Transversity in electroproduction of pseudoscalar mesons

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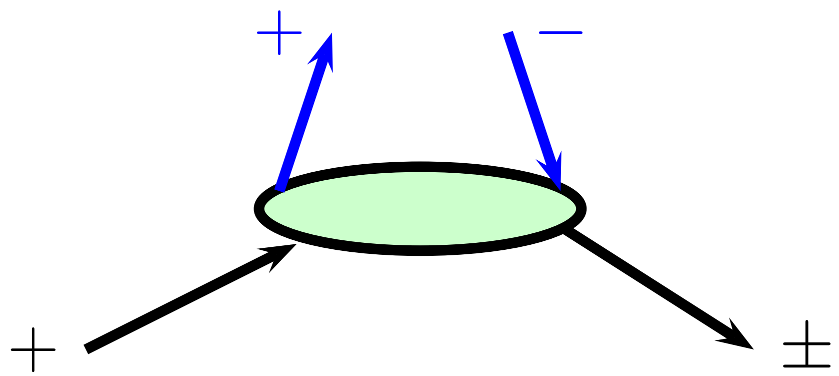
Outline:

- **Transverse spin**
- **Evidence for strong $\gamma_T^* \to \pi$ transitions**
- **Transversity in the handbag approach**
- **Parametrizations of the GPDs**
- **Results**
- **Summary**

Transverse spin



transversely pol. quarks
EV of σ_2 (σ_1):
$|\uparrow(\downarrow)\rangle = 1/\sqrt{2}\big[|+\rangle \pm i|-\rangle\big]$
requires helicity flip

inclusive: transversity distributions $\Delta_T q(x)$ ($h_1(x)$)
not accessible in DIS but in SIDIS (analysis Anselmino et al (09))

exclusive: transv. GPDs H_T , $\widetilde{H}_T$, E_T , $\widetilde{E}_T$ (lead. twist)
soft matrix elements $\sim \langle p'|\bar{q}(-z/2)i\sigma^{+i}q(z/2)|p\rangle$ Hoodbhoy-Ji (98), Diehl (01)
reduction formula: $H_T^q(x, \xi = t = 0) = \Delta_T q(x)$
difficult to access in exp: helicity flip of light quarks suppressed
only a few applications: Pire et al electroproduction of ρ_T
Liuti et al production of π^0
Goloskokov-K production of pseudoscalar mesons

An almost model-independent argument

consider pion electroproduction

sum and difference of single-flip ampl. ($\sim \sqrt{-t'}$ for $t' \to 0$)

$$\mathcal{M}^{N(U)}_{0+\mu+} = \frac{1}{2}\Big[\mathcal{M}_{0+\mu+} + (-)\mathcal{M}_{0+-\mu+}\Big] \qquad\qquad \mu = \pm 1$$

$$\Longrightarrow \qquad\qquad \mathcal{M}^{N(U)}_{0+-+} = +(-)\mathcal{M}^{N(U)}_{0+++}$$

like a one-particle-exchange of either Natural or Unnatural parity

nucleon helicity flip: $\qquad \mathcal{M}_{0--+} \sim t' \qquad \mathcal{M}_{0-++} \sim const$

sum and difference inconvenient

(const can be small (or zero) for dynamical reasons)

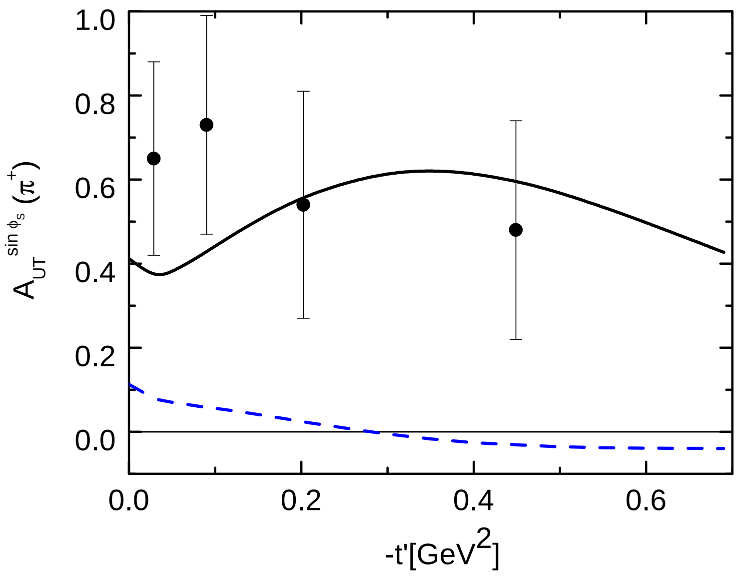
Experiment:

$\gamma p \to \pi^+ n$ cross section exhibits pronounced maximum

c cannot be small

Phillips (1967): Regge cuts necessary

Pion electroproduction



HERMES(09)

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

$\sin\phi_s$ harmonic very large

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

$A_{UT}^{\sin\phi_S} \propto \mathrm{Im}\left[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+}\right]$

