Hard Exclusive Meson Electroproduction

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Outline:

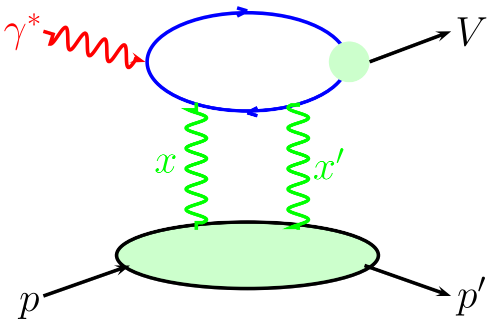
- **Handbag factorization and GPDs**
- **Transversely polarized photons matter**
- **Vector meson production**
- **Parameterizing GPDs**
- **Pion production (twist-3, transversity GPDs)**
- **Summary**

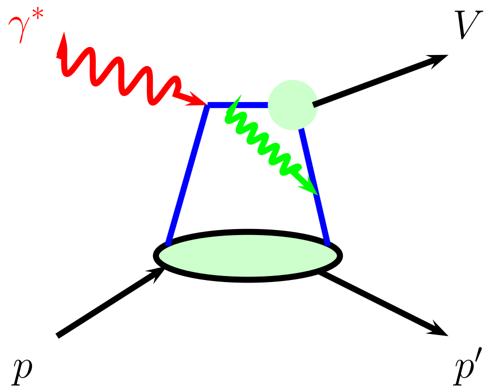
The handbag approach

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 $\gamma^*_L \to V_L, P$

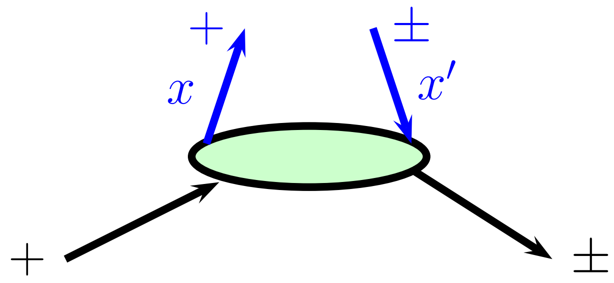
other transitions power suppressed
but often non-negligible (e.g. $\gamma^*_T \to V_T, \pi$)

GPDs

GPDs: $F = F(\bar{x}, \xi, t)$

$$F = H, E, \widetilde{H}, \widetilde{E}, H_T, \ldots$$

$$x = \frac{\bar{x}+\xi}{1+\xi} \quad x' = \frac{\bar{x}-\xi}{1-\xi}$$



constraints:

Forward limits from DIS: $H^q(\bar{x}, \xi = t = 0) = q(\bar{x})$, $\widetilde{H}^q \longrightarrow \Delta q(\bar{x})$

$H_T^q \longrightarrow \delta^q(\bar{x})$ trans. PDFs, known from SIDIS exp. Anselmino et al (07))

lowest moments (proton form factors): $F_1^q(t) = \int d\bar{x} H^q(\bar{x}, \xi, t)$, $F_1 = \sum e_q F_1^q$

$$E \longrightarrow F_2,\ \widetilde{H} \longrightarrow F_A$$

access to parton angular momentum (Ji's sum rule)

Fourier transform $\mathbf{\Delta} \longrightarrow \mathbf{b}$ ($\Delta^2 = -t$): information on parton localization in transverse position space

