GPDs from meson electroproduction and applications

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Outline:

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

  Extraction of GPDs from meson electroproduction

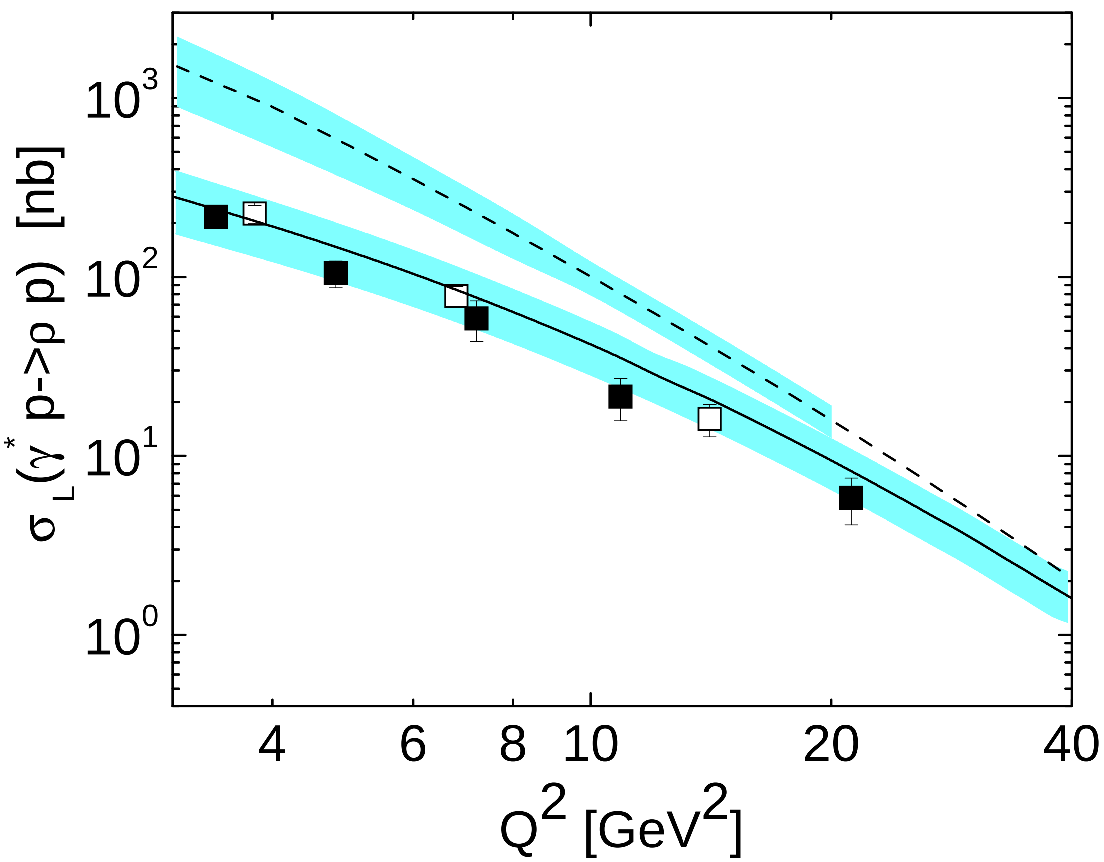
- **GPDs in transverse position space**
- **Predictions for DVCS, E and parton angular momentum**
- **Universality: Lepton pair production in exclusive processes**

  Predictions for other mesons (ω, K, η)

  Meson neutrino production

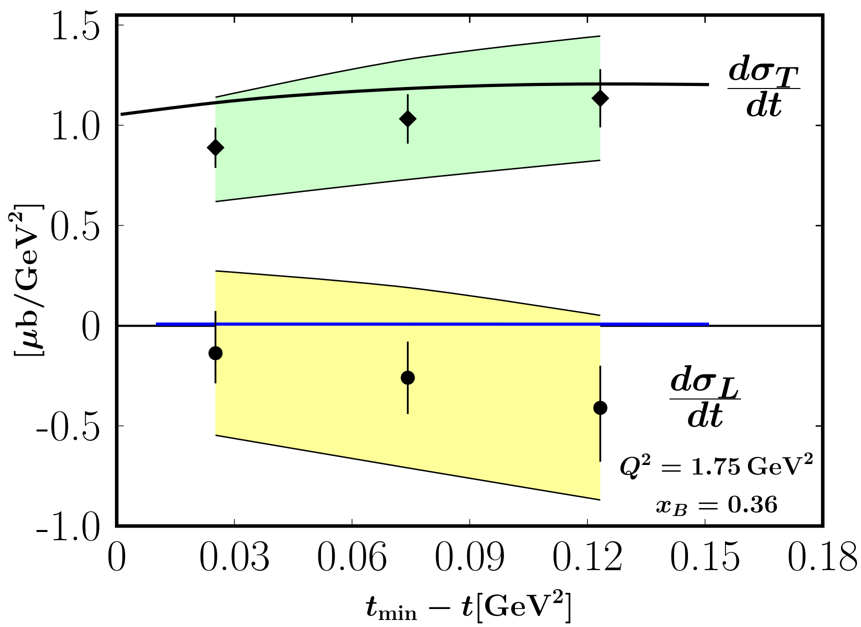
- **Summary**

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:

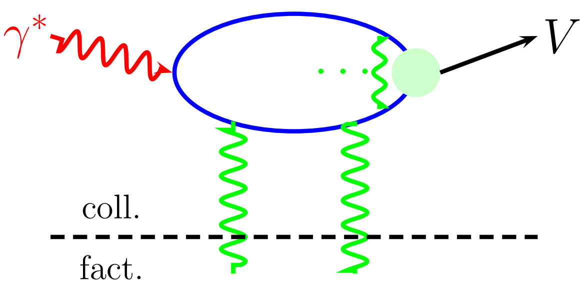
$A_{UT}^{\sin\phi_S}(\pi^+)$ HERMES(09); $d\sigma_{TT}/dt(\pi^0)$ CLAS(12)

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

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

(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 $w_i(\rho,\eta) \sim [(1-|\rho|)^2-\eta^2]^{n_i}$ $(n_g = n_{\rm sea} = 2, n_{\rm val} = 1$, 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 and η/π^0 cross section ratio 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