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

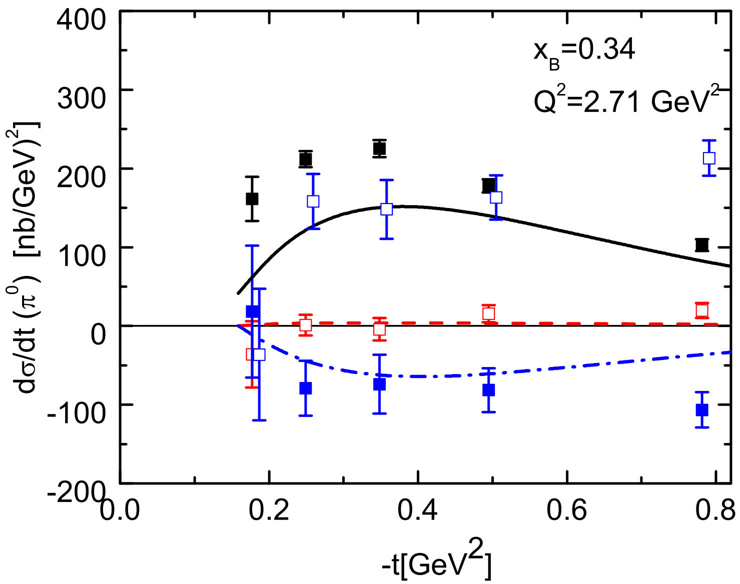
not vanishing in forward direction

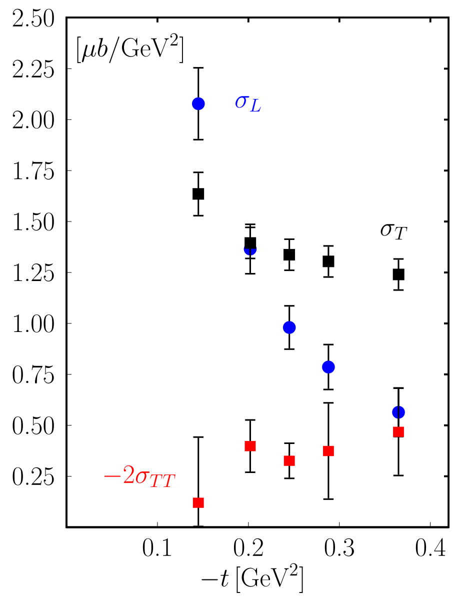
assumption: $|\mathcal{M}_{0--+}| \ll |\mathcal{M}_{0-++}|, |\mathcal{M}_{0+\pm+}|$

Transverse cross sections

$$\frac{d\sigma_T}{dt} \simeq \frac{1}{2\kappa}\Big[|\mathcal{M}_{0-++}|^2 + 2|\mathcal{M}^N_{0+++}|^2 + 2|\mathcal{M}^U_{0+++}|^2\Big] \qquad \frac{d\sigma_{TT}}{dt} \simeq -\frac{1}{2\kappa}\Big[|\mathcal{M}^N_{0+++}|^2 - |\mathcal{M}^U_{0+++}|^2\Big]$$

$$\frac{d\sigma_T}{dt} + 2\frac{d\sigma_{TT}}{dt} \simeq \frac{1}{2\kappa}\Big[|\mathcal{M}_{0-++}|^2 + 4|\mathcal{M}^U_{0+++}|^2\Big] \qquad \Rightarrow -2\frac{d\sigma_{TT}}{dt} \le \frac{d\sigma_T}{dt} \le \frac{d\sigma}{dt}$$





π^0 CLAS

unsep. cross sec.

π^+ $F-\pi$

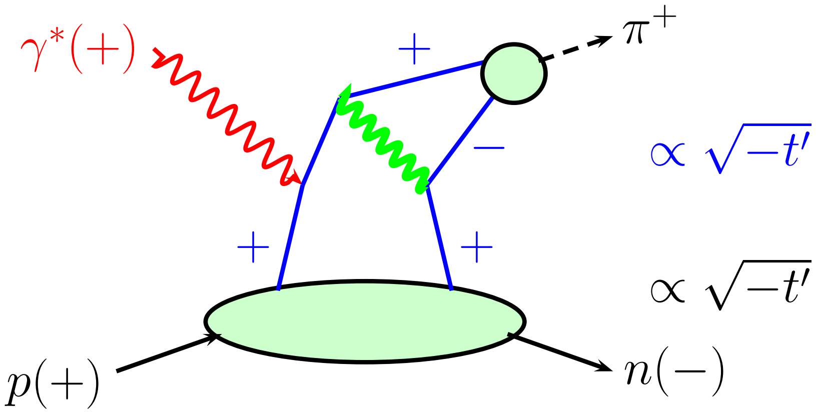
$Q^2 = 2.45\,\mathrm{GeV}^2$

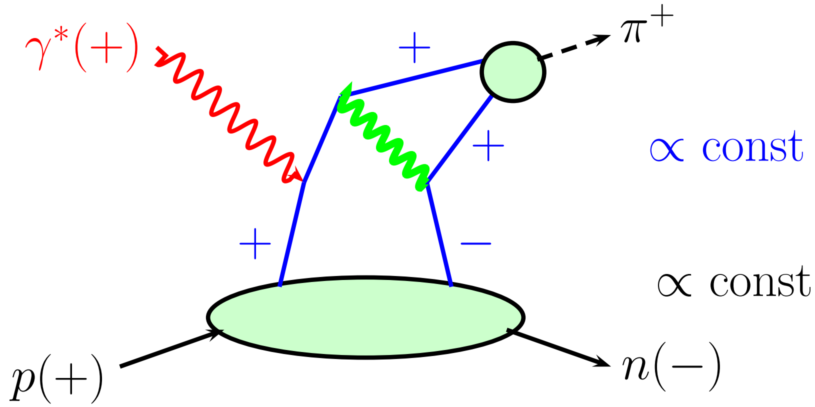
$W = 2.22\,\mathrm{GeV}$

$\pi^0 \quad \Longrightarrow |M^N_{0+++}|$ dominant (for $-t' > 0$ see forward dip)

$(d\sigma_L/dt << d\sigma_T/dt)$

Handbag: can $\mathcal{M}_{0-,++}$ be fed by ordinary GPDs?





