Twist-3 contributions to hard exclusive processes

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Zagreb, January 2018

Outline:

- **Perturbative QCD in hard exclusive processes**
- **The Handbag factorization**
- **Wide-angle Compton scattering**
- **Wide-angle photoproduction of pions**
- **Hard electroproduction of pions**
- **Photoproduction of pions again**
- **Summary**

Interest in hard physics

processes with a hard (large) scale $Q^2 =$ photon virtuality, $p_\perp^2, s, -t, -u$

- scattering off constituents, i.e off quarks and gluons (partons)
- scattering under control of pert. QCD and QED
- question: are we able to calculate observables?
- decisive help from factorization properties of QCD:

  if a hard scale is available

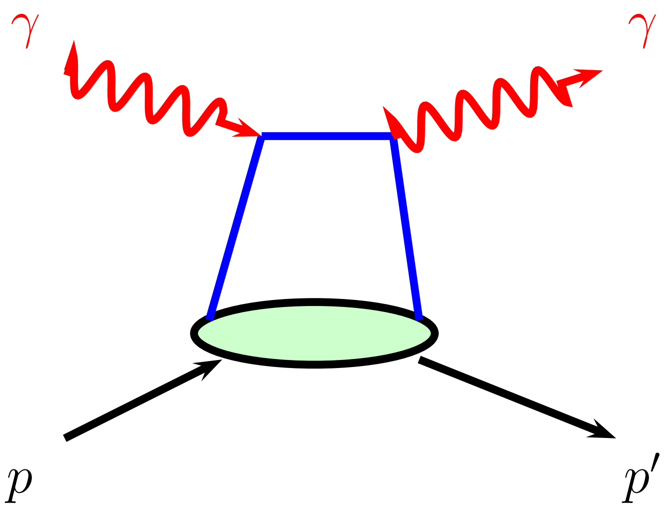
  processes often factorize into

  parton level subprocesses (pert. calculable within QCD/QED)

  and soft hadronic matrix elements (non-perturbative physics,

  to be modeled or extracted from experiment or lattice QCD)

The handbag factorization



factorization in a hard subprocess, e.g. $\gamma q \to \gamma q$, and a soft proton matrix element, parameterized as a General Parton Distribution

$$\langle p'\lambda' \mid \bar{\Psi}_q(-\bar{z}/2)\Gamma\Psi_q(\bar{z}/2) \mid p\lambda\rangle_{z^+=z_\perp=0}$$

$$(\Gamma = \gamma^+, \gamma^+\gamma_5, i\sigma^{+i},\ A^+ = 0)$$

two classes of hard exclusive reactions:

DEEP VIRTUAL e.g. DVCS or electroproduction of mesons

rigorous proof for factorization in generalized Bjorken regime of

large Q^2 and W but fixed x_B and $-t/Q^2 \ll 1$

WIDE-ANGLE e.g. RCS or photoproduction of mesons

arguments for factorization at large Mandelstam variables $s, -t, -u$

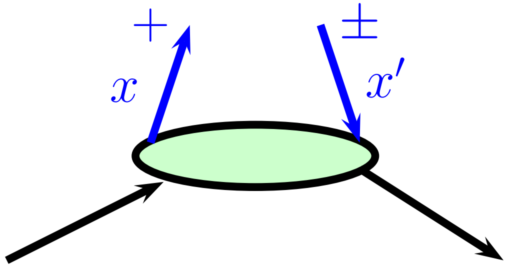
complementary: GPDs at small $-t$ in deep virtual and
GPDs at large $-t$ in wide-angle processes