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

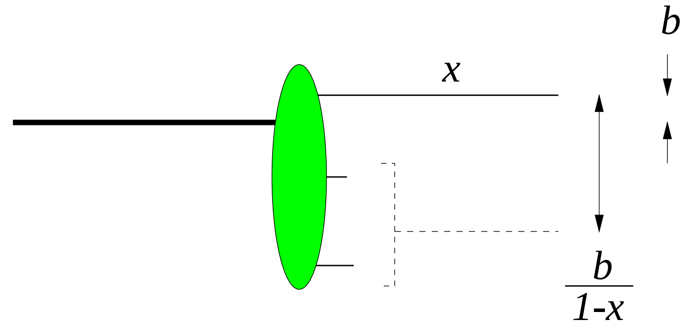
consider Fourier transform of H

work in hadron's center of momentum frame

$\sum x_i \mathbf{b_i} = 0$

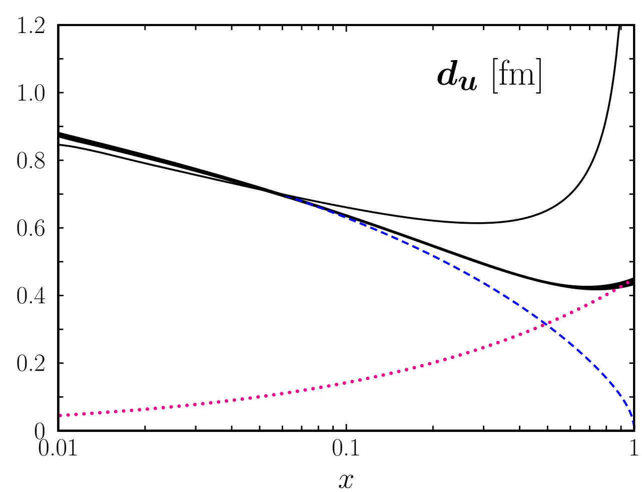
distance between active parton and

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 $x \to 1$



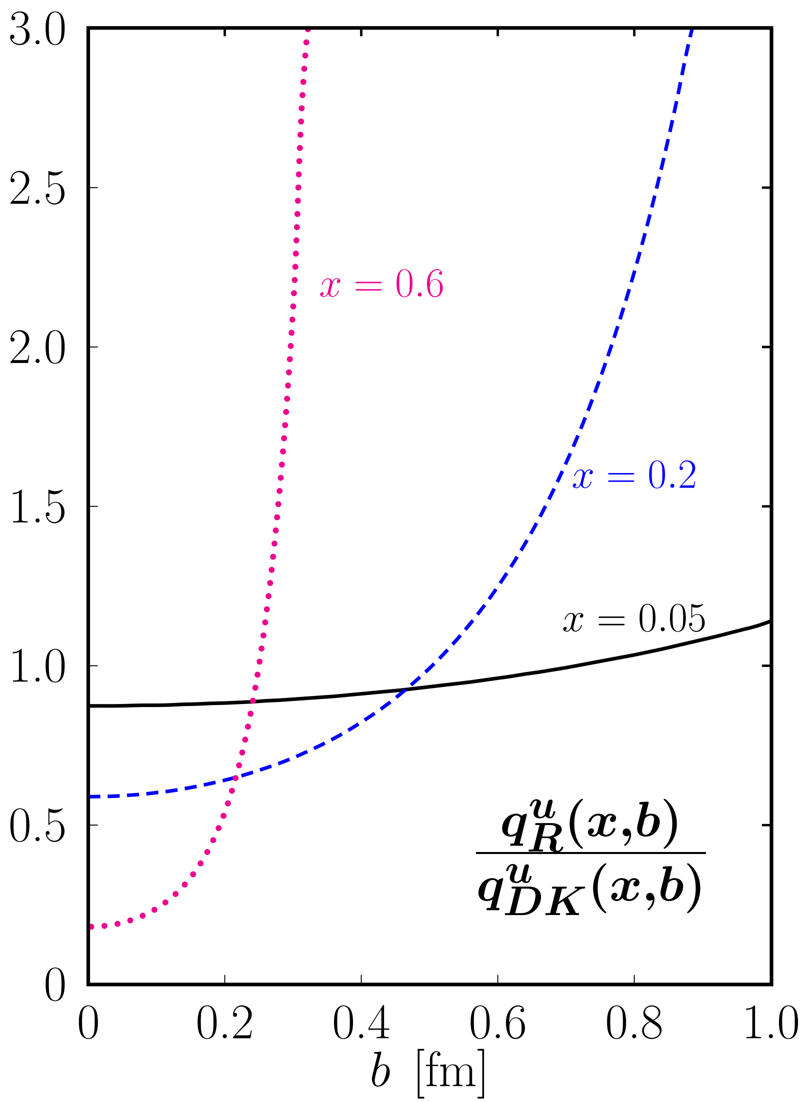
Regge-type term, A term, full profile fct

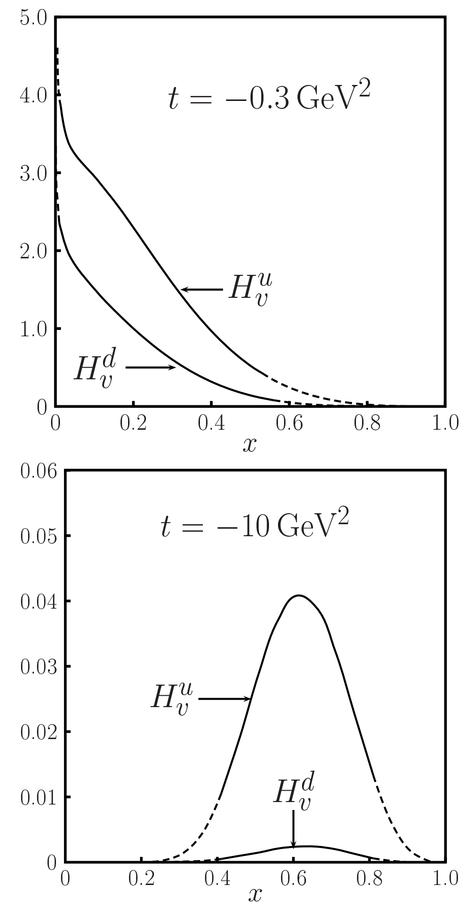
Regge-like profile fct can (only) be used

at small x (small $-t$)

(Regge-like: $A = 0$ and $(1-x)^3 \to 1$)

