Phenomenological Experience with hard Meson Electroproduction

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Outline:

- **Introduction**
- **Handbag factorization for meson electroproduction**
- **Transversely polarized photons matter**
- **Vector mesons**
- **Results for vector mesons**
- **Summary**

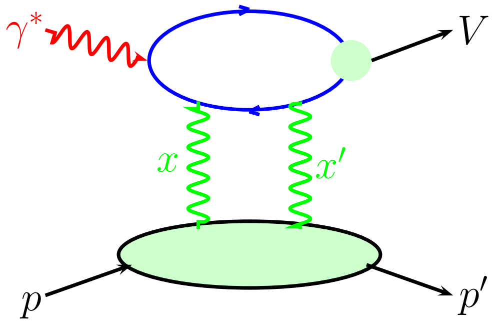
based on work done in collaboration with S. Goloskokov

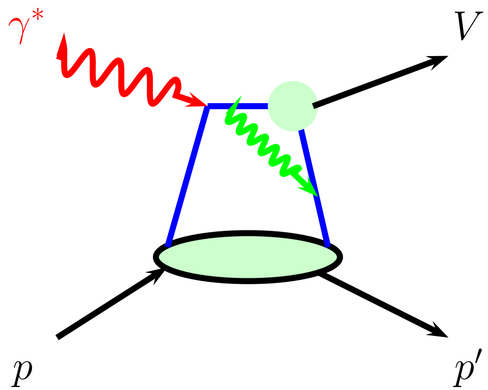
hep-ph/0501242, 0611290, arXiv:0708.3569, 0809.4126, 0906.0460

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

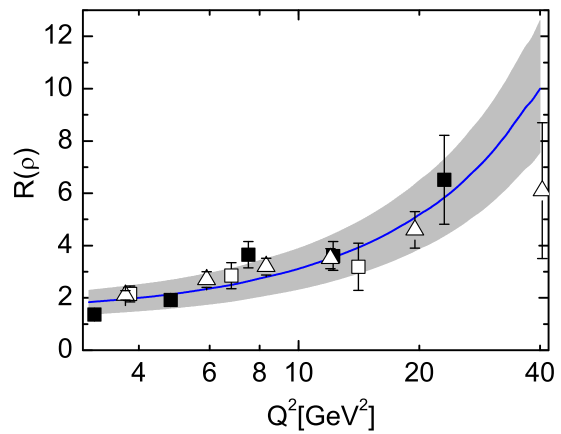
Transverse photon polarization matters

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

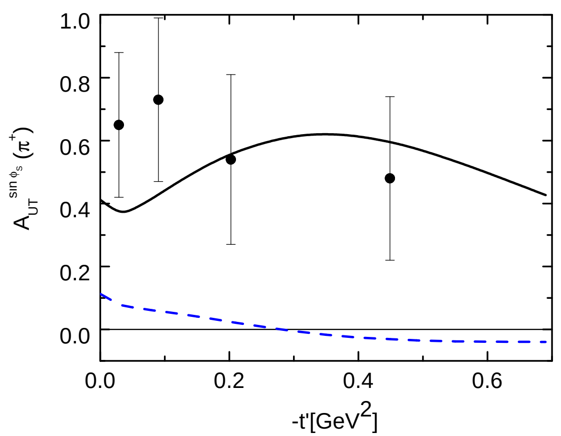
does not seem to vanish for $t' \to 0$

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

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

$\gamma_T^* \to P$ transitions substantial

$(H_T$, transversity)



HERMES (09)

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

Corrections to the l.-t. amplitudes?

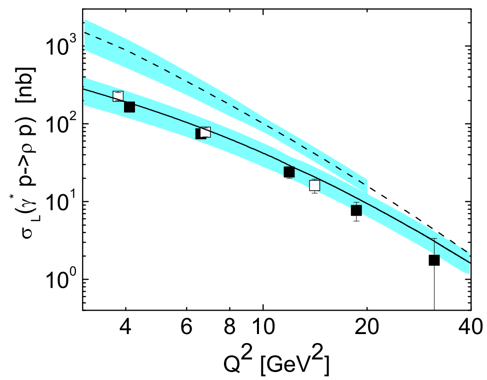
vector-meson electroproduction:

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:

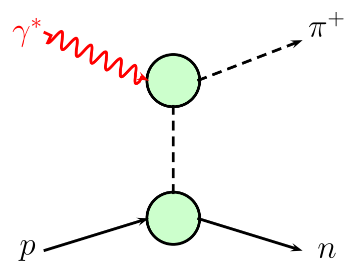
contribution from pion exchange

requires π elm form factor (measured there)

lead. twist only about a third of exp. value

fails with cross section by order of magnitude

additional contributions required



assump. of dominance of l.-t. contr. to LL ampl. at low Q^2 has no justification

(large power corr. not implausible: see $\pi^0\gamma$ form factor

BaBar data up to $\simeq 40\,\text{GeV}^2$ cannot be understood without them)

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

need to go beyond coll. factorization $\Longrightarrow k_\perp$ factorization (mod. pert. appr.)
(based on work by Ellis-Furmanski-Petronzio, Collins-Soper, Sterman et al)
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.