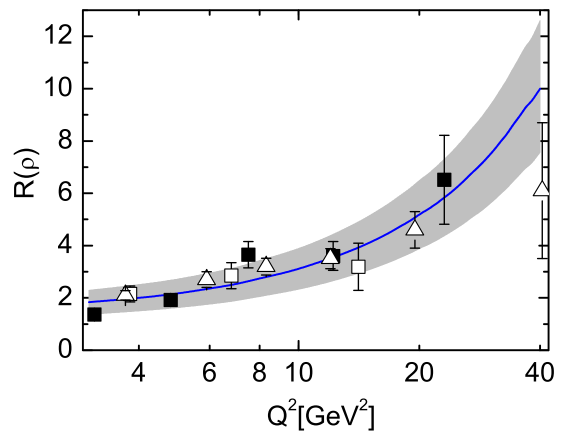
Transverse photon polarization matters

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

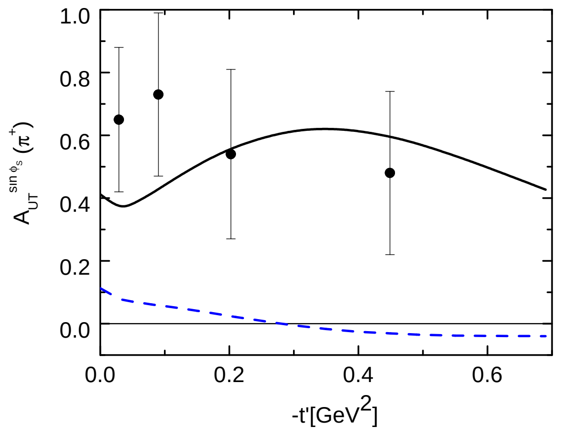
$\sin\phi_s$ moment very large

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

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

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

$\gamma^*_T \to P$ transitions substantial



HERMES

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

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.

$$\mathcal{M}_{\mu+,\mu+}(V) = \frac{e_0}{2}\left\{\sum_a e_a \mathcal{C}_V^{aa}\langle H_{\rm eff}^g\rangle_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle H_{\rm eff}^{ab}\rangle_{V\mu}\right\},$$

$$\mathcal{M}_{\mu-,\mu+}(V) = -\frac{e_0}{2}\frac{\sqrt{-t'}}{M+m}\left\{\sum_a e_a \mathcal{C}_V^{aa}\langle E^g\rangle_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle E^{ab}\rangle_{V\mu}\right\},$$

$\mathcal{C}_V^{ab}$ flavor factors, $M(m)$ mass of $B(p)$, $H_{\rm eff} = H - \xi^2/(1-\xi^2)E$
$F^{aa} = F^a \qquad F^{ab} = F^a - F^b \quad (a \neq b)$
$\langle F\rangle_{V\mu} = \sum_\lambda \int_{-1}^1 d\bar{x}\mathcal{H}^V_{\mu\lambda,\mu\lambda}(\bar{x},\xi,Q^2,t=0)F(\bar{x},\xi,t)$
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

What did (can) we learn about GPDs from DME?

What is probed by exp.: imag. parts $\propto$ GPDs at $\xi \simeq \bar{x}$ $+\mathcal{O}(<k_\perp^2>/Q^2)$

real parts - convolutions, dominated by $\bar{x}$ near ξ

$\xi \simeq 10^{-3}$ HERA

$\simeq 10^{-2}$ COMPASS

$\simeq 10^{-1}$ HERMES — $\bar{x} \geq 0.6$ not probed

$\simeq 0.1 - 0.4$ JLab — large $\bar{x}$ region important

LO, lead.twist accuracy (Teryaev (05)) e.g.:

$$\langle F \rangle = c\int_{-1}^{1} d\bar{x}\left[\frac{1}{\bar{x}-\xi+\imath\epsilon} + \frac{1}{\bar{x}+\xi-\imath\epsilon}\right] F(\bar{x},\xi,t)$$

$$\mathrm{Im}\langle F \rangle \sim F(\xi,\xi,t), \ \mathrm{Re}\langle F \rangle = cPV\int_0^1 d\bar{x}\frac{2\bar{x}^2}{\xi^2-\bar{x}^2}\, F(\bar{x},\bar{x},t)$$

As compared to DVCS:

disadvantage: need for GPDs and meson wave functions

advantages: allows for flavor separation (mesons select their valence quarks from the proton to lead. twist accuracy)

J/Ψ:	gluon	
ϕ:	gluon +sea	
ρ^0, ω:	gluon+sea+valence	mainly H
ρ^+, π^+:	valence	π^+: $\widetilde{H}, \widetilde{E}$

Parameterizing the GPDs

double distribution ansatz (Mueller *et al* (94), Radyushkin (99))

$$F_i(\bar{x},\xi,t') = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-\bar{x})\, f_i(\beta,\alpha,t') + D_i\, \Theta(\xi^2-\bar{x}^2)$$

DD: $f_i =$ zero-skewness GPD $\times$ weight fct (generating ξ dep.)

