Transversity in exclusive meson leptoproduction

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JLab, January 2015

Outline:

- **Evidence for strong $\gamma_T^* \to \pi$ transitions**
- **Transversity in the handbag approach**
- **Results for pseudoscalar mesons**
- **Vector mesons**
- **Summary**

An almost model-independent argument

consider pion leptoproduction

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

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

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

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

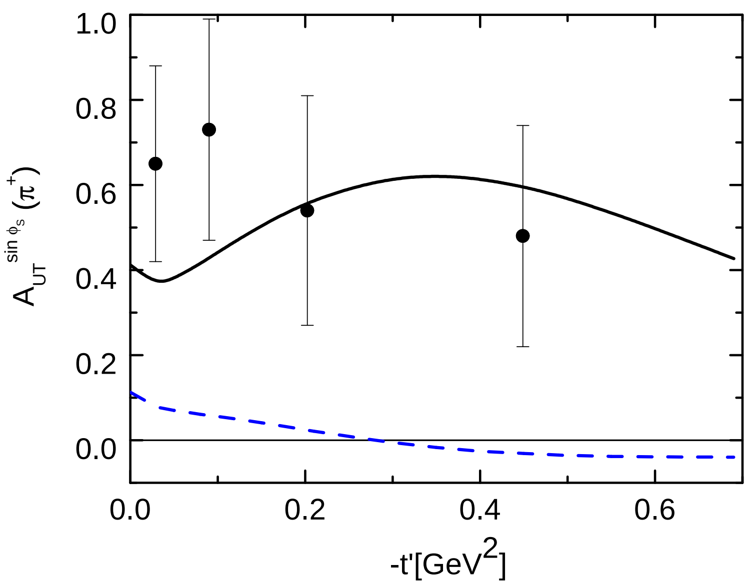
nucleon helicity flip: $\mathcal{M}_{0--+} \sim t'$ $\qquad \mathcal{M}_{0-++} \sim const$
sum and difference inconvenient
(constant may be small - or zero - for dynamical reasons)

Experiment:

Pion photoproduction: cross section exhibits pronounced maximum at $t=0$

$const.$ cannot be small   Phillips (1967): Regge cuts necessary

Pion leptoproduction



HERMES(09)

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

$\sin\phi_s$ modulation 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

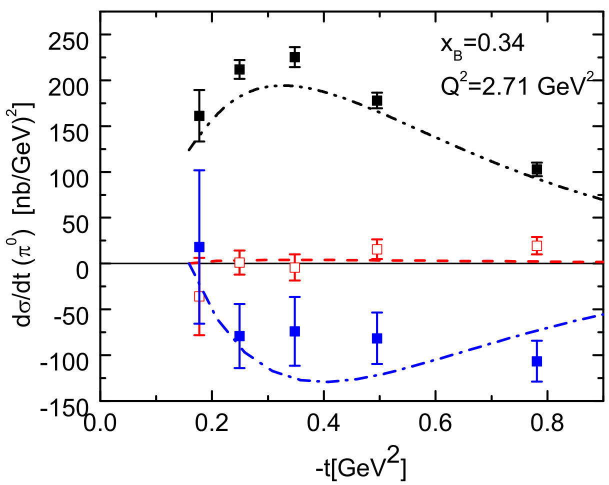
assumption: $|\mathcal{M}_{0--+}| \ll |\mathcal{M}_{0-++}|, |\mathcal{M}_{0+\pm+}|$

(ϕ_s orientation of target spin vector)

Transverse cross sections

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

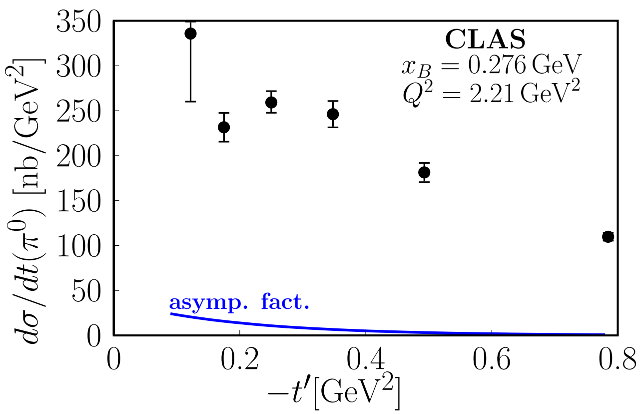
$$\Longrightarrow \left|\frac{d\sigma_{TT}}{dt}\right| \leq \frac{d\sigma_T}{dt} \leq \frac{d\sigma}{dt}$$