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

twist-3 w.f.
(suppressed by μ_π/Q)

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

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

transv. GPDs in long. amplitudes suppressed by extra $\sqrt{-t'}/Q$

$\gamma_T^* \to \pi$ in the handbag approach

see Diehl01, GK10, GK11 $\qquad \overline{E}_T \equiv 2\widetilde{H}_T + E_T \qquad \mu = \pm 1$

$$\mathcal{M}_{0+\mu+} = e_0 \frac{\sqrt{-t'}}{4m} \int d\bar{x} \Big\{ \big(H_{0+\mu-} - H_{0-\mu+}\big)\big(\overline{E}_T - \xi \widetilde{E}_T\big) + \big(H_{0+\mu-} + H_{0-\mu+}\big)\big(\widetilde{E}_T - \xi E_T\big) \Big\}$$

$$\mathcal{M}_{0-\mu+} = e_0 \sqrt{1-\xi^2} \int d\bar{x} \Big\{ H_{0-\mu+} \Big[H_T + \frac{\xi}{1-\xi^2}\big(\widetilde{E}_T - \xi E_T\big)\Big] + \big(H_{0+\mu-} - H_{0-\mu+}\big)\frac{t'}{4m^2}\widetilde{H}_T \Big\}$$

with parity conservation: $\qquad \mathcal{M}_{0+\pm+} = \mathcal{M}^N_{0+++} \pm \mathcal{M}^U_{0+++}$

time-reversal invariance: $\widetilde{E}_T$ is odd function of ξ

N: $\overline{E}_T$ with corrections of order ξ^2 $\qquad$ U: order ξ

small $-t'$: $\mathcal{M}_{0-++}$ mainly H_T with corrections of order ξ^2

$\mathcal{M}_{0--+}$ suppressed by t/Q^2 due to H_{0--+}

The twist-3 pion distr. amplitude

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

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

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

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

$\Longrightarrow \mu_\pi = m_\pi^2/(m_u + m_d) \simeq 2\,\mathrm{GeV}$ at scale $2\,\mathrm{GeV}$ (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)

$H_{0-,++} \neq 0$, Φ_P dominant, Φ_σ contr. $\propto t'/Q^2$

in coll. appr.: $H_{0-,++}$ singular $\mathbf{k}_\perp$ factorization (m.p.a.) regular

$$M_{0-++} = e_0\sqrt{1-\xi^2}\int dx H_{0-++}H_T\,, \qquad M_{0-++} = -e_0\frac{\sqrt{-t'}}{4m}\int dx H_{0-++}\overline{E}_T$$

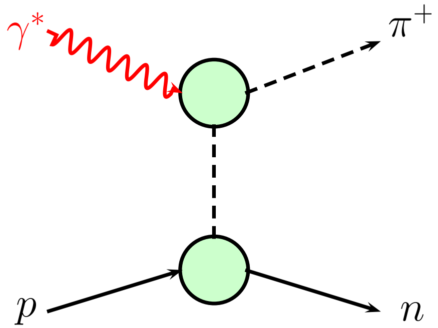
The $\gamma_L^* \to \pi$ amplitudes and pion pole

$$\mathcal{M}_{0+0+} = \frac{e_0}{2}\sqrt{1-\xi^2}\int dx (H_{0+0+} - H_{0-0-})\Big(\widetilde{H} - \frac{\xi^2}{1-\xi^2}\widetilde{E}_{\mathrm{n.p.}}\Big)$$

$$\mathcal{M}_{0-0+} = e_0\frac{\sqrt{-t'}}{4m}\int dx (H_{0+0+} - H_{0-0-})\xi\widetilde{E}_{\mathrm{n.p.}}$$

leading amplitudes for $Q^2 \to \infty$

For π^+ production - pion pole



$$\mathcal{M}^{\mathrm{pole}}_{0+0+} = -e_0\frac{2m\xi Q}{\sqrt{1-\xi^2}}\,\frac{\rho_\pi}{t-m_\pi^2}$$

$$\mathcal{M}^{\mathrm{pole}}_{0-0+} = -e_0\sqrt{-t'}Q\,\frac{\rho_\pi}{t-m_\pi^2}$$

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

$$\mathcal{M}^{\mathrm{pole}}_{0-\pm+} = \pm\sqrt{2}e_0 t'\sqrt{1-\xi^2}\,\frac{\rho_\pi}{t-m_\pi^2}\,!$$

$$\rho_\pi = \sqrt{2}g_{\pi NN}F_\pi(Q^2)F_{\pi NN}(t)$$

(see assumption 1 and following remarks)

Double distributions

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

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

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

advantage - polynomiality automatically satisfied

useful ansatz with relation to PDFs (reduction formula respected)

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

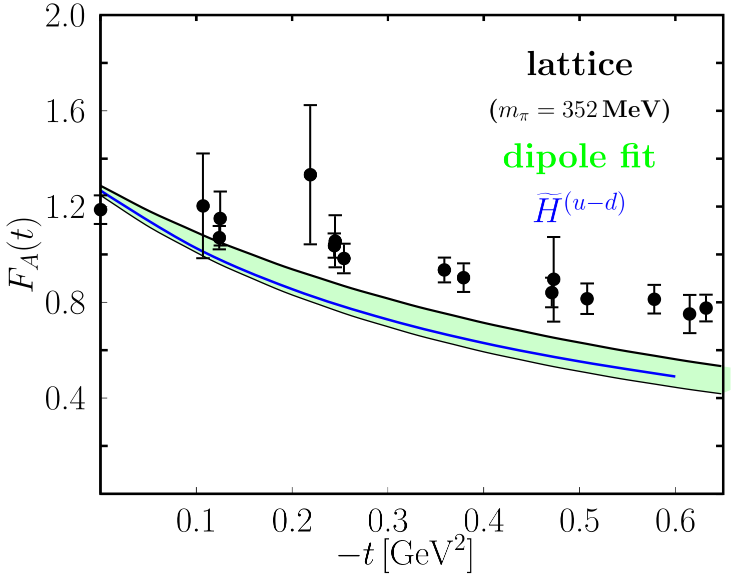
$\tilde{\alpha}_{h'}' = 0.45\,\mathrm{GeV}^{-2}$ $\tilde{b}_{h'} = 0.0$ t-dependence of Regge residue