$F(\bar{x},\xi=0,t) = f(\bar{x}) \exp\left[(b_f + \alpha'_f \ln(1/\bar{x}))t\right]$

$f = q, \Delta q, \delta^q$ for $H, \widetilde{H}, H_T$ or $c\bar{x}^{-\alpha_f(0)}(1-\bar{x})^{\beta_f}$

Regge-like t dep. large x, large $-t$ more complicated profile fct Diehl et al (04)

advantage: polynomiality and reduction formulas automatically satisfied

dual parameterization (Polyakov(99), Polyakov-Semenov(09))

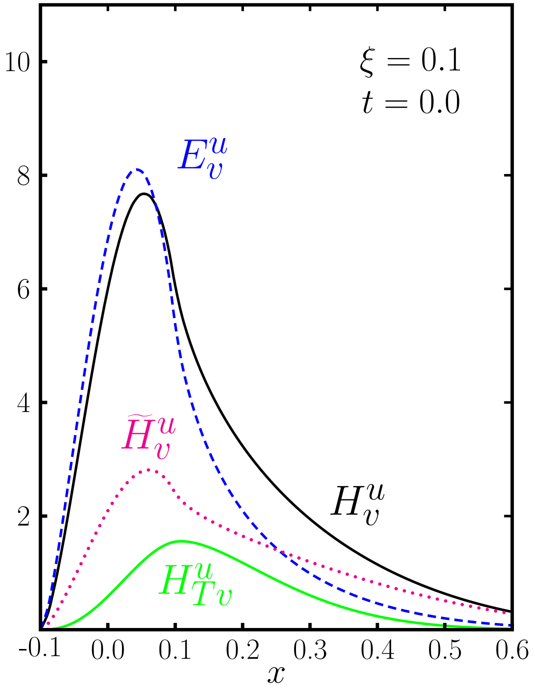
repres. of GPDs in terms of infinite sum of t-channel resonances - 'duality'

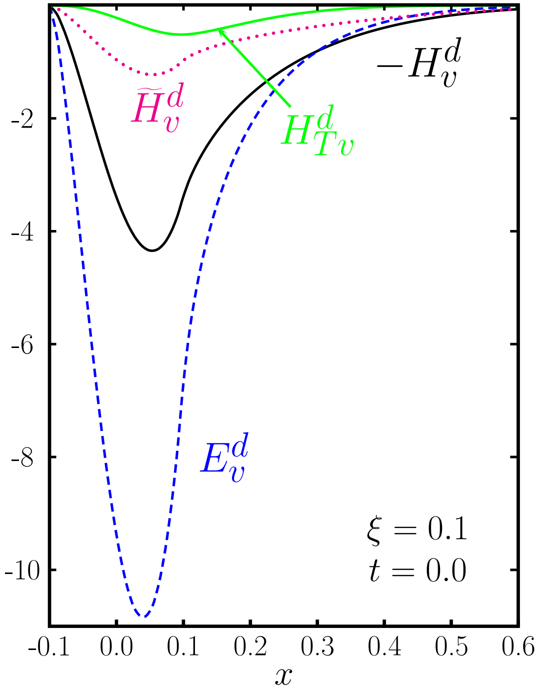
in practice: truncation of partial wave series at small j

e.g. Bechler-Mueller(09) for π^+ production:

zero-skewness GPD (as above) and rot. matrices $d^{j+m}_{0,m}(1/\xi)$

Valence quark GPDs





satisfy:

- polynomiality
- PDFs (if available)
- nucleon form factors
- positivity bounds

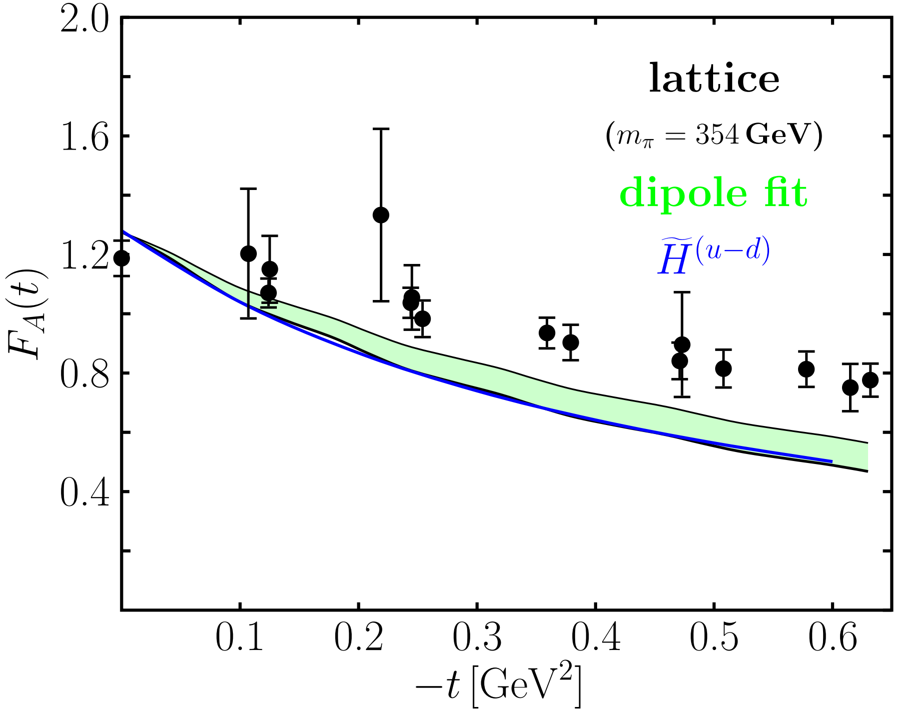
scale: $4GeV^2$

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

lowest moments

fix signs and rel. sizes if GPDs have no nodes and similar t dependence

Comparison with lattice results



Hägler (07), Göckeler (05)

lowest pion mass 352 MeV
no chiral extrapolation

exceptions:
2nd moments of H and E
$\Longrightarrow$ Ji's sum rule (see below)

Relative sizes of the moments and relative t dependence in reasonable agreement with DD ansatz
in general t dependences flatter than DD ansatz (and form factor data)

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

Numerical results for vector mesons

Goloskokov-K. 06, 07, 08, 09

subprocess amplitudes: mod. pert. approach (Sterman et al (93))

LO pQCD+ quark trans. mom. + Sudakov suppr. $\Rightarrow$ lead. twist for $Q^2 \to \infty$

