GPDs from meson electroproduction

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Outline:

- **Analysis: handbag approach, subprocess amplitudes**

  extraction of GPDs from meson electroproduction

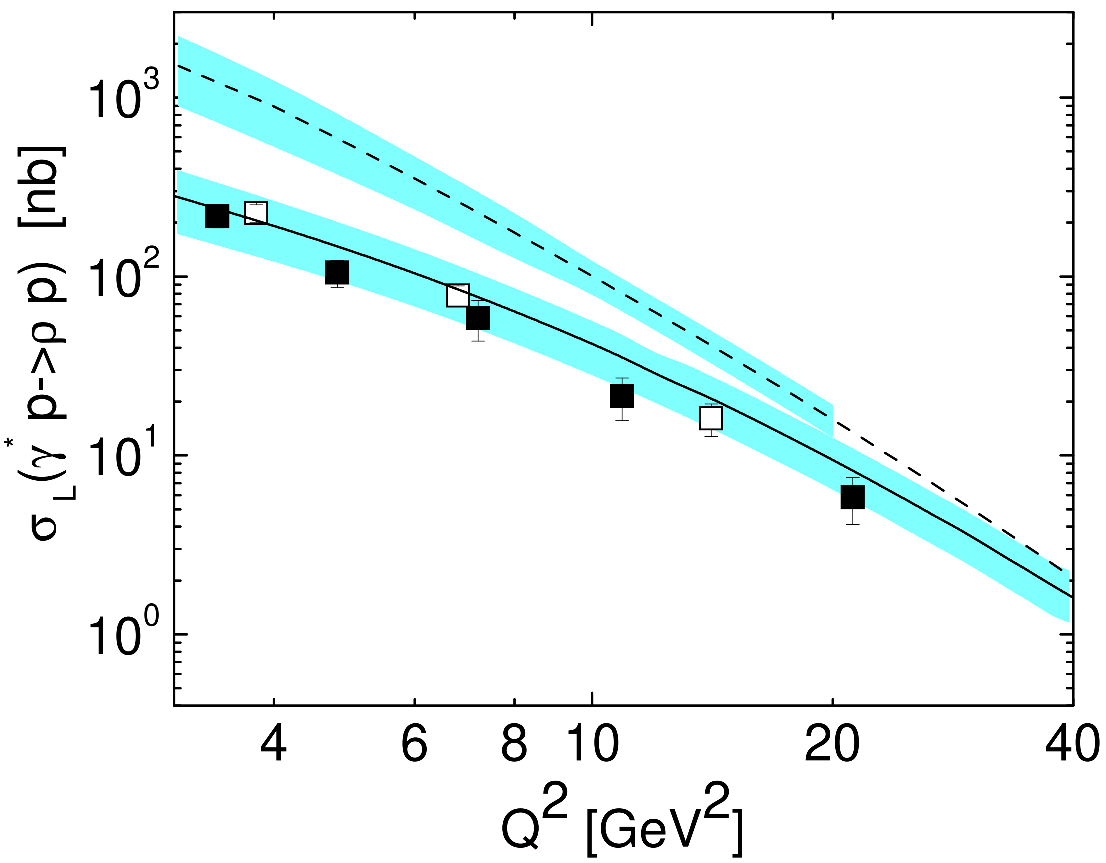
- **Universality: predictions for other processes**

  DVCS, ω, K, η

  lepton pair production in exclusive processes

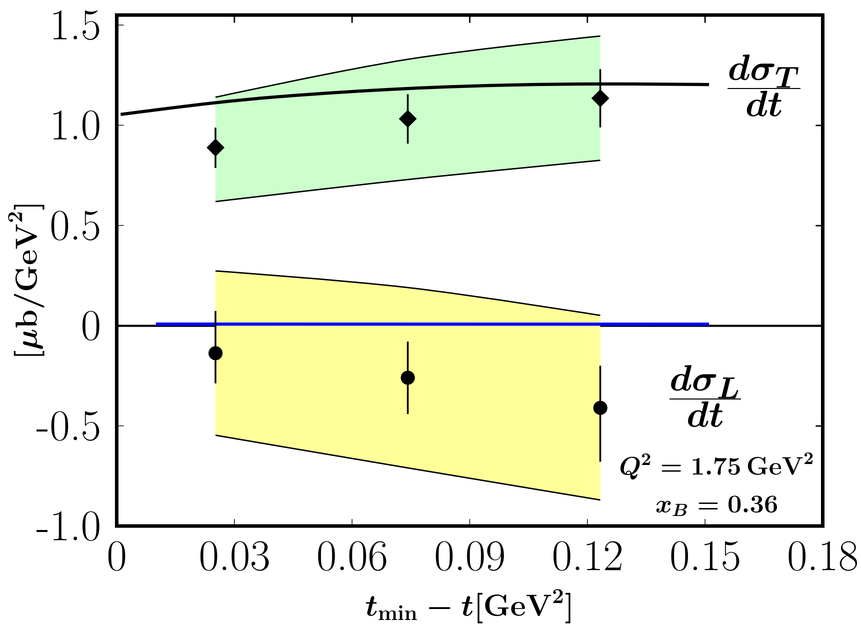
- **GPDs in transverse position space**
- **Parton angular momentum and GPD** E
- **Improvements**
- **Summary**

Leading-twist calculations of meson electroproduction fail



$W = 75\,\mathrm{GeV}$ HERA, ZEUS

Pion production: contributions from γ_T^* are large



Hall A collaboration π^0 production

Defurne et al (1608.01003)

(predictions from

Goloskokov-K. (1106.4897))

$d\sigma_T \gg d\sigma_L$ $(d\sigma \simeq d\sigma_T)$

like expectation for $Q^2 \to 0$

to be contrasted with

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

leading twist does not dominate (much larger Q^2 required for it)

Further evidence for contribution from transverse photons:

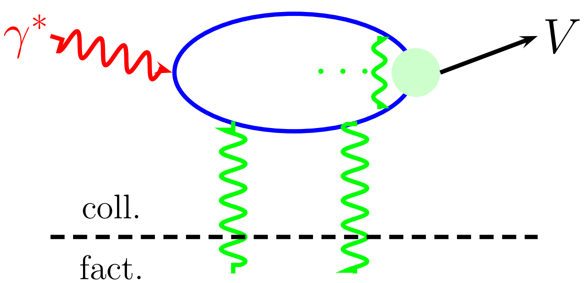
$A_{UT}^{\sin\phi_S}(\pi^+)$ HERMES(09); $d\sigma_{TT}/dt(\pi^0)$ CLAS(12)

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 $\Rightarrow \exp[-S]$

provides sharp cut-off at $b = 1/\Lambda_{\rm QCD}$

LO pQCD

+ quark trans. mom.

+ Sudakov supp.

$\Rightarrow$ asymp. fact. formula (lead. twist) for $Q^2 \to \infty$

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

$\hat{\Psi}_M \sim \exp[\tau\bar{\tau}b^2/4a_M^2]$ 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 $\tau, \bar{\tau} \to 0$) and suppresses higher order Gegenbauer terms strongly

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)

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

$\Longrightarrow$ (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)

twist-3 DAs $\Phi_P \equiv 1$, $\Phi_\sigma = 6\tau(1-\tau)$ in WW approx.

