Spin Effects in Hard Exclusive Electroproduction of Mesons

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Outline:

- **Introduction**
- **Handbag factorization for meson electroproduction**
- **The failure of the leading-twist approach**
- **Vector mesons (E, A_{UT}, J)**
- **Pions (pion pole, $\widetilde{H}$, $\widetilde{E}$, twist-3, results)**
- **Summary**

Spin is an inessential complication

of

particle physics

Spin effects are often

the death

of a model

Target asymmetries

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

Holds for vector and pseudoscalar mesons. Detailed info. on amplitudes

π^+: all measured; ρ^0, ϕ: only $\sin(\phi - \phi_s)$ asymmetry; for ω all

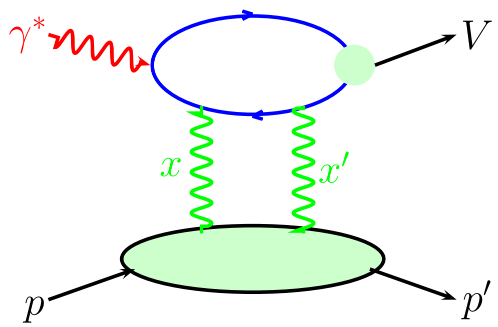
ϕ azimuthal angle between lepton and hadron plane; ϕ_s orientation of target spin vector; θ_γ rotation from direction of incoming lepton to virtual photon one

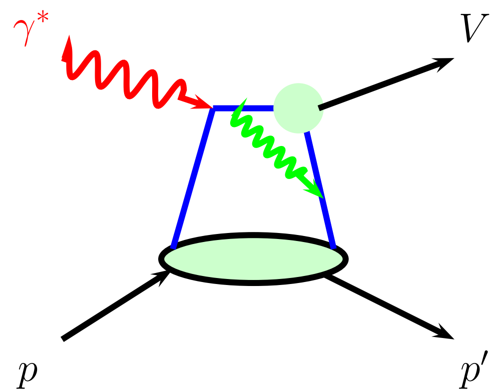
Electroproduction of mesons

rigorous proof of collinear factorization for $Q^2 \to \infty$
(Radyushkin (96); Collins et al (97))

hard subprocesses
$\gamma^* g \to V g\,,\ \gamma^* q \to V, P q$

and GPDs and meson w.f.
(encode the soft physics)





dominant transition $\gamma^*_L \to V_L, P$ other transitions power suppressed

As compared to DVCS:
disadvantage: two soft functions
advantages: diff. mesons $(\rho^0, \phi, \omega, \rho^+, K^{*0}, J/\Psi)$ allow for flavor separation
wealth of good data for Q^2 up to $\simeq 100\,\mathrm{GeV}^2$ and W up to $\simeq 200\,\mathrm{GeV}$

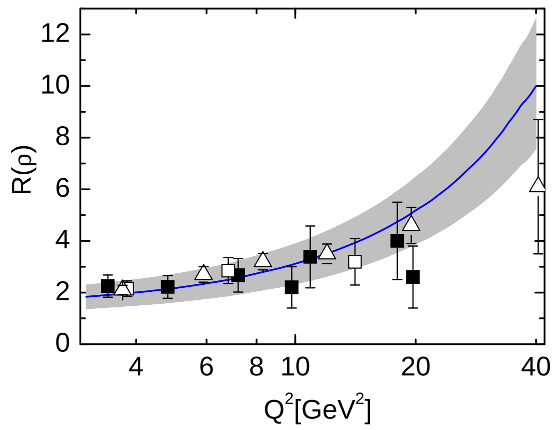
Transverse photon polarization matters

vector-meson electroproduction

$R = \sigma_L/\sigma_T$ (HERA $W \simeq 80\,\mathrm{GeV}$)

$\gamma_T^* \to V_T$ transitions substantial

power corr. and/or higher twist needed



various moments of π^+ cross section

measured with trans. pol. target

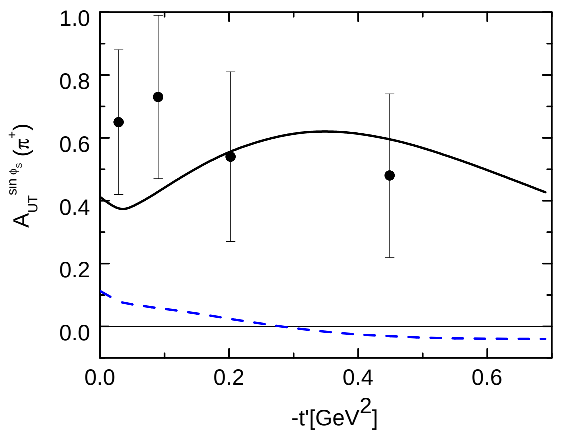
$\sin\phi_s$ moment very large

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

$A_{UT}^{\sin\phi_S} \propto \mathrm{Im} M^*_{0+,0+} M_{0-,++}$

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

fed by hel.-flip GPDs in handbag appr.



HERMES prel.

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

Corrections to the l.-t. amplitudes?

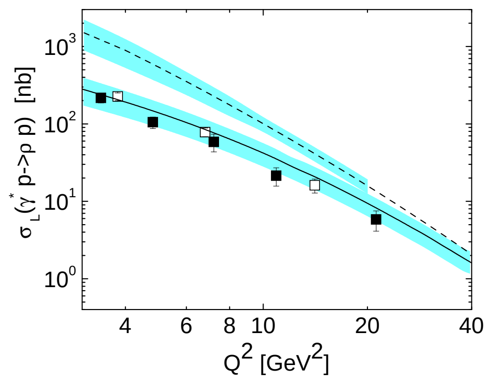
vector-meson electroproduction:

predictions for σ_L exceed data by a large factor

(HERA $W = 75\text{GeV}$ ρ)

power corr. and/or higher orders of pQCD?