FT with Regge-like profile function



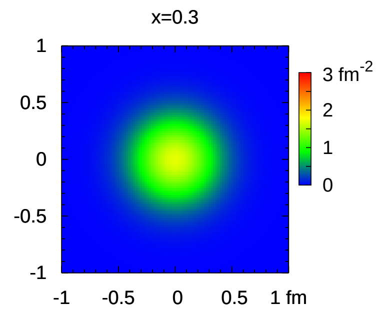


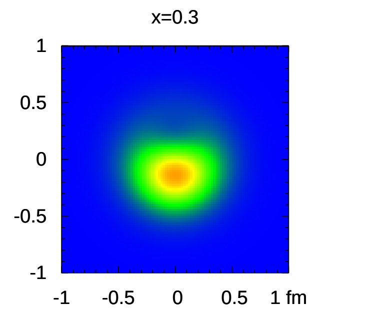
only reasonable for $x \lesssim 0.1$

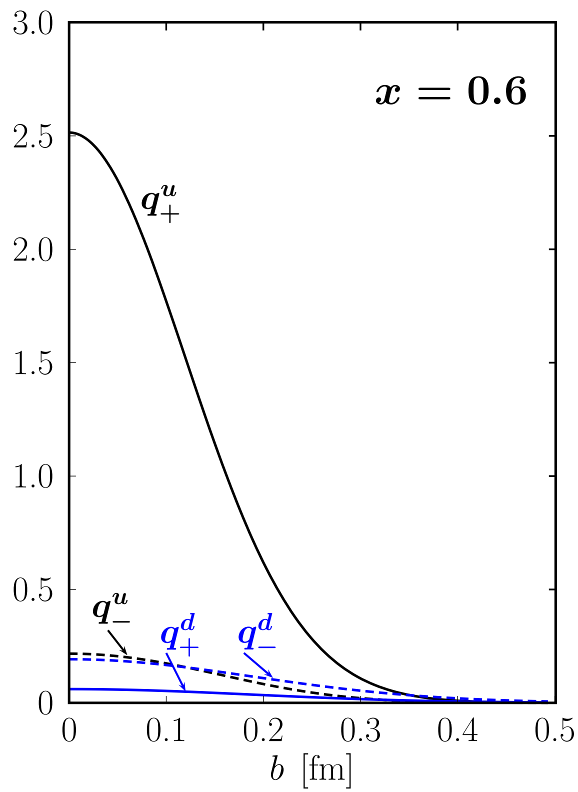
large x-region not explored by electroproduction

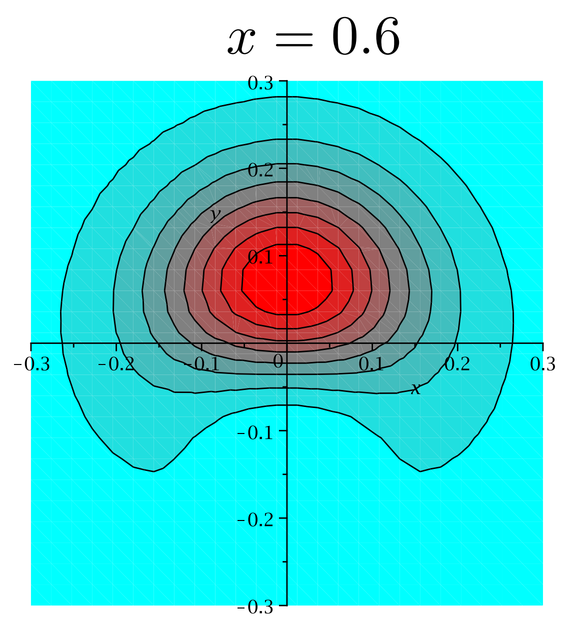
Densities in transverse position space at large x

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

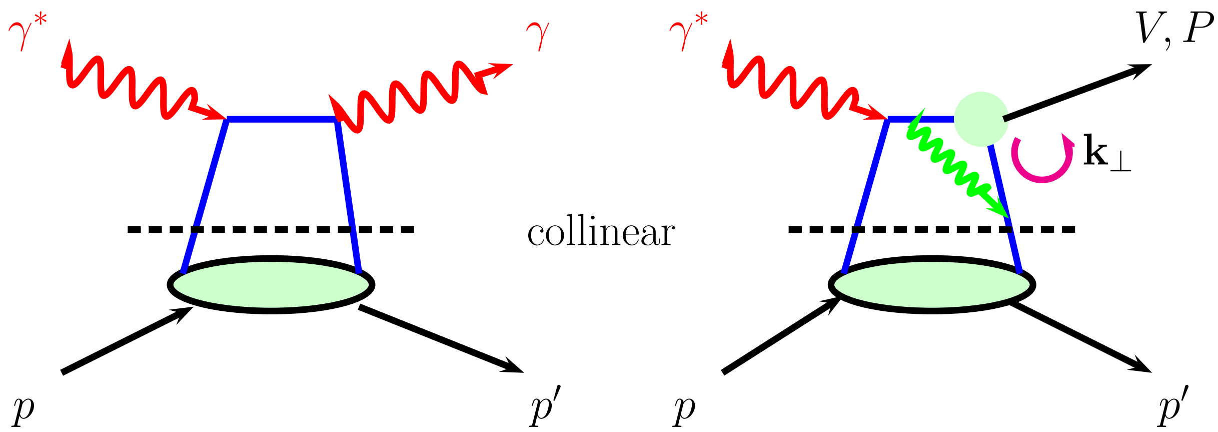
Brodsky et al(95)

