Twist-3 effects in electroproduction of mesons

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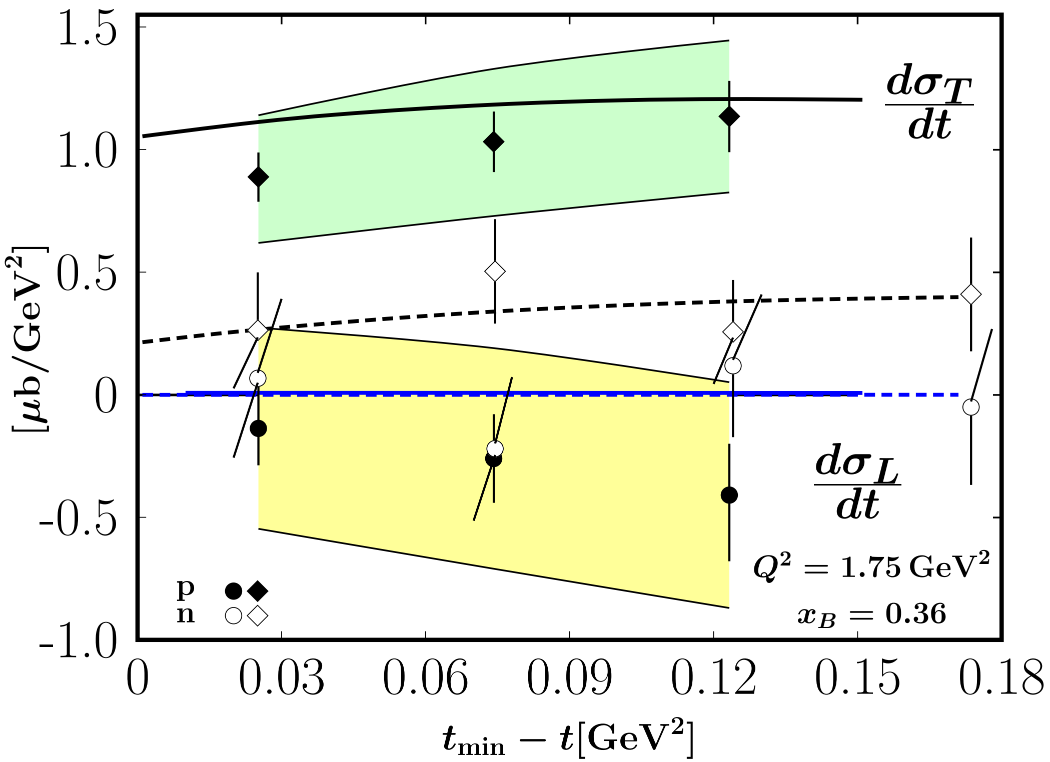
Outline:

- **Transversity in the handbag approach**
- **Twist-3 effects**
- **Results for pseudoscalar mesons**
- **Vector mesons**
- **Summary**

Hall A results on π^0 production



π^0 production

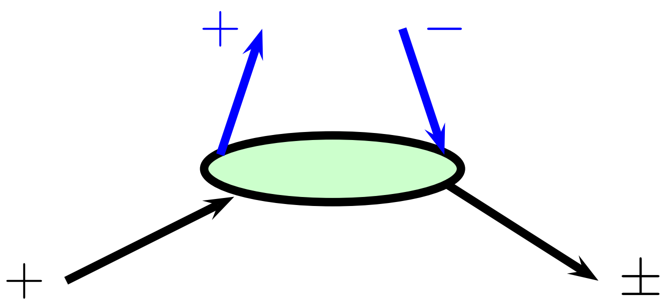
off protons and neutrons:

$d\sigma_T \gg d\sigma_L$ $\quad (d\sigma \simeq d\sigma_T)$ $\quad$ like expectation for $Q^2 \to 0$

to be contrasted with

QCD expectation for $Q^2 \to \infty$: $d\sigma_T \ll d\sigma_L$ ($d\sigma \simeq d\sigma_L$)

Transversity GPDs



transversity (helicity flip) GPDs
$H_T, \widetilde{H}_T, E_T, \tilde{E}_T$ (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)