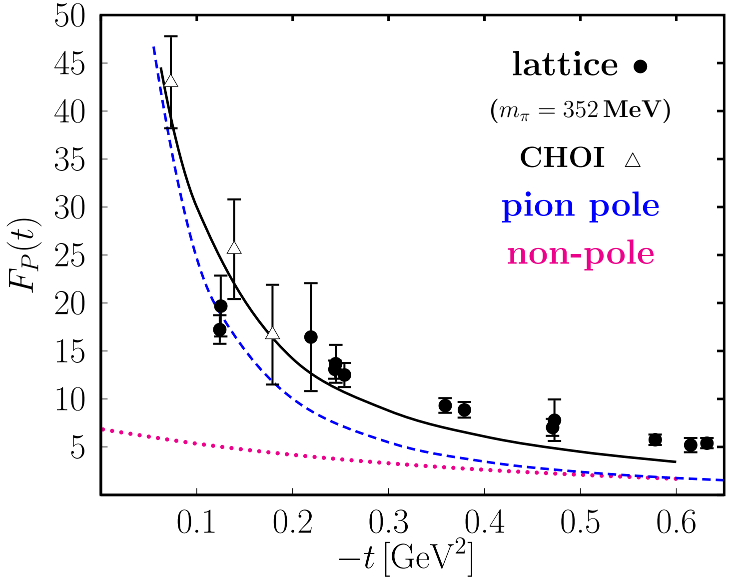
Regge intercept and residue at $t = 0$ included in PDF

$\widetilde{E}_{n.p.}$ analogously, forward limit parameterized as $\tilde{e}_q = \tilde{N}_q \beta^{-0.48}(1-\beta)^5$

$\tilde{N}_u = 14$ $\tilde{N}_d = 4$, $\tilde{\alpha}_e' = 0.45\,\mathrm{GeV}^{-2}$, $\tilde{b}_e = 0.9\,\mathrm{GeV}^{-2}$, values fitted to π^+ data

Comparison with lattice results





Hägler (07), Göckeler (05) lowest pion mass 352 MeV, no chiral extrapolation

in general at $t \simeq 0$ reasonable agreement but t dependences flatter than DD ansatz (and form factor data)
relative t dependence of moments in good agreement

Parametrization of H_T and $\overline{E}_T$

H_T: transversity PDFs Anselmino et al(09)

$\Delta_T q(x) = N^q_{H_T}\sqrt{x}(1-x)\big[q(x)+\Delta q(x)\big]$

DD ansatz

parameters: $\alpha(0)=-0.02$, $\alpha' = 0.45\,\mathrm{GeV}^{-2}$, $b=0$, $N^u = 0.78$, $N^d=-1.01$

$\overline{E}_T$: Lattice result for moments of $\overline{E}_T = 2\widetilde{H}_T + E_T$: QCDSF-UKQCD(06)

Large, same sign and almost same size for u and d quarks

$\overline{E}_T$ parameterization (like $\widetilde{E}_{\mathrm{n.p.}}$):

$e^a_T = \bar{N}^e_T e^{b_{eT}t} x^{-\alpha^e_T(t)}(1-x)^{\beta^a_{eT}}$

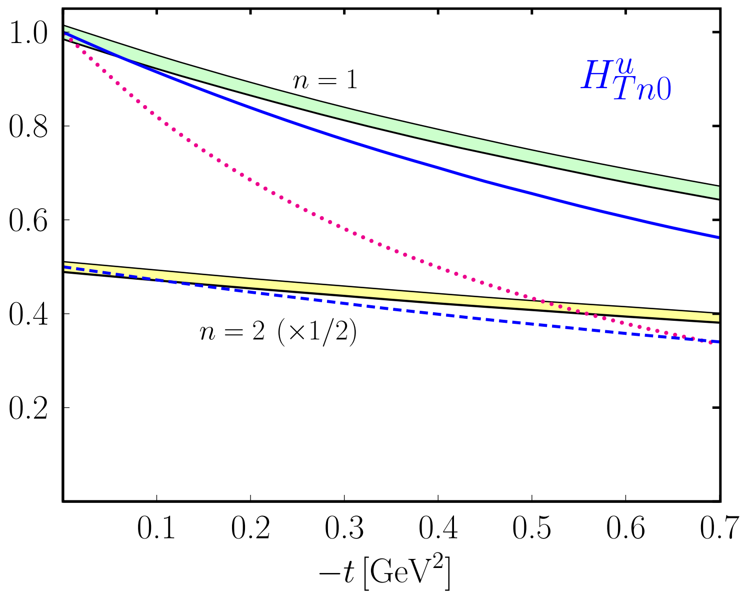
parameters: $\alpha(0)=0.3$, $\alpha' = 0.45\,\mathrm{GeV}^{-2}$, $b=0.5\,\mathrm{GeV}^{-2}$, $\bar{N}^u_T = 6.83$, $\bar{N}^d_T = 5.05$