(Diehl-Kugler 07, Ivanov 07)



π^+ electroproduction:

contribution from pion exchange

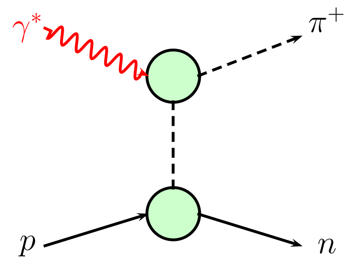
requires π elm form factor

(it is measured there)

lead. twist only about a third of exp. value

fails with cross section by order of magnitude

additional contributions required



new data on $F_{\pi\gamma}$ may change our understanding of pion DA

The $\gamma^* p \to VB$ amplitudes

consider large Q^2, W and small t;
kinematics fixes skewness: $\xi \simeq \frac{x_{\rm Bj}}{2-x_{\rm Bj}}[1+m_V^2/Q^2] \simeq x_{\rm Bj}/2$ + m.m.c.

$$\begin{aligned} \mathcal{M}_{\mu+,\mu+}(V) &= \frac{e_0}{2}\left\{\sum_a e_a \mathcal{C}_V^{aa}\langle H_{\rm eff}^g\rangle_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle H_{\rm eff}^{ab}\rangle_{V\mu}\right\}, \\ \mathcal{M}_{\mu-,\mu+}(V) &= -\frac{e_0}{2}\frac{\sqrt{-t}}{M+m}\left\{\sum_a e_a \mathcal{C}_V^{aa}\langle E^g\rangle_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle E^{ab}\rangle_{V\mu}\right\}, \end{aligned}$$

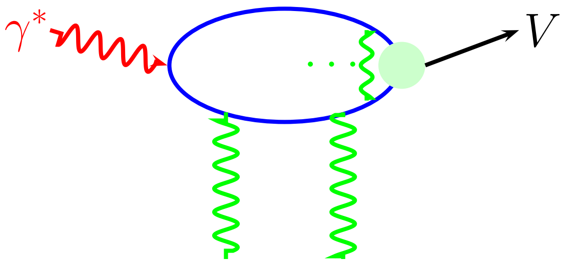
$\mathcal{C}_V^{ab}$ flavor factors, $M(m)$ mass of $B(p)$, $H_{\rm eff} = H - \xi^2/(1-\xi^2)E$
contributions from $\widetilde{H}$ to T-T amplitude neglected
electroproduction with unpolarized protons at small ξ:
E not much larger than H (see below) $\Longrightarrow H_{\rm eff} \to H$ for small ξ
$|M_{\mu'-,\mu+}|^2 \propto t/m^2$ neglected $\Longrightarrow$ probes H (exception ρ^+)
trans. polarized target: probes $Im[\langle E\rangle^* \langle H\rangle]$ interference
polarized beam and target: probes $Re[\langle H\rangle^* \langle \widetilde{H}\rangle]$ interference

Subprocess amplitudes

$F = H, E$ $\quad\lambda$ parton helicities

$$\langle F\rangle^{ab(g)}_{V\mu} = \sum_\lambda \int d\bar{x} \mathcal{H}^{Vab(g)}_{\mu\lambda,\mu\lambda}(\bar{x},\xi,Q^2,t=0)\, F^{ab(g)}(\bar{x},\xi,t)$$

$F^{aa} = F^a\,, \qquad F^{ab} = F^a - F^b \quad (a \neq b)$ (with flavor symmetry)



$$\mathcal{H}^{Vab}_{\mu\lambda,\mu\lambda} = \int d\tau d^2b\, \hat{\Psi}_{V\mu}(\tau,-\vec{b})\exp[-S(\tau,\vec{b},Q^2)] \times \hat{\mathcal{F}}^{ab}_{\mu\lambda,\mu\lambda}(\bar{x},\xi,\tau,Q^2,\vec{b})$$

LO pQCD

\+ quark trans. mom.

\+ Sudakov supp.

$\Rightarrow$ lead. twist for $Q^2 \to \infty$

Sudakov factor (Sterman et al)

$S \propto \ln \frac{\ln(\tau Q/\sqrt{2}\Lambda_{\rm QCD})}{-\ln(b\Lambda_{\rm QCD})}$ + NLL

$\hat{\mathcal{F}}$ FT of hard scattering kernel

e.g. FT of $\propto e_a/[k_\perp^2 + \tau(\bar{x}+\xi)Q^2/(2\xi)]$

regularizes also TT amplitude

in collinear appr:

$$\mathrm{TT}: \int_0^1 d\tau \frac{\Phi_V(\tau)}{\tau} \frac{1}{(1-\tau)t + \tau Q^2}$$

IR singular for large Q^2

regular for large $-t$ (wide-angles)

The first moments at $t = 0$

for orientation

(assuming that the GPDs have no nodes and similar t dependence)

	H	E	$\widetilde{H}$	$\widetilde{E}$
u_v	2	$\kappa_u = \quad 1.67$	0.93	?
d_v	1	$\kappa_d = -2.03$	-0.34	?

