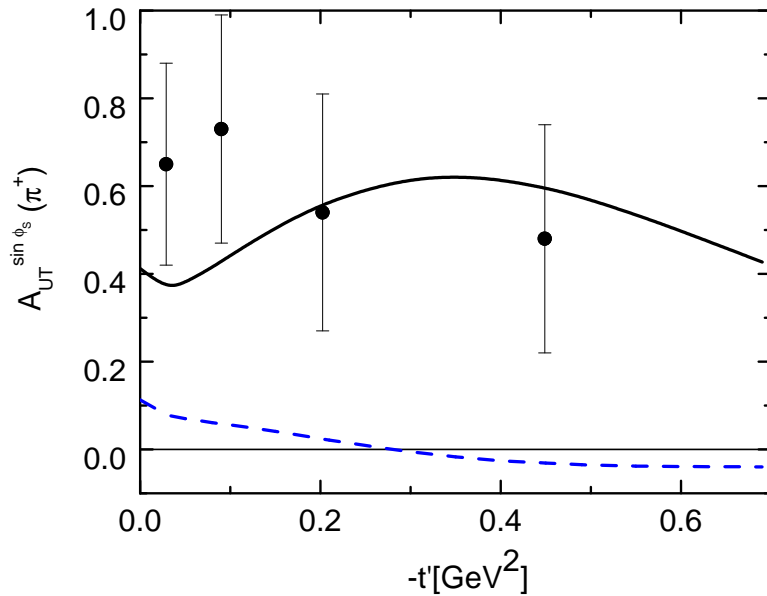
Mankiewicz et al (98), Frankfurt et al (99), Belitsky-Mueller (01),...

# Target asymmetries in electroproduction

observable	dominant interf. term	$\gamma^* p \rightarrow MB$ amplitudes	low $t'$ behavior
$A_{UT}^{\sin(\phi - \phi_s)}$	LL	$\text{Im} [\mathcal{M}_{0-,0+}^* \mathcal{M}_{0+,0+}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(\phi_s)}$	LT	$\text{Im} [\mathcal{M}_{0-,++}^* \mathcal{M}_{0+,0+}]$	const.
$A_{UT}^{\sin(2\phi - \phi_s)}$	LT	$\text{Im} [\mathcal{M}_{0\mp,-+}^* \mathcal{M}_{0\pm,0+}]$	$\propto t'$
$A_{UT}^{\sin(\phi + \phi_s)}$	TT	$\text{Im} [\mathcal{M}_{0-,++}^* \mathcal{M}_{0+,++}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(2\phi + \phi_s)}$	TT	$\propto \sin \theta_\gamma$	$\propto t'$
$A_{UT}^{\sin(3\phi - \phi_s)}$	TT	$\text{Im} [\mathcal{M}_{0-, -+}^* \mathcal{M}_{0+, -+}]$	$\propto (-t')^{(3/2)}$
$A_{UL}^{\sin(\phi)}$	LT	$\text{Im} [\mathcal{M}_{0-,++}^* \mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$

$\phi$  azimuthal angle between lepton and hadron plane;  $\phi_s$  orientation of target spin vector;  $\theta_\gamma$  rotation from direction of incoming lepton to virtual photon one  $\pi^+$ : all measured; detailed information on amplitudes

# Transverse photon polarization matters



HERMES(09)