π^0 data CLAS(12)

unsep. cross sec., $d\sigma_{LT}$, $d\sigma_{TT}$

$|M^N_{0+++}|$ dominant in $d\sigma_{TT}$



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

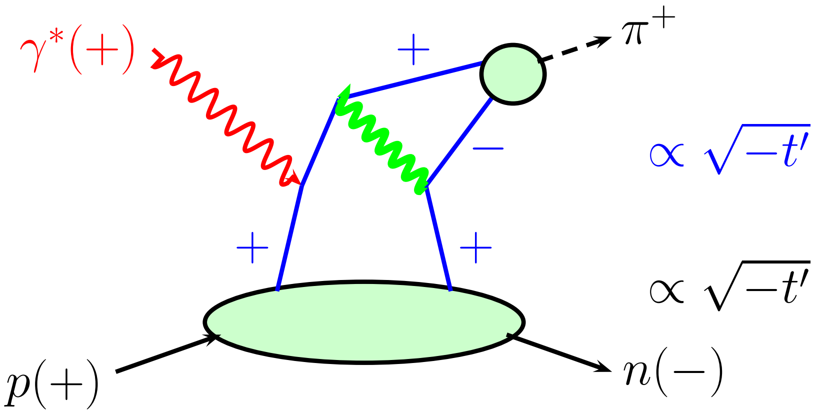
- consistent with $d\sigma_{LT}/dt \simeq 0$

for $t' \simeq 0$: $|M_{0-++}|$ is seen

$|M^U_{0+++}| \ll |M_{0-++}|, |M^N_{0+++}|$

How can we model $\mathcal{M}_{0-,++}$ in the handbag?

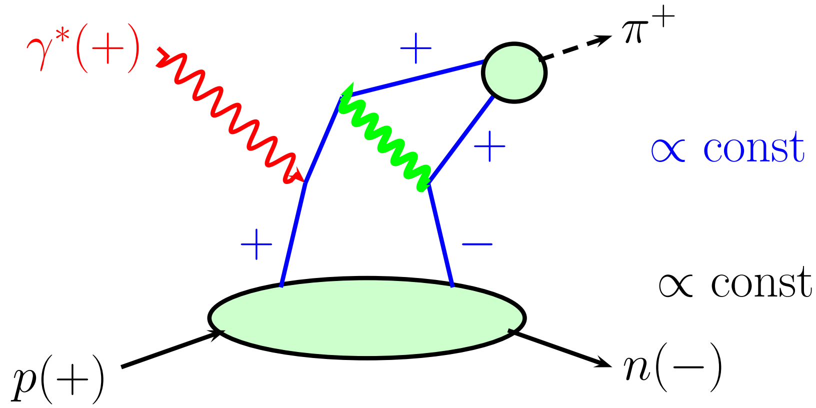
helicity-non-flip GPDs
$H, E, \widetilde{H}, \widetilde{E}$



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

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

helicity-flip (transv.) GPDs
$H_T, E_T, \widetilde{H}_T, \widetilde{E}_T$



transversity GPDs required
go along with twist-3 w.f.

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

(forced by angular momentum conservation)

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

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

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

with parity conserv. ($H_{0+\pm-} = -H_{0-\mp+}$): $\qquad \mathcal{M}_{0+\pm+} = \mathcal{M}^N_{0+++} \pm \mathcal{M}^U_{0+++}$

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

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

small $-t'$: $\mathcal{M}_{0-++}$ mainly H_T with corrections of order ξ^2 (no definite parity)

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

handbag explains structure of ampl. at least at small ξ and small $-t'$

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: $\Phi_P = 1, \quad \Phi_\sigma = \Phi_{AS} = 6\tau(1-\tau)$ Braun-Filyanov (90)

$H^{\mathrm{twist}-3}_{0-,++}(t=0) \neq 0$, Φ_P dominant, Φ_σ contr. $\propto t/Q^2$

in coll. appr.: $H^{\mathrm{twist}-3}_{0-,++}$ singular, in $\mathbf{k}_\perp$ factorization (m.p.a.) regular

$$M_{0-++} = e_0 \sqrt{1-\xi^2} \int dx H^{\mathrm{twist}-3}_{0-++} H_T\,, \qquad M_{0+\pm+} = -e_0 \frac{\sqrt{-t'}}{4m} \int dx H^{\mathrm{twist}-3}_{0-++} \bar{E}_T$$