$\rho^0 \sim e_u F^u - e_d F^d$ $\qquad\qquad$ $\rho^+ \sim F^u - F^d$

Numerical results

Goloskokov-K. 06, 07, 08

GPDs constructed from CTEQ6 PDFs through the double distribution ansatz

Gaussian wave fcts for the mesons $\Psi_{Vj}(\tau, \mathbf{k}_\perp) \propto \exp[-a_{Vj}^2 \mathbf{k}_\perp^2/(\tau\bar{\tau})]$

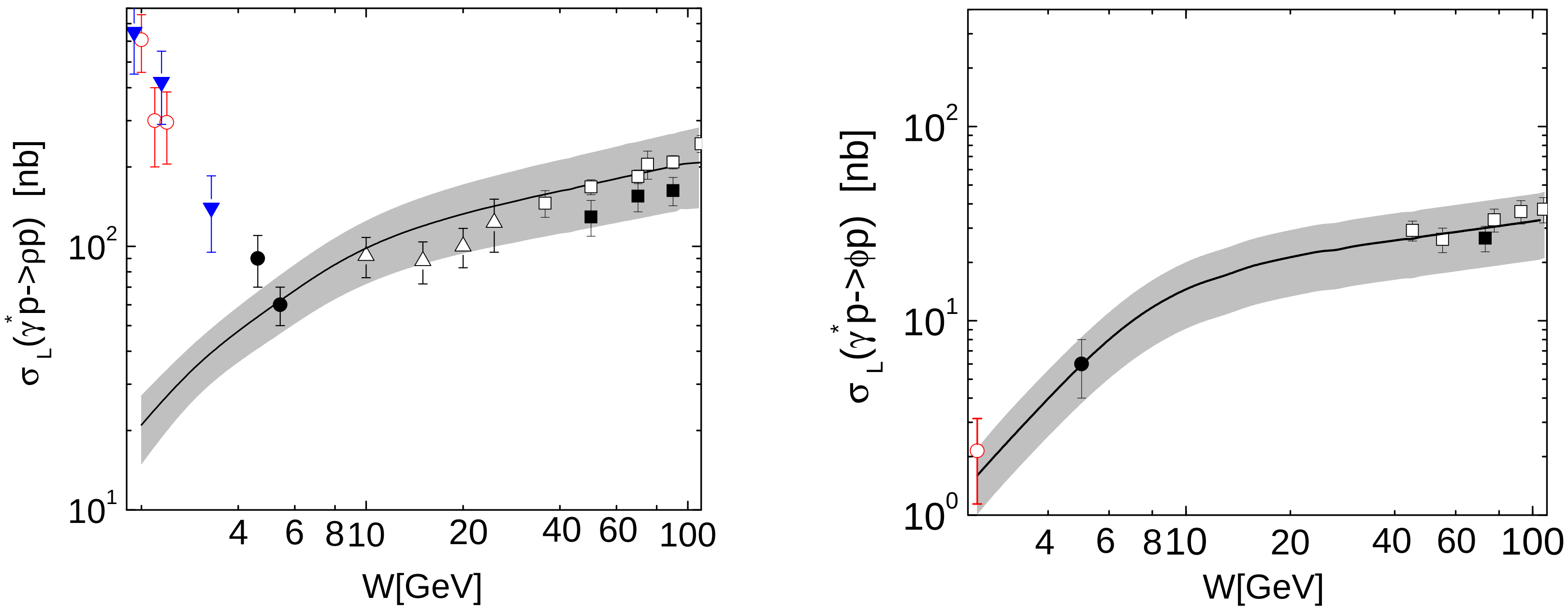
L an T different, free parameters - $a_{L,T}^V$ (transverse size $\langle k_\perp^2 \rangle^{1/2} \propto 1/a_{L,T}^V$)

meson wf. provides effects of order $\langle k_\perp^2 \rangle / Q^2$
GPDs mainly influence the $\xi(x_{Bj})$ dependence

separation of both effects possible

fit to all data from HERMES, COMPASS, E665, H1, ZEUS
cover large range of kinematics $Q^2 \simeq 3 - 100\,\mathrm{GeV}^2$ $W \simeq 5 - 180\,\mathrm{GeV}$

ρ^0 and ϕ cross sections



at $Q^2 = 4(3.8)\,\mathrm{GeV}^2$ E665 (△), HERMES (●), CORNELL (▲)

ZEUS (□), H1 (■), CLAS (○)

double distribution model too simple for valence quarks for large ξ?

breakdown of handbag physics? Lacking nucleon resonances?

ω, ρ^+ large at small W too? (Goloskokov-K (09))

JLAB12 may explore region close to minimum

What do we know about E_v?

analysis of Pauli FF for proton and neutron at $\xi = 0$ Diehl et al (04):

$$F_2^{p(n)} = \int_0^1 dx \Big[e_{u(d)} E_v^u(x, \xi = 0, t) + e_{d(u)} E_v^d(x, \xi = 0, t) \Big]$$

ansatz for small $-t$: $E_v^a = e_v^a(x) \exp\Big\{ t\big(\alpha' \ln(1/x) + B_a\big) \Big\}$

forward limit: $e_v^a = N_a x^{-\alpha_v(0)} (1-x)^{\beta_v^a}$ (analogously to PDFs)

N_a fixed from $\kappa_a = \int_0^1 dx E_v^a(x, \xi = 0, t = 0)$

fitting FF data provides: $\beta_v^u = 4$, $\beta_v^d = 5.6$

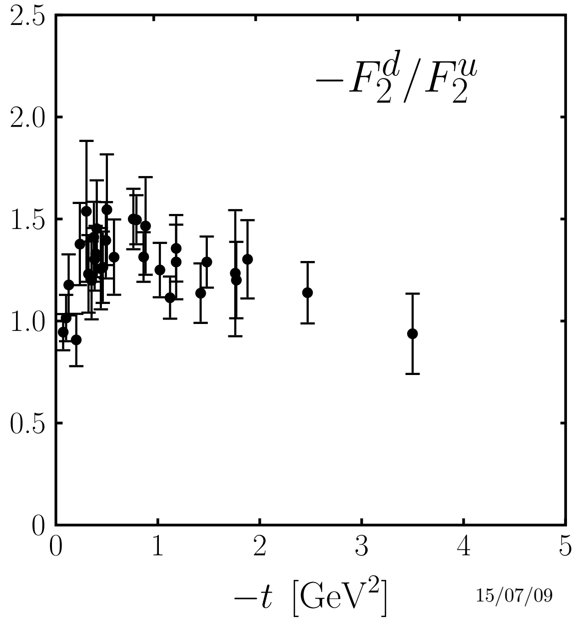
(other powers not excluded in 04 analysis)

new JLab data on $G^n_{E,M}$

up to $3.5(5.0)\,\mathrm{GeV}^2$ favor $\beta_v^u < \beta_v^d$

Input to double distribution model

(E_v^a is d.d. model at $\xi = 0$)



