# Exclusive meson production in the modified hard scattering approach

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**Outline:**

- **Introduction: handbag approach, subprocess amplitudes, GPDs**
- **Extraction of GPDs from hard exclusive meson electroproduction**
- **Pion electroproduction: transversely polarized photons and the pion pole**
- **Results for pseudoscalar mesons**
- **Transversity in vector-meson production**
- **Summary**

# Interest in exclusive meson electroproduction

- Can we understand this class of processes within QCD?
  In which kinematical region?
- Extraction of GPDs several reactions allow for flavor separation
- Universality test and use, with GPDs at disposal one can predict other exclusive processes
- In the limit $t \to 0$ we learn about parton angular momenta
  convenient: zero-skewness limit: PDFs plus GPD $E$ from exclusive processes
- Learn about parton localization in transverse position space
  Fourier transform $\Delta \to b$ ($\Delta^2 = t$), need rather large $t$ since $-t/Q^2 \ll 1$
  we need large $Q^2$ and large $t$ or constraints from other processes (nucleon form factors, wide-angle Compton scattering)

# Can we apply the asymp. fact. formula ?

rigorous proofs of collinear factorization in generalized Bjorken regime:

for $\gamma^*_L \to V_L(P)$ ($\gamma^*_T$ contr. suppressed by $1/Q$) $\quad$ ($Q^2, W \to \infty$, $x_{\rm B}$ fixed, $-t/Q^2 \ll 1$)

$\mathcal{K} = \int dx K(x,\xi,t)\mathcal{H}(x,\xi,Q^2)$ Radyushkin, Collins et al, Ji et al

possible power corrections not under control $\Longrightarrow$

unknown at which $Q^2$ asymptotic result can be applied

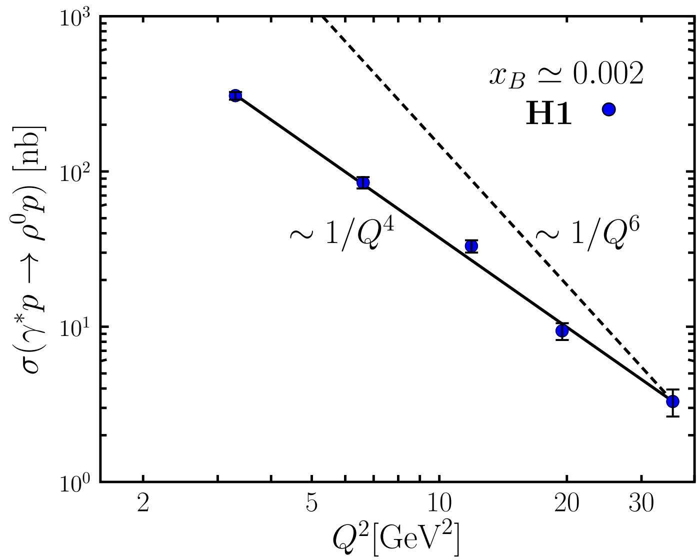
e.g. $\rho^0$ production: $\sigma_L/\sigma_T \propto Q^2$

experiment: $\simeq 2$ for $Q^2 \leq 10\,\mathrm{GeV}^2$

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

$\sigma_L \propto 1/Q^6$ at fixed $x_{\rm B}$

modified by $ln^n(Q^2)$ experiment:




Goloskokov-K (05,06,07,09,11): take into account transverse size of meson,

i.e. power corrections $1/Q^n$ to subprocess $\gamma^*_L q(g) \to V_L\, q(g)$

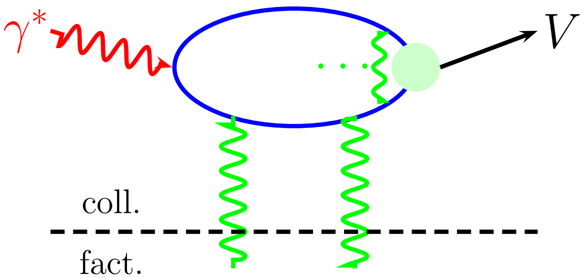
and generalize to other $\gamma^* \to V(P)$ transitions

# The subprocess amplitude for DVMP

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)

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

resummed gluon radiation to NLL $\Rightarrow \exp[-S]$

$$\mathcal{H}^M_{0\lambda,0\lambda} = \int d\tau d^2b\, \hat{\Psi}_M(\tau, -\mathbf{b})\, e^{-S} \hat{\mathcal{F}}_{0\lambda,0\lambda}(\bar{x}, \xi, \tau, Q^2, \mathbf{b})$$

LO pQCD

+ quark trans. mom.

+ Sudakov supp.