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

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

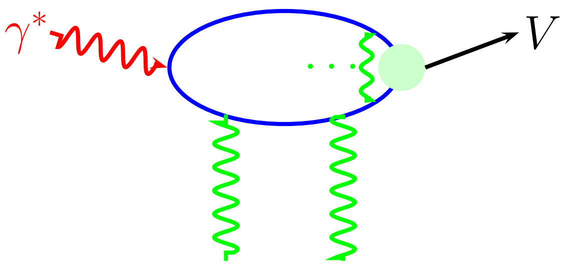
$\mathcal{C}_V^{ab}$ flavor factors, $M(m)$ mass of $B(p)$, $H_{\rm eff} = H - \xi^2/(1-\xi^2)E$
contributions from $\widetilde{H}$ to T-T amplitude not shown
electroproduction with unpolarized protons at small ξ:
E not much larger than H (see below) $\Longrightarrow H_{\rm eff} \to H$ for small ξ
$|M_{\mu-,\mu+}|^2 \propto t/m^2$ 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

$F = H, E$ λ 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:

TT: $\int_0^1 d\tau \frac{\Phi_V(\tau)}{\tau^2} \propto \int_0^1 \frac{d\tau}{\tau}$ IR singular

Double distributions

integral representation (i= valence, sea quarks, gluons)

$$H_i(\bar{x},\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-\bar{x})\, f_i(\beta,\alpha,t) + D_i\, \Theta(\xi^2-\bar{x}^2)$$

f_i double distributions — Mueller *et al* (94), Radyushkin (99)

advantage - polynomiality automatically satisfied

$D_i(\bar{x},t)$ ($i =$gluon, sea) additional free function, support $-\xi < \bar{x} < \xi$

parameterization of f_i in terms of forward limits and Regge-like t dependence (forw. limit of H: PDFs - reduction formula respected)

$$f_i(\beta,\alpha,t) \;=\; h_i(\beta)\, \exp[(b_i+\alpha_i'\ln(1/\beta))t]\, \frac{\Gamma(2n_i+2)}{2^{2n_i+1}\Gamma^2(n_i+1)}\, \frac{[(1-|\beta|)^2-\alpha^2]^{n_i}}{(1-|\beta|)^{2n_i+1}}$$

$h(\beta) \;=\; q(\beta), \beta g(\beta)$ (properly continued to $-1<\beta<0$)

$n_g = n_{\rm sea} = 2\,,\quad \alpha_g' = \alpha_{\rm sea}' = 0.15\,{\rm GeV}^{-2}$ (sea - gluon mixing under evolution)

$n_{\rm val} = 1\,,\quad \alpha_v' = 0.9\,{\rm GeV}^{-2}$

few free parameters (b_i)

if forw. limit unknown (e.g. E): $h_i \sim \beta^{\alpha_{R_i}(0)}(1-\beta)^{\alpha_i}$ more parameters

Numerical results for cross sections

H constructed from CTEQ6 PDFs through the double distr. ansatz
($D = 0$, sum rules and positivity bounds checked numerically)

Gaussian wave fcts for the mesons $\Psi_{Vj}(\tau, \mathbf{k}_\perp) \propto \exp[-a_{Vj}^2 \mathbf{k}_\perp^2/(\tau\bar{\tau})]$
(MPA: 'Gegenbauer filter' - higher Gegenbauer terms strongly suppressed at low Q^2)

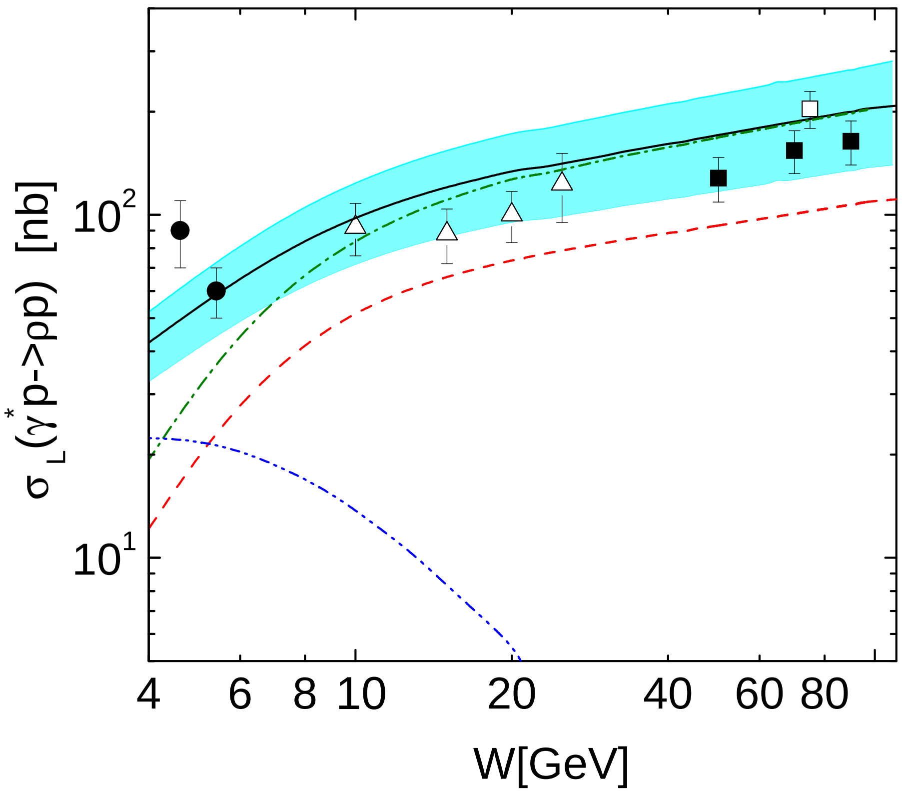
L an T different, free parameters - $a_{L,T}^V$ (transverse size $\langle k_\perp^2 \rangle^{1/2} \propto 1/a_{L,T}^V$)