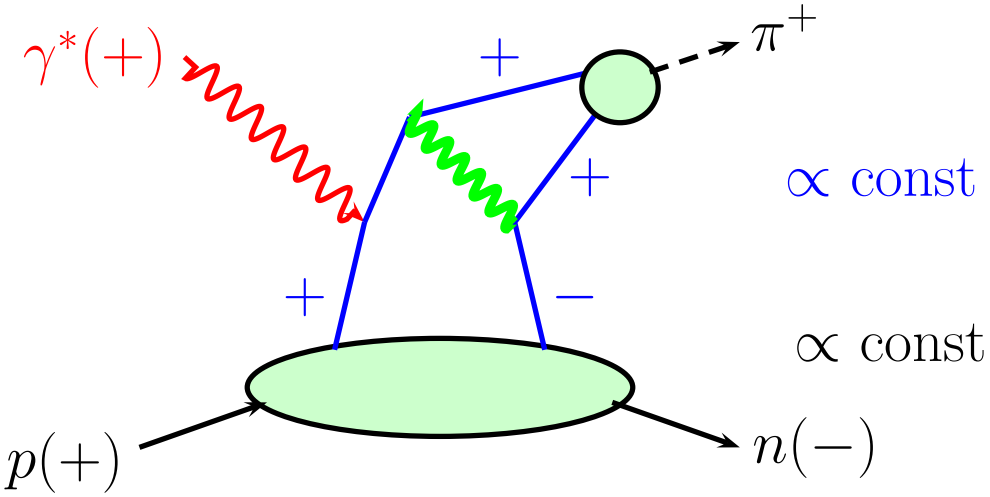
reduction formula: $H_T^q(x, \xi = t = 0) = \Delta_T q(x)$
transversity distributions $\Delta_T q(x)$ ($h_1(x)$)
not accessible in DIS but in SIDIS (analysis Anselmino et al (09))

difficult to access in exp: helicity flip of light quarks suppressed
only a few applications: Pire et al electroproduction of ρ_T, VV
Kivel gluon transversity
Huang et al wide-angle photoproduction of pions
Liuti et al production of π^0
Goloskokov-K production of mesons

Transversity GPDs in pion electroproduction

example: helicity non-flip amplitude $\mathcal{M}_{0-++}$

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



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

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

The twist-3 pion distr. amplitude

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

$$\sim q' \cdot \gamma\gamma_5\Phi + \mu_\pi\gamma_5\Big[\Phi_P - \imath\sigma_{\mu\nu}\big(\frac{q'^\mu k'^\nu}{q'\cdot k'}\frac{\Phi'_\sigma}{6} + q'^\mu\frac{\Phi_\sigma}{6}\frac{\partial}{\partial \mathbf{k}_{\perp\nu}}\big)\Big]$$

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

$$\langle \pi^+(q') \mid \bar{d}(x)\sigma_{\alpha\beta}\gamma_5 u(-x) \mid 0\rangle = -\frac{i}{3}f_\pi\mu_\pi\Big(q'_\alpha x_\beta - q'_\beta x_\alpha\Big)\int d\tau \mathrm{e}^{iq'x\tau}\Phi_\sigma(\tau)$$

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. $\int d\tau\Phi_{P(\sigma)}(\tau) = 1$)

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

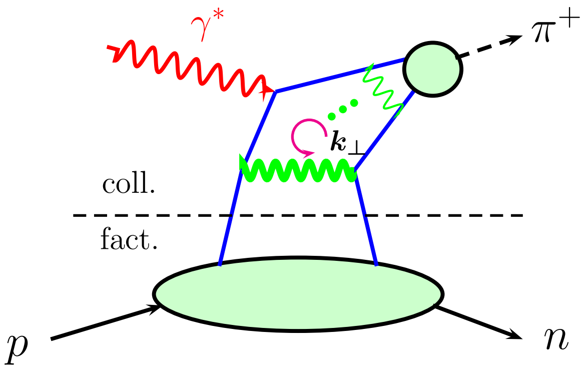
solution: $\Phi_P = 1, \quad \Phi_\sigma = \Phi_{AS} = 6\tau(1-\tau)$ Braun-Filyanov (90)

$H^{\mathrm{twist}-3}_{0-,++}(t=0) \neq 0$, 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

Calculation of subprocess amplitudes

mod. pert. approach - quark trans. momenta in subprocess
(emission and absorption of partons from proton collinear to proton momenta)
transverse separation of color sources $\Longrightarrow$ gluon radiation