F_A and WACS K_{LL}

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

wide-angle photopro. of π^0

DVCS



leading-twist, LO accuracy, collinear for consistency

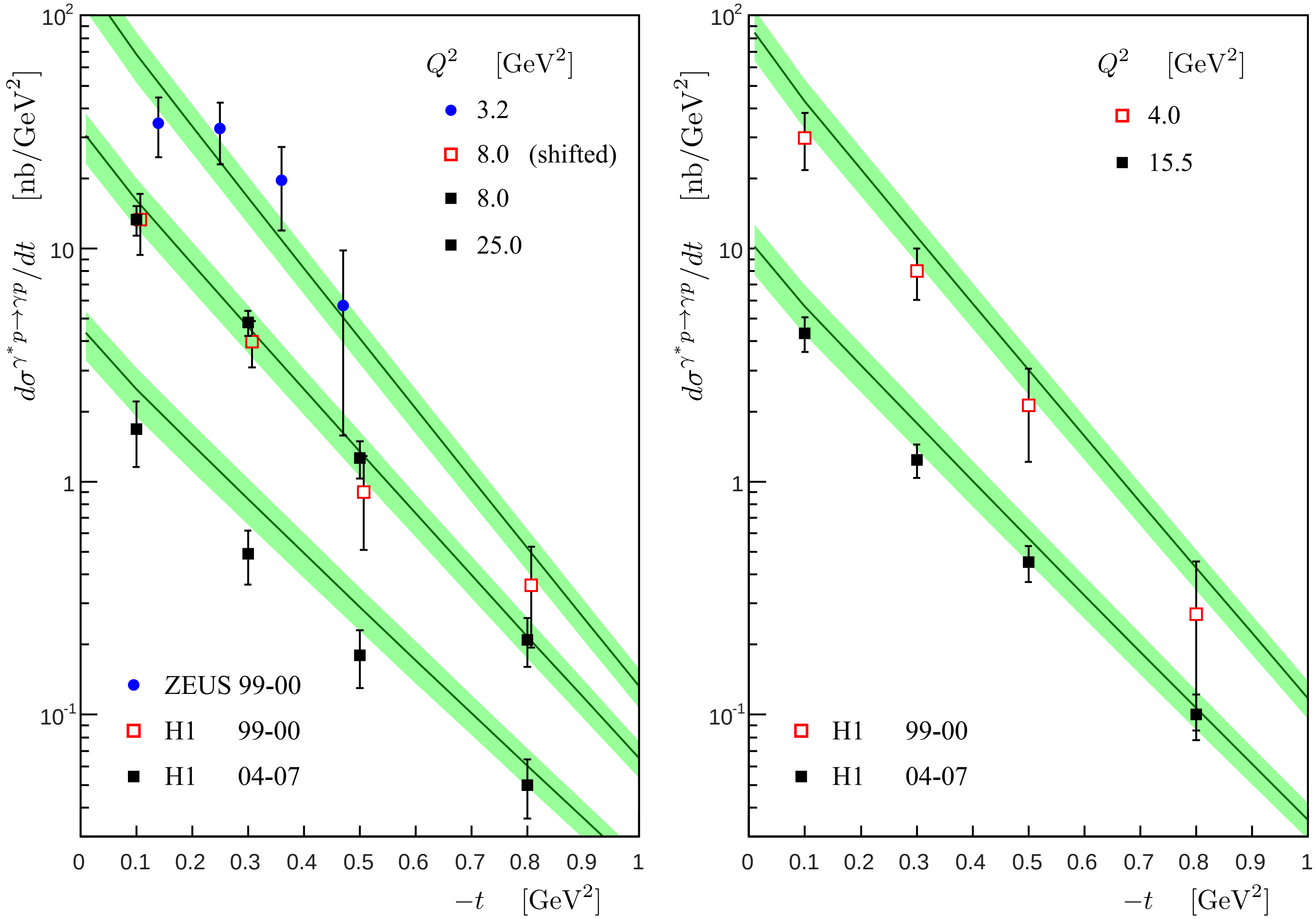
with H most of the DVCS observables can be computed

good agreement with all data from HERMES, HERA

except for Jlab6 kinematics (large skewness)

power corrections needed   Braun et al 1401.7621

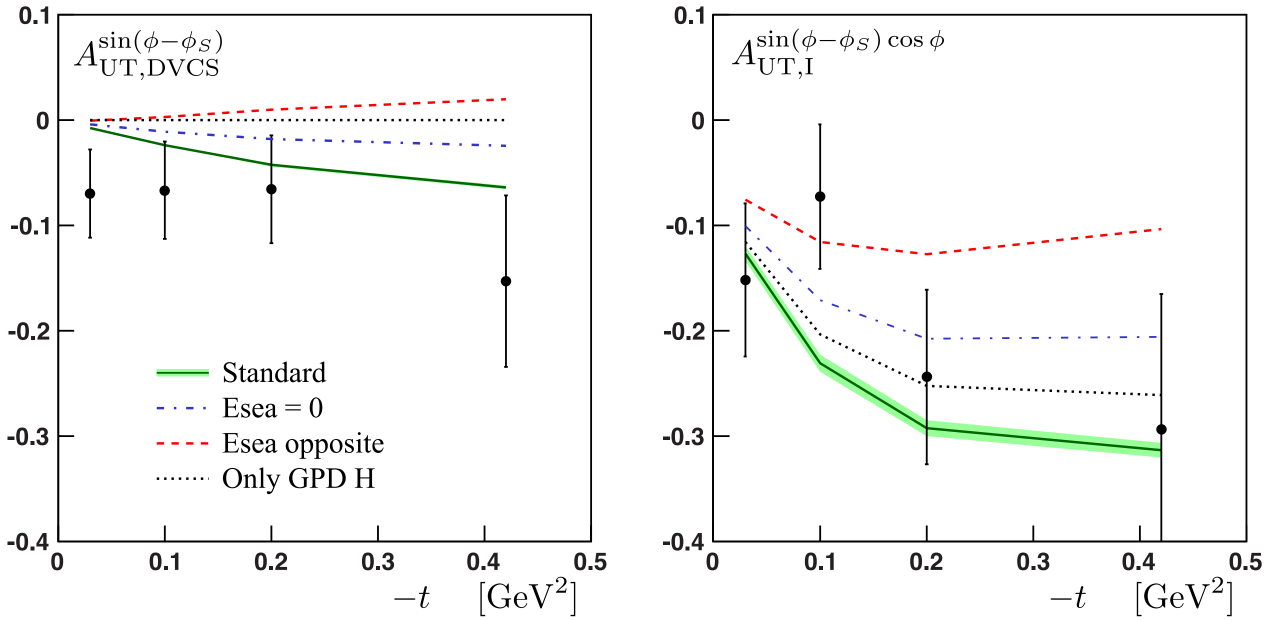
DVCS at HERA



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

leading-twist accuracy parameter-free computation UNIVERSALITY

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))

$$\frac{b^2}{m^2}\left(\frac{\partial e_s(x,b)}{\partial b^2}\right)^2 \leq s^2(x,b) - \Delta s^2(x,b)$$

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

Application: Angular momenta of partons

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

q^a_{20}, g_{20} from ABM11 (NLO) PDFs $\qquad (a = u, d, s, \bar{u}, \bar{d}, \bar{s})$