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 $Q^2 \simeq 3 - 100\,\mathrm{GeV}^2$ $W \simeq 5 - 180\,\mathrm{GeV}$
main features of H fairly well fixed

Results on cross sections

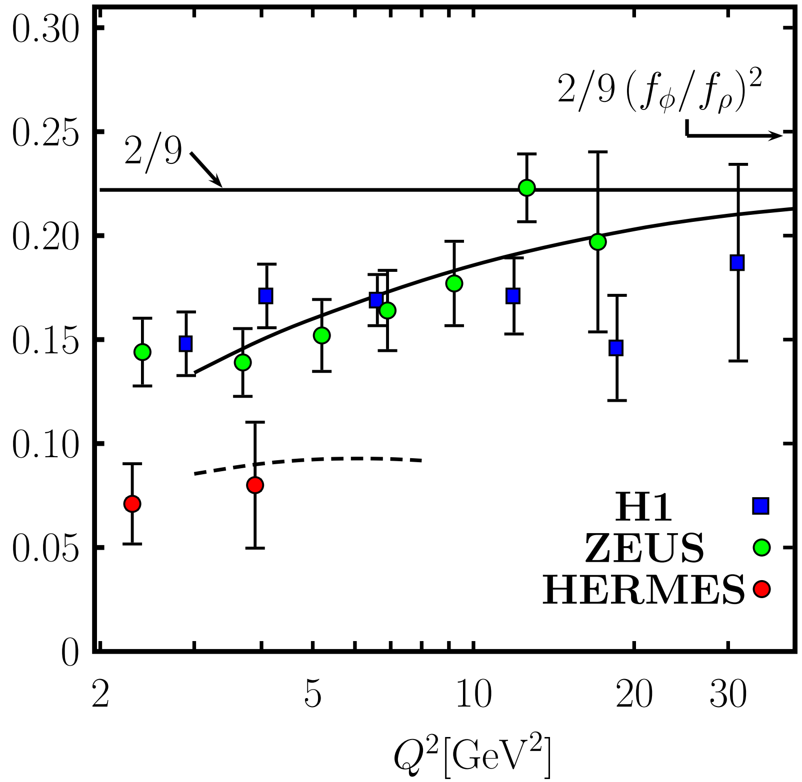


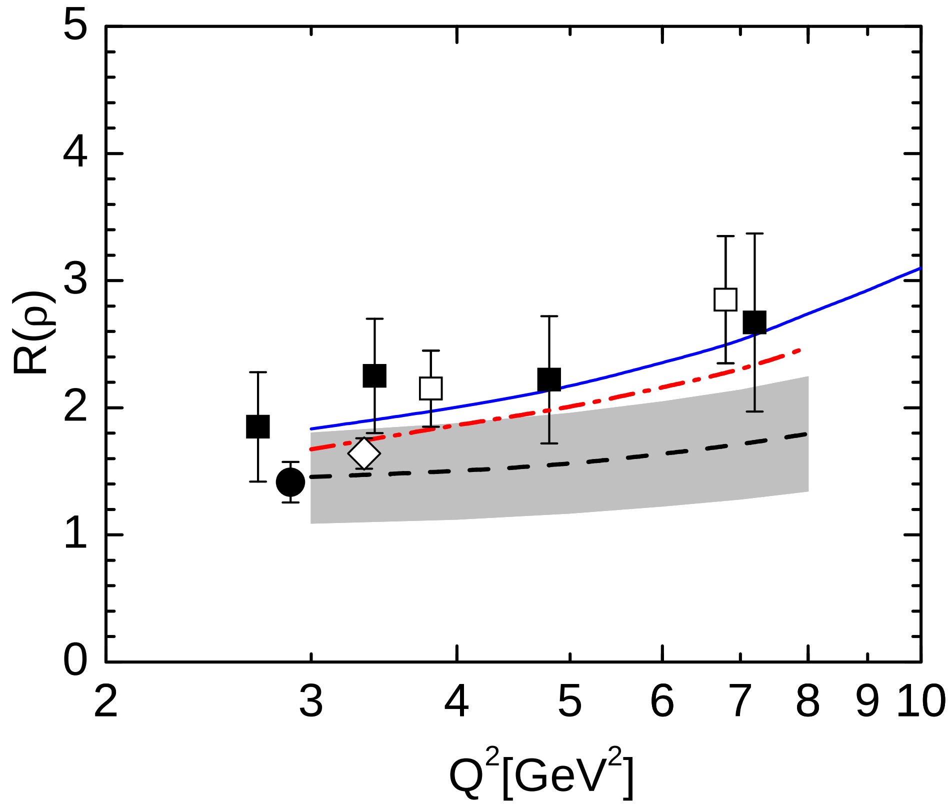
$Q^2 = 3.8\,\mathrm{GeV}^2$,

glue+sea, glue, valence +interf.

gluons (+ sea) dominant
for COMPASS kinematics

data: H1 (open), ZEUS (filled squares), E665 (triangles), HERMES (circles)





$\sigma_L(\phi)/\sigma_L(\rho)$

suppression due to a,

SU(3) breaking in sea, valence quarks

R at $W = 90(10, 5)\,\mathrm{GeV}$

data: H1, ZEUS, COMPASS (diamond),

HERMES (circle)

COMPASS data on ρ and ϕ may verify dominance of gluons ($+$ sea)

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 $-t$: $E_v^a = e_v^a(x) \exp\Big\{t\big(\alpha'_v \ln(1/x) + b_a^e\big)\Big\}$

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

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