GPDs

D. Müller et al (94), Ji(97), Radyushkin (97)

$$K(\bar{x},\xi,t) = H, E, \widetilde{H}, \widetilde{E}, H_T, E_T, \widetilde{H}_T, \widetilde{E}_T$$

$$x = \frac{\bar{x}+\xi}{1+\xi} \quad x' = \frac{\bar{x}-\xi}{1-\xi} \qquad \xi = \frac{(p-p')^+}{(p+p')^+}$$



for quarks ($\xi < \bar{x} < 1$) and gluons

(antiquarks for $-1 < \bar{x} < -\xi$, $q\bar{q}$ pairs $-\xi < \bar{x} < \xi$)

properties:

reduction formula $H^q(\bar{x}, \xi = t = 0) = q(\bar{x})$, $\widetilde{H}^q \to \Delta q(\bar{x})$, $H_T^q \to \delta^q(\bar{x})$

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

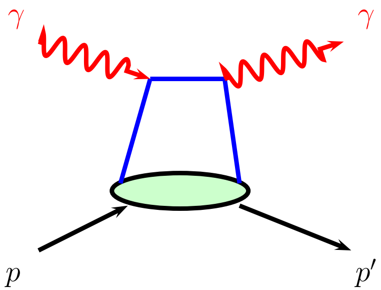
$$E \to F_2,\ \widetilde{H} \to F_A,\ \widetilde{E} \to F_P$$

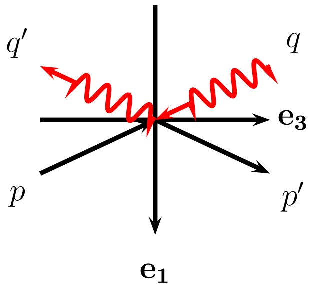
polynomiality, universality, evolution, positivity constraints

Ji's sum rule $\quad J_q = \frac{1}{2}\int_{-1}^{1} d\bar{x}\,\bar{x}\,[H^q(\bar{x},\xi,t=0) + E^q(\bar{x},\xi,t=0)]$

FT $\mathbf{\Delta} \to \mathbf{b}$ ($\Delta^2 = -t$): information on parton localization in trans. position space

The handbag contribution to WACS





$s, -t, -u \gg \Lambda^2$

$\Lambda \sim \mathcal{O}(1\mathrm{GeV})$

typical hadronic scale

- work in a symmetric frame: (otherwise additional contr.)

  $$p^{(\prime)} = [p^+, \frac{m^2 - t/4}{2p^+}, \pm\mathbf{\Delta}_\perp] \qquad \xi = \frac{(p-p')^+}{(p+p')^+} = 0 \qquad t = -\Delta_\perp^2$$

- assumption:

  parton virtualities $k_i^2 < \Lambda^2$, intrinsic transverse momenta $k_{\perp i}^2/x_i < \Lambda^2$

- consequences

  $\hat{s} = (k_j + q)^2 \simeq (p+q)^2 = s$

  $\hat{u} = (k_j - q')^2 \simeq (p - q')^2 = u$

  and $x_j, x_j' \simeq 1$

  propagators poles avoided

  active partons approximately on-shell

  collinear with parent hadrons

- physical situation: hard photon-parton scattering and

  soft emission and reabsorption of partons by hadrons

The Compton amplitudes

Radyushkin hep-ph/9803316; DFJK hep-ph/9811253; Huang-K.-Morii hep-ph/0110208

$s,\ -t,\ -u \gg \Lambda^2$ (light-cone helicities)

$$\mathcal{M}_{\mu'+,\mu+} = 2\pi\alpha_{\rm elm}\Big\{\mathcal{H}_{\mu'+,\mu+}\big[R_V + R_A\big] + \mathcal{H}_{\mu'-,\mu-}\big[R_V - R_A\big]\Big\}$$

$$\mathcal{M}_{\mu'-,\mu+} = \pi\alpha_{\rm elm}\frac{\sqrt{-t}}{m}\Big\{\mathcal{H}_{\mu'+,\mu+} + \mathcal{H}_{\mu'-,\mu-}\Big\}R_T$$

$$R_V(t) = \sum_q e_q^2 \int_0^1 \frac{dx}{x} H_v^q(x,\xi=0,t) \qquad E_v^q \to R_T \qquad \widetilde{H}_v^q \to R_A$$