$Q^2 \simeq 2.5 \text{ GeV}^2$ ,  $W = 3.99 \text{ GeV}$

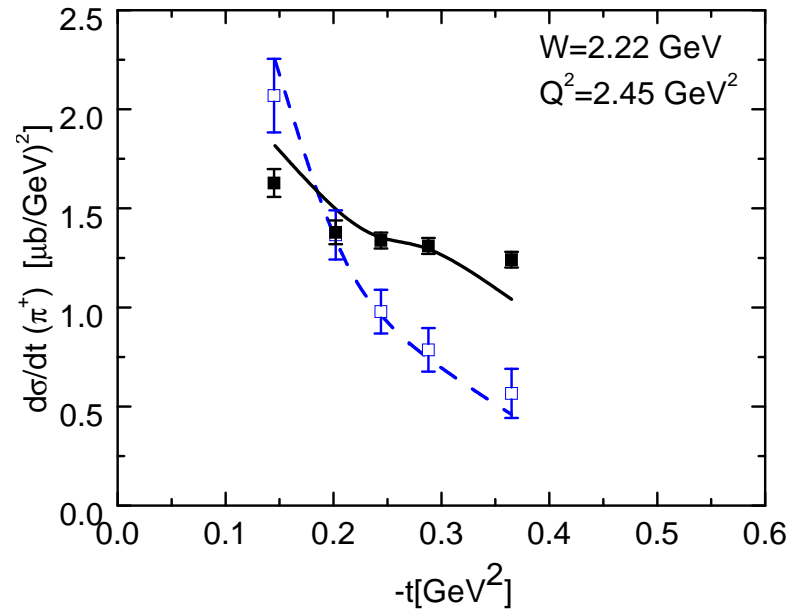
$\sin \phi_s$  moment very large

does not seem to vanish for  $t' \rightarrow 0$

$$A_{UT}^{\sin \phi_s} \propto \text{Im} \left[ M_{0-,++}^* M_{0+,0+} \right]$$

n-f. ampl.  $\mathcal{M}_{0-,++}$  required

$\gamma_T^* \rightarrow P$  transitions substantial

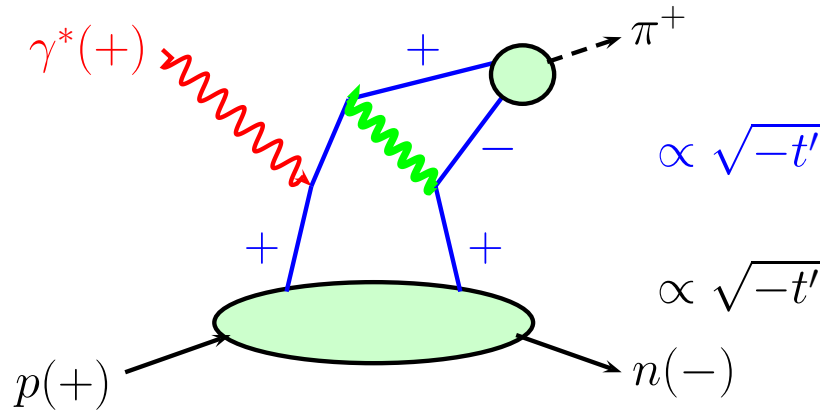


JLab  $F_\pi - 2(08)$

black:  $\sigma_T$     blue:  $\sigma_L$

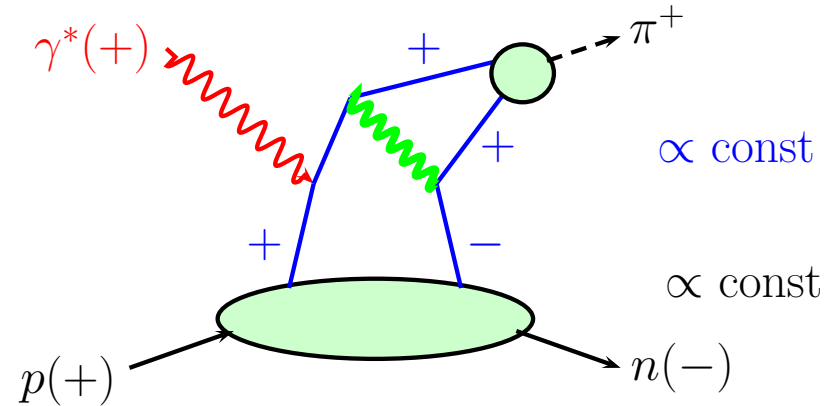
$\sigma_T$  large at large  $-t$

# $\mathcal{M}_{0-,++}$ within the handbag approach



lead. twist pion wave fct.  $\propto q' \cdot \gamma \gamma_5$   
 (perhaps including  $\mathbf{k}_\perp$ )

$$\mathcal{M}_{0-,++} \propto t'$$



twist-3 w.f.

$$\mathcal{M}_{0-,++} \propto \text{const}$$

helicity flip GPDs ( $H_T, E_T, \tilde{H}_T, \tilde{E}_T$ ) required  
 Hoodbhoy-Ji (98), Diehl (01)