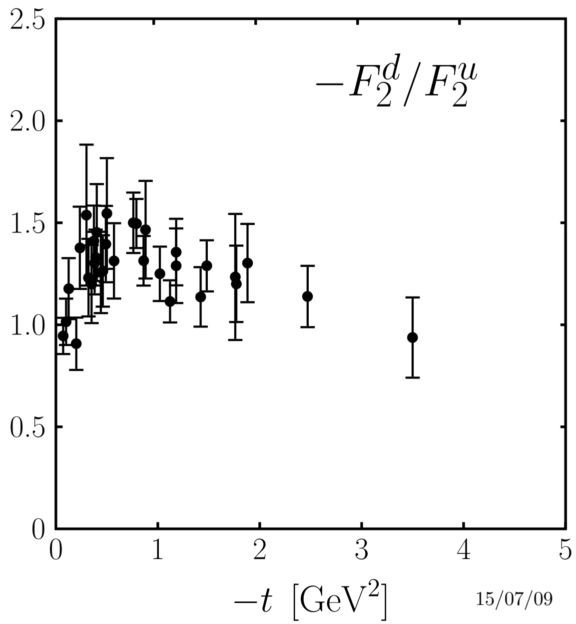
fitting FF data provides: $\beta_v^u = 4$, $\beta_v^d = 5.6$

(other powers not excluded in 04 analysis)

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

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

Input to double distribution ansatz



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)

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

and Regge-like t dependence:

$$\propto \exp\left\{ t\big(\alpha_i' \ln(1/x) + b_i^e\big) \right\}$$

input to double distribution ansatz for E

Variants of E and Ji's sum rule

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

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

var.	β^u_{val}	β^d_{val}	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

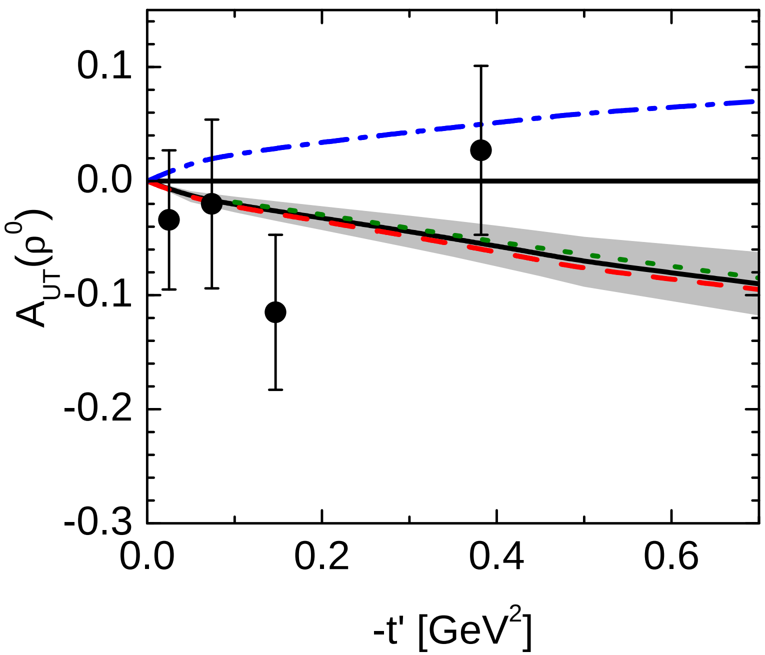
J^i quoted at scale $4\,\text{GeV}^2$ (spread indicates uncertainties of present knowledge)