Sudakov factor Sterman et al(93)

$$S(\tau, \mathbf{b}_\perp, Q^2) \propto \ln \frac{\ln(\tau Q/\sqrt{2}\Lambda_{\rm QCD})}{-\ln(b_\perp \Lambda_{\rm QCD})} + \text{NLL}$$

resummed gluon radiation to NLL $\Rightarrow \exp[-S]$
provides sharp cut-off at $b_\perp = 1/\Lambda_{\rm QCD}$

$$\mathcal{H}_{0\pm\mu+} = \int d\tau d^2 b_\perp\, \hat{\Psi}^\pi_{\pm+}(\tau, -\mathbf{b}_\perp)\, e^{-S} \hat{\mathcal{F}}_{0\pm\mu+}(x, \xi, \tau, Q^2, \mathbf{b}_\perp)$$

$\hat{\Psi}^\pi_{+-} \sim \exp[\tau\bar{\tau} b_\perp^2/4a_M^2]$ LC wave fct of pion
$\hat{\mathcal{F}}$ FT of hard scattering kernel
e.g. $\propto 1/[k_\perp^2 + \tau(x+\xi)Q^2/(2\xi)] \Rightarrow$ Bessel fct

LO pQCD
+ quark trans. mom.
+ Sudakov supp.
$\Rightarrow$ asymp. fact. formula (lead. twist) for $Q^2 \to \infty$

(recent lattice QCD result: $a_2 = 0.1364(154)(145)$ Braun et al(15)
Sudakov factor suppresses higher Gegenbauer terms)

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

see Diehl01, Goloskokov-K.09 $\qquad \bar{E}_T \equiv 2\widetilde{H}_T + E_T \qquad \mu = \pm 1$

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

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--+}

Amplitudes for pion production

leading $\gamma_L^* \to \pi$ amplitudes for $Q^2 \to \infty$:

$$\mathcal{M}_{0+0+} = \frac{e_0}{2}\sqrt{1-\xi^2}\int dx\big[H^{\text{tw}-2}_{0+0+} + H^{\text{tw}-2}_{0-0-}\big]\big[\widetilde{H} - \frac{\xi^2}{1-\xi^2}\widetilde{E}\big]$$

$$\mathcal{M}_{0-0+} = e_0\frac{\sqrt{-t'}}{4m}\xi\int dx\big[H^{\text{tw}-2}_{0+0+} + H^{\text{tw}-2}_{0-0-}\big]\widetilde{E}$$

$\gamma_T^* \to \pi$ amplitudes (at least at small ξ and small $-t'$):

$$M_{0-++} = e_0\sqrt{1-\xi^2}\int dx H^{\text{tw}-3}_{0-++} H_T$$

$$M_{0+\pm+} = -e_0\frac{\sqrt{-t'}}{4m}\int dx H^{\text{tw}-3}_{0-++}\bar{E}_T$$

$$M_{0--+} = 0$$

suppressed by μ_π/Q as compared to $\gamma_L^* \to \pi$ amplitudes

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

double-distr. ansatz input: zero-skewness GPDs $K(x,t) = k(x)e^{t(b-\alpha' \ln x)}$

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

H_T: transversity PDFs Anselmino et al(09)