## A twist-3 contribution

$$\mathcal{M}_{0-, \mu+}^{\text{twist-3}} = e_0 \sqrt{1 - \xi^2} \int_{-\xi}^1 d\bar{x} \left\{ \mathcal{H}_{0-, \mu+} \left[ H_T^{(3)} - \frac{\xi}{1 - \xi^2} (\xi E_T^{(3)} - \tilde{E}_T^{(3)}) \right] \right. \\ \left. + (\mathcal{H}_{0+, \mu-} - \mathcal{H}_{0-, \mu+}) \frac{t'}{4m^2} \tilde{H}_T^{(3)} \right\}$$

$$\mathcal{M}_{0+, \mu+}^{\text{twist-3}} = e_0 \frac{\sqrt{-t'}}{2m} \int_{-\xi}^1 d\bar{x} \left\{ (\mathcal{H}_{0+, \mu-} - \mathcal{H}_{0-, \mu+}) \tilde{H}_T^{(3)} \right. \\ \left. + [(1 - \xi)\mathcal{H}_{0+, \mu-} - (1 + \xi)\mathcal{H}_{0-, \mu+}] E_T^{(3)} / 2 \right. \\ \left. + [(1 - \xi)\mathcal{H}_{0+, \mu-} + (1 + \xi)\mathcal{H}_{0-, \mu+}] \tilde{E}_T^{(3)} / 2 \right\}$$

at small  $\xi$  and small  $t'$ :  $H_T$  dominant in  $\mathcal{M}_{0-, ++}$

in  $\mathcal{M}_{0-, -+}$  suppressed by  $t'/Q^2$

twist-3 in long. amplitudes suppressed by  $\sqrt{-t'}/Q$



## The twist-3 pion distr. amplitude

projector  $q\bar{q} \rightarrow \pi$  (3-part.  $q\bar{q}g$  contr. neglected) Beneke-Feldmann (01)

$$\sim q' \cdot \gamma \gamma_5 \Phi + \mu_\pi \gamma_5 \left[ \Phi_P - i \sigma_{\mu\nu} (\dots \Phi'_\sigma + \dots \Phi_\sigma \partial / \partial \mathbf{k}_\perp \nu) \right]$$

definition:  $\langle \pi^+(q') | \bar{d}(x) \gamma_5 u(-x) | 0 \rangle = f_\pi \mu_\pi \int d\tau e^{-i\tau q' \cdot x} \Phi_P(\tau)$

local limit  $x \rightarrow 0$  related to divergency of axial vector current

$$\implies \mu_\pi = m_\pi^2 / (m_u + m_d) \simeq 2 \text{ GeV at scale } 2 \text{ GeV (conv. } \int d\tau \Phi_P(\tau) = 1)$$

Eq. of motion:  $\tau \Phi_P = \Phi_\sigma / N_c - \tau \Phi'_\sigma / (2N_c)$

solution:  $\Phi_P = 1, \quad \Phi_\sigma = \Phi_{AS}$  Braun-Filyanov (90)

$\mathcal{H}_{0-,++} \neq 0$ ,  $\Phi_P$  dominant,  $\Phi_\sigma$  contr.  $\propto t'/Q^2$