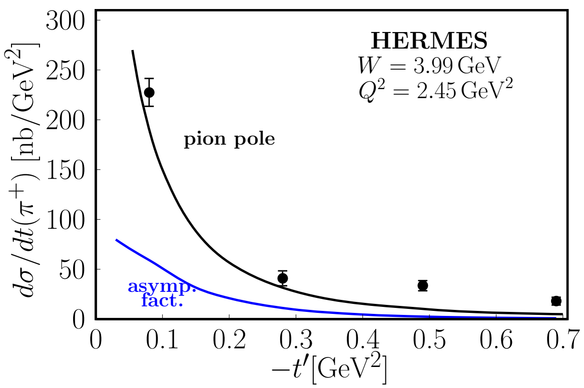
(suppressed by μ_π/Q as compared to $L \to L$ amplitudes)

The pion pole

$$\mathcal{M}_{0+0+} = \frac{e_0}{2}\sqrt{1-\xi^2}\langle \widetilde{H} - \frac{\xi^2}{1-\xi^2}\widetilde{E}\rangle \qquad \mathcal{M}_{0-0+} = e_0\frac{\sqrt{-t'}}{4m}\xi\langle\widetilde{E}\rangle$$

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

For π^+ production - pion pole: (Mankiewicz et al (98), Penttinen et al (99))



$$\widetilde{E}^u_{\rm pole} = -\widetilde{E}^d_{\rm pole} = \Theta(|x| \le \xi)\frac{mf_\pi g_{\pi NN}}{\sqrt{2}\xi}\frac{F_{\pi NN}(t)}{m_\pi^2 - t}\Phi_\pi(\frac{x+\xi}{2\xi})$$

$$\Longrightarrow \frac{d\sigma_L^{\rm pole}}{dt} \sim \frac{-t}{Q^2}\left[\sqrt{2}e_0 g_{\pi NN}\frac{F_{\pi NN}(t)}{m_\pi^2 - t}Q^2 F_\pi^{\rm pert}(Q^2)\right]^2$$

understimates c.s.(blue l.) $\qquad F_\pi^{\rm pert.} \simeq 0.3-0.5 F_\pi^{\rm exp.}$

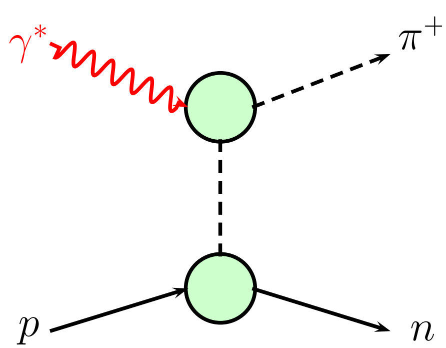
(F_π measured in π^+ electroproduction at Jlab)

Goloskokov-K(09): $F_\pi^{\rm pert} \to F_\pi^{\rm exp}$

knowledge of the sixties suffices to explain data (small $-t$)

Bechler-Mueller(09): consider α_s as a free parameter

$\to \alpha_s \simeq 1$



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

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

opposite sign for u and d quarks but u larger than d

Alternative: normalize to lattice moments

$\bar{E}_T$: only available lattice result for moments: QCDSF-UKQCD(06)

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

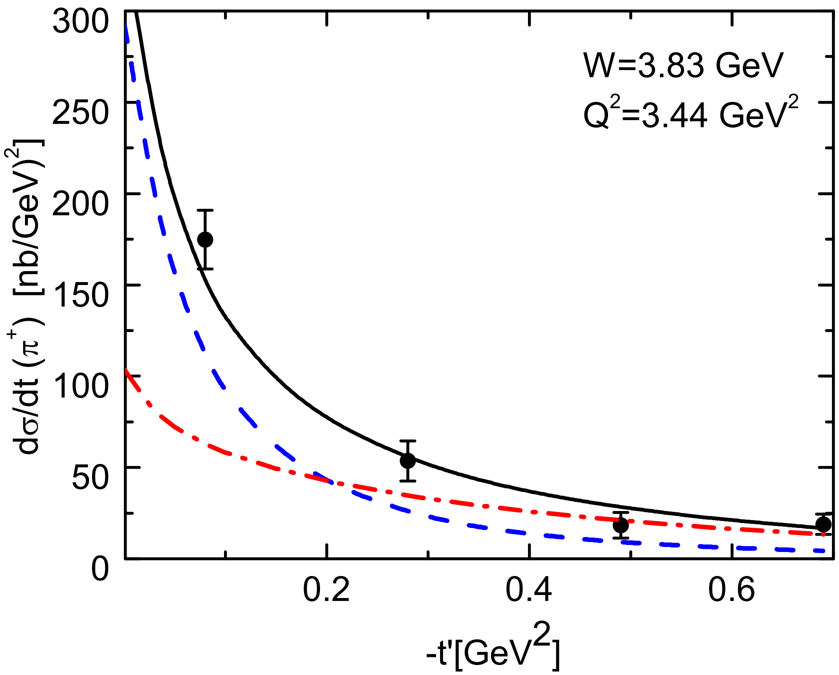
$\bar{E}_T$ parameterization: $e^a_T = \bar{N}^e_T e^{b_{eT}t} x^{-\alpha^e_T(t)}(1-x)^{\beta^a_{eT}}$