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

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

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

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

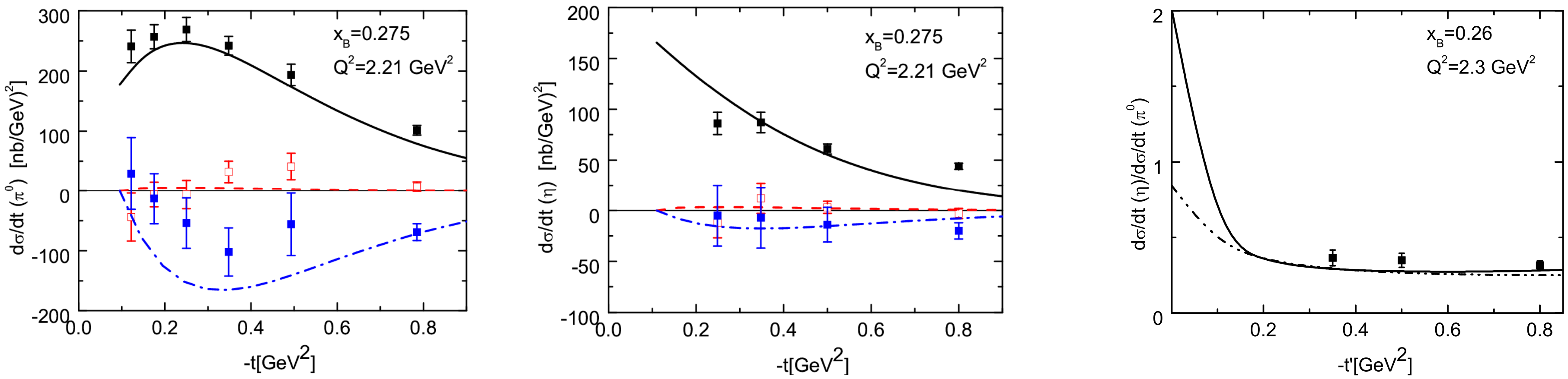
adjusted to lattice results

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

energy dependence: essentially given by $\alpha(0)$

CLAS data on π^0 and η production

Bedlinsky et al (12)



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: $\eta/\pi^0 \simeq 1$ $\qquad (\eta = (\cos\theta_8 - \sqrt{2}\sin\theta_1)\eta_q)$

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

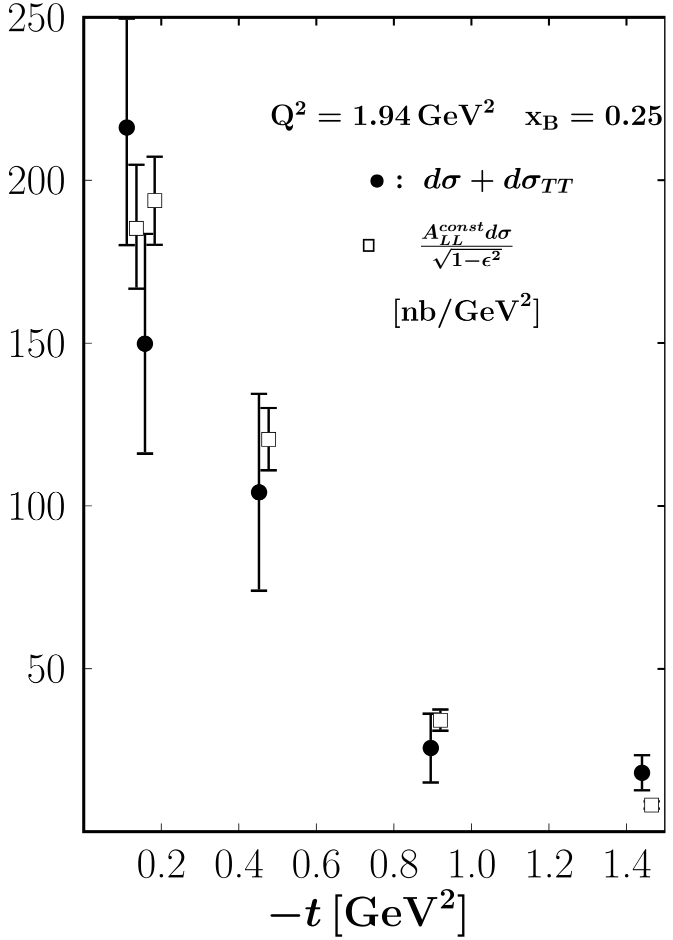
$t' \simeq 0$ $\widetilde{H}, H_T$ dominant (see also Eides et al(98) assuming dominance of $\widetilde{H}$ for all t')

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

Contributions from other transversity GPDs?

if only H_T and $\bar{E}_T$ contribute:

$$\frac{A_{LL}^{\rm const}}{\sqrt{1-\epsilon}}\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \frac{d\sigma_{TT}}{dt} \simeq \frac{d\sigma}{dt} + \frac{d\sigma_{TT}}{dt} \sim |\langle H_T\rangle|^2$$



violation of relation would indicate contributions from other transv. GPDs, e.g. from $\widetilde{H}_T$ ($\propto t'$)