$\Rightarrow$ asymp. fact. formula

(lead. twist) for $Q^2 \to \infty$

$\hat{\Psi}_M \sim \exp[\tau\bar{\tau}b^2/4a_M^2]$ LC wave fct of meson

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

e.g. $\propto 1/[k_\perp^2 + \tau(\bar{x}+\xi)Q^2/(2\xi)] \Rightarrow$ Bessel fct

Sudakov factor generates series of power corr. $\sim (\Lambda^2_{\rm QCD}/Q^2)^n$ (from soft regions)

provides sharp cut-off at $b = 1/\Lambda_{\rm QCD}$ and suppresses higher order Gegenbauer terms

for HERA kinematics: similar to leading-log appr., color dipole model

Frankfurt et al (96), Nemcik et al (97),...

unintegrated gluon GPD Martin et al (99)

# Parametrizing the GPDs

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

$$K^i(x,\xi,t) = \int_{-1}^{1} d\rho \int_{-1+|\rho|}^{1-|\rho|} d\eta\, \delta(\rho+\xi\eta-x)\, K^i(\rho,\xi=0,t) w_i(\rho,\eta) + D_i\, \Theta(\xi^2-\bar{x}^2)$$

weight fct $w_i(\rho,\eta) \sim [(1-|\rho|)^2-\eta^2]^{n_i}$ ($n_g = n_{\rm sea} = 2, n_{\rm val} = 1$, generates $\xi$ dep.)

zero-skewness GPD $K^i(\rho,\xi=0,t) = k^i(\rho)\exp\left[(b_{ki} - \alpha'_{ki}\ln(\rho))t\right]$

$k = q, \Delta q, \delta^q$ for $H, \widetilde{H}, H_T$ or $N_{ki}\rho^{-\alpha_{ki}(0)}(1-\rho)^{\beta_{ki}}$ for $E, \widetilde{E}, \bar{E}_T$

Regge-like $t$ dep. (for small $-t$ reasonable appr.), $D$-term neglected

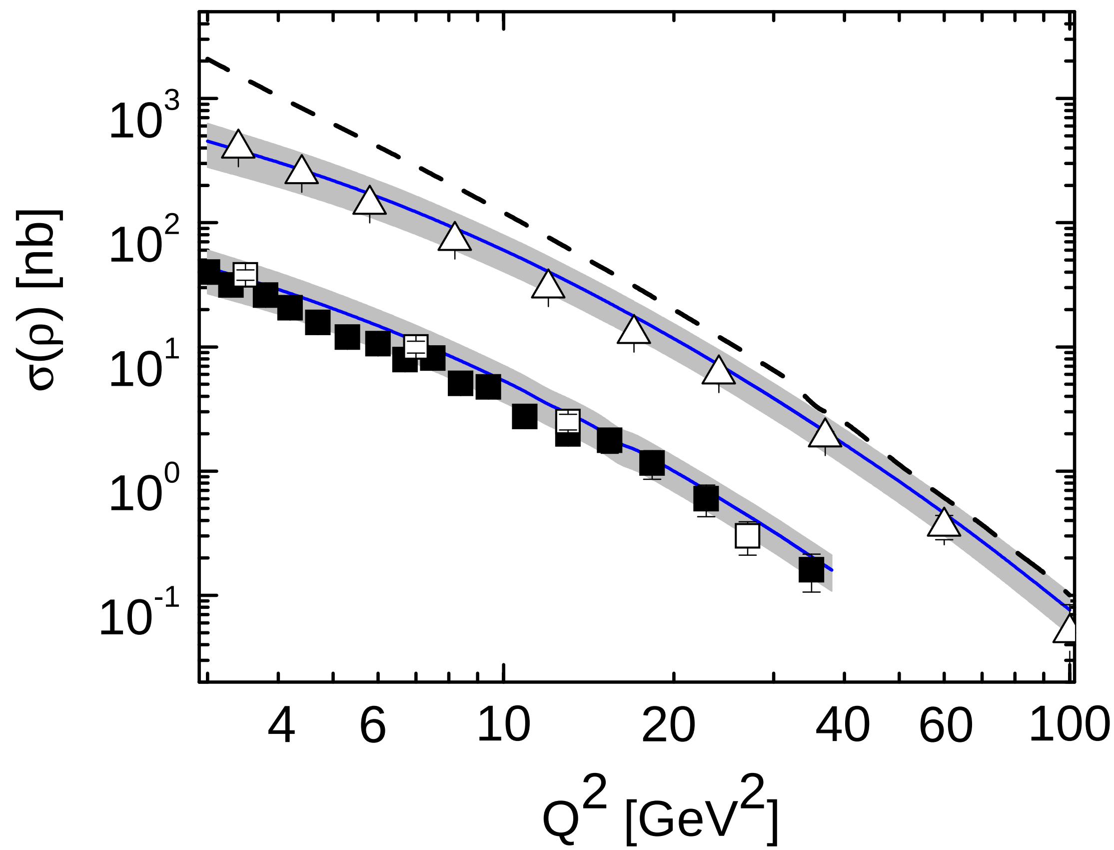
advantage: polynomiality and reduction formulas automatically satisfied
positivity bounds respected (checked numerically)