$\widetilde{E}$ decouples at $\xi = 0$; $\quad H_v^q = H^q - H^{\bar{q}}$ (sea quarks neglected)

subprocess amplitudes: $\mathcal{H}_{++++} = 2\sqrt{-s/u} \quad \mathcal{H}_{-+-+} = 2\sqrt{-u/s}$ (+ NLO)

R_i to be evaluated from $\xi = 0$ GPDs

Diehl-K 1302.4604

Analysis of nucleon form factors

need for Compton ffs, i.e. need for GPDs at large $-t$

deeply virtual processes provide GPDs only at small $-t$

but large $-t$ GPDs from nucleon ffs through sum rules:

$$F_i^{p(n)} = e_u F_i^{u(d)} + e_d F_i^{d(u)}\,, \qquad F_i^a = \int_0^1 dx K_v^a(x, \xi = 0, t)$$

Dirac (Pauli) ff: $\quad K = H(E) \quad$ (normalization from $\kappa_q = \int_0^1 dx E_v^q(x, \xi = t = 0)$)

axial form factor: $\widetilde{H}$ $\qquad$ (κ anomalous magn. moment)

ansatz $\qquad K_i^a(x, \xi = 0, t) = k_i^a(x) \exp\left[t f_i^a(x)\right]$

profile fct: $\qquad f_i^a = (B_i^a + \alpha_i'^a \ln 1/x)(1-x)^3 + A_i^a x(1-x)^2$

forward limits $\qquad H: \quad q(x) \qquad \widetilde{H}: \quad \Delta q(x)$

E: $e_i = N_i x^{\alpha_i}(1-x)^{\beta_i}$ $\qquad$ additional parameters

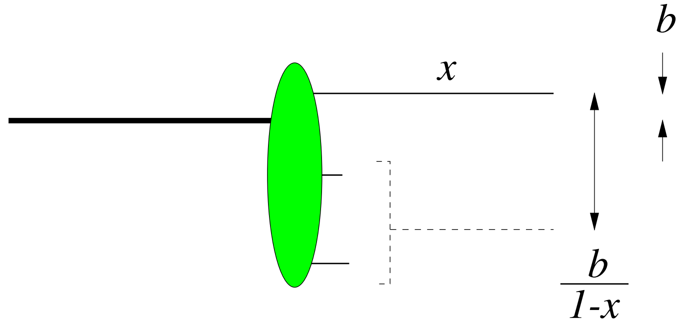
DFJK hep-ph/0408173; update: Diehl-K, 1302.4604 fit to all

$G_M^i, G_E^i/G_M^i$ data ($i = p, n$) and use of ABM11, DSSV09 parton densities

strong $x - t$ correlation

Estimate of proton radius

Approx: distance between active parton and cluster of spectators



work in hadron's center of momentum frame

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

Fourier transform of H

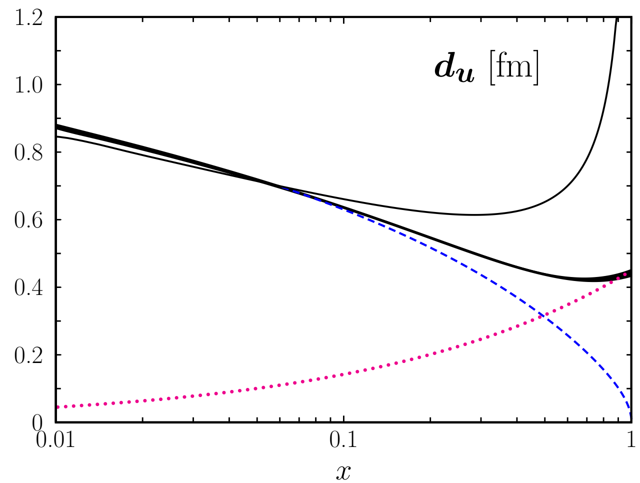
$$q(x, \mathbf{b}) = \frac{1}{4\pi} \frac{q(x)}{f_q(x)} \exp\left[-b^2/(4 f_q(x))\right]$$