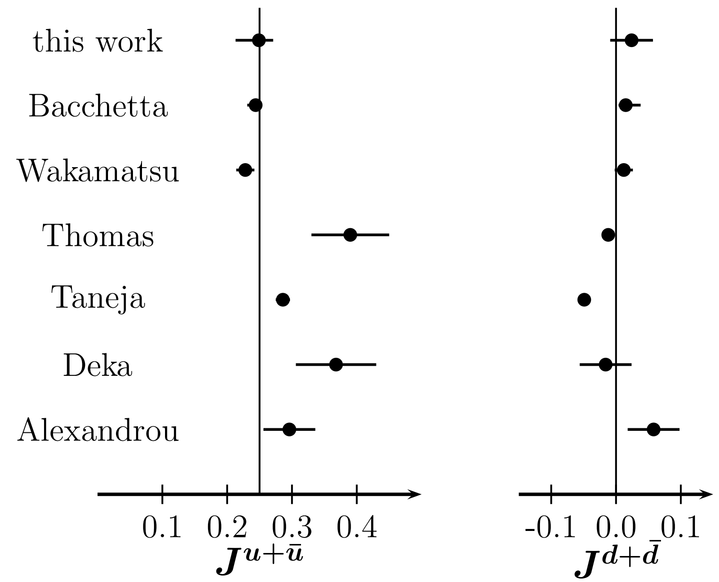
$e^{a_v}_{20}$ (=0.163, -0.122) from form factor analysis Diehl-K. (13):

$e^s_{20} \simeq 0 \ldots - 0.024$ from analysis of A_{UT} in DVCS and positivity. bound

e^g_{20} $(= -\sum e^{a_v}_{20} - 6e^s_{20})$ (Goloskokov-K (09), K. 1410.4450)

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

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

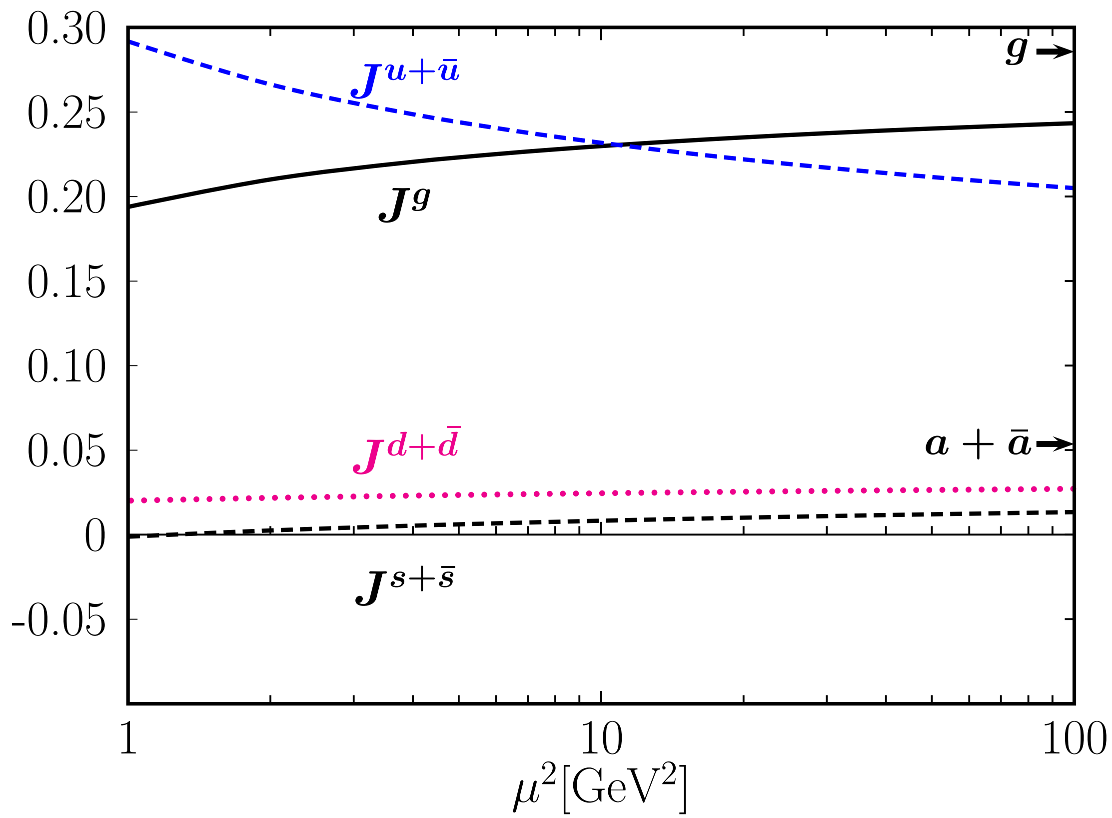


$\sum J^i = 1/2$ (spin of the proton)

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)

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

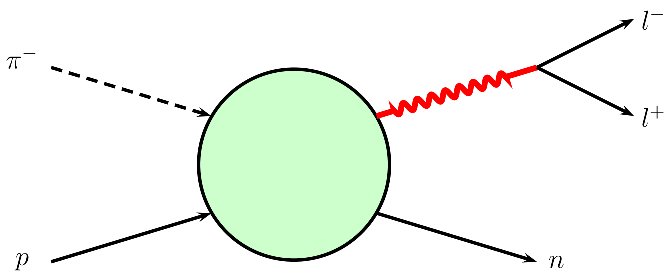
Lepton-pair production in exclusive processes

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)

The exclusive Drell-Yan process



Berger-Diehl-Pire (01): leading-twist, LO analysis of long. cross section
(i.e. exploiting asymp. factor. formula)
(detailed reanalysis Sawada et al, 1605.00364)

we know that leading-twist analysis of π^+ production fails with JLAB, HERMES data by order of magnitude