$\mathcal{H}_{0-++} \neq 0$ for $t \to 0$ (from Φ_P, contr. from $\Phi_\sigma \propto t/Q^2$ neglected)

$\mathcal{H}_{0-++} \propto \mu_\pi/Q$ $\mu_\pi = m_\pi^2/(m_u + m_d) \simeq 2$ GeV at scale 2 GeV

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

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

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

analysis and results different

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 $w_i(\rho,\eta) \sim [(1-|\rho|)^2-\eta^2]^{n_i}$ $(n_g = n_{\text{sea}} = 2, n_{\text{val}} = 1$, generates ξ 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)

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 ρ^0 and ϕ 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^{val}
  (E negligible, others don't contr.) (only free parameters a_V)
- analysis of π^+ 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 γ_T^* (H_T)
  fixes pion pole and $H_T^{(3)}$ (no clear signal for $\widetilde{E}$)
- π^0 cross section from CLAS (large skewness!),
  SDME and A_{UT} for ρ^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
- $\widetilde{H}, \widetilde{E}, H_T, \bar{E}_T$ for gluons and sea quarks unknown as yet, E_{sea} see below
  $E_T, \widetilde{E}_T$ unknown

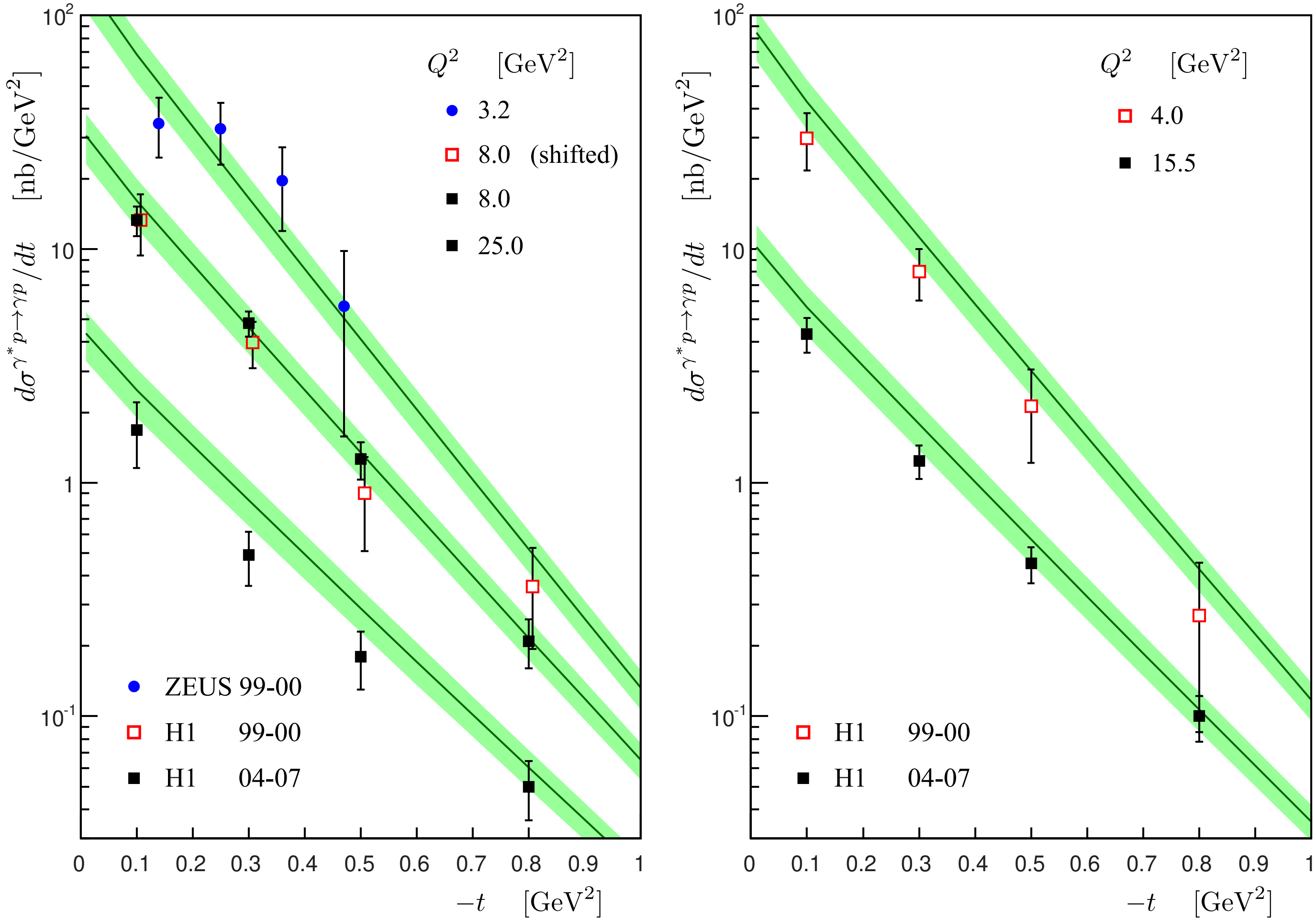
Universality

extracted GPDs allow predictions for other processes and checks

very important and interesting

- DVCS: parameter free, LO,leading twist, K-Moutarde-Sabatie 1210.6975
  good agreement data, except for Jlab6 data (large skewness)
  power corrections needed Braun et al 1401.7621
- ω production: need for ω wave fct (including $\pi - \omega$ form factor)
  GK 1497.1141 agrees with SDME from HERMES
  problems with prel. SDME from COMPASS
- $\gamma^* n \to \pi^0 n$, $\gamma^* p \to \eta p$, $\gamma^* p \to K^+ \Lambda$, need for η and kaon wf. and mixing
  GK 1106.4897 agreement with Jlab data (see below)
- neutrino production of mesons
  Pire et al, 1711.04608; Kopeliovich et al. 1401.6964; Siddikov-Schmidt, 1611.07294
  no data as yet, will come from MINERVA