$$\bar{E}_T = 2\widetilde{H}_T + E_T$$

# What has been done?

- analysis of FF with help of sum rules (DFJK(04), update: Diehl-K 1302.4604) using CTEQ6 (ABM11, DSSV11) PDFs, fixes $H, E, \widetilde{H}$ for valence quarks
- analysis of $d\sigma_L/dt$ for $\rho^0$ and $\phi$ production Goloskokov-K, hep-ph/0611290
  data from H1, ZEUS, E665, HERMES
  for $Q^2 \gtrsim 3\,\mathrm{GeV}^2$ and $W \gtrsim 4\,\mathrm{GeV}$ ($\xi \lesssim 0.1$, $-t \lesssim 0.5\,\mathrm{GeV}^2$)
  fixes $H$ for sea quarks and gluons for given $H^{\mathrm{val}}$
  ($E$ negligible, others don't contr.) (only free parameters $a_V$)
- analysis of $\pi^+$ production, Goloskokov-K, 0906.0460
  $d\sigma/dt$ and $A_{UT}$ data from HERMES ($W \simeq 4\,\mathrm{GeV}$, $Q^2 \simeq 2-5\,\mathrm{GeV}^2$)
  evidence for strong contr. from $\gamma_T^*$ ($H_T$)
  fixes pion pole and $H_T^{(3)}$ (no clear signal for $\widetilde{E}$)
- $\pi^0$ cross section and $\eta/\pi^0$ cross section ratio from CLAS (large skewness!),
  SDME and $A_{UT}$ for $\rho^0$ prod. HERMES, Goloskokov-K, 1106.4897, 1310.1472
  fixes $H_T$ and $\bar{E}_T = 2\widetilde{H}_T + E_T$ for valence quarks, (lattice QCD)
- $\widetilde{H}, \widetilde{E}, H_T, \bar{E}_T$ for gluons and sea quarks unknown as yet
  rough estimate of $E_{sea}$ from $A_{UT}^{DVCS}$ $E_T, \widetilde{E}_T$ unknown

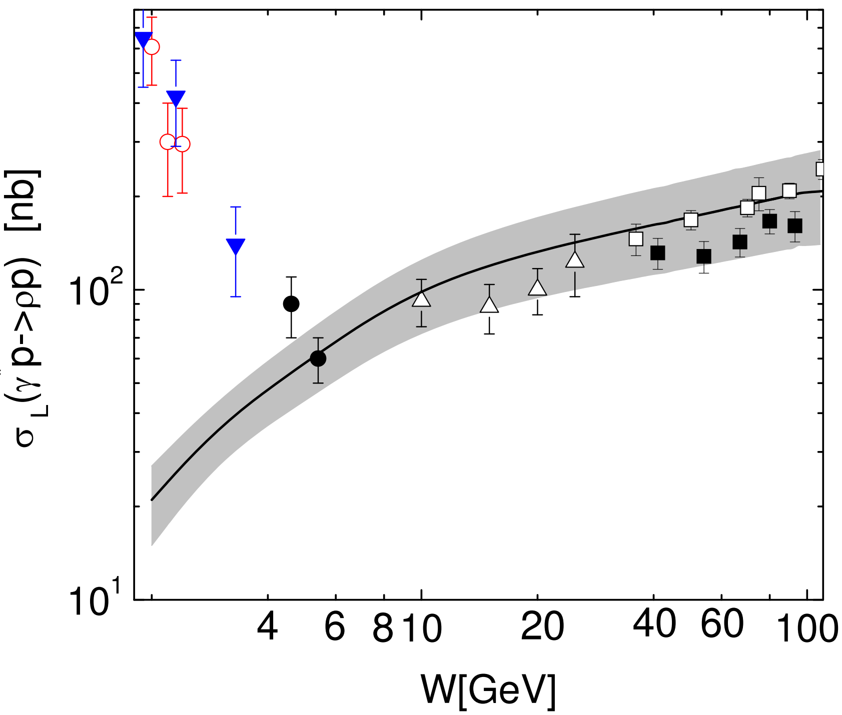
# Result for $\rho^0$ production

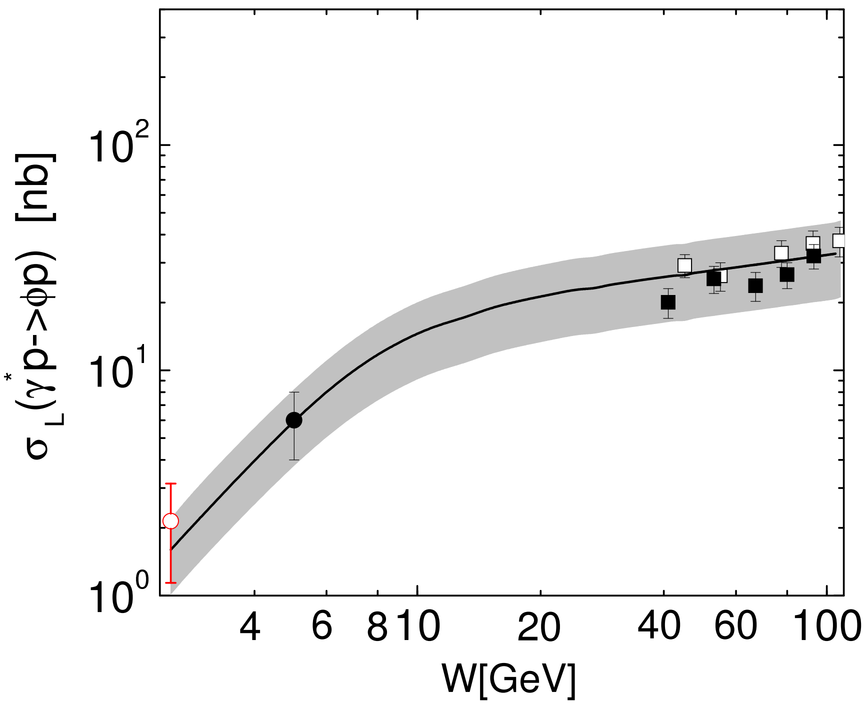



$W = 90$ and 75 GeV (divided by 10) solid (open) symbols: H1 (ZEUS)