GPDs constructed from CTEQ6 PDFs through the double distr. ansatz

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

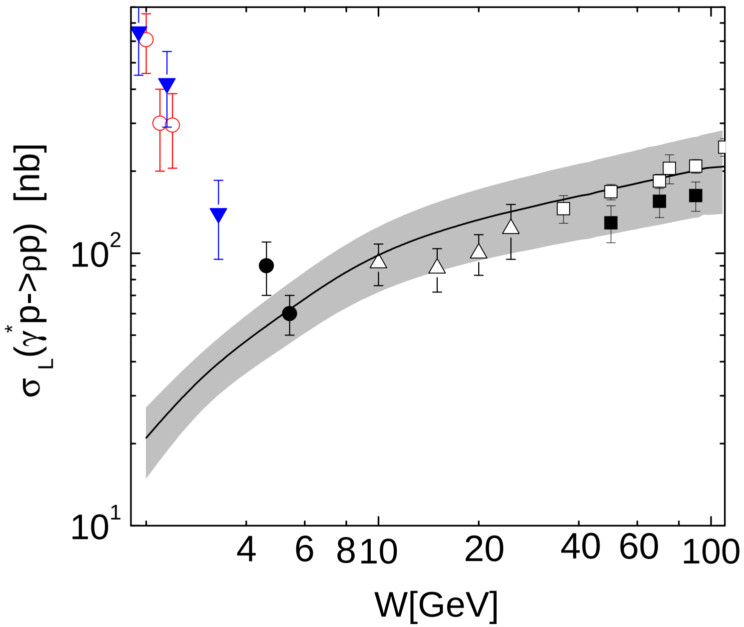
L an T different, free parameters - $a_{L,T}^V$ (transverse size $\langle k_\perp^2 \rangle^{1/2} \propto 1/a_{L,T}^V$)

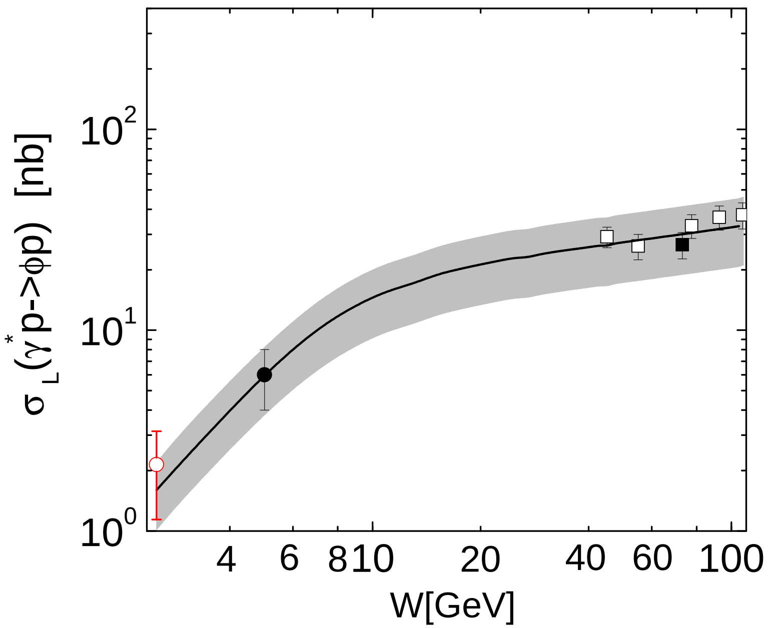
fit to all data from HERMES, COMPASS, E665, H1, ZEUS

cover large range of kinematics $Q^2 \simeq 3 - 100\,\mathrm{GeV}^2$ $W \simeq 5 - 180\,\mathrm{GeV}$

probes H

ρ^0 and ϕ cross sections





at $Q^2 = 4(3.8)\,\mathrm{GeV}^2$ E665 ($\triangle$), HERMES ($\bullet$), CORNELL ($\blacktriangle$)
ZEUS ($\square$), H1 ($\blacksquare$), CLAS ($\circ$)

Goloskokov-K (09)

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

breakdown of handbag physics?

ω, ρ^+ very large at small W too CLAS

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):

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

ansatz for small $-t$: $E_v^a = e_v^a(x) \exp\left\{t\big(\alpha_v' \ln(1/x) + b_a^e\big)\right\}$