E for gluons and sea quarks

sum rule (Ji's s.r. and momentum s.r. of DIS) at $t = \xi = 0$

$$\int_0^1 dx x e_g(x) = e_{20}^g = -\sum e_{20}^{a_v} - 2\sum e_{20}^{\bar{a}}$$

valence term very small, in particular if $\beta_v^u \leq \beta_v^d$

$\Rightarrow$ gluon and sea quark moments cancel each other almost completely

positivity bound forbids large sea $\Rightarrow$ gluon small too

parameterization (flavor symm. sea for E assumed)

$$e^i = N_i x^{-\alpha_g(0)}(1-x)^{\beta^i}$$

input to double distribution model for E

Solutions for E and Ji's sum rule

$$\langle J^a \rangle = \frac{1}{2}\left[q_{20}^a + e_{20}^a\right] \qquad \langle J^g \rangle = \frac{1}{2}\left[g_{20} + e_{20}^g\right]$$

$(\xi = 0)$ $\langle J \rangle$ means average value of three component of J

var.	β_{val}^u	β_{val}^d	β^g	β^s	N_g	N_s	J^u	J^d	J^s	J^g
1	4	5.6	-	-	0.000	0.000	0.250	0.020	0.015	0.214
2	4	5.6	6	7	-0.873	0.155	0.276	0.046	0.041	0.132
3	4	5.6	6	7	0.776	-0.155	0.225	-0.005	-0.011	0.286
4	10	5	7	-	0.523	0.000	0.209	0.013	0.015	0.257

J^i quoted at scale $4\,\mathrm{GeV}^2$ (spread indicates uncertainties of present knowledge)

$\sum J^i = 1/2$, the spin of the proton

characteristic, stable pattern: for all variants J^u and J^g are large, others small

The first moments at $t = 0$

for orientation

(assuming that the GPDs have no nodes and similar t dependence)

	H	E	$\widetilde{H}$	$\widetilde{E}$
u_v	2	$\kappa_u = \quad 1.67$	0.93	?
d_v	1	$\kappa_d = -2.03$	-0.34	?

L and S

$$\langle J^{u_v} \rangle = 0.211(17) \qquad \langle J^{d_v} \rangle = 0.000(19) \qquad \text{at scale } 4\,\mathrm{GeV}^2$$

Lattice (Hägler et al (07)): $\langle J^{u} \rangle = 0.214(27)\,,\ \langle J^{d} \rangle = -0.001(27)$

at m_π(phys) sea quark contributions seem to be small

orbital angular momenta: subtract contribution from spin

$$\langle L^i \rangle := \langle J^i \rangle - \Delta q^i$$

valence quarks (for variants 1, 2, 3): $\langle L^{u_v} \rangle \simeq -0.241\,,\ \langle L^{d_v} \rangle \simeq 0.155\,,$

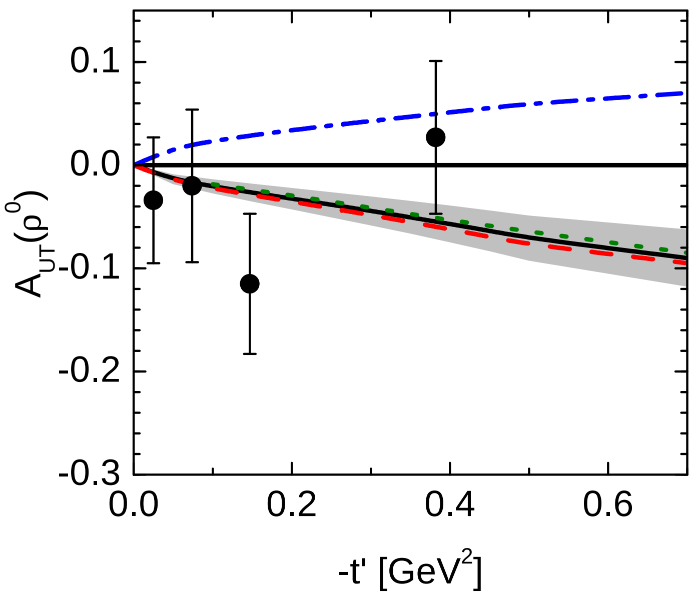
Δg very small: $\langle L^g \rangle \simeq \langle J^g \rangle$

(note: for gluons no gauge inv. separation into L and S

$\langle L^g \rangle$ defined as $\langle J^g \rangle - \int dx \Delta g(x)$ Ji (96), Burkardt-BC (08))