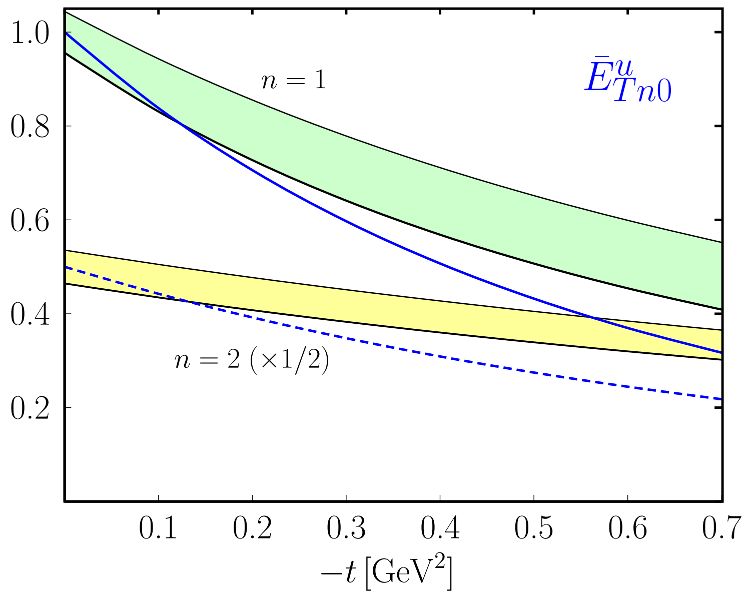
adjusted to lattice results

Burkardt related to Boer-Mulders fct $\langle\cos(2\phi)\rangle$ in SIDIS $-$ same pattern

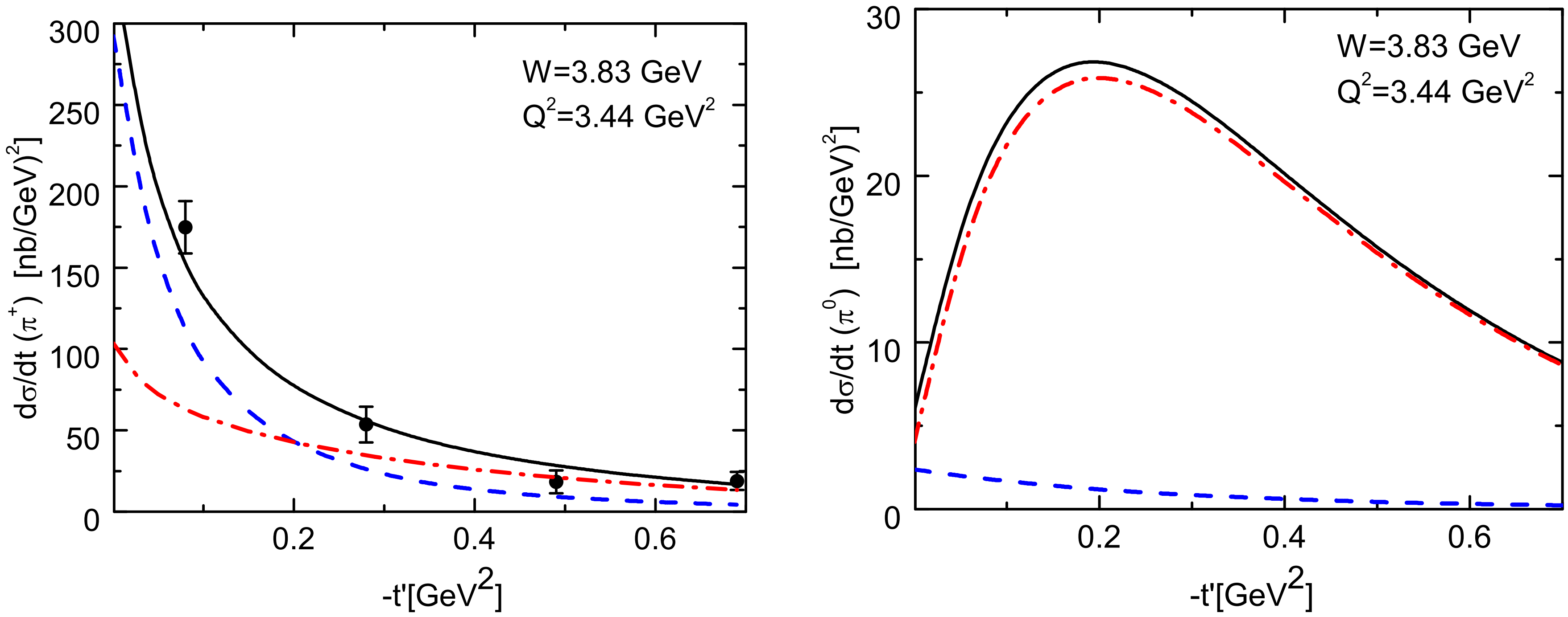
	lattice	this work		lattice	this work
H^u_{T10}	$0.857(13)$	0.585	$\bar{E}^u_{T10}$	$2.93(13)$	2.93
H^u_{T20}	$0.268(6)$	0.123	$\bar{E}^u_{T20}$	$0.420(31)$	0.360
H^d_{T10}	$-0.212(5)$	-0.153	$\bar{E}^d_{T10}$	$1.90(9)$	1.90
H^d_{T20}	$-0.052(2)$	-0.021	$\bar{E}^d_{T20}$	$0.260(23)$	0.199

H_T lattice moments are larger by about factor of 2 as those constructed from transversity PDFs with help of DD ansatz