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

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

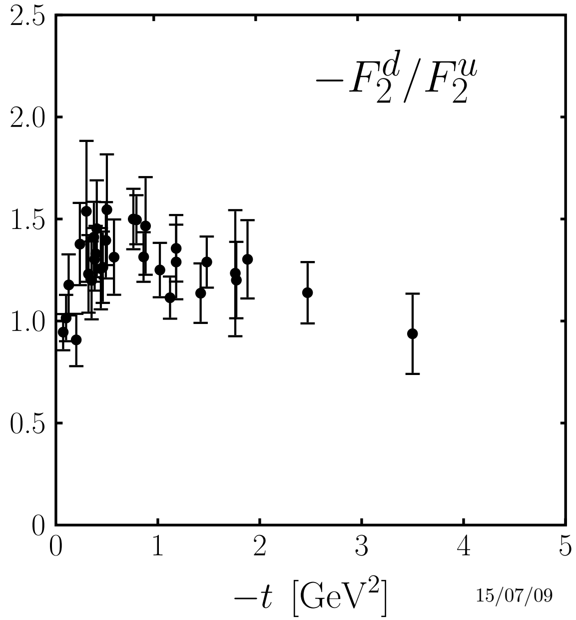
fitting FF data provides: $\beta_v^u = 4$, $\beta_v^d = 5.6$

(other powers not excluded in 04 analysis)

new JLab data on $G_{E,M}^n$

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

Input to double distribution model



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

Simplest variant (1): neglect E^g, E^{sea} (other variants also used)

Ji's sum rule (at scale $4\,\text{GeV}^2$):

$J^u = 0.250 \quad J^d = 0.020 \quad J^s = 0.015 \quad J^g = 0.214 \quad \sum J^i \simeq 1/2$

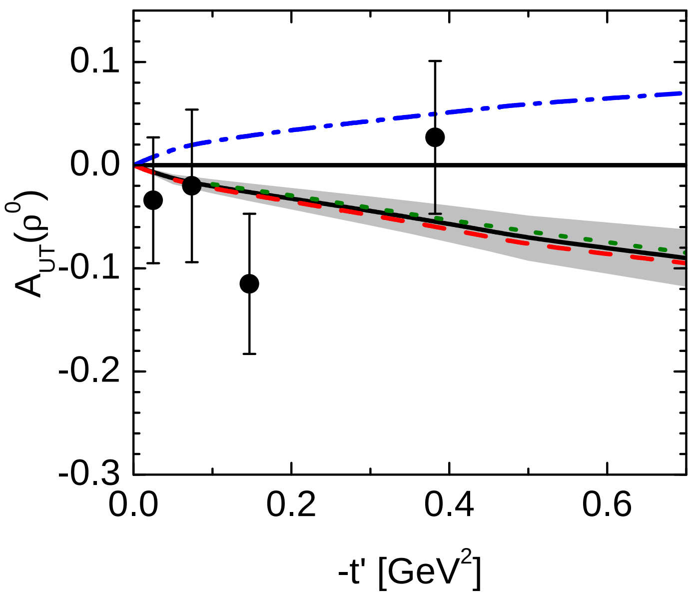
$\Longrightarrow J^{u_v} = 0.211(17) \quad J^{d_v} = 0.000(19)$ (Diehl et al (04))

lattice Hägler et al (07) at m_π(phys): $J^u = 0.214(27) \quad J^d = -0.001(27)$

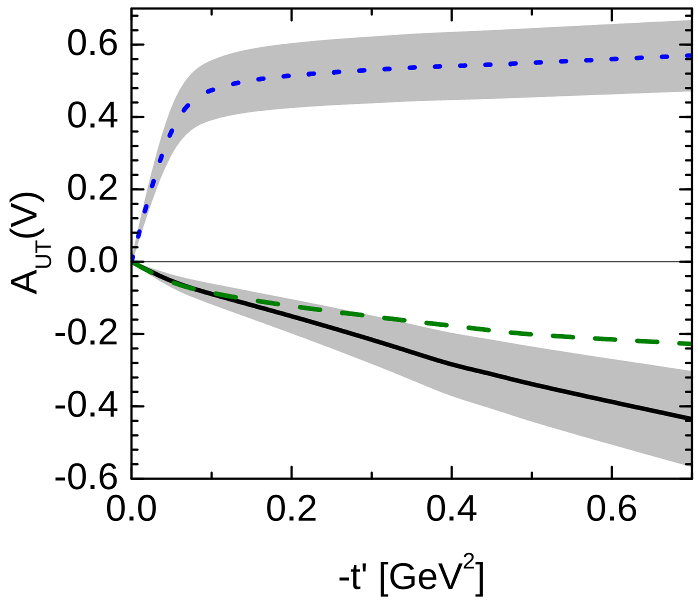
sea quark contr. seems to be small

Results for $A_{UT}(V)$

Goloskokov-K (08)



preliminary data: HERMES (07)