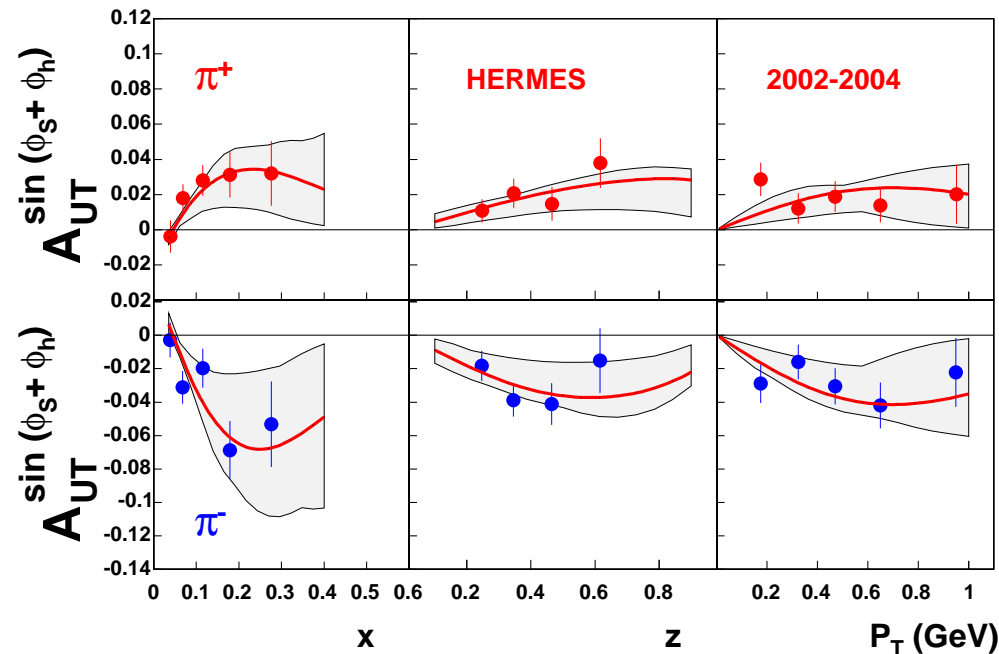
# Modeling $H_T$

small  $\xi$ : use double distr. model;  $H_T^a(x, 0, 0) = \delta^a(x)$

take transversity PDF from [Anselmino et al \(07\)\(08\)](#)

large errors

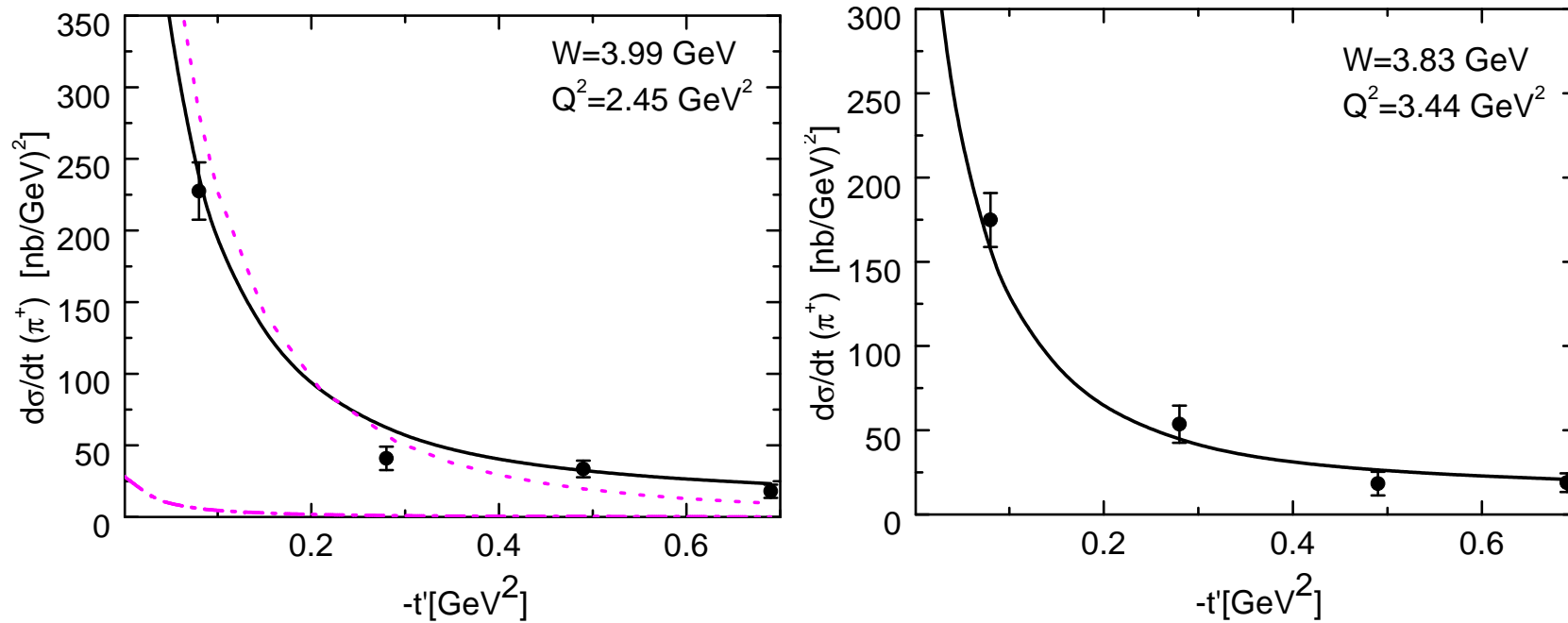
$$\delta^a = 7.46 N_T^a x(1-x)^5 [q_a(x) + \Delta q_a(x)] \quad N_T^u = 0.5 \quad N_T^d = -0.6$$