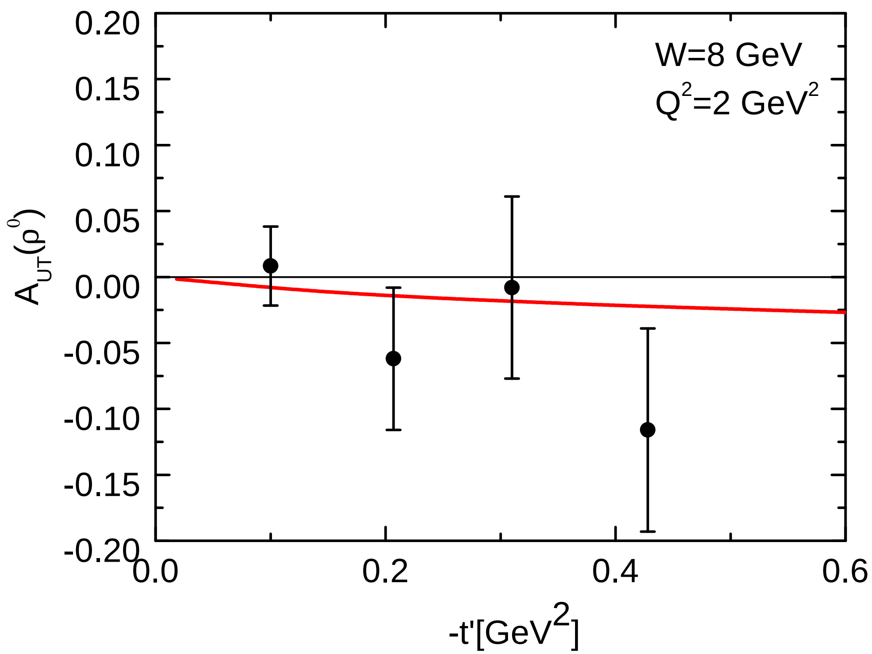
$\sum J^i = 1/2$, the spin of the proton

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

Results for $A_{UT}(V)$

data: HERMES (08) COMPASS prel.





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

variant 1, 2, 3, 4

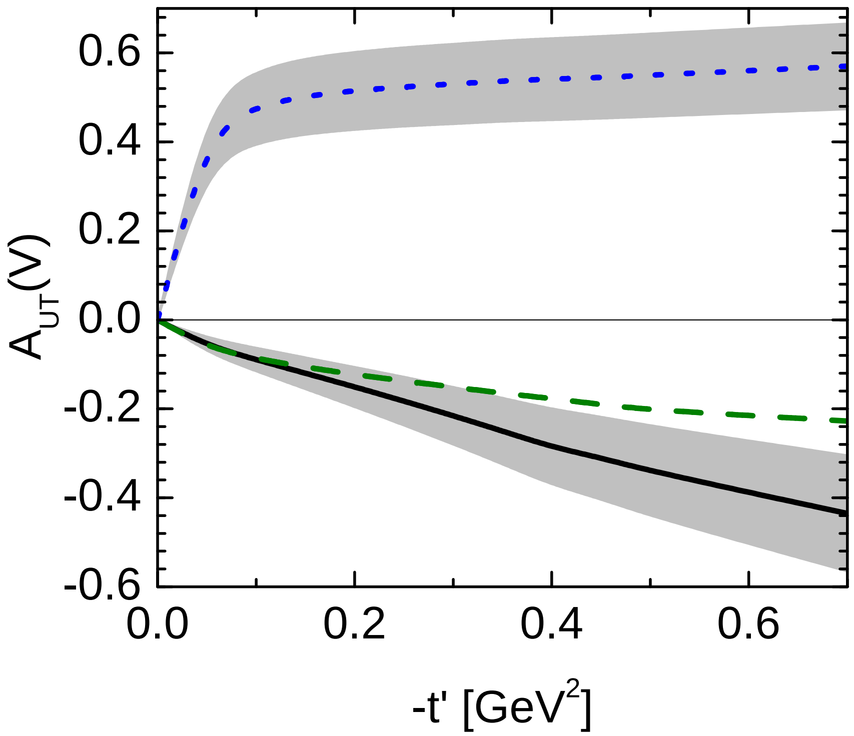
$W = 8\,\mathrm{GeV} \quad Q^2 = 2\,\mathrm{GeV}^2$

variant 1

negative value of A_{UT} favored, variant 4 disfavored

$A_{UT}(\phi) \simeq 0$ in agreement with prel. HERMES data

Results continued



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

will likely improve knowledge of E for valence quarks

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

What is probed by experiment:

imaginary parts $\propto$ GPDs at $\xi \simeq x \quad + \mathcal{O}(< k_\perp^2 > / Q^2)$

real parts - convolutions, dominated by x near ξ (see also disp. rel.)