leading-twist dominance for $Q^2 \gtrsim 60\,\mathrm{GeV}^2$

# $W$ dependence



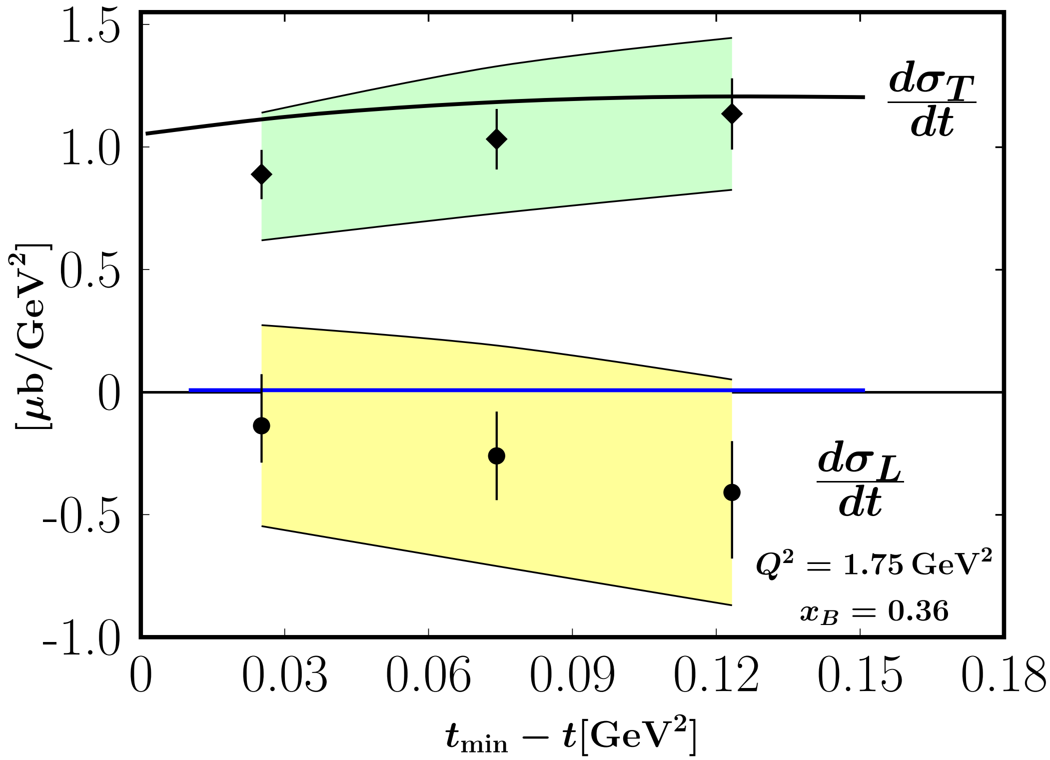

$Q^2 \simeq 4\,\mathrm{GeV}^2$ data from H1, Zeus, HERMES, CLAS, FNAL

behaviour of $\rho$ c.s. below $W \simeq 4\,\mathrm{GeV}$ not understood (large $\xi$, large $-t_0$)

$\sigma(\omega)$ behaves similar, probably valence quark effect

likely not a $D$ term

# Hall A results on $\pi^0$ production




Defurne et al (1608.01003)

$\pi^0$ production (off protons)

predictions from

Goloskokov-K. (1106.4897)

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

to be contrasted with

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

Further evidence for contributions from transverse photons:

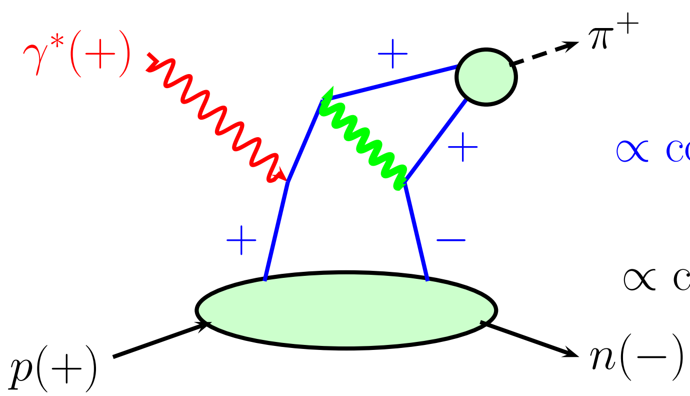
$A_{UT}^{\sin\phi_s}(\pi^+)$ HERMES(09); $\qquad d\sigma_{TT}/dt(\pi^0)$ CLAS(12)