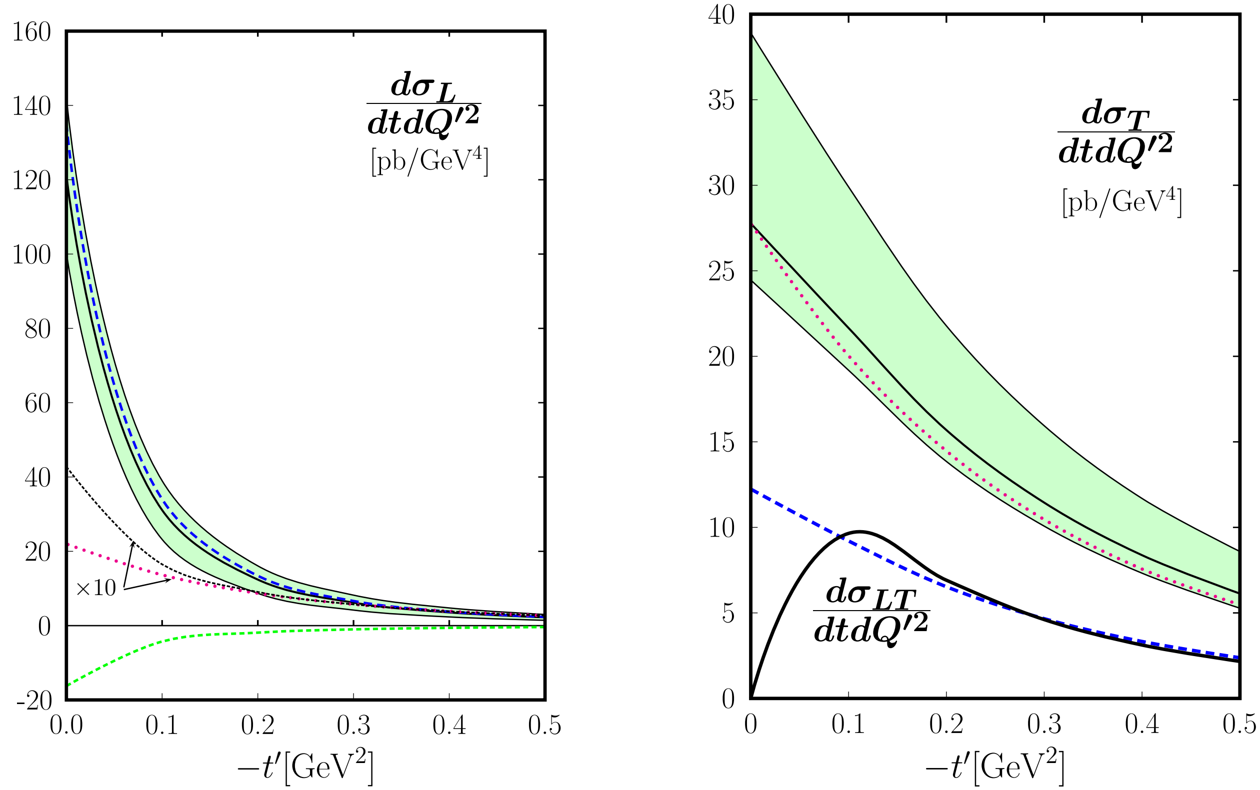
Therefore . . .

(Goloskokov-K. 1506.04619)

a reanalyis of the exclusive Drell-Yan process seems appropriate
making use of what we have learned from analysis of pion production

- take into account transverse photons and transversity GPDs
- retaining quark transverse momenta in the subprocess (the MPA)

Results on the Drell-Yan cross sections



$Q'^2 = 4\,\mathrm{GeV}^2$ and $s = 20\,\mathrm{GeV}^2$ solid lines with error bands: full result

pion pole, $|\langle\widetilde{H}^{(3)}\rangle|^2$, interference, short dashed: leading-twist contribution

time-like pion FF: $Q'^2|F_\pi(Q'^2)| = 0.88 \pm 0.04\,\mathrm{GeV}^2$ (CLEO, BaBar, $J/\Psi \to \pi^+\pi^-$)

phase $(\exp[i\delta(Q'^2)])$ from disp. rel. Belicka et al(11) for $Q'^2 < 8.9\,\mathrm{GeV}^2$

$\delta = 1.014\pi + 0.195(Q'^2/\mathrm{GeV}^2 - 2) - 0.029(Q'^2/\mathrm{GeV}^2 - 2)^2$

for $Q'^2 \geq 8.9\,\mathrm{GeV}^2$: $\delta = \pi$, the LO pQCD result

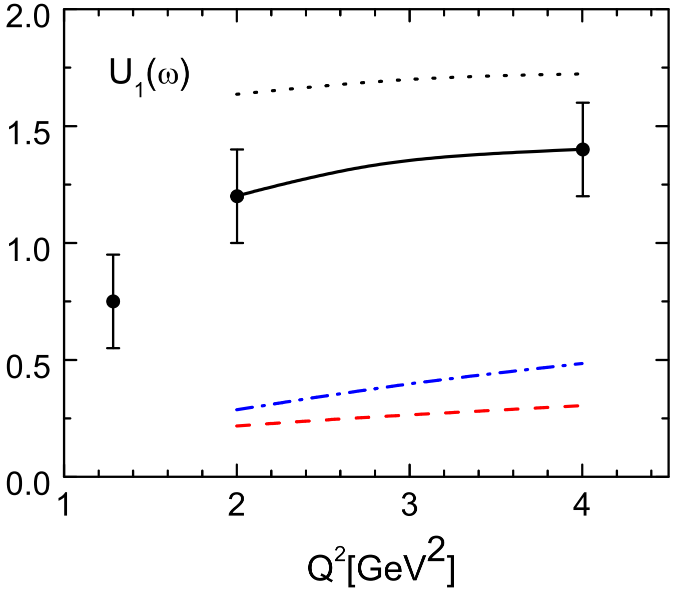
Remarks on processes with time-like virtual photons

- time-like excl. processes difficult to understand theoretically
  e.g. no satisfactory explanation of time-like elm form factors
  within pert. QCD

- Drell-Yan process $\pi^- p \to l^+ l^- X$
  large K-factor needed (larger than NLO corr. Sutton et al (92))
  now understood as 'threshold logs' $(Q'^2/(x_1 x_2 s) \to 1)$
  (gluon radiation resummed to NLL Sterman(87), Catani-Trentadue(89))
  leading finally to reasonable fits of data and extraction of PDFs for the
  pion with plausible behavior for $x \to 1$ Aicher-Schäfer-Vogelsang (11)

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

ω SDMEs



unnatural parity contribution

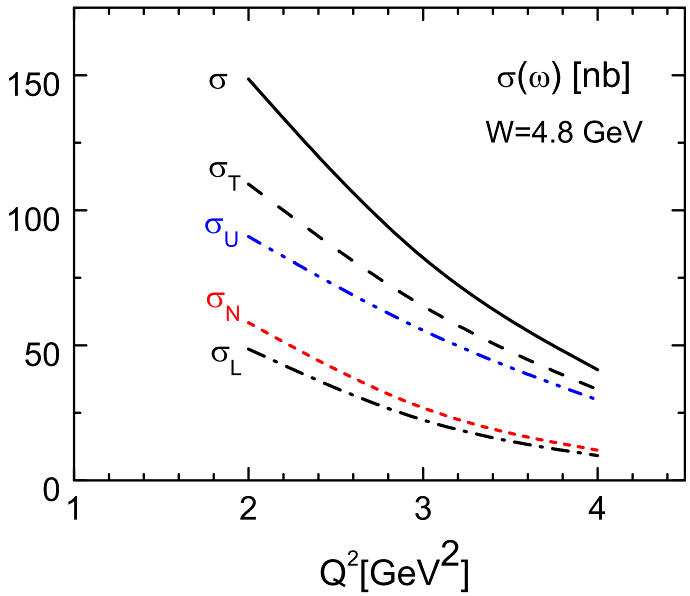
$$U_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1} = 2\frac{d\sigma_U}{d\sigma}$$