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

variant 1, 2, 3, 4

variant 1 for ω, ρ^+, K^{*0}

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

except for ρ^+: since $H_v^u - H_v^d$ small and $E_v^u - E_v^d$ large

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 $\widetilde{H}^{(3)} = \widetilde{H}_v^u - \widetilde{H}_v^d$ and $\widetilde{E}^{(3)} = \widetilde{E}_v^u - \widetilde{E}_v^d$
(including the pion pole)
for π^0 production: $e_u\widetilde{H}_v^u - e_d\widetilde{H}_v^d$ and $e_u\widetilde{E}_v^u - e_d\widetilde{E}_v^d$ (without pion pole)
JLab kinematics: π^0 cross section underestimated by handbag appr (as for ρ^0)?

full pion FF needed and extra $\widetilde{E}$ see Goloskokov-K(09),Bechler-Müller (09)

Bechler-Müller (09): leading-twist analyses with $\alpha_s^{\rm eff} = 0.8$, only LL ampl.
Goloskokov-K(09): plus twist-3 effect for LT ampl. (transversity GPDs)
Ahmad et al (08): only π^0 production with contr. from transversity GPDs

A twist-3 contribution

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

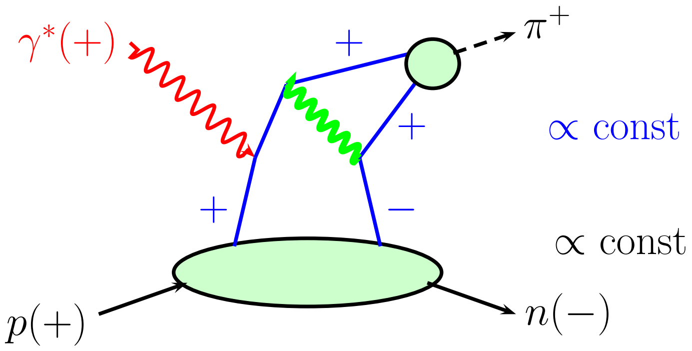
$\mathcal{M}_{0-++}$ fed by handbag dynamics

but with transversity GPDs

(Hoodbhoy-Ji (98), Diehl (01))

and twist-3 pion wave fct

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



twist-3 pion DA: $\langle \pi^+(q')|\bar{d}(x)\gamma_5 u(-x)|0\rangle = f_\pi \mu_\pi \int d\tau e^{q'\cdot x\tau}\Phi_P(\tau)$