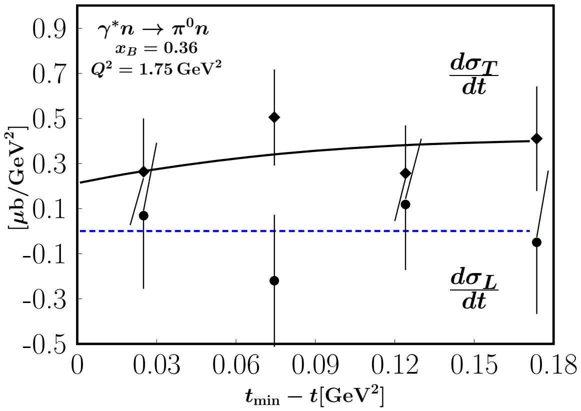
DVCS at HERA

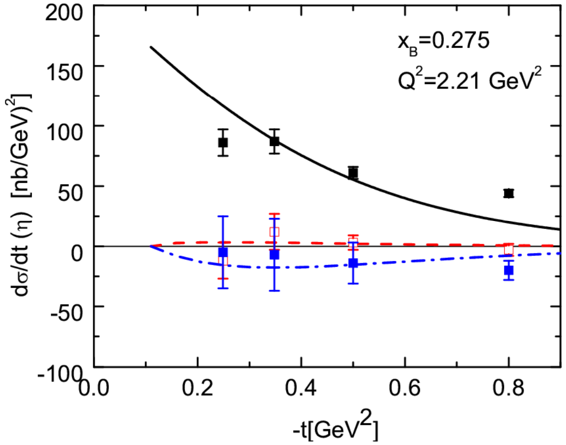


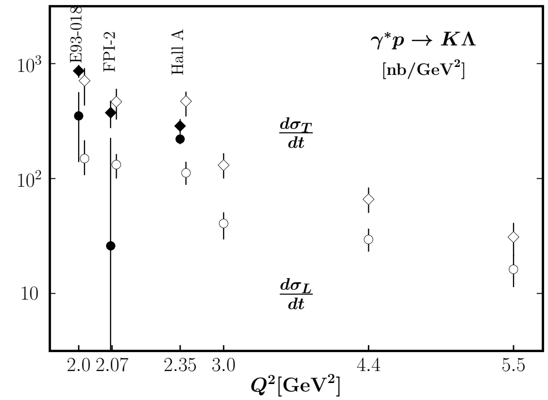
$W \simeq 90\,\mathrm{GeV}$ data from ZEUS, H1 K-Moutarde-Sabatie (1210.6975)

leading-twist accuracy parameter-free computation UNIVERSALITY

Pseudoscalar mesons: comparison with data







$\gamma^* n \to \pi^0 n$

data: Hall A

$\gamma^* p \to \eta p$

data: CLAS

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

data: E93-018,FPI-2,Hall A

$\frac{1}{\sqrt{2}}[e_u K^d - e_d K^u]$

$\frac{1}{\sqrt{2}}[e_u K^u + e_d K^d]$

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

flavor symm. sea assumed

Lepton-pair production in exclusive processes

related to electroproduction

- same GPDs
- $\hat{s} - \hat{u}$ $(l - P)$ crossed subprocess $(P = \gamma, \pi, K)$
- $\mathcal{H}^{P\to\gamma^*}(\hat{u}, \hat{s}) = -\mathcal{H}^{\gamma^*\to P}(\hat{s}, \hat{u})$
- equivalent to $Q^2 \to -Q'^2$

- timelike DVCS   Pire et al, 1203.4392, 1407.0413, 1407.1990
- $\pi^- p \to l^+ l^- n$ Goloskokov-K, 1506.04619
- $p(\pi)p \to l^+ l^- p(\pi)p$ double handbag   Pivovarov-Teryaev(14)
  Goloskokov-K-Teryaev (in preparation)

hard exclusive scattering processes with time-like virtual photons
no data as yet but predictions

experimental verification of predictions important

FT to transverse position space

$$k^a(x,\mathbf{b}) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}\mathbf{\Delta}_\perp} K^a(x,\xi=0,t\;=\;-\mathbf{\Delta}_\perp^2)$$

$$K^a = k_a(x)\exp\left[-tf_a(x)\right]$$

$$k^a(x,\mathbf{b}) = \frac{1}{4\pi}\frac{k_a(x)}{f_a(x)}\exp\left[-b^2/(4f_a(x))\right]$$

more general profile fct. DFJK(04), Diehl-K 1302.4604, (de Teramond et al 1801.09154,

$f_a = (B_a + \alpha'_a \ln 1/x)(1-x)^3 + A_a x(1-x)^2$ Moutarde et al 1807.07620)

density interpretation of FT: Burkhardt(00), Diehl-Hägler(05)

$q(x,\mathbf{b})$ density of unpolarized quark in an unpolarized proton

$q^\pm = \frac{1}{2}[q(x,\mathbf{b}) \pm \Delta q(x,\mathbf{b})]$ quarks with helicity (anti)parallel to proton helicity

$q_X(x,\mathbf{b}) = q(x,\mathbf{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}e(x,\mathbf{b})$ unpolarized quark in proton polarized along X direction

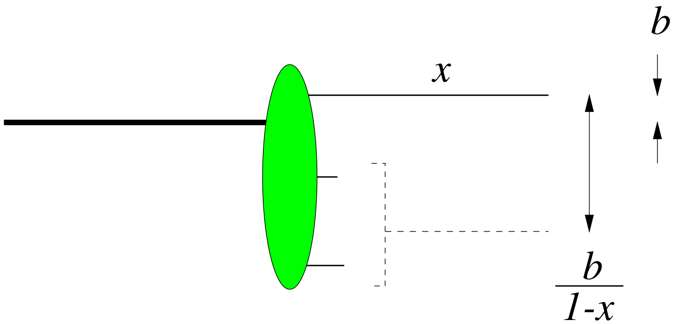
$q_T^x(x,\mathbf{b}) = \frac{1}{2}[q(x,\mathbf{b}) - \frac{b_y}{m}\frac{\partial}{\partial b^2}\bar{e}_T(x,\mathbf{b})]$ transversely pol. quark (x direction) in unpolarized proton

...

Estimate of proton radius

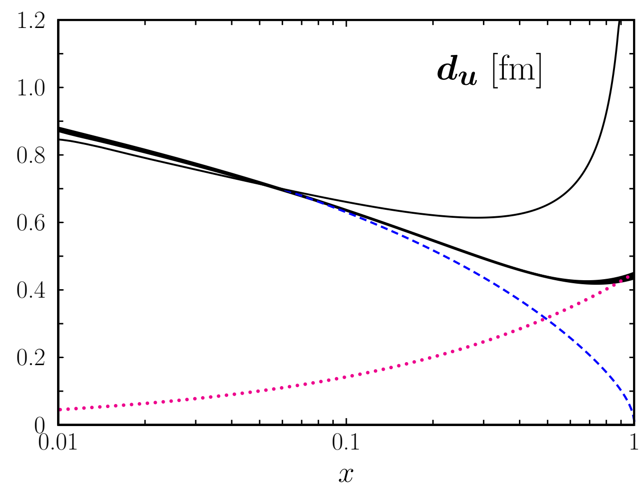
consider Fourier transform of H

work in hadron's center of momentum frame
$\sum x_i \mathbf{b_i} = 0$
distance between active parton and cluster of spectators:



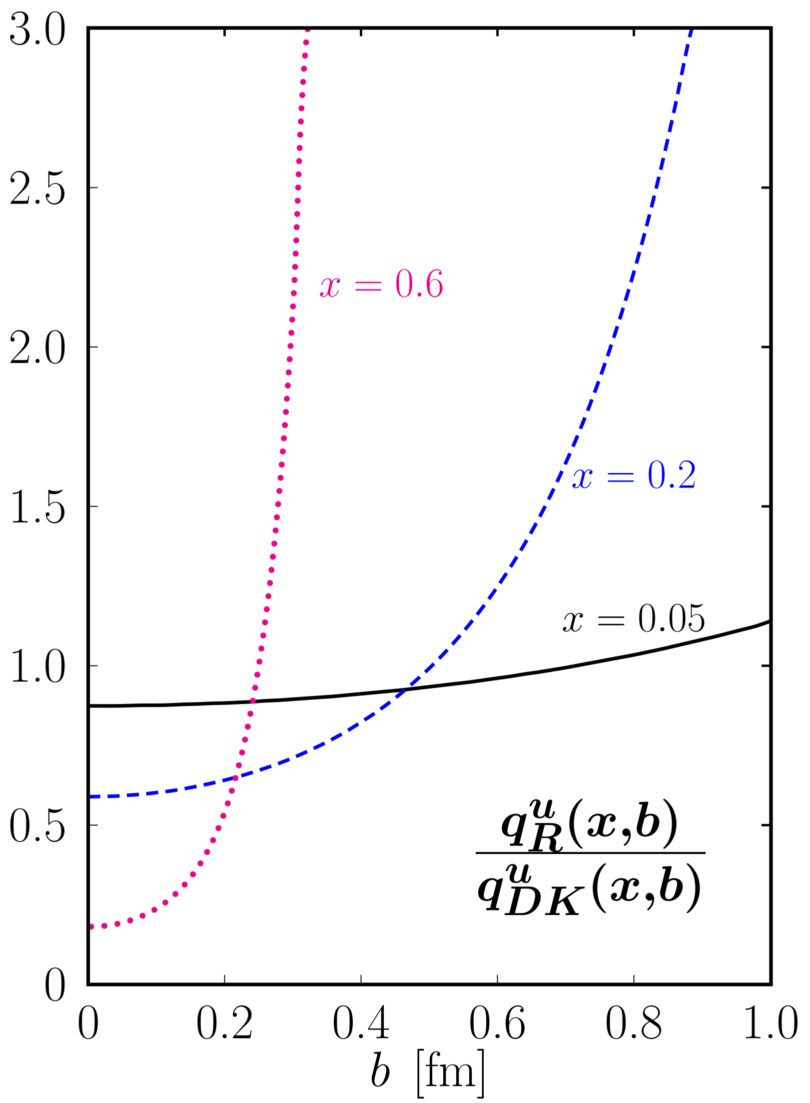
$$d_q(x) = \frac{\sqrt{\langle b^2 \rangle_x^q}}{1-x} = \frac{2\sqrt{f_q(x)}}{1-x} \to 2\sqrt{A_q}$$

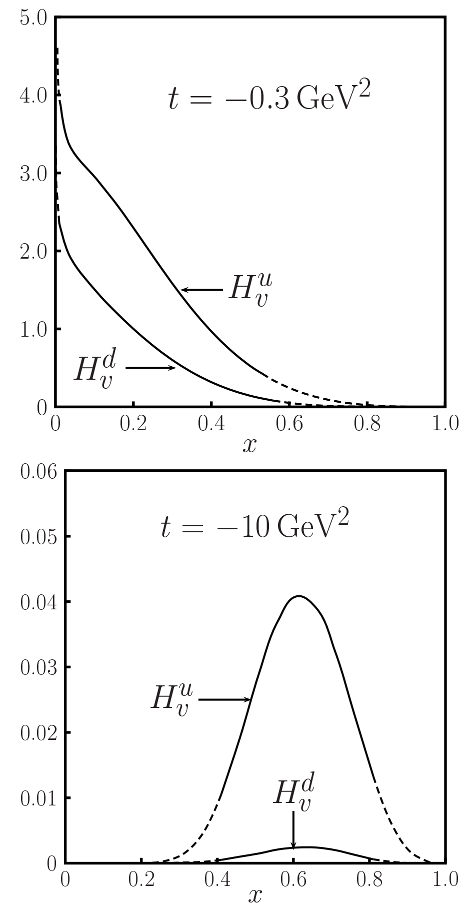
for $x \to 1$



Regge-type term, A term, full profile fct
Regge-like profile fct can (only) be used at small x (small $-t$)
(Regge-like: $A = 0$ and $(1-x)^3 \to 1$)

FT with Regge-like profile function?



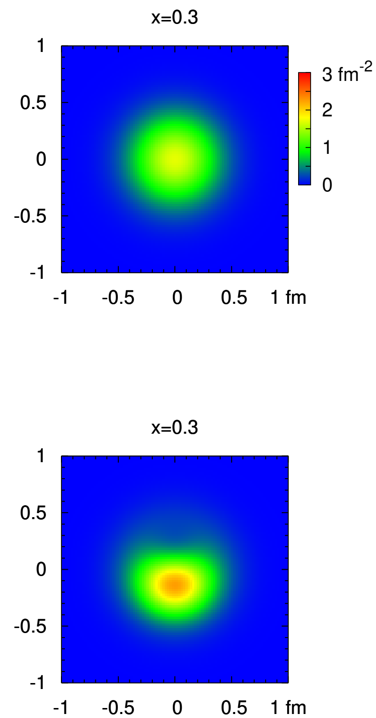


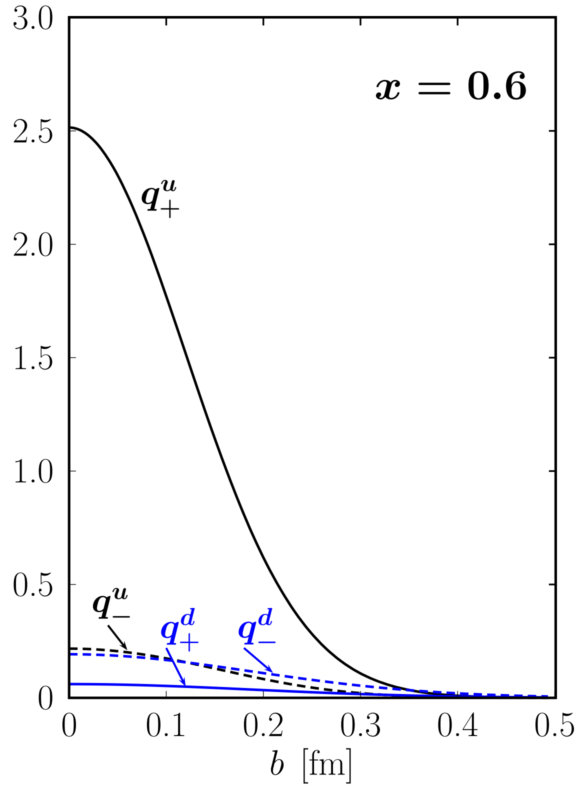
only reasonable for
$x \lesssim 0.1$

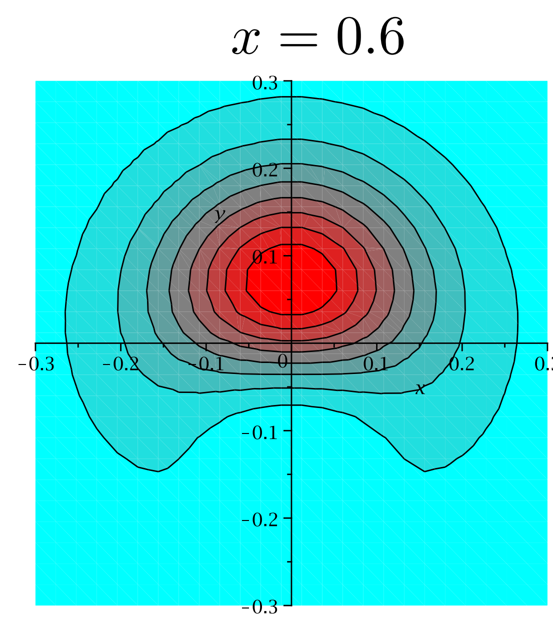
large x-region not explored by electroproduction