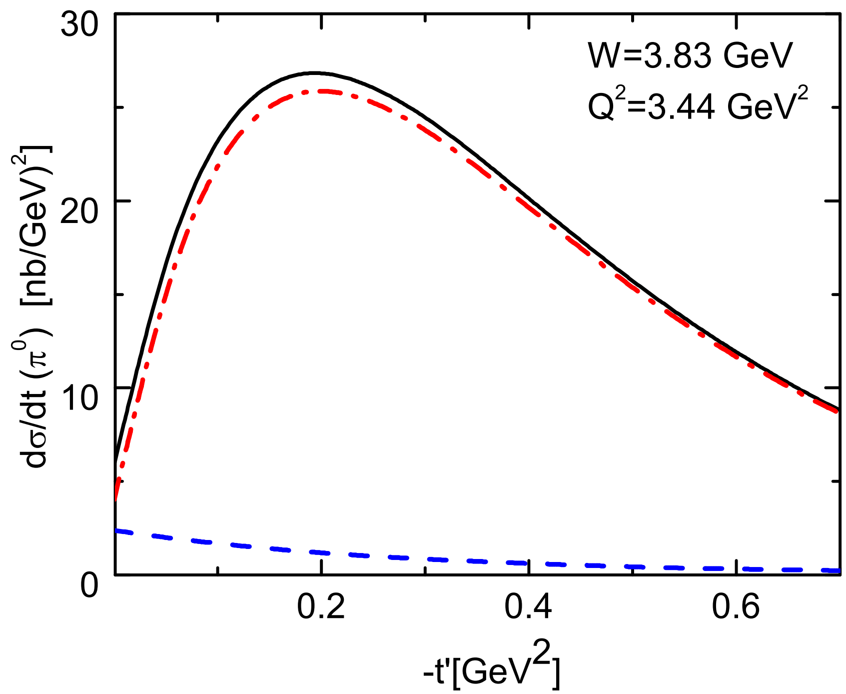
parameters: $\alpha(0)=0.3$, $\alpha'=0.45\,\mathrm{GeV}^{-2}$, $b=0.5\,\mathrm{GeV}^{-2}$, $\bar{N}^u_T = 6.83$, $\bar{N}^d_T = 5.05$

adjusted to lattice results

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

H_T and $\bar{E}_T$ in pion electroproduction





unseparated (longitudinal, transverse) cross sections

π^+: pion pole and $\propto K^u - K^d$ $\qquad$ π^0: no pion pole and $\propto e_u K^u - e_d K^d$

consider $u - d$ signs: $\bar{E}_T$ same, $\widetilde{H}, H_T$ opposite sign

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

$\bar{E}_T$ small for π^+, large for π^0

Analysis of CLAS data

$\widetilde{H}$ from Diehl-K (13) based on DSSV (11)