$\overline{E}_T$ in pion electroproduction



unseparated (longitinal, transverse) cross sections

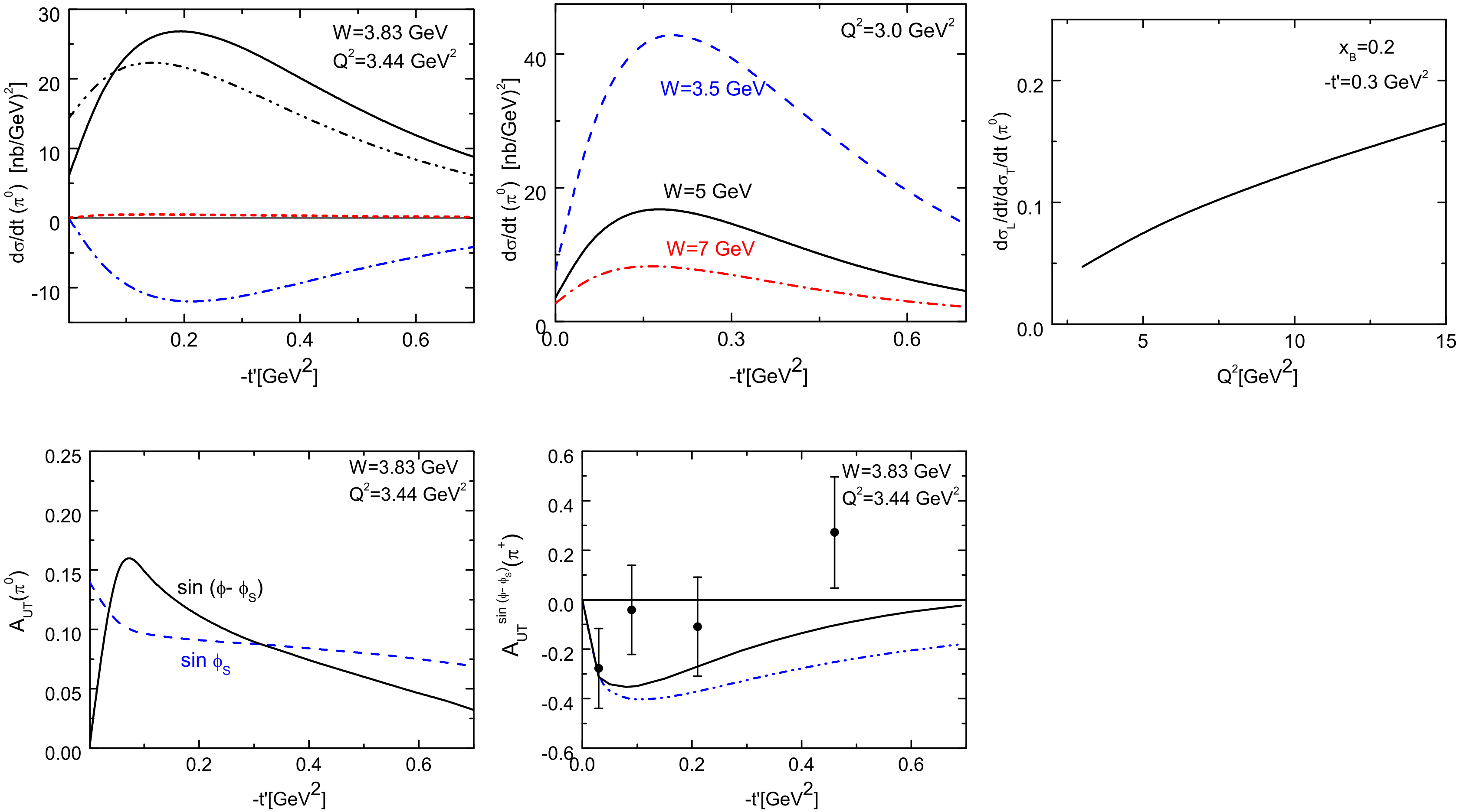
π^+: pion pole and $\propto F^u - F^d$ $\qquad$ π^0: no pion pole and $\propto 2F^u + F^d$

consider $u - d$ signs: $\quad \overline{E}_T$, $\widetilde{E}^{n.p.}$ same, $\quad \widetilde{H}, H_T$ opposite sign

$\Longrightarrow$ $\quad \widetilde{H}$ and H_T large for π^+, small for π^0

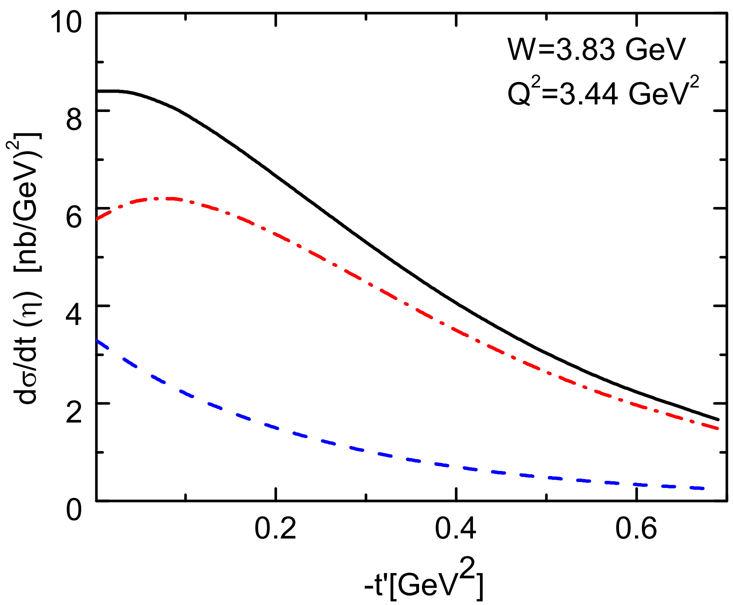
$\widetilde{E}^{n.p.}$ and $\overline{E}_T$ small for π^+, large for π^0