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

for $x \to 1$

Regge-type term, A term, full profile fct

Regge-like profile fct can (only) be used at small x (small $-t$)

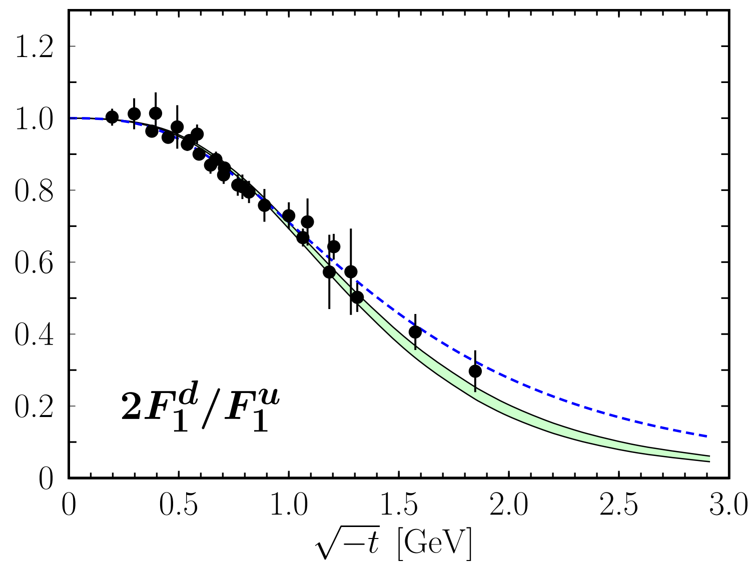


Large–t behavior of flavor form factors

at large t: dominance of narrow region of large x:

$q_v \sim (1-x)^{\beta_q}$, $f_q \sim A_q(1-x)^2$ (analogously for F_2^q)

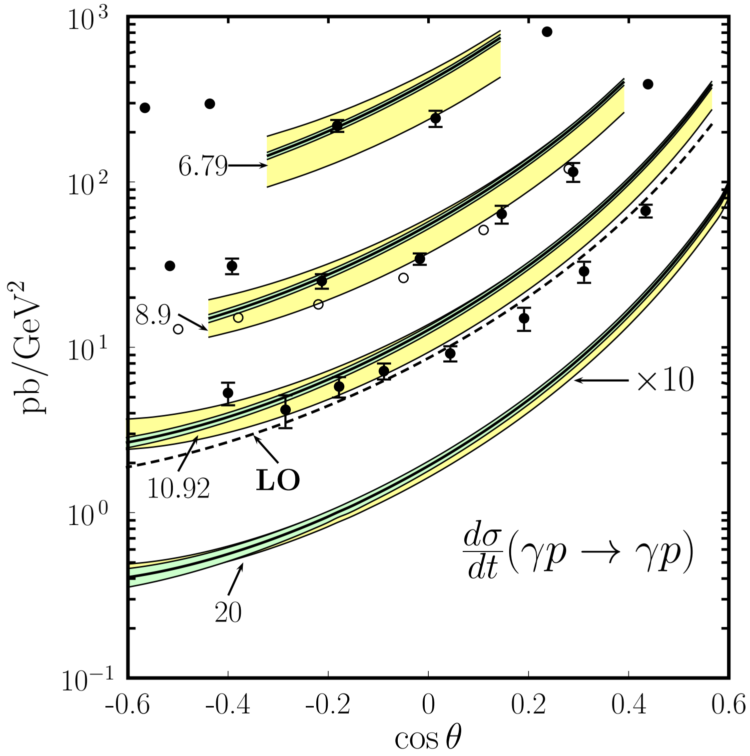
Saddle point method provides $1 - x_s = \left(\frac{2}{\beta_q} A_q |t|\right)^{-1/2}$ $F_1^q \sim |t|^{-(1+\beta_q)/2}$