Results for $A_{UT}(V)$

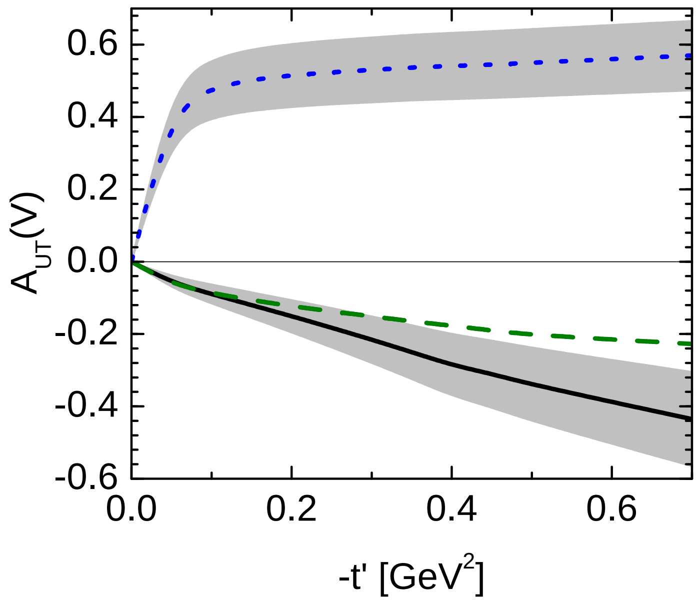
Goloskokov-K (08)



$W = 5\,\mathrm{GeV} \qquad Q^2 = 3\,\mathrm{GeV}^2$

variant 1, 2, 3, 4

preliminary data: HERMES (07)



variant 1 for ω, ρ^+, K^{*0}

t dependence controlled by trivial factor $\sqrt{-t'}$

except for ρ^+: since $H(E)^u_v - H(E)^d_v$

E non-negligible in cross section, contribution from helicity flip ampl. $\propto t'$

more data on ρ^0, ω, ϕ from HERMES and COMPASS will come

Exclusive electroproduction of pions

as for vector-mesons with replacement $H \Rightarrow \widetilde{H}$ and $E \Rightarrow \widetilde{E}$

for π^+ production: only $\widetilde{H}_v^u - \widetilde{H}_v^d$ and $\widetilde{E}_v^u - \widetilde{E}_v^d$ contribute
and pion pole

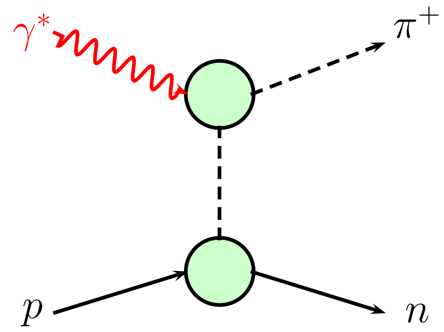
Mankiewicz et al (98), Vanderhaeghen et al (99), Belitsky-Mueller (01),...
leading-twist calculation with double distr. model for $\widetilde{H}$ input Δq and
$\widetilde{E}_v^u = -\widetilde{E}_v^d = \frac{1}{\sqrt{2}}\Theta(|\,\bar{x}\,| \leq \xi)\frac{\Phi_\pi(\tau)}{\xi}\frac{m g_{\pi NN} f_\pi}{m_\pi^2 - t} F_{\pi N}(t)$
provides l.t. result for pion FF
(about 1/3 of exp. value measured in same reaction CLAS (06))
fails with cross section by order of magnitude
full pion FF needed, see Goloskokov-K(09),Bechler-Mueller (09)

The pion pole contribution

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

$$\rho_\pi = \sqrt{2} g_{\pi NN} F_\pi(Q^2) F_{\pi NN}(t')$$
$$F_\pi = [1 + Q^2/(0.50\mathrm{GeV}^2)]^{-1}$$
$$F_{\pi NN} = (\Lambda_N^2 - m_\pi^2)/(\Lambda_N^2 - t')$$

$$\begin{aligned}
\mathcal{M}^{\rm pole}_{0+,0+} &= -e_0 \frac{2m\xi Q}{\sqrt{1-\xi^2}} \frac{\rho_\pi}{t-m_\pi^2}\,, \\
\mathcal{M}^{\rm pole}_{0-,0+} &= +e_0 Q\sqrt{-t'}\, \frac{\rho_\pi}{t-m_\pi^2}\,, \\
\mathcal{M}^{\rm pole}_{0+,\pm+} &= \pm 2\sqrt{2} e_0 \xi m \sqrt{-t'}\, \frac{\rho_\pi}{t-m_\pi^2}\,, \\
\mathcal{M}^{\rm pole}_{0-,\pm+} &= \pm\sqrt{2} e_0 t' \sqrt{1-\xi^2}\, \frac{\rho_\pi}{t-m_\pi^2}\,.
\end{aligned}$$



ampls. for transv. pol. photons disappear for forward scattering

cross sections like $\gamma p \to \pi^+ n$ or $p\bar{p} \to n\bar{n}$, should show forward dip

but exhibit pronounced spike experimentally (width $\mathcal{O}(m_\pi^2)$)

ways out: conspirator (Phillips(67)), poor man's absorption model (Williams(70)), Regge cuts (Rhanama-Storrow(82)), nucleon exchange (gauge invariance)

modifies non-flip amplitude

$$\mathcal{M}^{\rm pole}_{0-,++} \Longrightarrow \sqrt{2} e_0 (t_0 - m_\pi^2) \sqrt{\frac{1+\xi}{1-\xi}} \frac{\rho_\pi}{t-m_\pi^2} \qquad \text{too small}$$

Can $\mathcal{M}_{0-,++}$ be fed by ordinay GPDs?