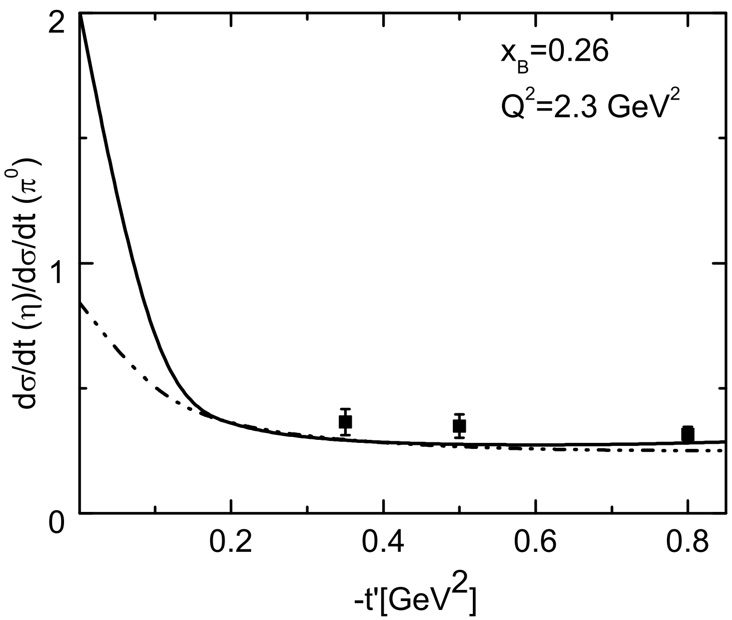
Results for pion production



Goloskokov-K (10),(11) optimized for small ξ and large W

η/π^0 ratio





data CLAS (prel.)

$$\frac{d\sigma(\eta)}{d\sigma(\pi^0)} \simeq \left(\frac{f_\eta}{f_\pi}\right)^2 \frac{1}{3} \left|\frac{e_u\langle F^u\rangle + e_d\langle F^d\rangle}{e_u\langle F^u\rangle - e_d\langle F^d\rangle}\right|^2 \qquad (f_\eta = 1.26 f_\pi)$$

if F^u and F^d have opposite sign: $\eta/\pi^0 \simeq 1$

if F^u and F^d have same sign: $\eta/\pi^0 < 1$

$t' \simeq 0$ $\widetilde{H}, H_T$ dominant (see also Eides et al(98))

$t' \neq 0$ $\overline{E}_T$ dominant

Strangeness production

e.g. $\gamma^* p \to K^+ \Lambda(\Sigma^0)$

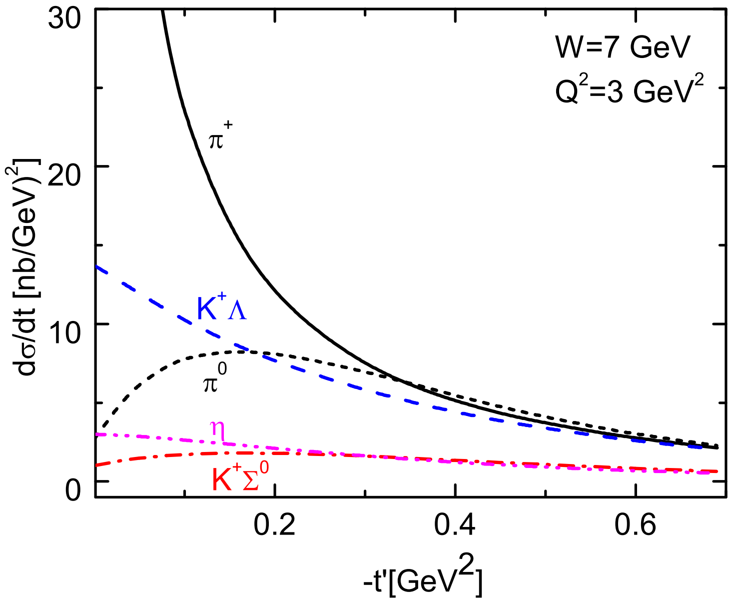
similar to π^+ production

Kaon pole (smaller than pion pole)

and

twist-3 effect with

$\mu_K = m_K^2/(m_u + m_s) \simeq 2.0\,\mathrm{GeV}$



would probe $\widetilde{H}$, $\widetilde{E}$ and H_T for flavor symmetry breaking in sea

e.g.

$$F_{p\to\Sigma^0} = -F_v^d + (F^s - F^{\bar{d}})\,,$$

$$F_{p\to\Lambda} = -\frac{1}{\sqrt{6}}\Big[2F_v^u - F_v^d + (2F^{\bar{u}} - F^{\bar{d}} - F^s)\Big]$$