# Transverse photons in the handbag approach

need subprocess amplitude for $\gamma_T^* \to \pi$, non-vanishing for $t \to 0$

there is only one: $\mathcal{H}_{0-,++}$ (angular momemtum conservation:

$$\mathcal{H}_{\nu'\mu'\nu\mu} \sim \sqrt{-t}^{|\nu-\mu-\nu'+\mu'|} \text{ for } t \to 0)$$




$\propto$ const

$\propto$ const

$\Longrightarrow$ parton helicity flip transv. GPDs $H_T, E_T, \widetilde{H}_T, \widetilde{E}_T$ are required

go along with twist-3 pion wf. ($q$ and $\bar{q}$ forming the pion, have same helicity)

# The twist-3 pion distr. amplitude

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

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

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

Eq. of motion: $\tau\Phi_P = \Phi_\sigma/N_c - \tau\Phi'_\sigma/(2N_c)$ Braun-Filyanov (90)

solution: $\Phi_P = 1, \quad \Phi_\sigma = \Phi_{AS} = 6\tau(1-\tau)$ (WW approx.)

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

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

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

(suppr. by $\mu_\pi/Q$ as compared to $L \to L$) $\mathcal{M}_{0--+} = 0$

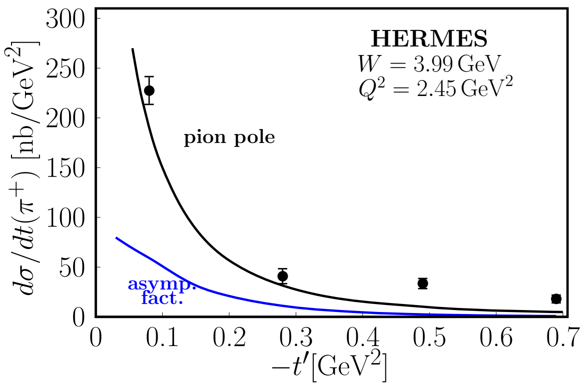
prominent role of transversity GPDs also claimed by Ahmad et al (09) (analysis different)

# The pion pole

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

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

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




$$\widetilde{E}^u_{\text{pole}} = -\widetilde{E}^d_{\text{pole}} = \Theta(|x| \leq \xi)\frac{m f_\pi g_{\pi NN}}{\sqrt{2}\xi}\frac{F_{\pi NN}(t)}{m_\pi^2 - t}\Phi_\pi\Big(\frac{x+\xi}{2\xi}\Big)$$

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

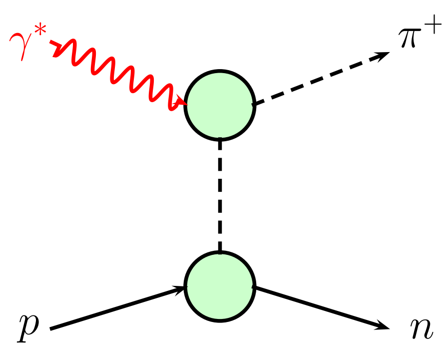
understimates c.s.(blue l.) $\quad F_\pi^{\text{pert.}} \simeq 0.3 - 0.5 F_\pi^{\text{exp.}}$

($F_\pi$ measured in $\pi^+$ electroproduction at Jlab)

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

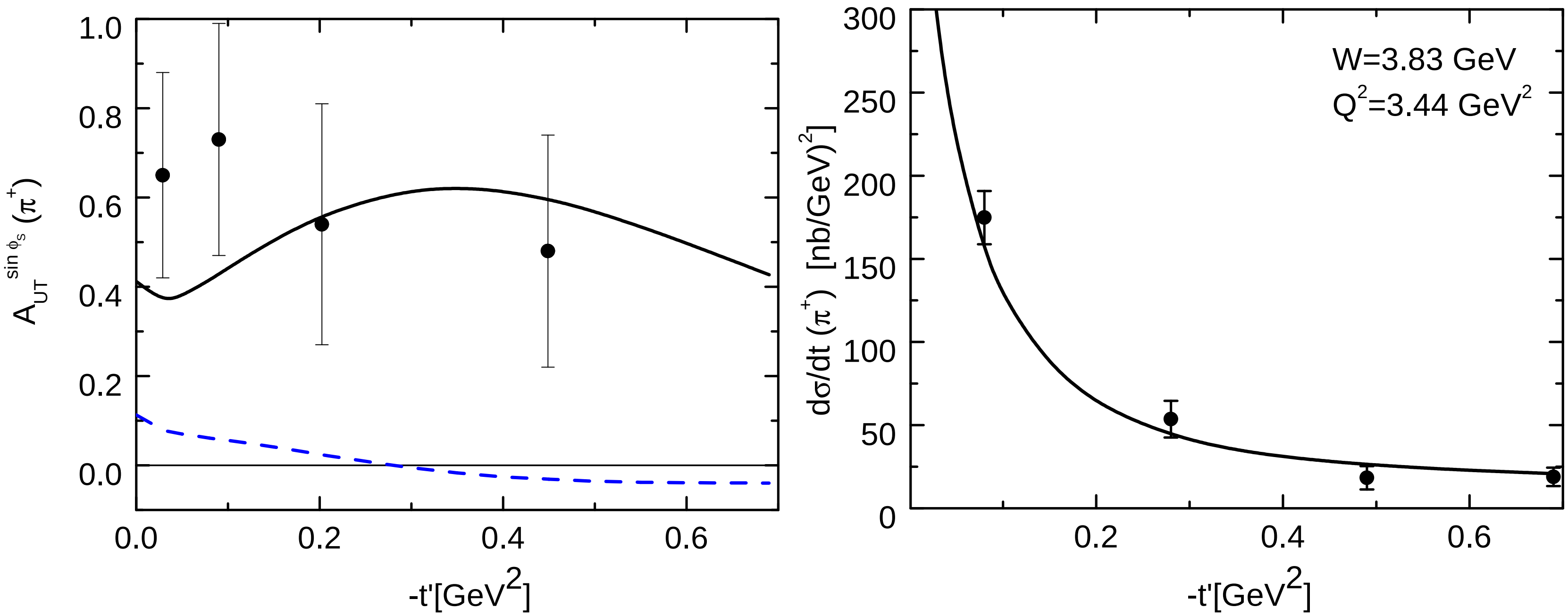
knowledge of the sixties suffices to explain