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

$\simeq 10^{-2}$ COMPASS

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

$\simeq 0.1 - 0.4$ JLab $\quad$ large x region important

As compared to DVCS:

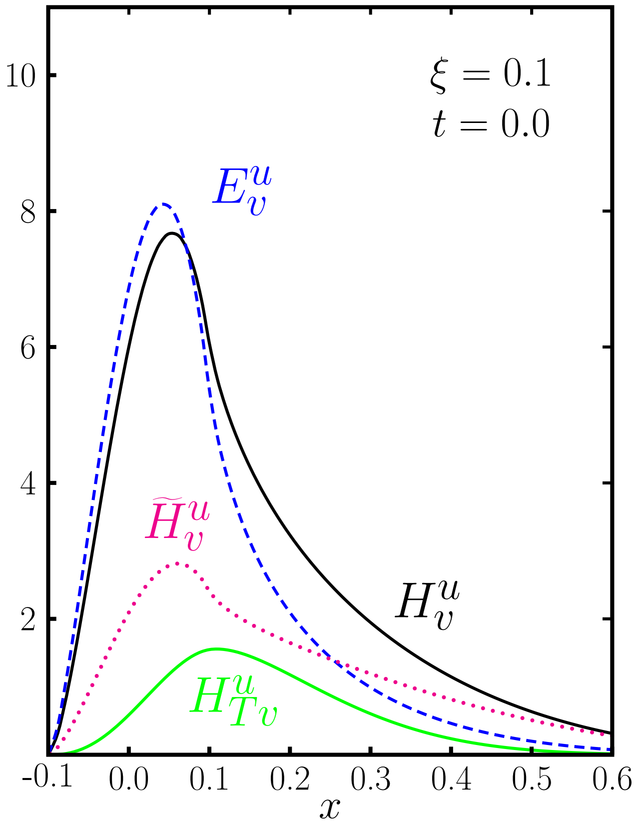
disadvantage: need for GPDs and meson wave functions

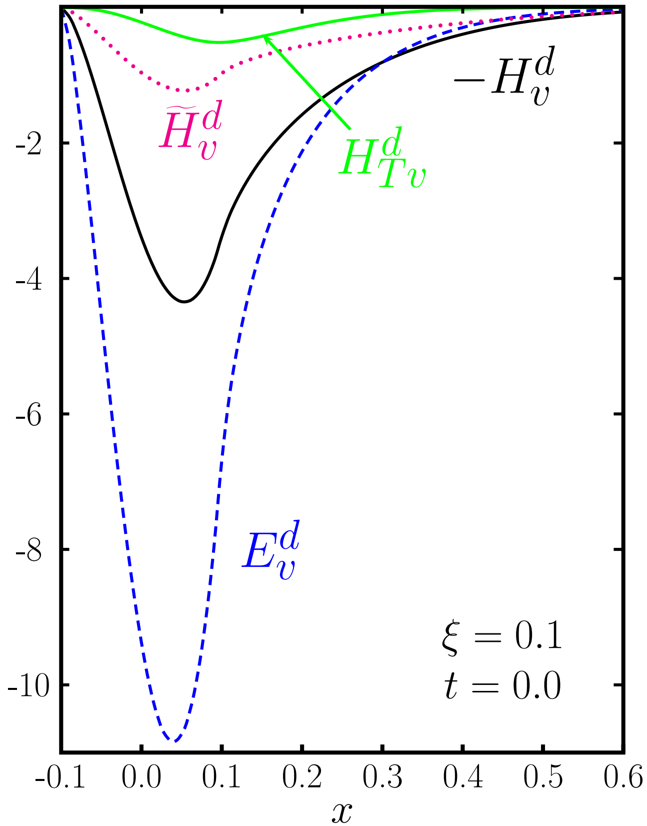
advantages: allows for flavor separation (mesons select their valence quarks from the proton to lead. twist accuracy)

J/Ψ:	gluon
ϕ:	gluon +sea
ρ^0, ω:	gluon+sea+valence
ρ^+, π^+:	valence

π^+: $\widetilde{H}, \widetilde{E}$

Valence quark GPDs





	H	E	$\widetilde{H}$
u_v	2	$\kappa_u = \quad 1.67$	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