lead. twist pion wave fct. $\propto q' \cdot \gamma\gamma_5$

perhaps including $\mathbf{k}_\perp$ $\qquad\qquad$ $\mathcal{M}_{0-,++} \neq 0$

but $\quad p_+ q_+ \to n_- q_+ \quad \propto \sqrt{-t'}$

$\mathcal{H}_{0\pm,+\pm} \quad \propto \sqrt{-t'} \qquad \Longrightarrow \mathcal{M}_{0-,++} \propto t'$

dynamics different from handbag appr. with helicity non-flip GPDs required

A twist-3 contribution

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

$$\mathcal{M}^{\rm twist-3}_{0-,\mu+} = e_0\sqrt{1-\xi^2}\int_{-1}^{1} d\bar{x}\,\Big\{\mathcal{H}_{0-,\mu+}\big[H_T^{(3)} - \frac{\xi}{1-\xi^2}(\xi E_T^{(3)} - \widetilde{E}_T^{(3)})\big]\Big\} + \mathcal{O}(\frac{t'}{m^2})$$

lead. twist $q'\cdot\gamma\gamma_5 \quad\Longrightarrow \mathcal{H}_{0-,++}=0$

twist-3 (3-part. contr. neglected: $\tau\Phi_P = \Phi_\sigma/N_c - \tau\Phi'_\sigma/(2N_c)$

solution: $\Phi_P = 1, \Phi_\sigma = \Phi_{AS}$)

$\sim \mu_\pi\gamma_5\Big[\Phi_P - \imath\sigma_{\mu\nu}(\ldots\Phi'_\sigma + \ldots\Phi_\sigma\partial/\partial\mathbf{k}_{\perp\nu})\Big]$ Beneke-Feldmann (01)

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

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

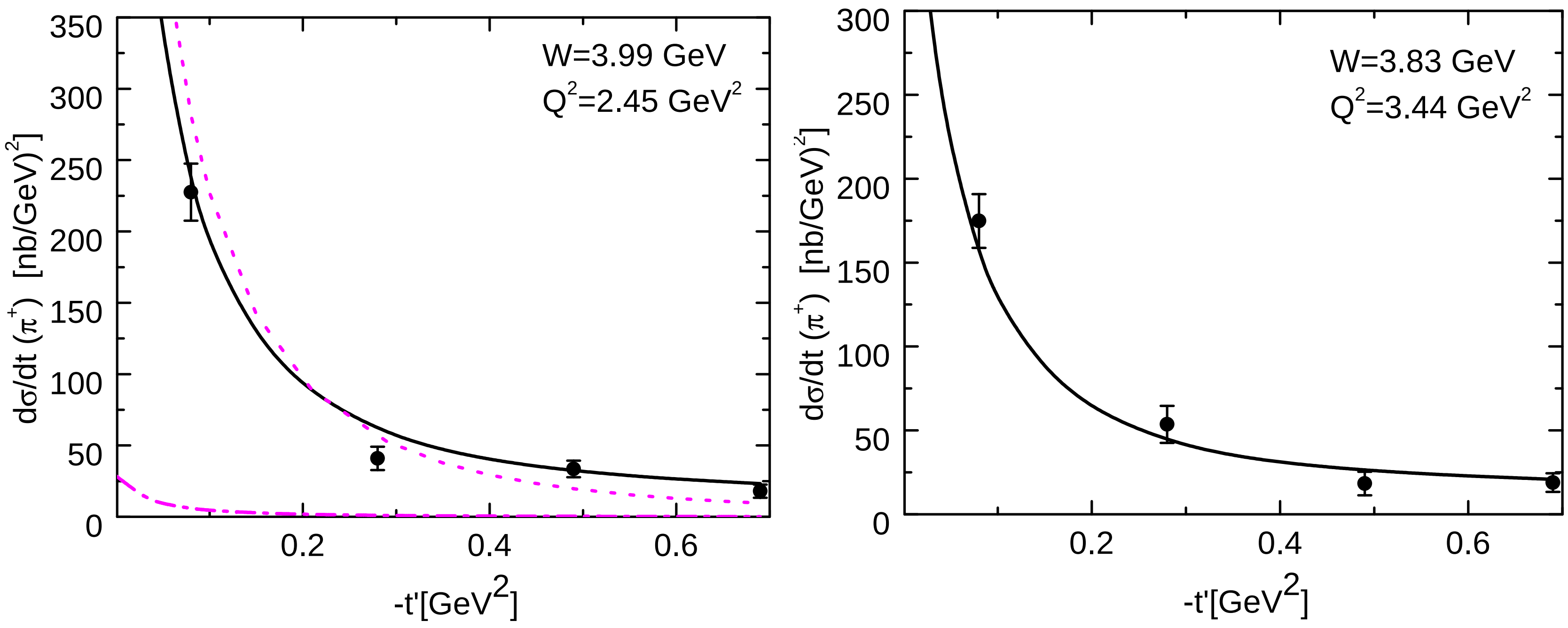
in coll. appr.: $\mathcal{H}_{0-,++}$ infr. sing. and double pole $1/(x-\xi)^2$ m.p.a. regular

small ξ: H_T should dominate; take transversity PDF from Anselmino et al (07)