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

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

twist-3 large, only suppressed by μ_π/Q

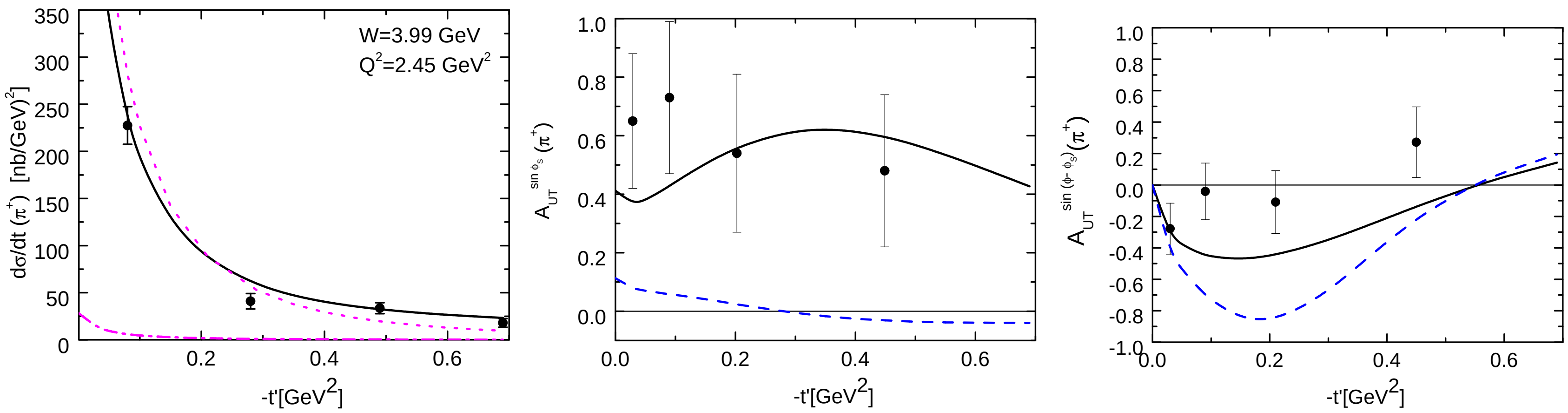
$\Phi_P = 1$ (under neglect of $q\bar{q}g$ Fock state) Braun-Halperin (90)

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

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

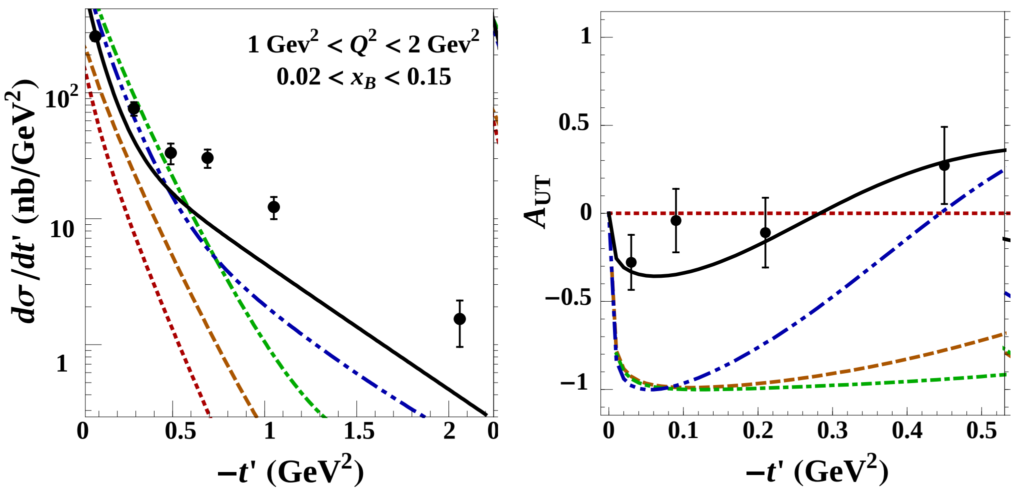
input to double distr. ansatz

Results on π^+ production



Goloskokov-K (09) $Q^2 = 2.5\,\mathrm{GeV}^2 \quad W = 3.99\,\mathrm{GeV}$

data HERMES (07)(08)



Bechler-Müller (09)

only LL amplitudes

(black lines)

Summary

- handbag approach: fair agreement with cross section data for vector mesons at small ξ has been found
  GPDs (H) modeled through reggeized double distributions and subprocess calculated within mod. pert. approach
  few free parameters (a_V)
  extension to large ξ (JLab kinematics) seems to be difficult
- single spin asymmetries will fix E; probably dominated by valence quarks; E^g and $E^{\rm sea}$ probably small
- first attempts to understand π^+ electroproduction
  required are GPDs $\widetilde{H}$ and $\widetilde{E}$, pion exchange and a twist-3 effect for transversely pol. photons
  (e.g. helicity-flip GPD H_T and twist-3 pion wave fct.)