$\pi^+$ data at small $-t$ and large $Q^2$



# $A_{UT}$ for $\pi^+$ 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 $t' \to 0$

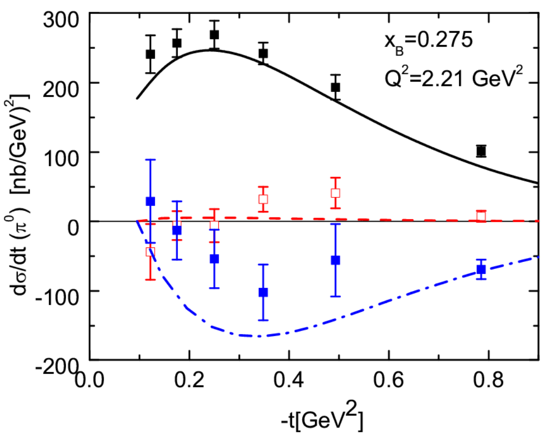
$$A_{UT}^{\sin\phi_s} \propto \mathrm{Im}\Big[\mathcal{M}^*_{0-++}\mathcal{M}_{0+0+}\Big]$$

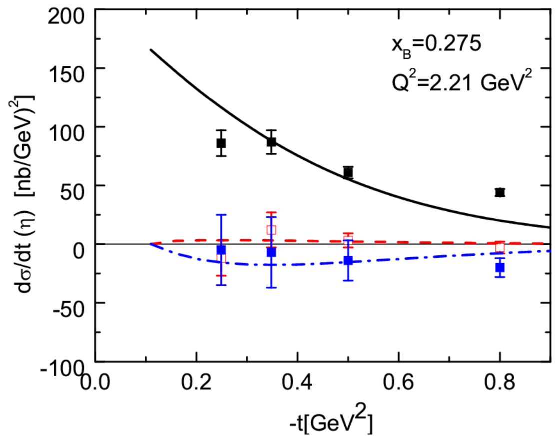
non-flip amplitude $\mathcal{M}_{0-++}$ required (not forced to vanish in forward direction by angular momentum conservation) pion pole dominant at small $-t$

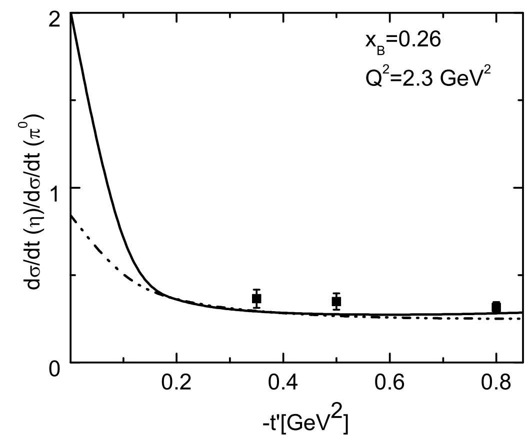
evidence for $\mathcal{M}_{0-++} \sim \mathcal{H}_T$

# CLAS data on $\pi^0$ and $\eta$ production

Bedlinsky et al (12) — Goloskokov-K (11)




unseparated (longitinal, transverse) cross sections

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

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)