L-T interference

$$\frac{d\sigma_{LT}}{dt} \sim \mathrm{Re}\Big[M^*_{0-0+}M_{0-++}\Big] \sim \mathrm{Re}\Big[\langle H_T\rangle\langle\widetilde{E}\rangle^*\Big]$$
$$A_{LU}\sigma_0 \sim \mathrm{Im}\Big[M^*_{0-0+}M_{0-++}\Big] \sim \mathrm{Im}\Big[\langle H_T\rangle\langle\widetilde{E}\rangle^*\Big]$$

no data at small ξ

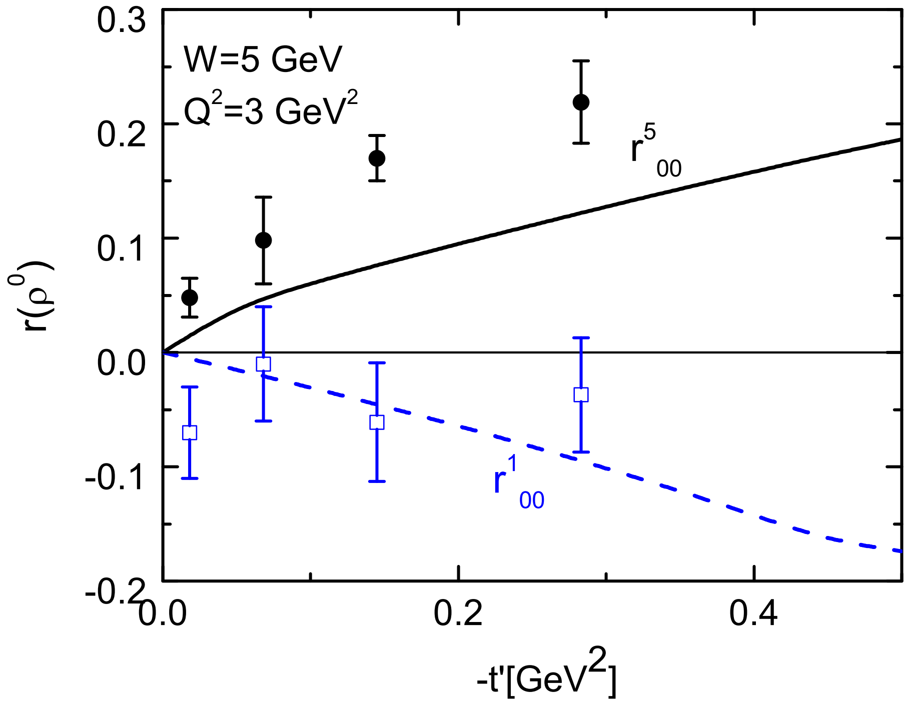
data on π^0 production at larger ξ from CLAS - small but non-zero

from our GPDs: both quantities practically zero -

understimate of H_T and/or $\widetilde{E}_{\mathrm{n.p.}}$?

see als deep dip of forward cross section

Transversity in vector meson electroproduction?



SDME for ρ^0 production

data HERMES

$$r^5_{00} \sim \mathrm{Re}\big[\mathcal{M}_{0+0+}\mathcal{M}^*_{0+++}\big]$$
$$r^1_{00} \sim -|\mathcal{M}_{0+++}|^2$$

twist-3 effect $\sim m_\rho/Q$ (not enhanced by chiral condensate)

Summary

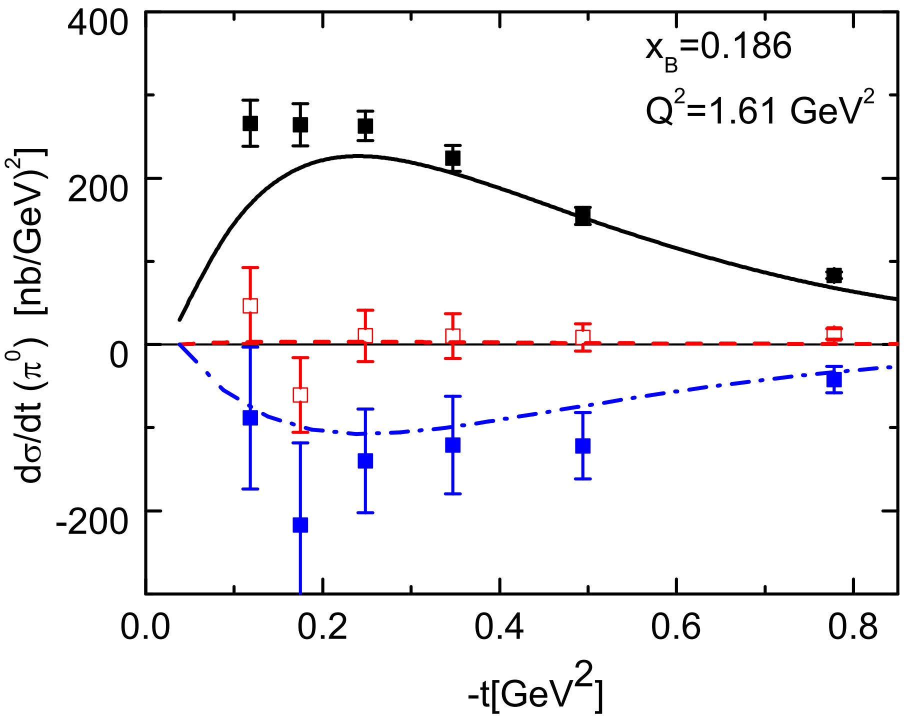
- analysis of pseudoscalar meson electroproduction within handbag approach complicated, many GPDs contribute
- clear indications in data (CLAS,HERMES) for strong contributions from $\gamma_T^* \to \pi$ transitions
- within handbag approach $\gamma_T^* \to \pi$ transitions are related to transversity (helicity-flip) GPDs accompanied by a twist-3 pion wave fct.
- H_T constrained by transversity PDFs - from analysis of A_{UT} for SIDIS
  $\overline{E}_T$ constrained by lattice results
- fit to HERMES π^+ data and interesting predictions for other channels
- trends and magnitudes of large ξ CLAS data reproduced

CLAS result for π^0 production

CLAS results at low W, i.e. at large skewness

Quantitative comparison with our results is to be done with utmost caution

(cf. difficulties with ρ^0 production)



prel. Data: CLAS

unseparated cross section

σ_{LT}

σ_{TT}

see also Hall A (dip)