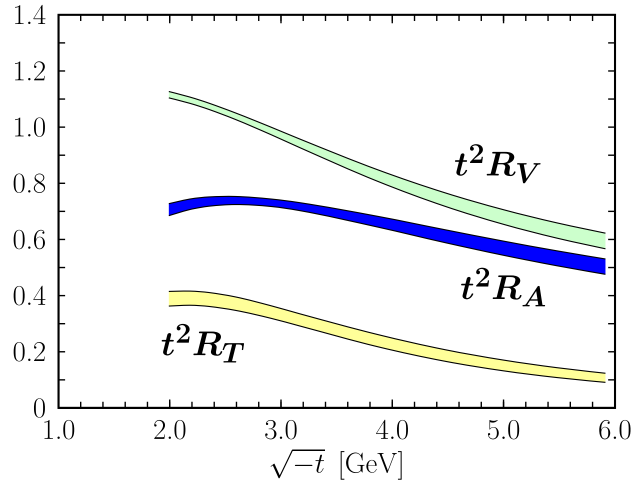


ABM PDFs: $\beta_u \simeq 3.4$, $\beta_d \simeq 5$,

power laws from wave fct overlaps: Dagaonkar-Jain-Ralston (14)

The Compton cross section





$$\frac{d\sigma}{dt} = \frac{d\hat{\sigma}}{dt}\left\{\frac{1}{2}\,\frac{(s-u)^2}{s^2+u^2}\left[R_V^2(t) + \frac{-t}{4m^2}\,R_T^2(t)\right] + \frac{1}{2}\,\frac{t^2}{s^2+u^2}R_A^2(t)\right\} + \mathcal{O}(\alpha_s)$$

$$\frac{d\hat{\sigma}}{dt} = 2\pi\frac{\alpha_{\rm elm}^2}{s^2}\left[-\frac{u}{s} - \frac{s}{u}\right]$$