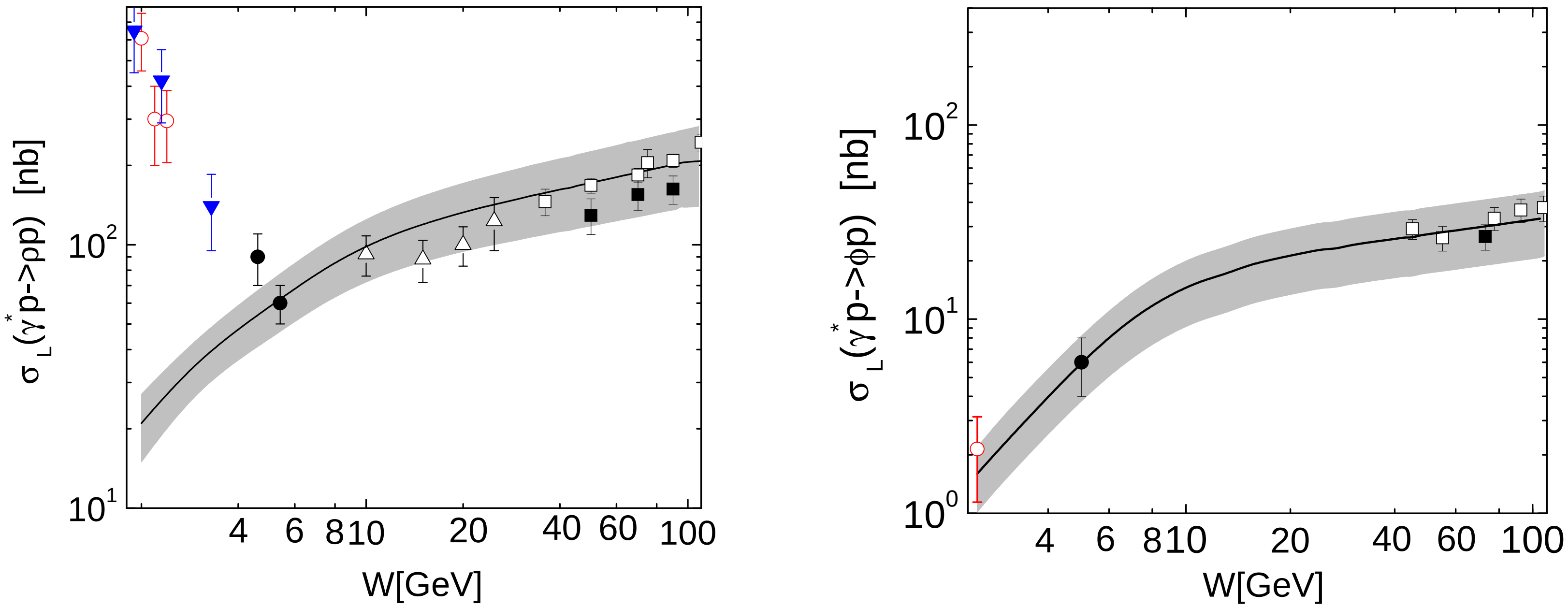
Summary

- MPA accounts for most features of DME including power corrections for $W \gtrsim 4\,\mathrm{GeV}$ $\quad Q^2 \gtrsim 3\,\mathrm{GeV}^2$ $\quad$ and small t
  unsettled: rel. phase between LL and TT too small, see $\mathrm{Re}\, r^5_{10}$
  not yet calculated for vector mesons: $T \to L$ ampl., e.g. seen in r^5_{00}
  (twist-3 as for π^+, $\mathcal{M}_{0-++}$, H_T)

- DD ansatz for GPDs (parameterized by forward limits, Regge-like t dep. and meson DAs as weight fcts) seems to be flexible enough;
  analytic properties may be a useful additional constraint (Müller)
  detailed comparison of different sets of GPDs is needed

- DVCS: not analysed by us (lack of man power)
  we want to 'finish' meson production first
  from our GPDs we can work out DVCS to NLO for
  COMPASS kinematics in princple

ρ^0 and ϕ cross sections



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

ZEUS (□), H1 (■), CLAS (○)

Goloskokov-K (09)