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

input to double distr. ansatz

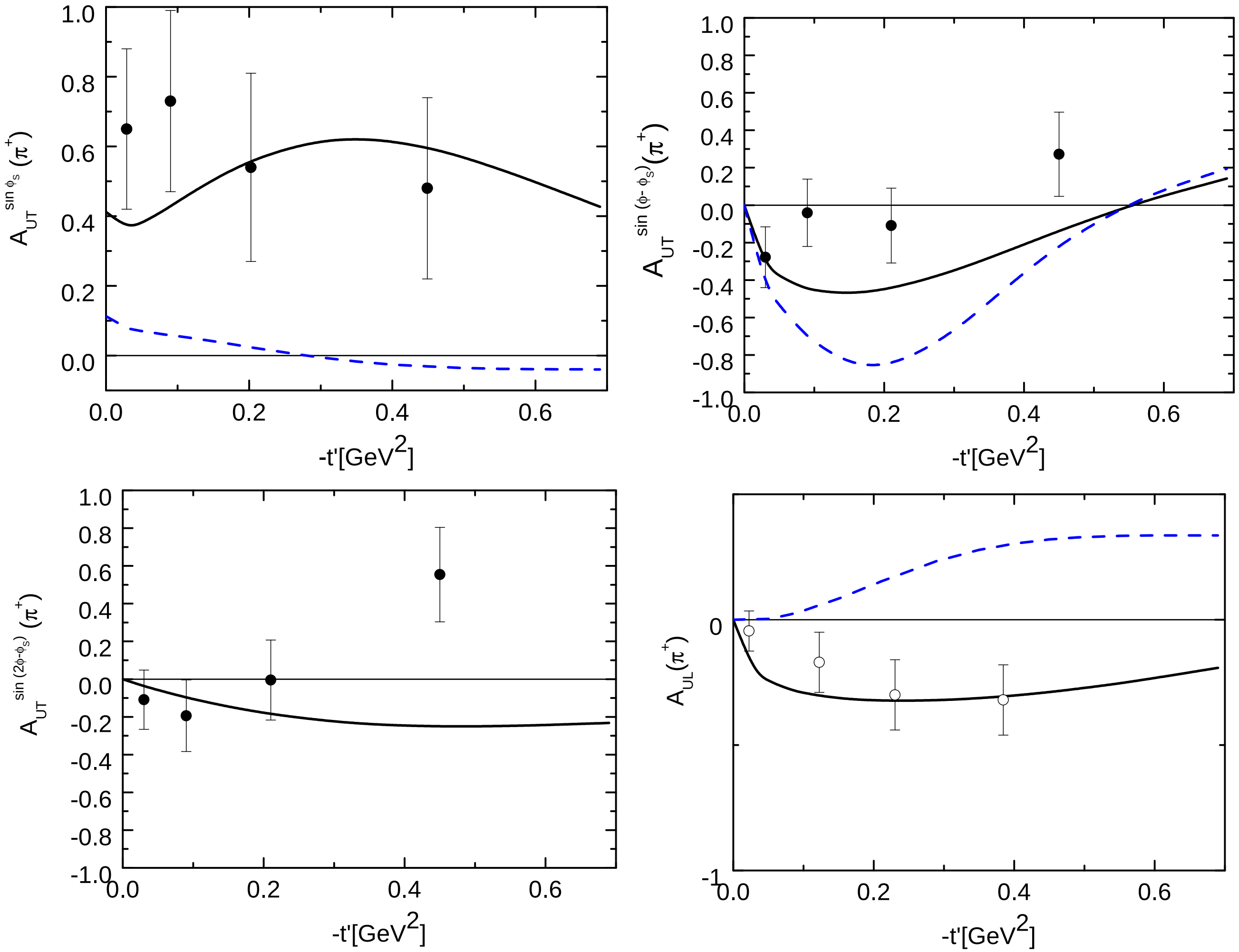
Results on unseparated π^+ cross section



data from HERMES 07 Goloskokov-K (09)

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

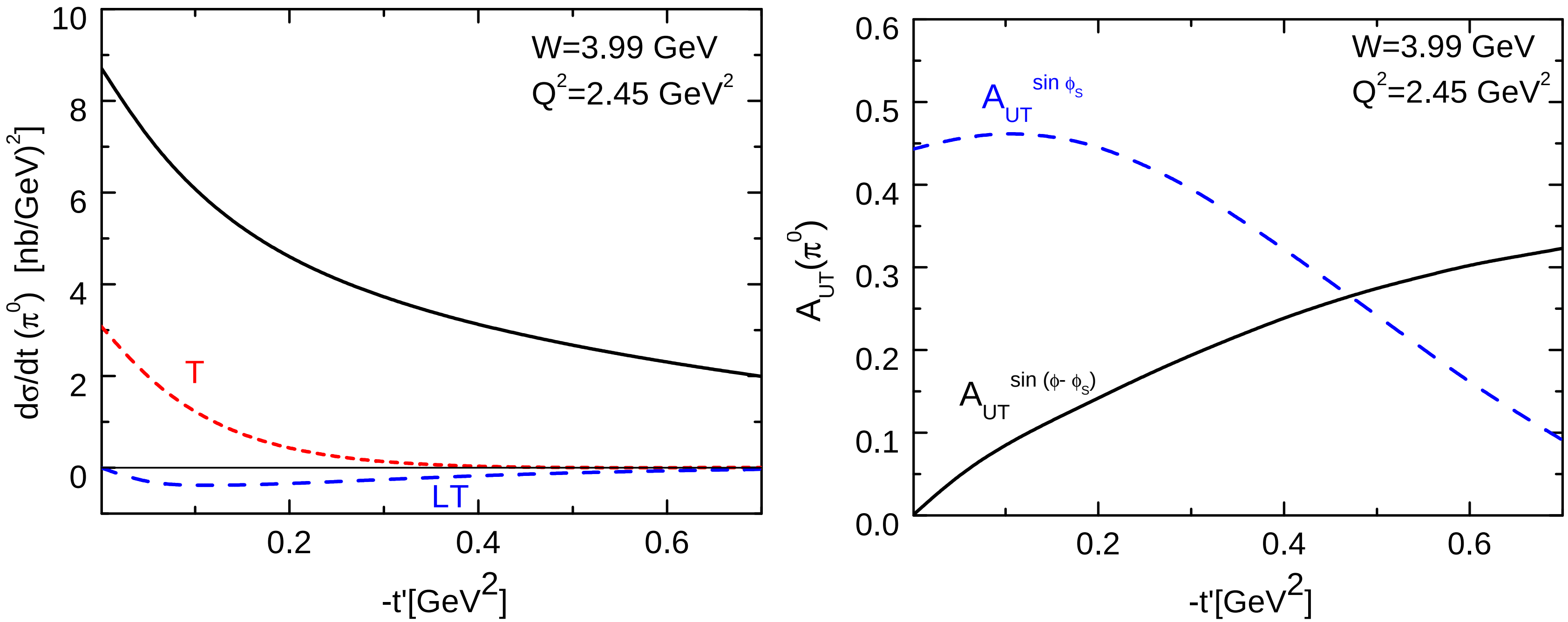
Results on target asymetries



prel. data on A_{UT} HERMES (08); A_{UL} HERMES(02) Goloskokov-K (09)

blue: without twist-3 contr.; other asym.: $|A_{UT}| < 0.1$ agree with exp.