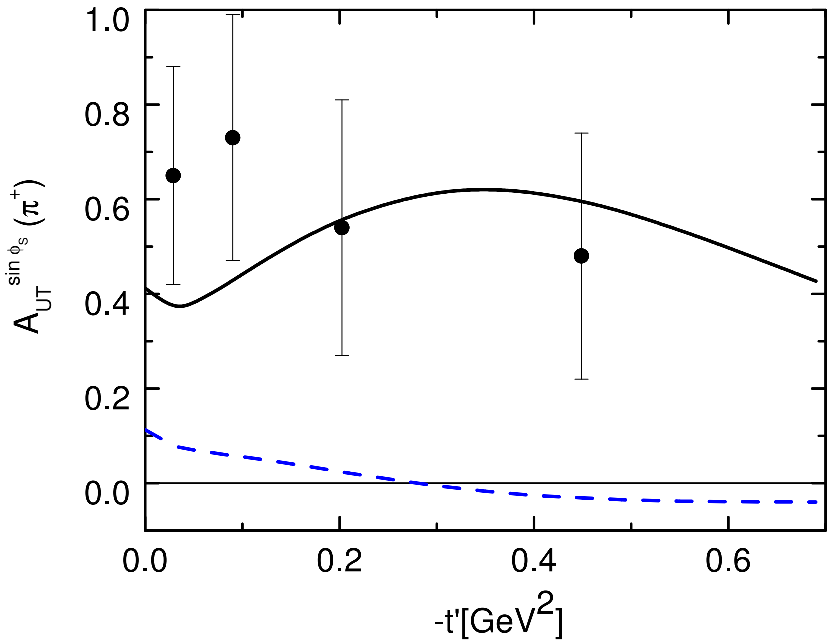
data for π^0 production

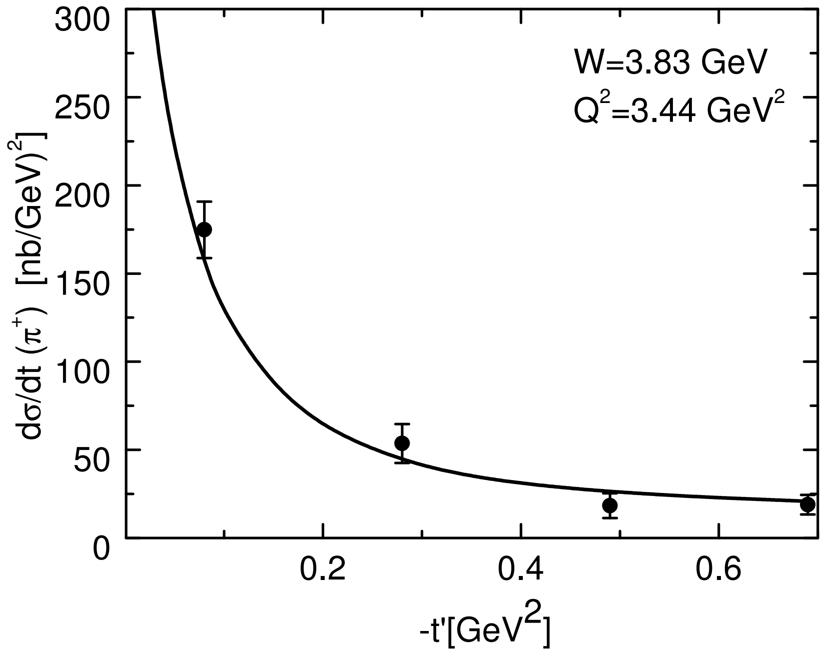
Bedlinsky et al, Kim et al (CLAS)

agreement within errors

A_{UT} for π^+ production

data HERMES(09) ($Q^2 = 2.5\,\mathrm{GeV}^2$; $W = 3.99\,\mathrm{GeV}$)





$\sin\phi_s$ modulation very large and does not seem to vanish for $t' \to 0$

$$A_{UT}^{\sin\phi_s} \propto \mathrm{Im}\Big[\mathcal{M}^*_{0-++}\mathcal{M}_{0+0+}\Big]$$

non-flip amplitude $\mathcal{M}_{0-++}$ required (not forced to vanish in forward direction by angular momentum conservation - as $\mathcal{M}_{0+0+}$) pion pole