Densities in transverse position space at large x

only for valence quarks as yet; for gluons and strange quarks?







d quark density in unpolarized and polarized proton (in X direction)

proton f.f.

u quarks with same helicity as the proton dominates

in agreement with pQCD

Brodsky et al(95)

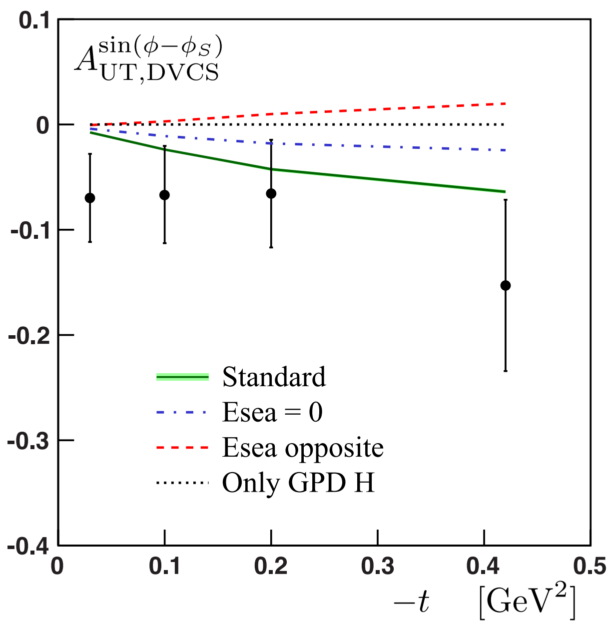
F_A and WACS K_{LL}

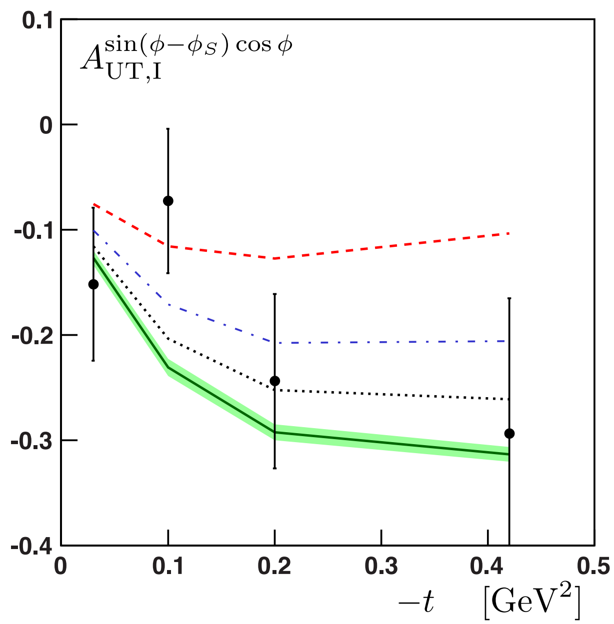
transversely pol. u quark (in x direction) in unpolarized proton

wide-angle photopro. of π^0

Parton angular momentum

Target asymmetry in DVCS





data: HERMES(08)

$\langle Q^2 \rangle \simeq 2.5\,\mathrm{GeV}^2$

$\langle x_\mathrm{B} \rangle \simeq 0.09$

theory:

K-Moutarde-Sabatie(12)

$A_{UT,DVCS}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}\left[\mathcal{E}^*\mathcal{H}\right]$

$\Rightarrow \mathcal{E}^{\mathrm{sea}}$ seen

from BH-DVCS interference

separate contr. from

$\mathrm{Im}\,\mathcal{H}$ and $\mathrm{Im}\,\mathcal{E}$

positivity bound for FTs forbids large sea $\Longrightarrow$ gluon small too (Diehl-Kugler(07))

$$\frac{b^2}{m^2}\left(\frac{\partial e_s(x,b)}{\partial b^2}\right)^2 \leq s^2(x,b) - \Delta s^2(x,b) \qquad e_{20}^g + \sum_a e_{20}^a = 0$$

negative $\mathcal{E}^{\mathrm{sea}}$ favored in both cases

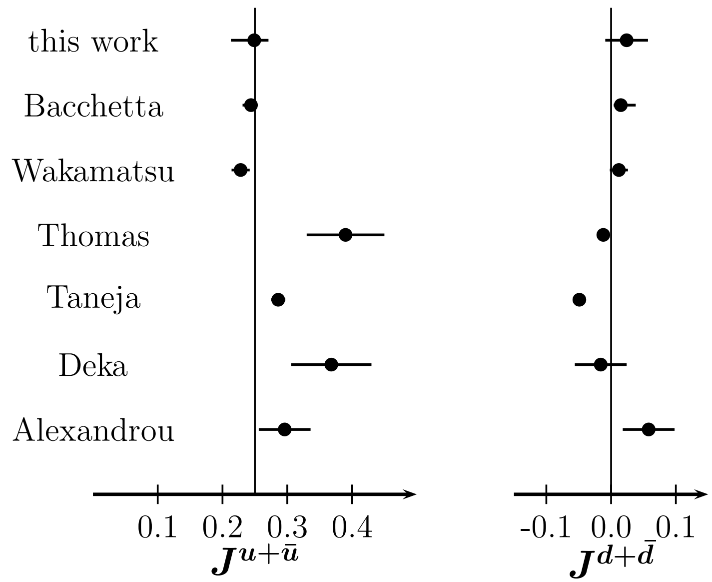
Application: Angular momenta of partons

$$J^a = \frac{1}{2}\Big[q_{20}^a + e_{20}^a\Big] \qquad J^g = \frac{1}{2}\Big[g_{20} + e_{20}^g\Big] \qquad (\xi = t = 0)$$

q_{20}^a, g_{20} from ABM11 (NLO) PDFs $(a = u, d, s, \bar{u}, \bar{d}, \bar{s})$
$e_{20}^{a_v}$ (=0.163, -0.122) from form factor analysis Diehl-K. (13):
$e_{20}^s \simeq 0 \ldots - 0.024$ from analysis of A_{UT} in DVCS and positivity. bound
e_{20}^g $(= -\sum e_{20}^{a_v} - 6e_{20}^s)$ (Goloskokov-K (09), K. 1410.4450)

at scale $2\,\mathrm{GeV}$:

$$J^{u+\bar{u}} = 0.249^{+0.022}_{-0.036}\,;$$
$$J^{d+\bar{d}} = 0.024^{+0.033}_{-0.033}\,;$$
$$J^{s+\bar{s}} = 0.005^{+0.014}_{-0.014}\,;$$
$$J^{g} = 0.221^{-0.067}_{+0.084}\,.$$