Results on π^0 electroproduction



pion exchange absent Goloskokov-K(09)

Other twist-3 estimate: Ahmad et al (08)
(subprocess viewed as form factors for $\gamma - \pi$ transitions under the action of vector and axial-vector currents)

Summary

- phenomenology of DVME within the handbag approach is complicated, many GPDs contribute, still a lot of work to be done
- GPDs modeled through reggeized double distributions and subprocess calculated within mod. pert. approach
  few free parameters (a_V)
- fair agreement with cross section data for vector mesons
  for $Q^2 \simeq 3 \dots 100\,\mathrm{GeV}^2$, $W \simeq 5 \dots 180\,\mathrm{GeV}$ (only H matters)
- E constructed with the help of Pauli FF, sum rules and positivity bounds
- data on A_{UT} will fix E and hence details on parton angular momenta better
- first attempts to understand π^+ electroproduction, is complicated required are GPDs $\widetilde{H}$ and $\widetilde{E}$, pion exchange and a twist-3 effect for transversely pol. photons (helicity-flip GPD H_T and twist-3 pion wave fct.)

Technical advantages of wide-angle scattering

TT amplitude in collinear approximation ($\Phi(\tau) = 6\tau\bar{\tau}[1 + \cdots]$)

$$\int_0^1 d\tau \frac{\Phi(\tau)}{\tau} \frac{1}{\bar{\tau}t + \tau Q^2}$$

IR singular for large Q^2
regular for large $-t$

Twist-3 in collinear appr.:
eq. of motion (neglecting 3-particle contr.): $\tau\Phi_P = \Phi_\sigma/N_c - \tau\Phi'_\sigma/(2N_c)$
solution: $\Phi_P = 1 \qquad \Phi_\sigma = 6\tau\bar{\tau}$

$$\int_0^1 d\tau \Phi_\sigma \frac{t}{\bar{\tau}t + \tau Q^2}$$

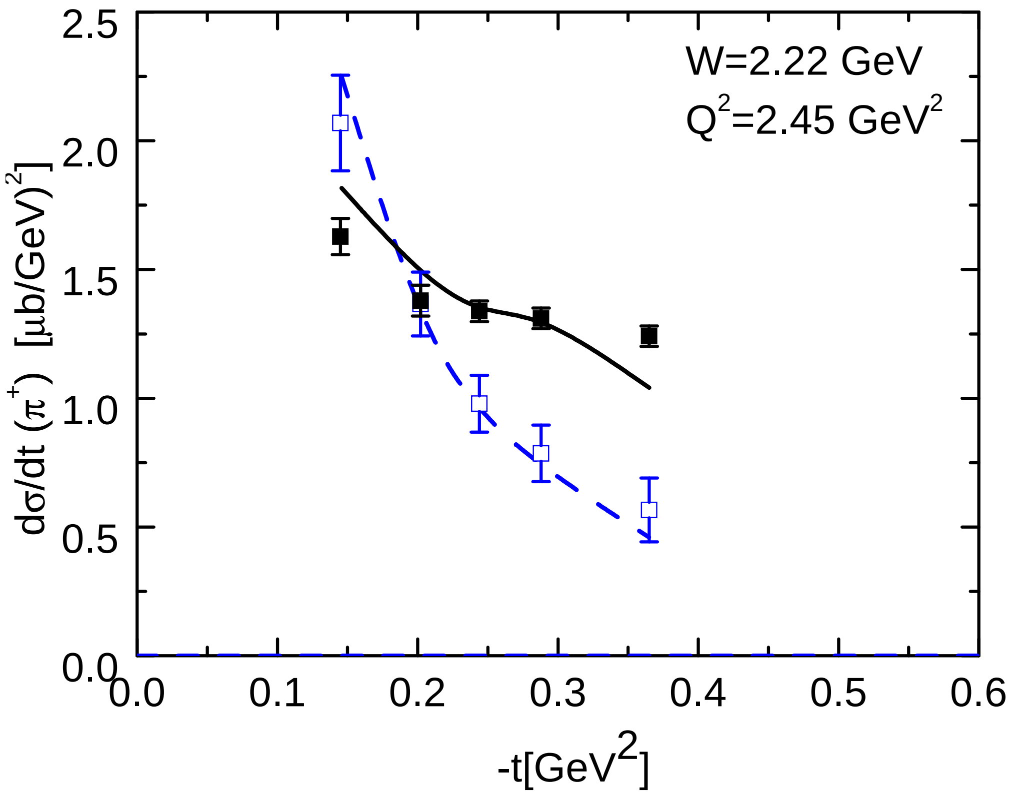
$\Rightarrow \quad \propto t/Q^2 \int d\tau/\tau$ at large Q^2
$\Rightarrow \quad \propto \int d\tau/\bar{\tau}$ IR sing. at large $-t$

$$\int_0^1 d\tau \Phi_P \frac{1}{\bar{\tau}t + \tau Q^2}$$

$\Rightarrow \quad \propto \int d\tau/\bar{\tau}(\tau)$ IR singular

for wide-angle photoproduction infrared singularities from Φ_P and Φ_σ cancel but not for large Q^2

Comparison with $F_\pi - 2$ data



H_T slightly modified at large x