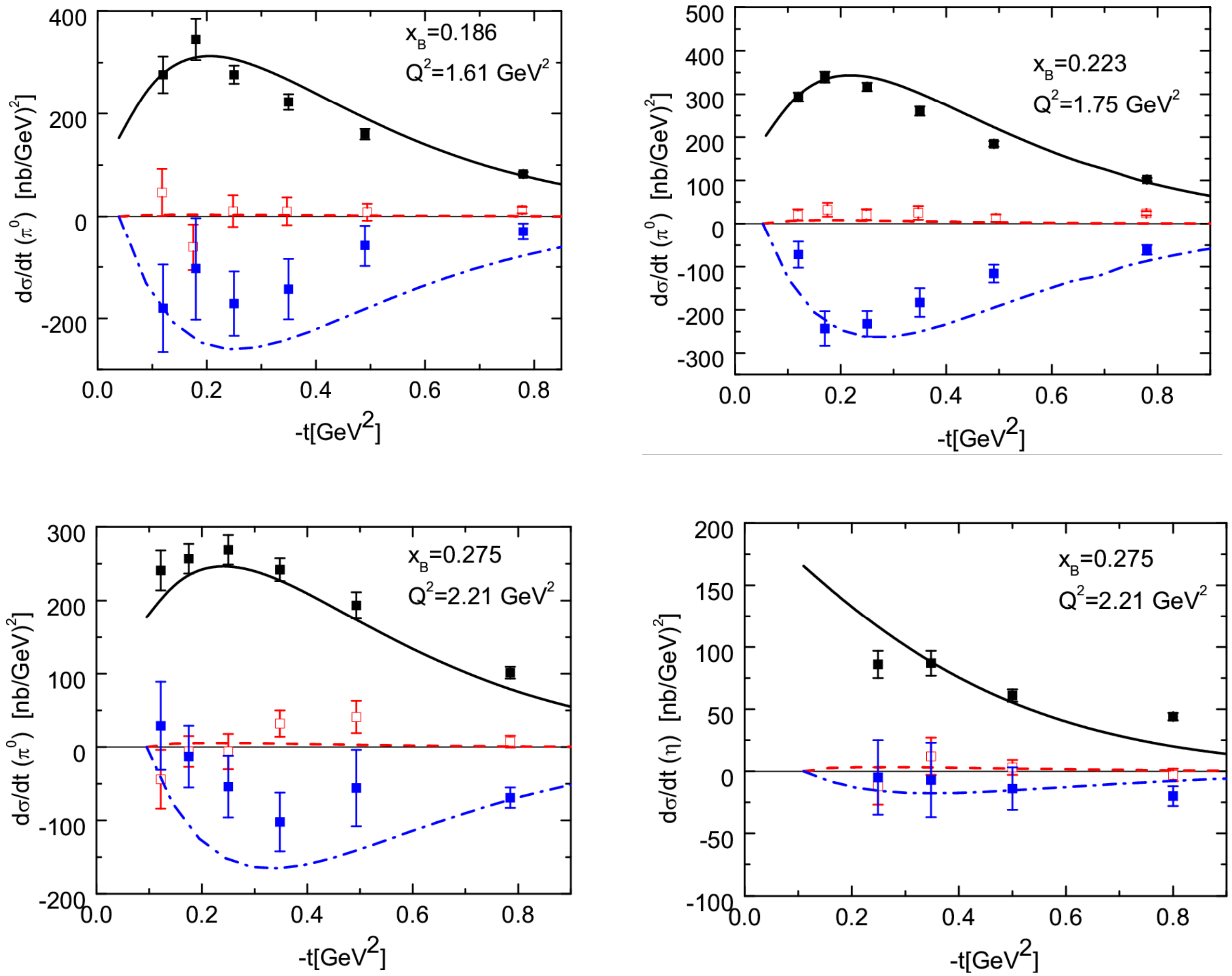
$H_T, \bar{E}_T$ as mentioned before (normalized to lattice QCD results)

NEW:

$\mu_\pi = 2.65\,\mathrm{GeV} \simeq \mu_\eta$ according to current quark masses (PDG)

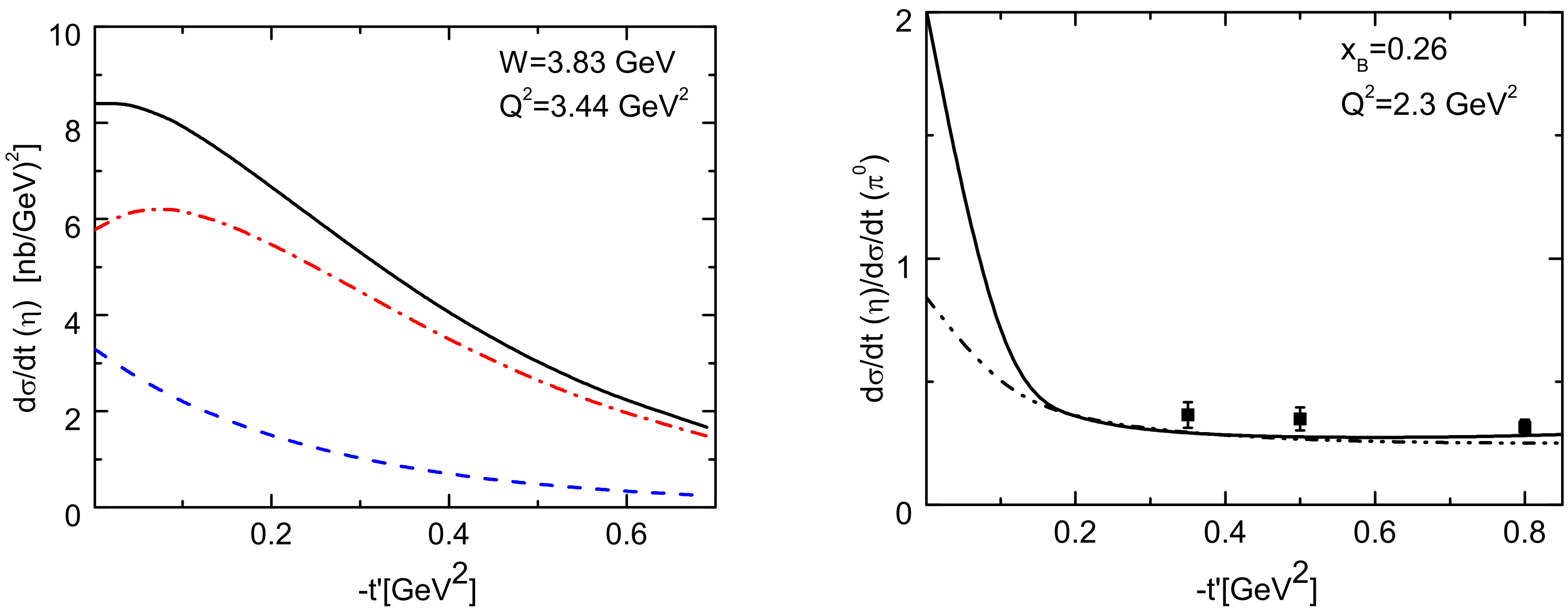
$$\xi = \frac{x_\mathrm{B}}{2-x_\mathrm{B}}\Big[1 + \frac{2}{2-x_\mathrm{B}}\frac{m_\pi^2}{Q^2} - 2x_\mathrm{B}^2\frac{1-x_\mathrm{B}}{2-x_\mathrm{B}}\frac{m^2}{Q^2} + 2x_\mathrm{B}\frac{1-x_\mathrm{B}}{2-x_\mathrm{B}}\frac{t}{Q^2}\Big]$$