combined analysis of  
transv. PDFs and Collins fcts.  
HERMES and COMPASS SIDIS  
and BELLE  $e^+e^- \rightarrow h_1 h_2 X$  data  
 $A_{UT}^{\sin(\phi+\phi_s)} \propto \delta \otimes \Delta \hat{\sigma} \otimes \Delta^N D_{\pi/q \uparrow}$

fixes scale of  $H_T$ ,  $t$ -dependence free ( $\alpha'_T = 0.45 \text{ GeV}^{-2}$ ,  $b_T = 0.9 \text{ GeV}^{-2}$ )

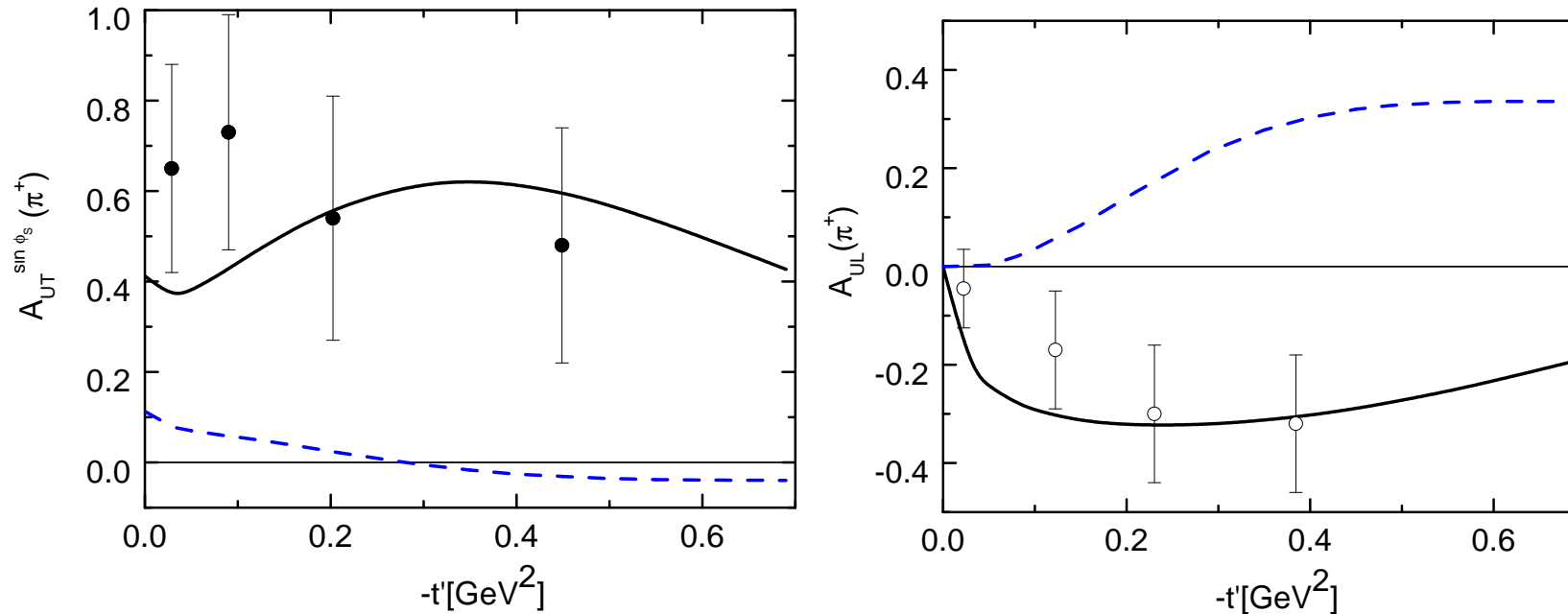
# Results on unseparated $\pi^+$ cross section



data from [HERMES 07](#)

magenta lines: pion pole contr. (unseparated and transverse cross sections)