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

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

strong unnat. parity contr. - pion pole

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

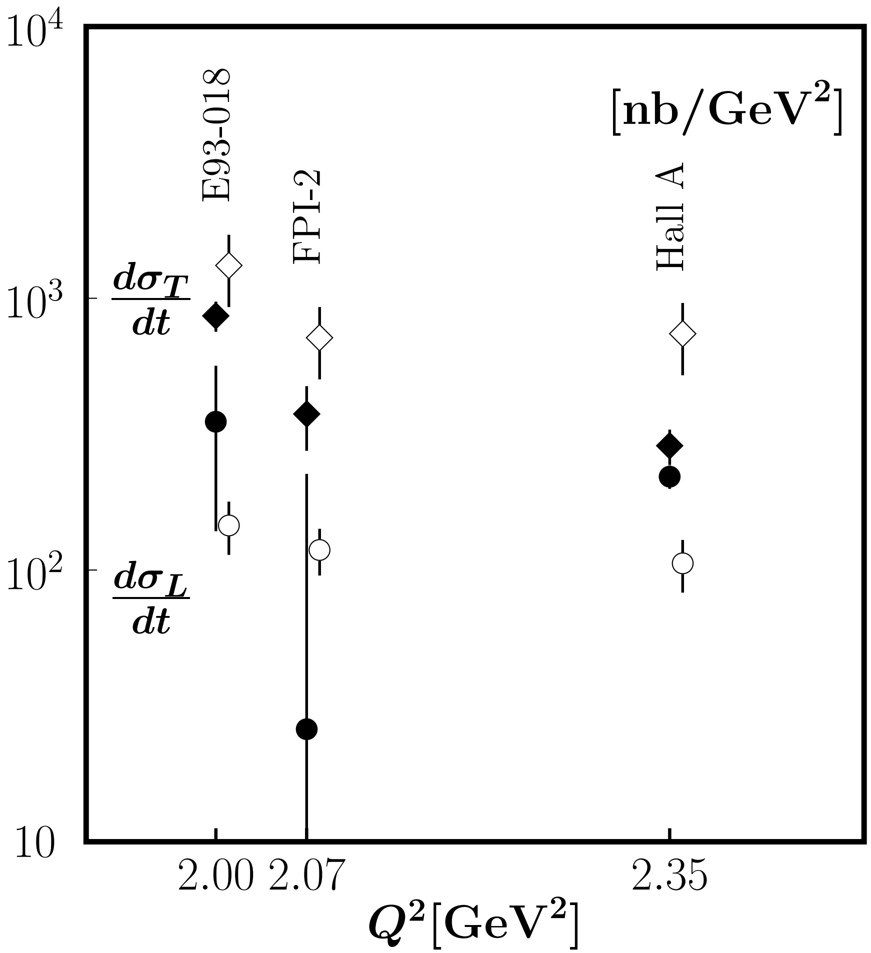


various cross sections

different from ρ^0 and

from $Q^2 \to \infty$ expectation

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



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

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

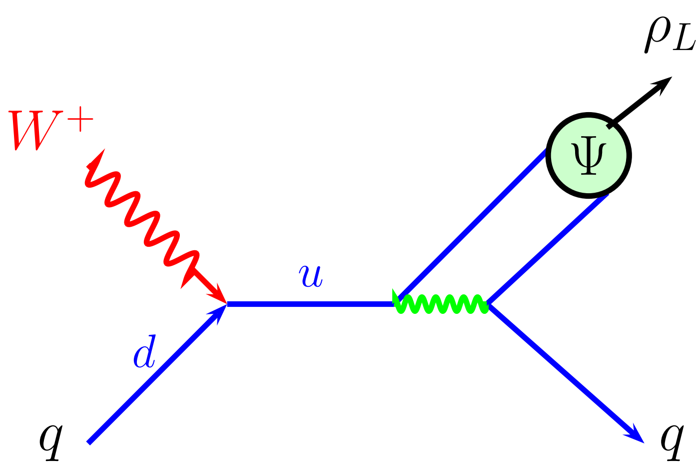
flavor symmetric sea assumed

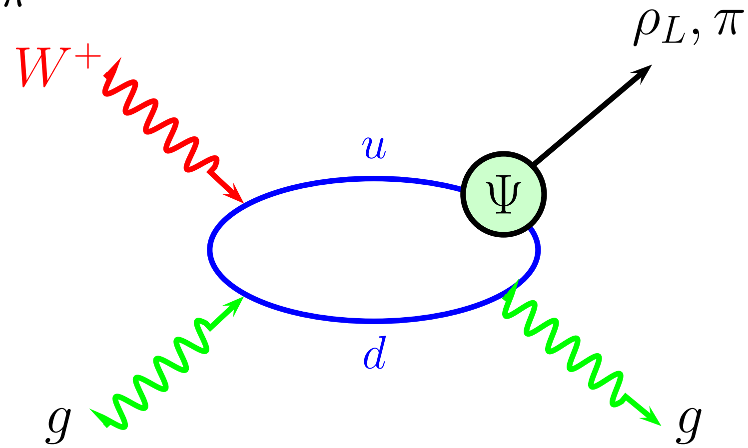
kaon/pion pole $\sim [(t-m_\pi^2)/(t-m_k^2)]^2$

also prediction for π^0 production off neutrons, η production, ρ^0 prod. with transversity GPDs (SDME)

Meson neutrino production

V-A theory all 4 helicity non-flip GPDs contribute





H_g contribution dominant Pire et al(17)
π and ρ_L amplitudes are proportional
twist-3 contribution $(H_T, \bar{E}_T)$ small
Kopeliovich et al(14)