reduces $-t_0 = 4m^2\xi^2/(1-\xi^2)$ (see also Braun et al(14))



data: Bedlinsky et al (12)

η/π^0 ratio



data CLAS (prel.) unseparated (longitinal, transverse) cross sections

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

if K^u and K^d have opposite sign: $\eta/\pi^0 \simeq 1$ $\quad (\eta = (\cos\theta_8 - \sqrt{2}\sin\theta_1)\eta_q)$

if K^u and K^d have same sign: $\eta/\pi^0 < 1$ $\quad$ (FKS scheme)

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

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

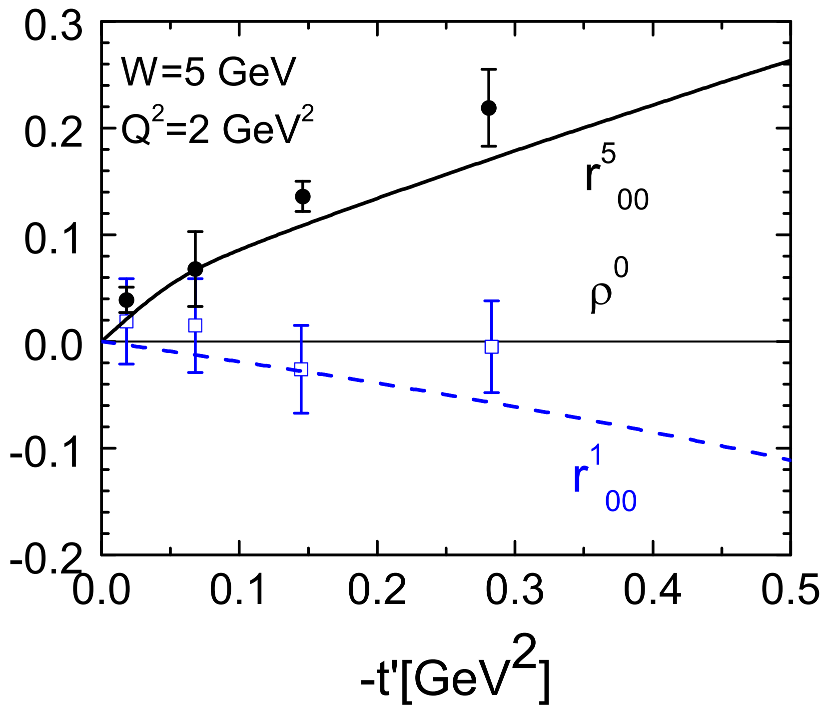
Transversity in vector meson leptoproduction

as for pions: $\gamma_T^* \to V_L$ amplitudes, same subprocess amplitude
except $\Psi_\pi \to \Psi_V$, i.e. $f_\pi \to f_V$, $\mu_\pi/Q \to m_V/Q$