# Results on target asymmetries

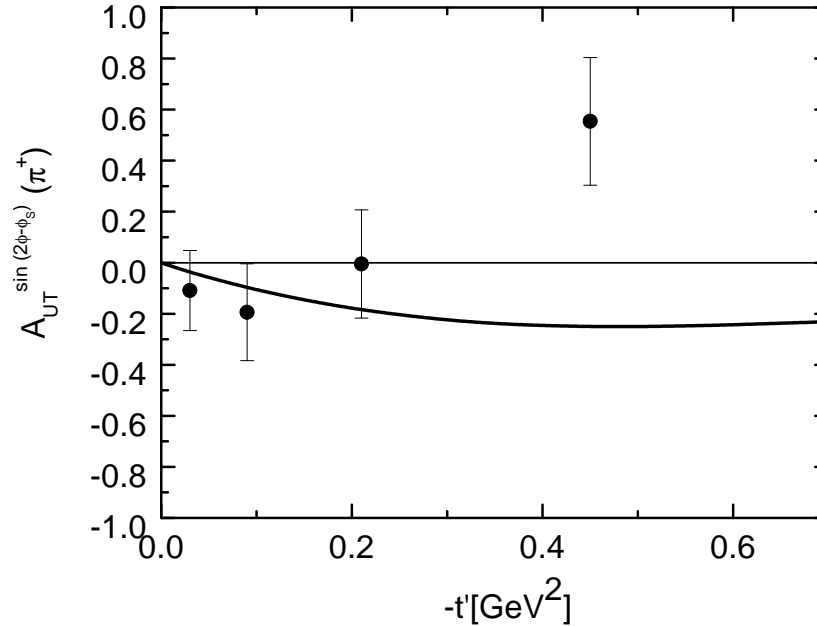
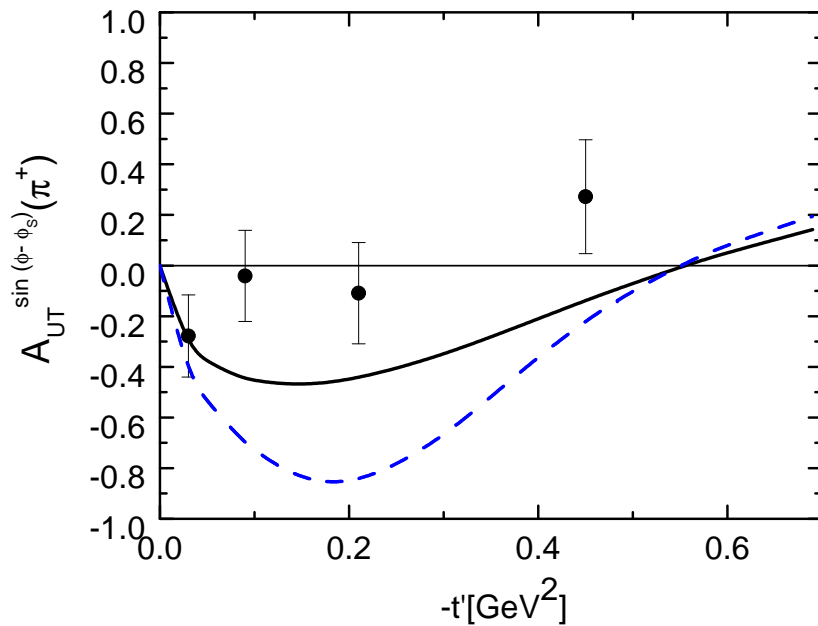


$$Q^2 = 2.5 \text{ GeV}^2 \quad W = 3.99 \text{ GeV}$$

data on  $A_{UT}$  HERMES (08);  $A_{UL}$  HERMES(02)

blue lines: without twist-3 contr.

# Results continued



$$Q^2 = 2.5 \text{ GeV}^2 \quad W = 3.99 \text{ GeV}$$

data on  $A_{UT}$  HERMES (08)

blue: only LL contr.

other asymmetries:  $|A_{UT}| < 0.1$  in agreement with exp.

# Summary

- analysis of  $\pi^+$  electroproduction within handbag approach, full pion form factor taken into account;  $\tilde{H}$ ,  $\tilde{E}$  modeled with double distr. ansatz
- clear indication in data for contr. from  $\gamma_T^* \rightarrow \pi$  transitions amplitude  $\mathcal{M}_{0-,++}$  particular important
- within handbag approach  $\mathcal{M}_{0-,++}$  is fed by transversity (chiral odd) GPDs accompanied by twist-3 pion wave fct.
- $H_T$  modeled with double distr., forward limit - transversity PDFs - taken from analysis of  $A_{UT}$  for SIDIS
- relates transversity in excl. processes to transversity in inclusive data
- fair description of data