$\sum J^i = 1/2$ (spin of the proton)
need better determination of E^s and/or E^g
e.g. smaller errors of A_{UT} in DVCS or in J/Ψ production Koempel et al(11)

Improvements

Pseudoscalar mesons

Regali: translated MAPLE code to C^{++}

specialized to $d\sigma/dt(\pi^0)$ for COMPASS

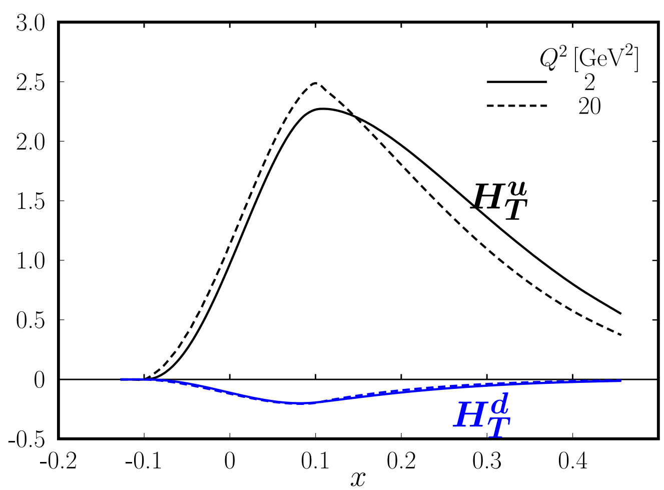
runs at Jlab as well (V. Kubarowsky) includes $\gamma^* n \to \pi^0 n$ and $\gamma^* p \to \eta p$

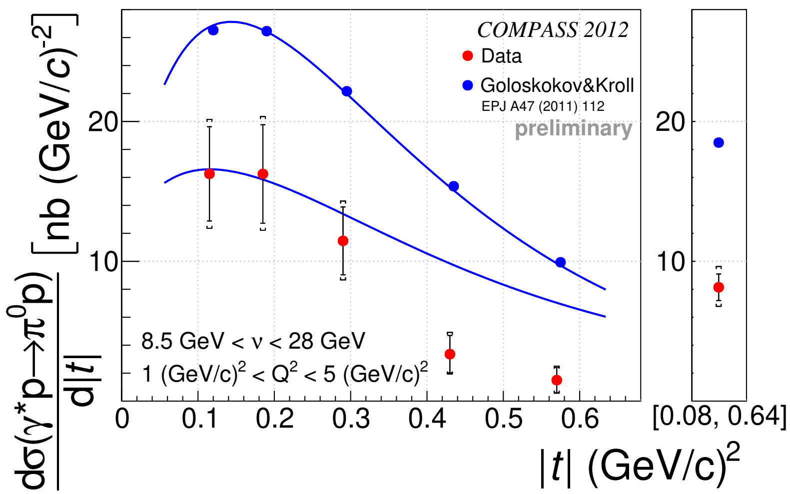
helicity amplitudes are evaluated: spin observables trivial (one line of code)

evolution: not yet included but Vinnikov code for $\widetilde{H}, \tilde{E}$

MAPLE code for $H_T, \bar{E}_T$

minor effect but should be included for $Q^2 \gtrsim 8\,\mathrm{GeV}^2$





COMPASS: energy dependence!

$\bar{E}_T \sim x^{-\alpha} \quad \alpha = 0.3 \to 0$

fit of all data needed

Vector mesons

C^{++} code lacking as yet

Evolution: approx. by forward evolution, Vinnikov code should now be used

most important: H^g forward evolution OK

valence quark GPDs unimportant (only data for $Q^2 \simeq 4\,\mathrm{GeV}^2$)

sea quark GPDs needs improvement Diehl-Kugler 0711.2184

D-term: neglected, no signal of it in meson electroproduction data

use available information on D-term Polyakov-Schweitzer, 1805.06596

1st term of Gegenbauer series and asymptotic form

$W = 5\mathrm{GeV}$, $Q^2 \simeq 4\mathrm{GeV}^2$: $\sigma_L^D(\phi) = 4.5 \cdot 10^{-3}\mathrm{nb}$ HERMES 7 nb

fixed Q^2: $\sigma_L^D \sim 1/W^4$ experimentally increasing

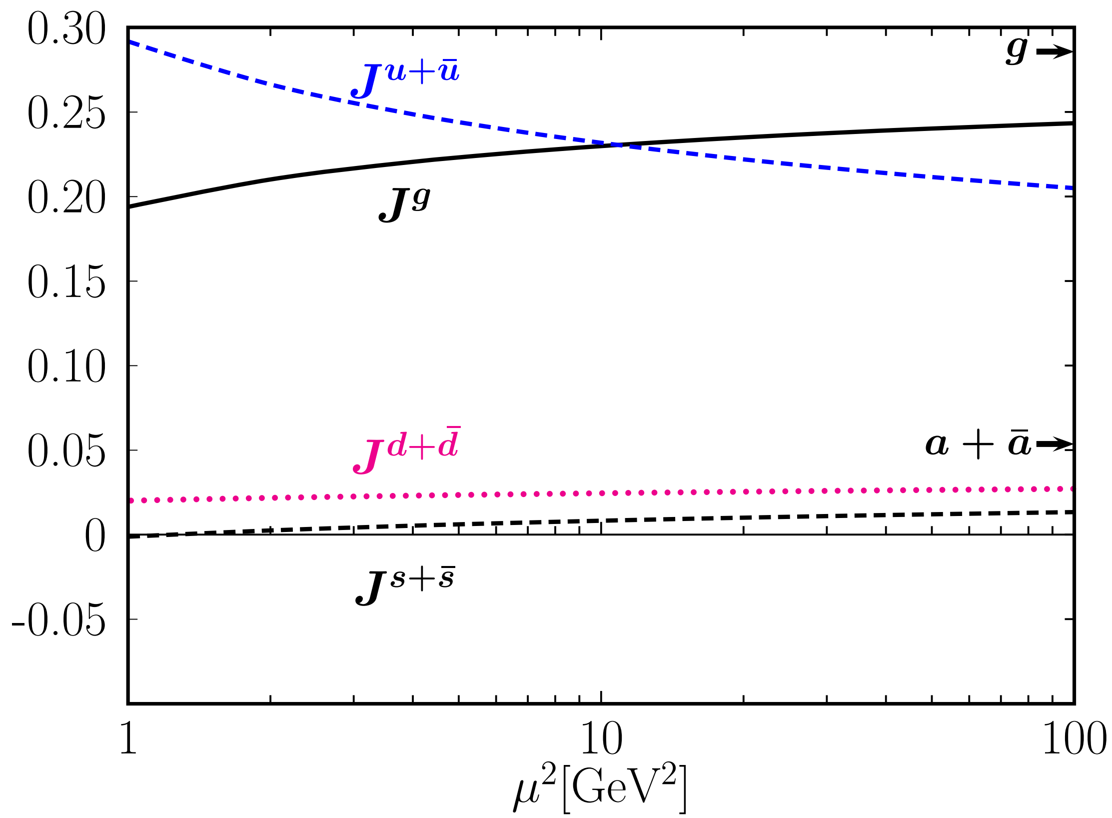
small effects: transversity GPDs and $\pi \to \rho$ transition form factors