$\gamma_T^* \to V_L$ amplitudes somewhat smaller than the $\gamma_T^* \to \pi$ ones but competition with $\langle H \rangle$ (for gluons and quarks) instead with $\langle \widetilde{H} \rangle$ ($|\langle H \rangle| \gg |\langle \widetilde{H} \rangle|$)
$\Longrightarrow$ small transversity effects for vector mesons
only seen in some of the SDMEs and in spin asymmetries

examples from Goloskokov-K(13,14) estimates, not fits

Spin density matrix elements

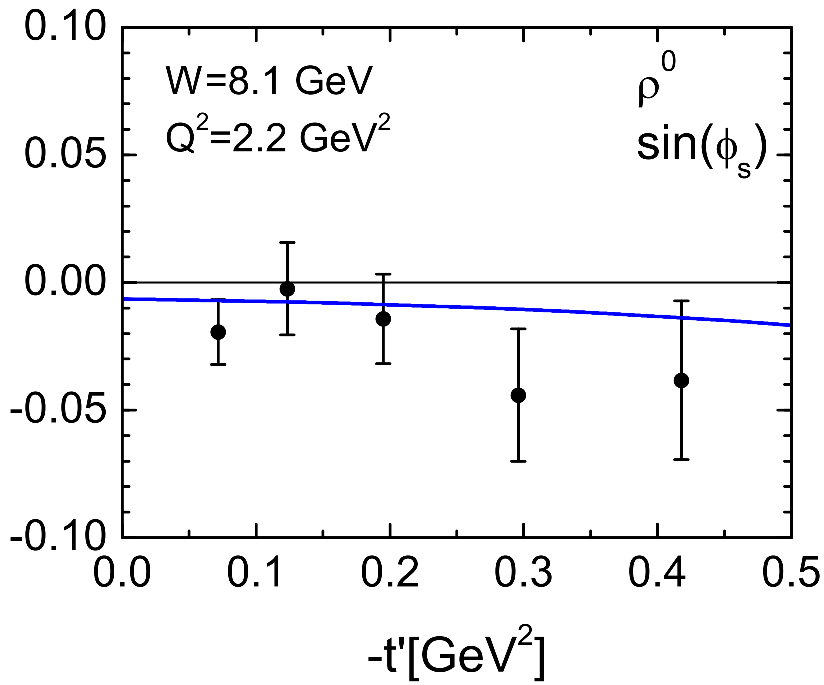


SDME from HERMES(09)

$r^1_{00} \sim -|\langle \bar{E}_T \rangle|^2 \qquad r^5_{00} \sim \mathrm{Re}\big[\langle \bar{E}_T \rangle^* \langle H \rangle\big]$

Asymmetries

$\sin(\phi - \phi_s)$ modulations: contr. from leading-twist dominant
contr. from transv. GPDs unimportant



data from COMPASS(13)

$$A_{UT}^{\sin(\phi_s)} \sim \mathrm{Im}\big[\langle H_T\rangle^* \langle H\rangle\big]$$

Gluon transversity?

only non-flip subprocess ampl. with gluon helicity-flip $\mathcal{H}_{--,++}$ (helicities ± 1)
$\Longrightarrow$ contribution to $\gamma_T^* \to V_{-T}$ amplitudes $\mathcal{M}_{-\mu\nu'\mu\nu}$
SDME (HERMES(09), H1(09)): $\gamma_T^* \to V_{-T}$ ampl. are small, compatible with zero
consistent with small gluon transv. GPDs

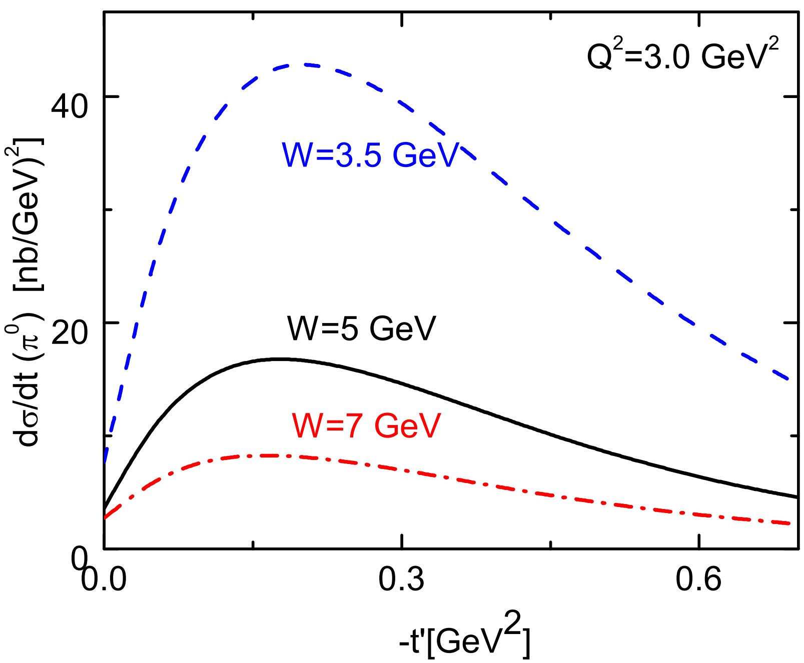
not in contradiction with large quark transv. GPDs:
gluon and quark transv. GPDs evolve independently with scale
Hoodbhoy-Ji(98), Belitsky et al(00)