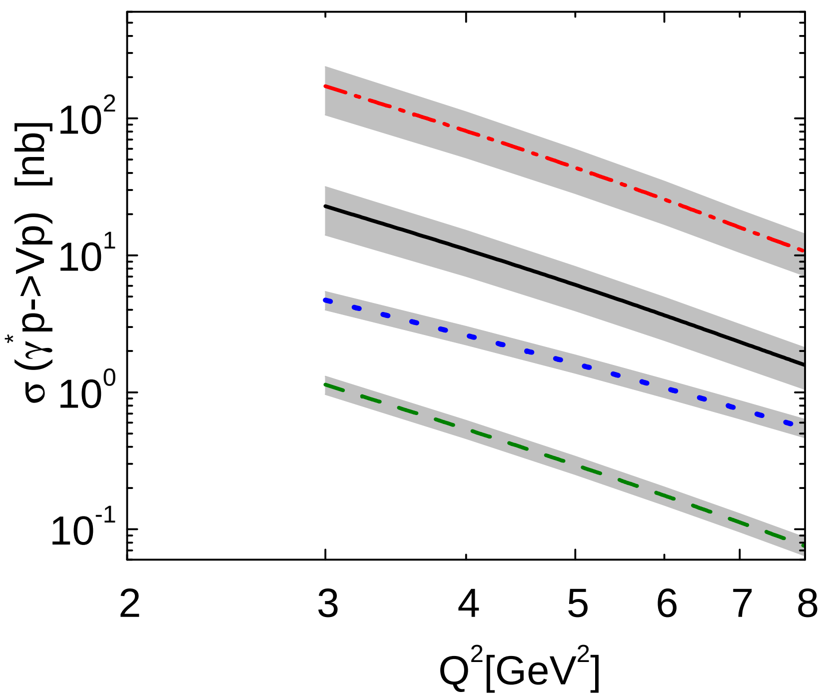
ω, ρ^+ very large at small W too

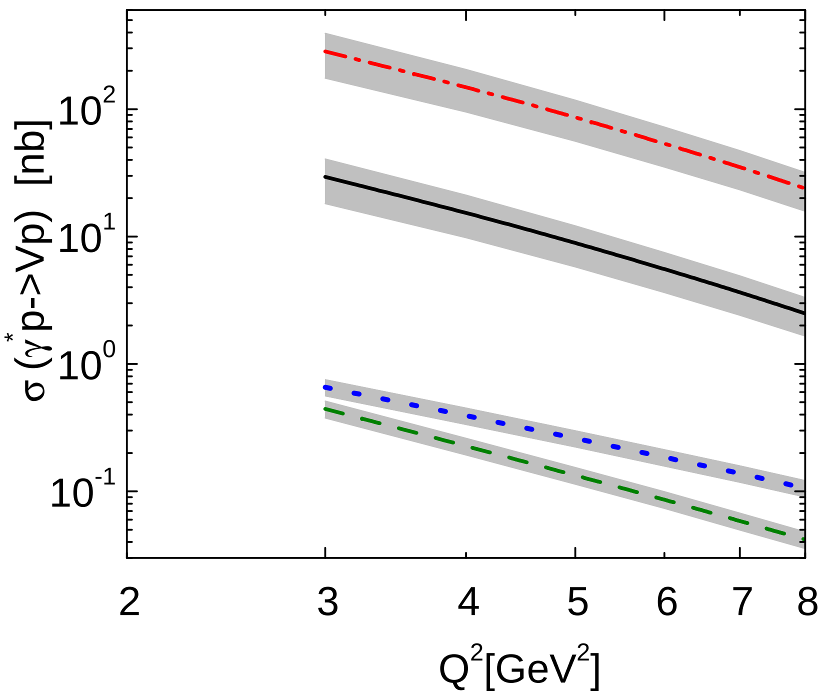
double distribution model too simple for valence quarks for large ξ?

breakdown of handbag physics? Lacking nucleon resonances? (Mueller)

implications for DVCS?

Cross sections for ω, ρ^+ and K^{*0}





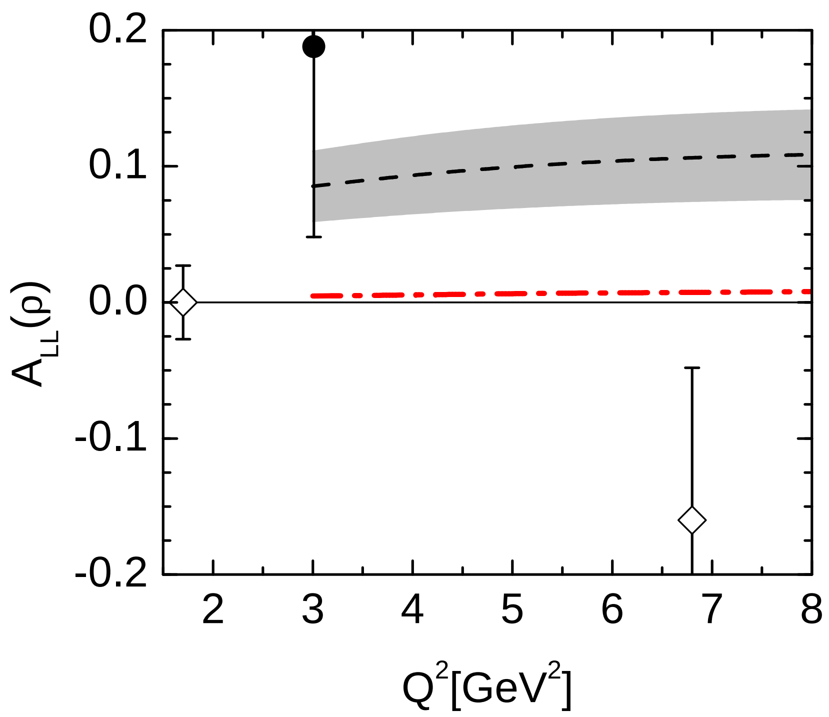
results for HERMES and COMPASS ($W = 5, 10\,\mathrm{GeV}$) ρ^0, ω, ρ^+, K^{*0}

W dependence controlled by Regge behaviour $\sigma \propto W^{4(\alpha(0)-1)}$ at fixed Q^2

ρ^0 , ω : $\alpha - 1 = \delta \simeq 0.1$ diffractive (gluon + sea)

ρ^+ : $\alpha - 1 \simeq -0.5$ K^{*0} intermediate

valence quark contributions die out quickly with increasing W at small ξ



A_{LL} at $W = 5(10)\,\mathrm{GeV}$ probes $\mathrm{Re}\,[< \widetilde{H} >^{*} < H >]$

data: HERMES (circles), COMPASS (diamond)