($\pi \to \omega$ large effect)

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 ρ^0 ($\gtrsim 2\,\mathrm{GeV}$ for ϕ, π)
- From the combined analysis of nucleon form factors, DVMP (and DVCS for $E^{\rm sea}$) 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)
- This set of GPDs allows for calculations of other hard exclusive processes (DVCS, ω, $Kaon$ and η lepton-pair production . . .) test of universality
- and to obtain first results on parton angular momenta
- Evaluation of transverse localization of partons in the proton only possible for valence quarks 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)

Evolution of the angular momenta



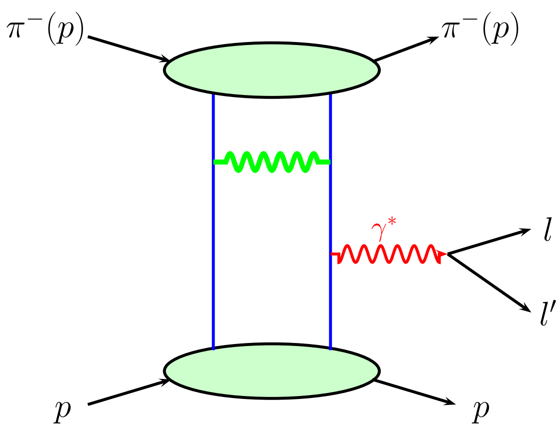
$$e_{20}^{a_v}(Q^2) = e_{20}^{a_v}(Q_0^2)\, e^{-d_{qq} s} \qquad d_{qq} = \frac{32}{75} \qquad d_+ = \frac{56}{75}$$

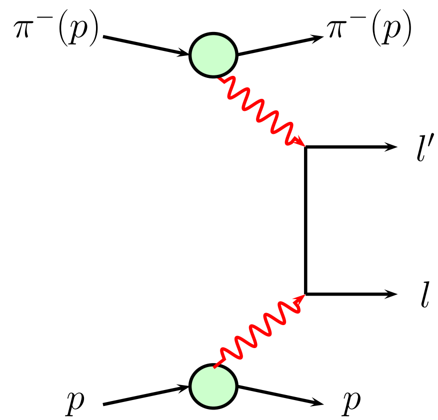
$$\Sigma_e(Q^2) = \sum_a \left(e_{20}^{a} + e_{20}^{\bar{a}}\right) = -e_{20}^{g}(Q^2) = \Sigma_e(Q_0^2)\, e^{-d_+ s}$$

$n_f = 4$ $\qquad s = \ln \frac{\ln (Q^2/\Lambda_{QCD}^2)}{\ln (Q_0^2/\Lambda_{QCD}^2)}$ $\qquad$ small charm contribution not shown