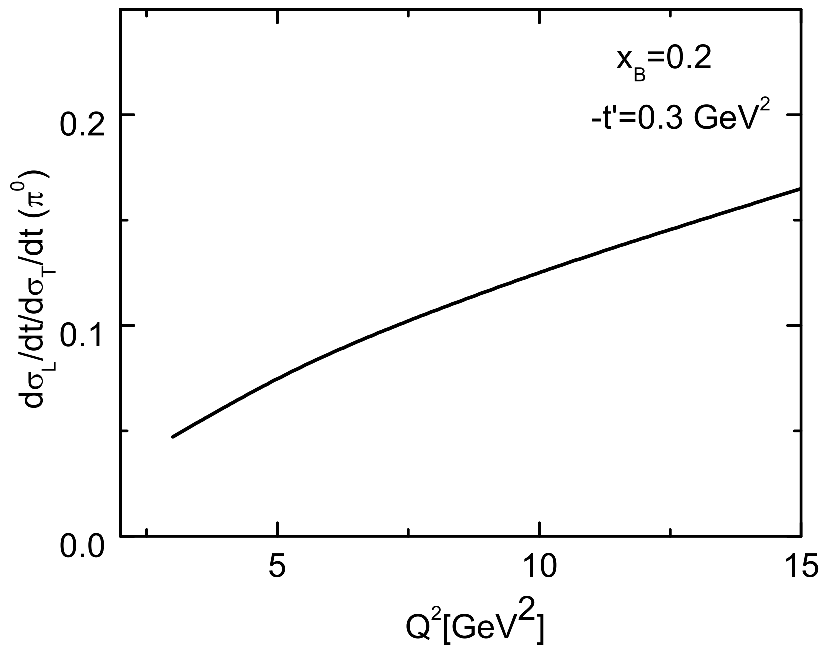
gluon transv. contribution to $\gamma_T^* \to \gamma_{-T}$ DVCS at NLO
Hoodbhoy-Ji(98), Belitsky-Müller (00)

Summary

- 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 and $\bar{E}_T$ constrained by lattice results
  transversity PDFs from analysis of A_{UT} in SIDIS (Anselmino et al)
  underestimate H_T
- fit to HERMES π^+ data and interesting predictions for other channels
  trends and magnitudes of large ξ CLAS data reproduced
- transversity effects also seen in ρ^0 and ω production ($\gamma_T^* \to V_L$ transitions)
  SDME - $\bar{E}_T$; asymmetries - H_T
- only estimates as yet (except π^+); for fits data on π^0 cross section at small ξ required

Results for pion production

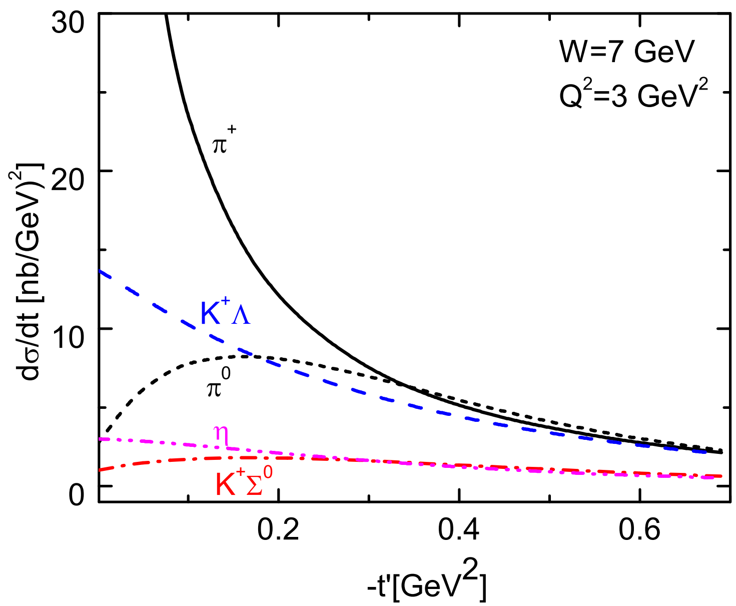




Goloskokov-K (10),(11) optimized for small ξ and large W

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.

$$K_{p\to\Sigma^0} = -K_v^d + (K^s - K^{\bar{d}})\,,$$

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