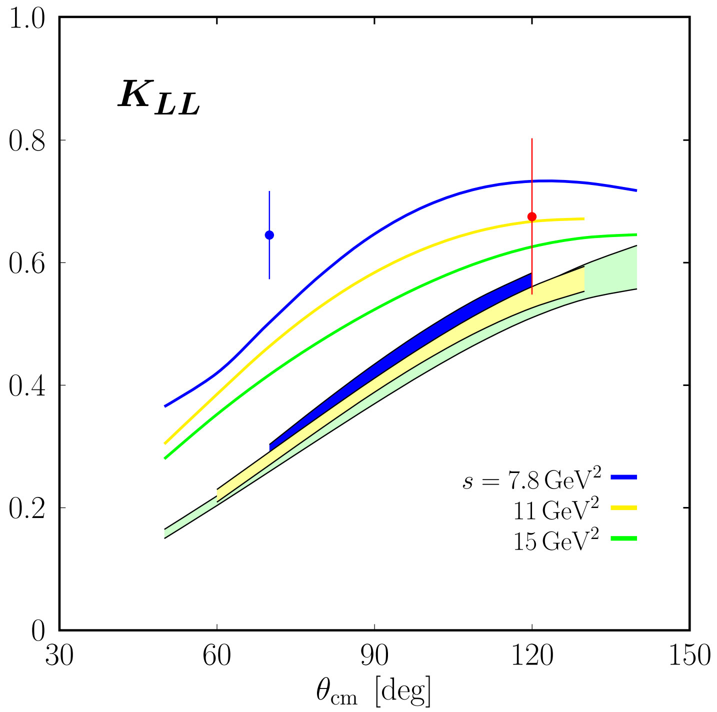
Klein-Nishina cross section

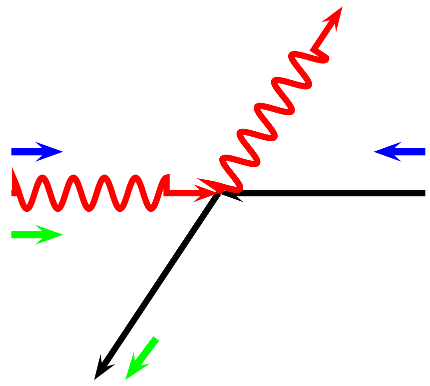
$-t, -u > 2.5$ GeV^2

data: JLab E99-114

form factors from $\xi = 0$ anlaysis

Helicity correlation A_{LL} and K_{LL}





Klein-Nishina result

$\hat{A}_{LL} = \hat{K}_{LL} = \frac{s^2-u^2}{s^2+u^2}$

$A_{LL} = K_{LL} \simeq \hat{A}_{LL}\,\frac{R_A}{R_V}$

JLab E99-114 ($s = 6.9\text{GeV}^2 \quad u = -1.04\text{GeV}^2$)

JLab E07-002 ($s = 7.8\text{GeV}^2 \quad t = -2.1\text{GeV}^2$)

application of handbag mechanism is at the limits

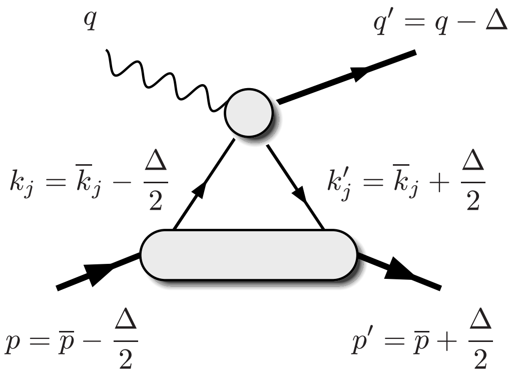
R_A badly known since F_A badly known, old data for $-t \lesssim 2\,\text{GeV}^2$ Kitagaki (83)

MINERvA? or K_{LL} from Jlab?

Photoproduction of pions

arguments for handbag factorization as for WACS

$$s,\ -t,\ -u \gg \Lambda^2$$



$$\mathcal{M}^{\pi}_{0+\mu+} = \frac{e_0}{2}\Big\{\mathcal{H}^{\pi}_{0+\mu+}\,[R^{\pi}_V + R^{\pi}_A] + \mathcal{H}^{\pi}_{0-\mu-}\,[R^{\pi}_V - R^{\pi}_A]\Big\}$$

$$\mathcal{M}^{\pi}_{0+\mu-} = \frac{e}{2}\Big\{\mathcal{H}^{\pi}_{0+\mu+} + \mathcal{H}^{\pi}_{0-\mu-}\Big\}R^{\pi}_T$$

For each flavor: $R^{\pi q}_i \simeq R^q_i$ known, universality

$$R^{\pi^0}_i = \frac{1}{\sqrt{2}}\left[e_u R^u_i - e_d R^d_i\right] \qquad R^{\pi^+}_i = R^{\pi^-}_i = R^u_i - R^d_i$$

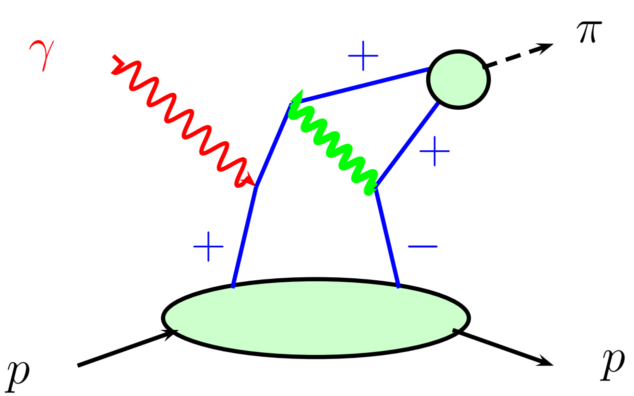
leading twist formation of meson (expected to be dominant for $s, -t, -u \gg \Lambda^2$)

$$\mathcal{H}^{\pi^0}_{0\lambda\mu\lambda} = 2\pi\alpha_s f_\pi \frac{C_F}{N_C}\langle 1/\tau\rangle_\pi \sqrt{-t/2}\,\frac{(1+\mu)s - (1-\mu)u}{su}$$

cross section too small by factor 50 - 100

Huang-K., hep-ph/0005318

Photoproduction: Transversity GPDs?