evidence for $\mathcal{M}_{0-++} \sim \langle H_T \rangle$

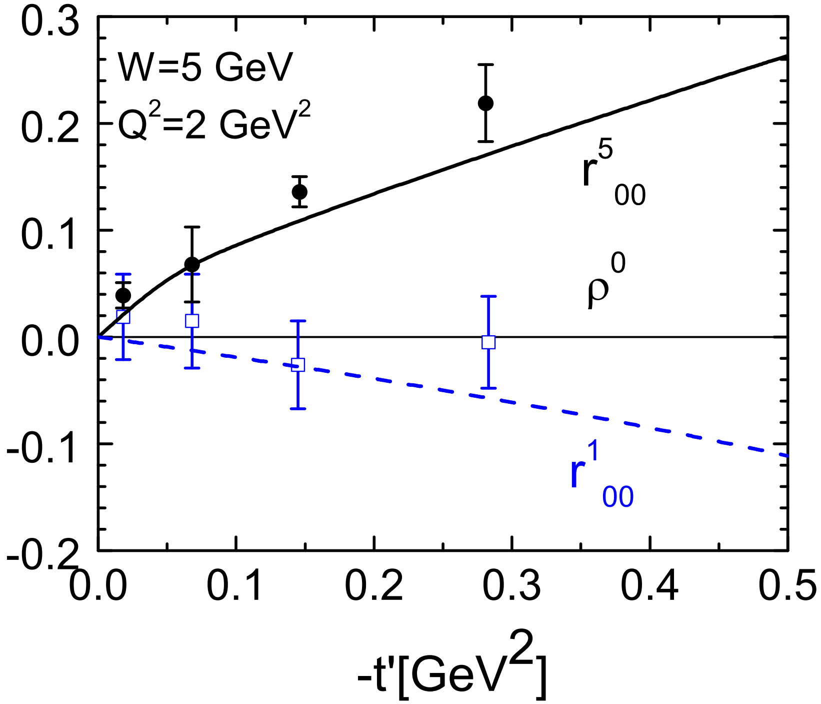
Transversity in vector meson leptoproduction

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 of about same size than the $\gamma_T^* \to \pi$ ones but compete 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)

Spin density matrix elements

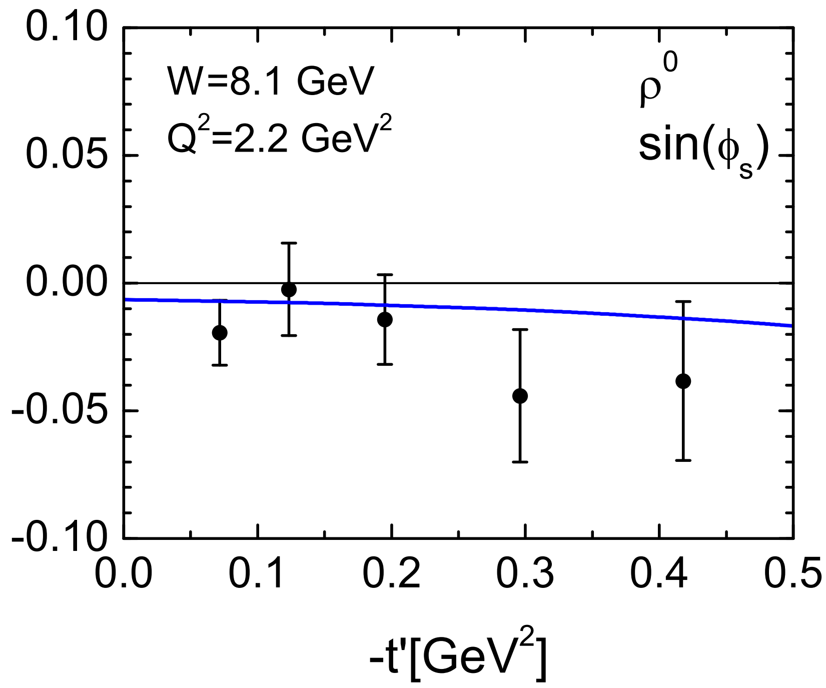


SDME from HERMES(09)

$r^1_{00} \sim -|\langle \bar{E}_T \rangle|^2$ $\qquad r^5_{00} \sim \mathrm{Re}\big[\langle \bar{E}_T \rangle^* \langle H \rangle\big]$ (no fit)

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 experimental evidence for strong contributions from $\gamma_T^* \to \pi$ transitions from HALL A, also seen in CLAS and HERMES data
- within handbag approach $\gamma_T^* \to \pi$ transitions are related to transversity (helicity-flip) GPDs accompanied by a twist-3 pion wave fct.
- transversity effects also seen in ρ^0 and ω production ($\gamma_T^* \to V_L$ transitions) SDME - $\bar{E}_T$; asymmetries - H_T