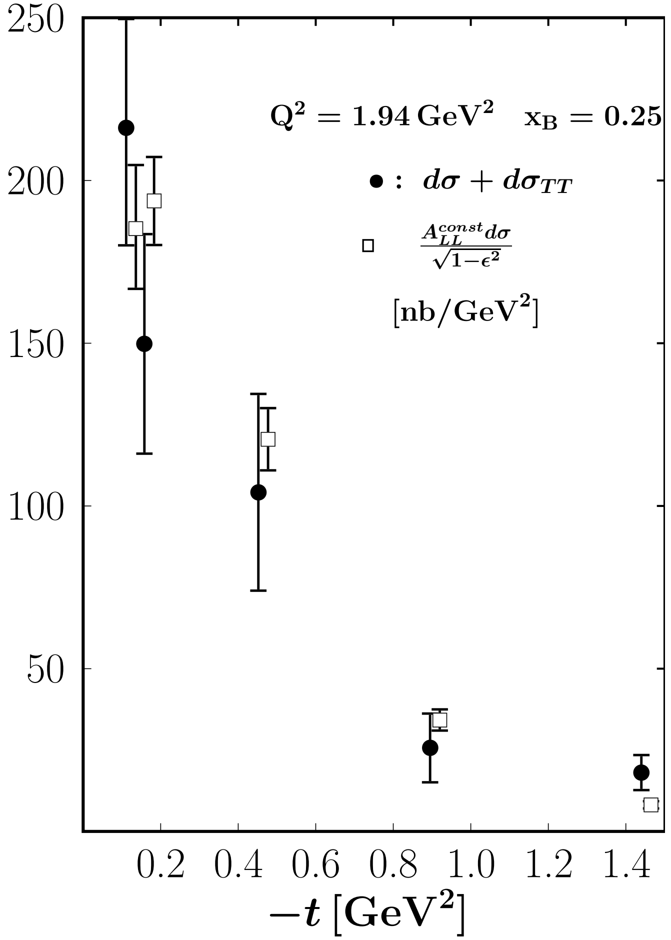
$t' \simeq 0$ $\widetilde{H}, H_T$ dominant (see also Eides et al(98) assuming dominance of $\widetilde{H}$ for all $t'$)

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

# Contributions from other transversity GPDs?

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

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



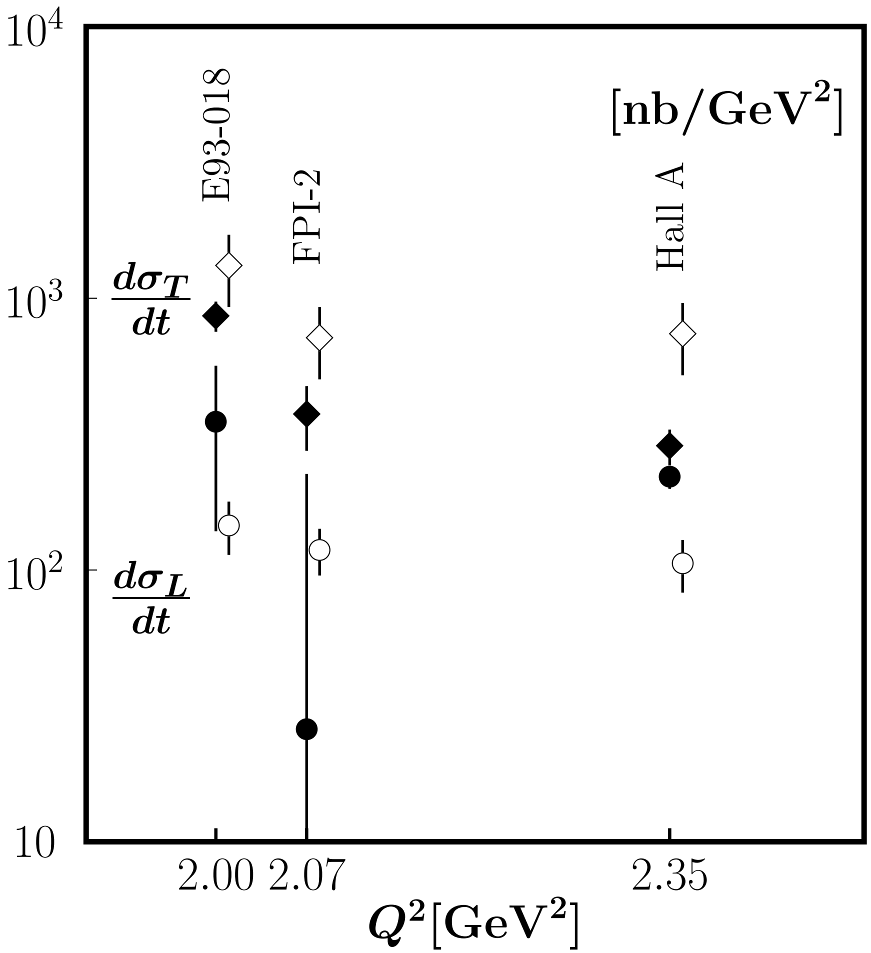

violation of relation would indicate contributions from other transv. GPDs, e.g. from $\widetilde{H}_T$ ($\propto t'$)

data for $\pi^0$ production

Bedlinsky et al, Kim et al (CLAS)