Huang-Jakob-K-Passek-Kumericki, hep-ph/0309071

$H_T, E_T, \widetilde{H}_T, \tilde{E}_T$

transversity GPDs go along with

twist-3 pion wave functions

fed subprocess ampl. $\mathcal{H}_{0-\mu+}$ and $\mathcal{H}_{0+\mu-}$

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: $\langle \pi^+(q') \mid \bar{d}(x)\gamma_5 u(-x) \mid 0\rangle = f_\pi \mu_\pi \int d\tau e^{iq'x\tau}\Phi_P(\tau)$

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. $\int d\tau \Phi_P(\tau) = 1$)

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

solution: $\Phi_P = 1, \quad \Phi_\sigma = \Phi_{AS} = 6\tau(1-\tau)$ Braun-Filyanov (90)

$$\Longrightarrow \qquad \mathcal{H}_{0-\mu+} = \mathcal{H}_{0+\mu-} = 0$$

Electroproduction of pions

Collins-Frankfurt-Strikman (96): factorization in generalized Bjorken regime of large Q^2, large W but fixed x_B (small $-t$)

leading-twist amplitudes for longitudinally polarized photons

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

$t' = t - t_0 \qquad t_0 = -4m^2\xi^2/(1-\xi^2)$ $\qquad$ ($\xi \neq 0$, phases)

amplitudes for transversally polarized photons are suppressed by $1/Q$

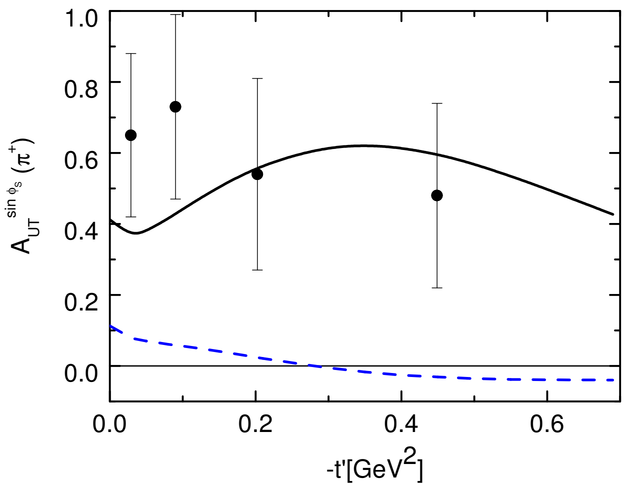
many leading-twist predictions for pion production

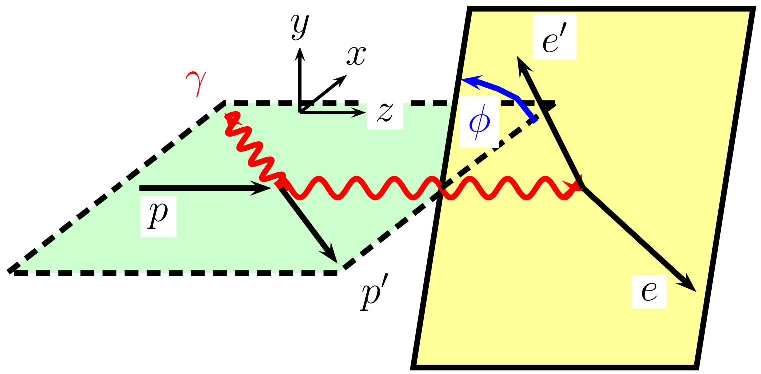
e.g. Mankiewicz et al (98), Frankfurt et al(99), Diehl al et(01), ...

all fail by order of magnitude in comparison with experiment

- strong corrections to long. amplitudes needed
- contributions from transverse photons are not suppressed