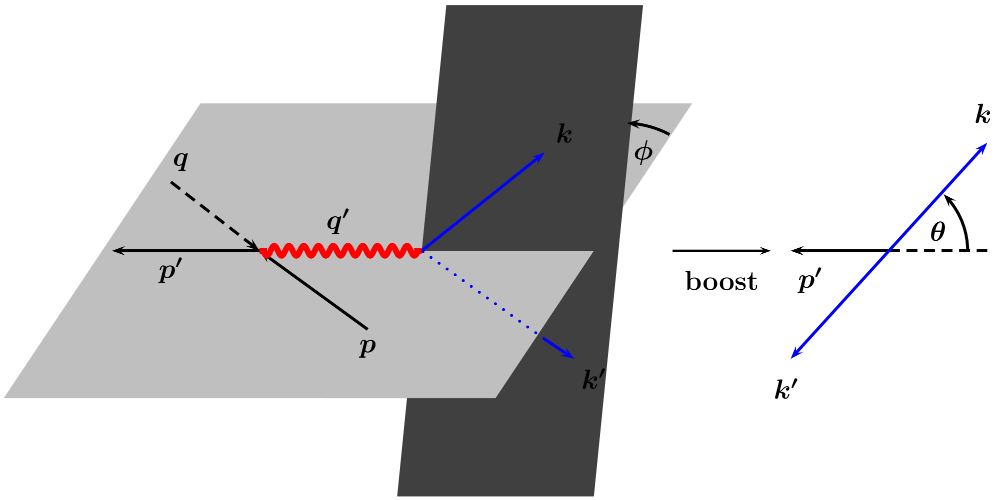
MINERVA 1409.3835
$\nu A \to \mu\pi A$
$E_\nu = 1.5 - 20\mathrm{GeV}$, Q^2?

NLO corrections for π and K production Siddikov-Schmidt(16)
nuclear effects only substantial for $x_B \lesssim 0.1$ Schmidt-Siddikov(15)

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^{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)

Cross section



k momentum of l^-
$\tau = Q'^2/(s-m^2)$
the time-like analogue
of x_B

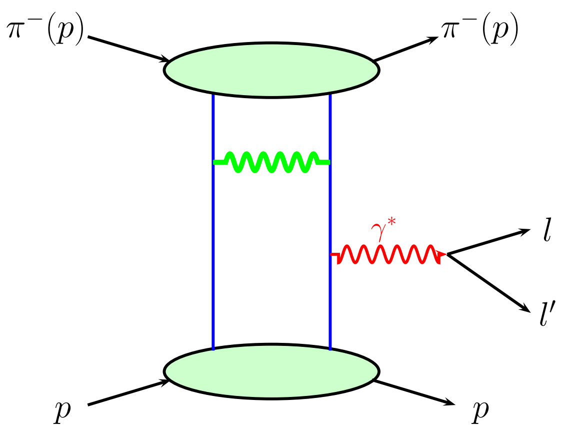
$$\frac{d\sigma}{dt dQ'^2 d\cos\theta d\phi} = \frac{3}{8\pi}\left\{\sin^2\theta \frac{d\sigma_L}{dt dQ'^2} + \frac{1+\cos^2\theta}{2}\frac{d\sigma_T}{dt dQ'^2} + \frac{1}{\sqrt{2}}\sin(2\theta)\cos\phi \frac{d\sigma_{LT}}{dt dQ'^2} + \sin^2\theta\cos(2\phi)\frac{d\sigma_{TT}}{dt dQ'^2}\right\}$$

$$\frac{d\sigma_L}{dt dQ'^2} = \frac{\alpha_{\rm elm}}{48\pi^2}\frac{\tau^2}{Q'^6}\sum_{\nu'}|\mathcal{M}_{0\nu',0+}|^2 \qquad \frac{d\sigma_T}{dt dQ'^2} = \frac{\alpha_{\rm elm}}{48\pi^2}\frac{\tau^2}{Q'^6}\sum_{\mu=\pm1,\nu'}|\mathcal{M}_{\mu\nu',0+}|^2$$

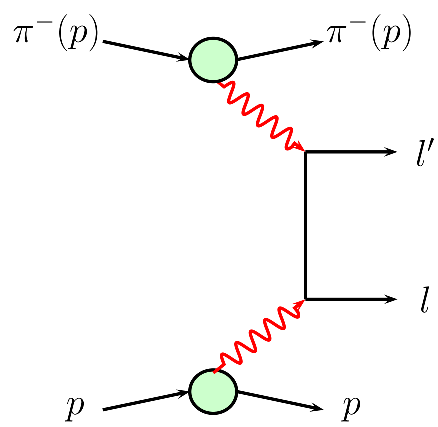
partial cross sections analogous to pion production

Lepton-pair production in exclusive hadron-hadron collisions

Pivovarov-Teryaev (14): double handbag



access to pion GPD

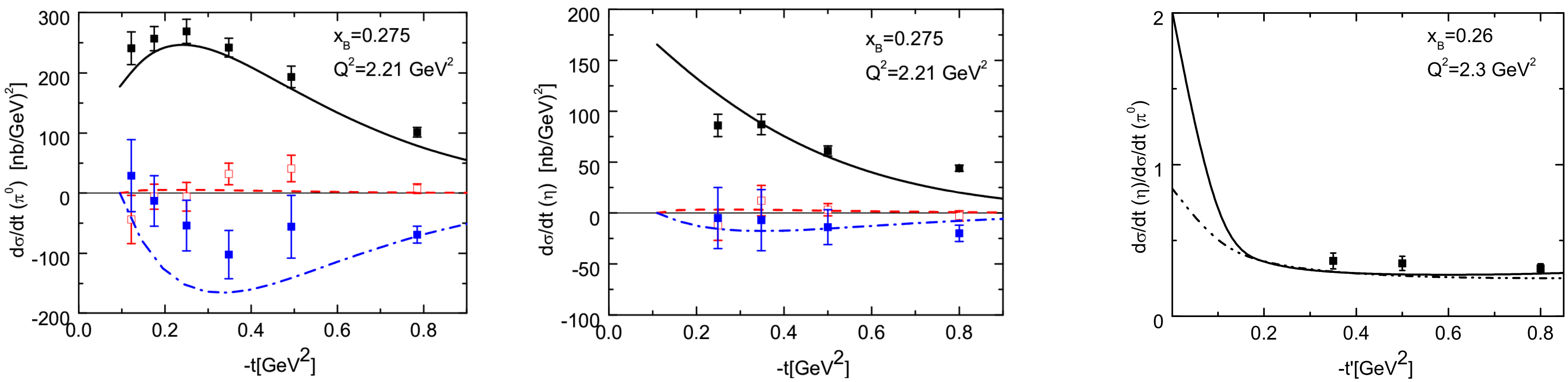


elm. contribution

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

η production

Bedlinsky et al (1405.0988) theory: Goloskokov-K (1106.4897)



unseparated (longitinal, transverse) cross sections

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

if K^u and K^d have opposite sign: $\eta/\pi^0 \simeq 1$ $\quad(\eta = (\cos\theta_8 - \sqrt{2}\sin\theta_1)\eta_q)$

if K^u and K^d have same sign: $\eta/\pi^0 < 1$ $\quad$ (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