agreement within errors

# $\gamma^* p \to K^+ \Lambda$




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

E93-018 $W = 1.85\,$GeV

$$t = t_0 = -0.74\,\mathrm{GeV}^2$$

FPI-2 $W = 2.39$ GeV, $t = -0.4\,\mathrm{GeV}^2$

Hall A $W = 2.08\,$GeV

$$t = t_0 = -0.57\,\mathrm{GeV}^2$$

same GPDs as for pions, no fits

flavor symmetric sea assumed

kaon/pion pole $\sim [(t - m_\pi^2)/(t - m_k^2)]^2$

From pion electroproduction we learn about $H_T$ and $\bar{E}_T$

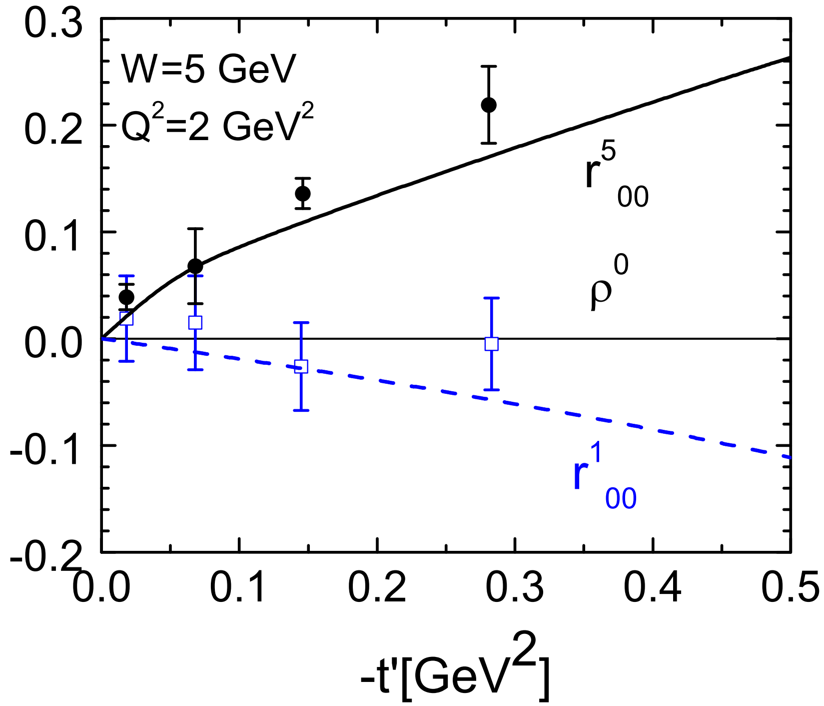
and not about $\widetilde{H}$, $\tilde{E}$

# Transversity in vector meson electroproduction

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 the same strength as the $\gamma_T^* \to \pi$ ones but
competition with $\mathcal{H}$ (for gluons and quarks) instead with $\widetilde{\mathcal{H}}$ $(|\mathcal{H}| \gg |\widetilde{\mathcal{H}}|)$
$\Longrightarrow$ small transversity effects for vector mesons
to be seen in some of the SDMEs and in spin asymmetries
examples from Goloskokov-K(13,14) predictions, not fits

# Spin density matrix elements




SDME from HERMES(09)

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

# Applications

exploiting universality: our set of GPDs allows for parameter free calculations of other hard exclusive reactions (except of possible wave fct effects)

- $\nu_l p \to lPp$ Kopeliovich et al, 1401.1547, 1401.6547
  Schmidt-Siddikov, 1501.04306
  Pire et al, 1705.11088
  V-A structure leads to different combinations of GPDs no data
- $ep \to \nu_e \pi^- p$ Siddikov-Schmidt, 1709.01405 no data
- timelike DVCS Pire et al, 1203.4392,1407.0413,1407.1990 no data
- $\pi^- p \to l^+ l^- n$ Goloskokov-K, 1506.04619 no data
- $\gamma^* p \to \omega p$ Goloskokov-K, 1407.1141
  compared with SDMEs from HERMES(14) and $A_{UT}$ from HERMES(15)
  prominent role of pion pole, $\pi \to \omega$ trans. form factor
- DVCS K-Moutarde-Sabatie, 1210.6975 Müller et al in 1108.1713
  compared to data from Jlab, HERMES, H1, ZEUS
  good agreement with small skewness data, less good with Jlab data

# Summary

- The handbag approach, generalized to transverse photons and with meson size corrections, describes all DVMP data for $Q^2 \gtrsim 2\,\mathrm{GeV}^2$ and $W \gtrsim 4\,\mathrm{GeV}$ for $\rho^0$ ( $\gtrsim 2\,\mathrm{GeV}$ for $\phi, \pi$)
- From the combined analysis of nucleon form factors, DVMP a set of GPDs has been extracted ($H, E, \widetilde{H}, H_T, \bar{E}_T$ for valence quarks, gluon and sea quarks only for $H$, $E^{\rm sea}$ from DVCS )
- This set of GPDs allows for calculations of other hard exclusive processes (DVCS, $\omega$, $Kaon$ and $\eta$ production) test of universality
- and to obtain first results on parton angular momenta (1410.4450)
- Evaluation of transverse localization of partons in the proton only possible for valence quarks in $H$ and $E$ as yet.
  For others large $-t$ behaviour unknown
- The GPDs need improvements: (of course)
  possible (and necessary) with new data from COMPASS, JLAB12 and EIC
  framework PARTONS Berthou et al(1512.06174)