Lepton-pair production in exclusive hadron-hadron collisions

Pivovarov-Teryaev (14): double handbag

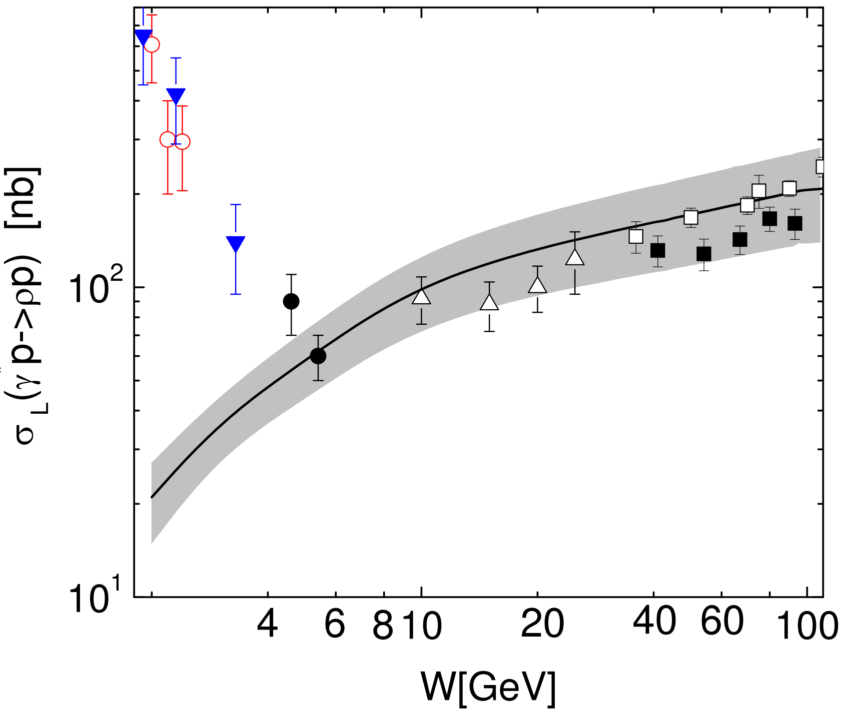


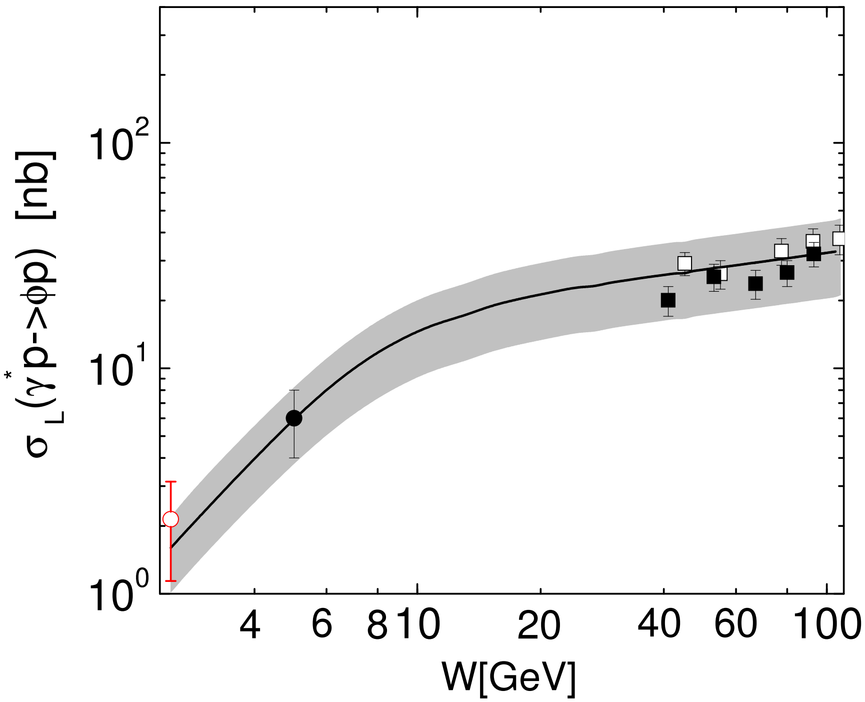


access to pion GPD

elm. contribution
$\sim F_{\rm elm}^{\pi(p)} F_{\rm elm}^{p}$

W dependence of ρ^0 and ϕ production cross section





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

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

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

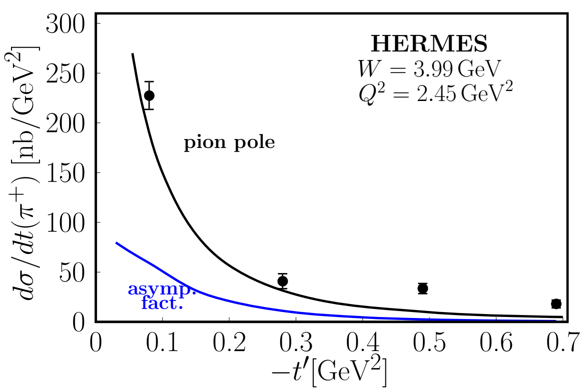
likely not a D term

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 π^+ production - pion pole: (Mankiewicz et al (98), Penttinen et al (99))



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

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

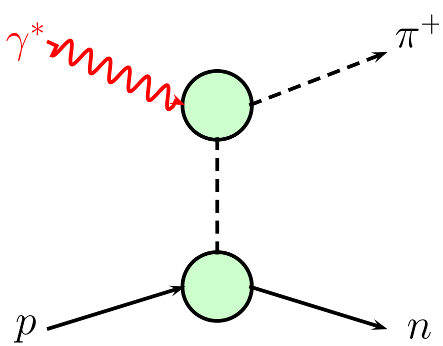
understimates c.s.(blue l.) $\qquad F_\pi^{\rm pert.} \simeq 0.3{-}0.5 F_\pi^{\rm exp.}$

(F_π measured in π^+ electroproduction at Jlab)

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

knowledge of the sixties suffices to explain

π^+ data at small $-t$ and large Q^2

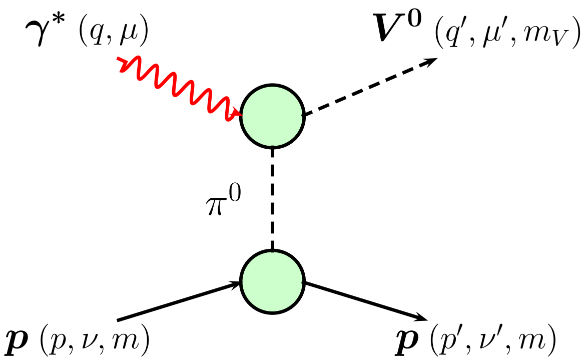


ω production

important ingredient: pion pole (as for π^+ production)

does not contribute to $\gamma_L^* \to V_L$ clearly not leading twist

Goloskokov-K (1407.1141)



$$\langle \omega | j_\kappa^{\rm el}(0) | \pi \rangle = e_0 g_{\gamma^* \pi\omega}(Q^2, t) \varepsilon(\kappa, q, \epsilon_\omega, q')$$

large Q^2, small $-t$: $g_{\gamma^*\pi\omega}(Q^2, t) \simeq g_{\pi\omega}(Q^2)$

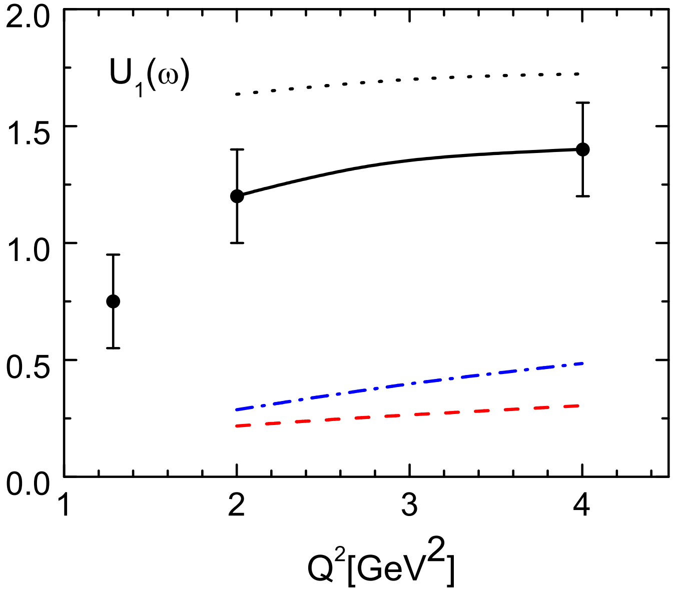
dominant $\gamma_T^* \to V_T$ transitions

(suppressed by $1/Q$ as compared to $\gamma_L^* \to V_L$)

subdominant $\gamma_L^* \to V_T$ (suppressed by $1/Q^2$)

HERMES(1407.2119) ω SDMEs at $W = 4.8\,\mathrm{GeV}$:

ω SDMEs



unnatural parity contribution

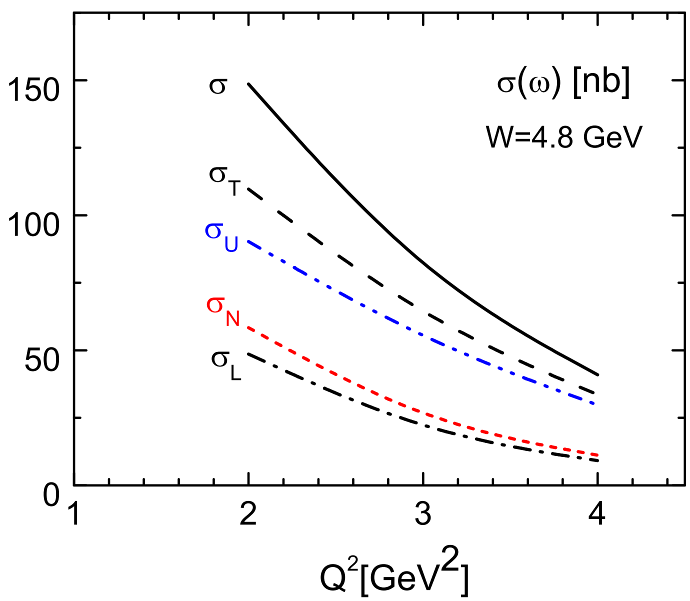
$$U_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1} = 2\frac{d\sigma_U}{d\sigma}$$

$W = 4.8(8)\,\mathrm{GeV}$, without pion pole,

dotted 3.5 GeV, $t' = -0.08\,\mathrm{GeV}^2$

strong unnat. parity contr. - pion pole

allows for extraction of $|g_{\pi\omega}|$



various cross sections

different from ρ^0 and

from $Q^2 \to \infty$ expectation