Evidence for contributions from transverse photons





HERMES(09): A_{UT} asymmetry at $Q^2 \simeq 2.5\,\mathrm{GeV}^2$,$W = 3.99\,\mathrm{GeV}$
measured with unpolarized beam and transversely polarized target

$\sin\phi_s$ modulation very large and does not vanish for $t' \to 0$

(ϕ_s orientation of target spin vector with respect to lepton plane)

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

n-f. ampl. $\mathcal{M}_{0-,++}$ required
(not forced to vanish for $t' \to 0$
by angular momentum conservation)

results from Goloskokov-K(09)

The twist-3 contribution

explain transverse ampl. by transversity GPDs and twist-3 pion DA

$q\bar{q}g$ Fock component of pion neglected

solution: $\Phi_P = 1, \quad \Phi_\sigma = \Phi_{AS} = 6\tau\bar{\tau} \qquad (\bar{\tau} = 1 - \tau)$ Braun-Filyanov (90)

$H^{\rm twist-3}_{0-,++}(t=0) \neq 0$, Φ_P dominant, Φ_σ contr. $\propto t/Q^2$ neglected

different because $1/(\tau t - \bar{\tau} Q^2)$

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

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

$$\mathcal{M}_{0--+} \simeq 0 \qquad\qquad \bar{E}_T = 2\widetilde{H}_T + E_T$$

suppressed by μ_π/Q as compared to $L \to L$ amplitudes

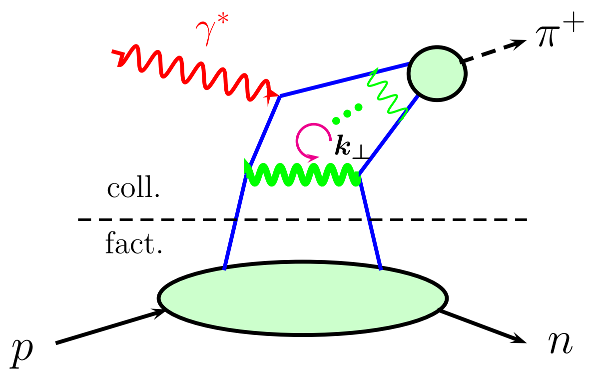
μ_π/Q of order 1 in current experiments

The subprocess amplitude

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



LO pQCD

$+$ quark trans. mom.

$+$ Sudakov supp.

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

Sudakov factor Sterman et al(93)

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

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

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

$$\mathcal{H}_{0\pm\mu+} = \int d\tau d^2 b_\perp \, \hat{\Psi}^\pi_{\pm+}(\tau, -\mathbf{b}_\perp)\, e^{-S} \hat{\mathcal{F}}_{0\pm\mu+}(\bar{x}, \xi, \tau, Q^2, \mathbf{b}_\perp)$$

$\hat{\Psi}^\pi_{++} \sim \exp[\tau\bar{\tau} b_\perp^2/4a_M^2]$ LC wave fct of pion

$\hat{\mathcal{F}}$ 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 intrinsic $k_\perp$ in wave fct: series $\sim (a_M Q)^{-n}$

Parametrizing the GPDs

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

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

weight fct $w_i(\rho,\eta) \sim [(1-|\rho|)^2 - \eta^2]^{n_i}$ ($n_{\rm sea}=2, n_{\rm val}=1$, generates ξ dep.)
zero-skewness GPD $K^i(\rho,\xi=0,t) = k^i(\rho)\exp\left[(b_{ki}+\alpha'_{ki}\ln(1/\rho))t\right]$

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

Regge-like t dep. (for small $-t$ reasonable appr.)

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

Details of the parametrization

$\widetilde{H}$: taken from analysis of nucleon form factors (sum rules) Diehl-K.(13)

H_T: PDFs $\delta^q(x) = N^q_{H_T}\sqrt{x}(1-x)\big[q(x) + \Delta q(x)\big]$ Anselmino et al(09)

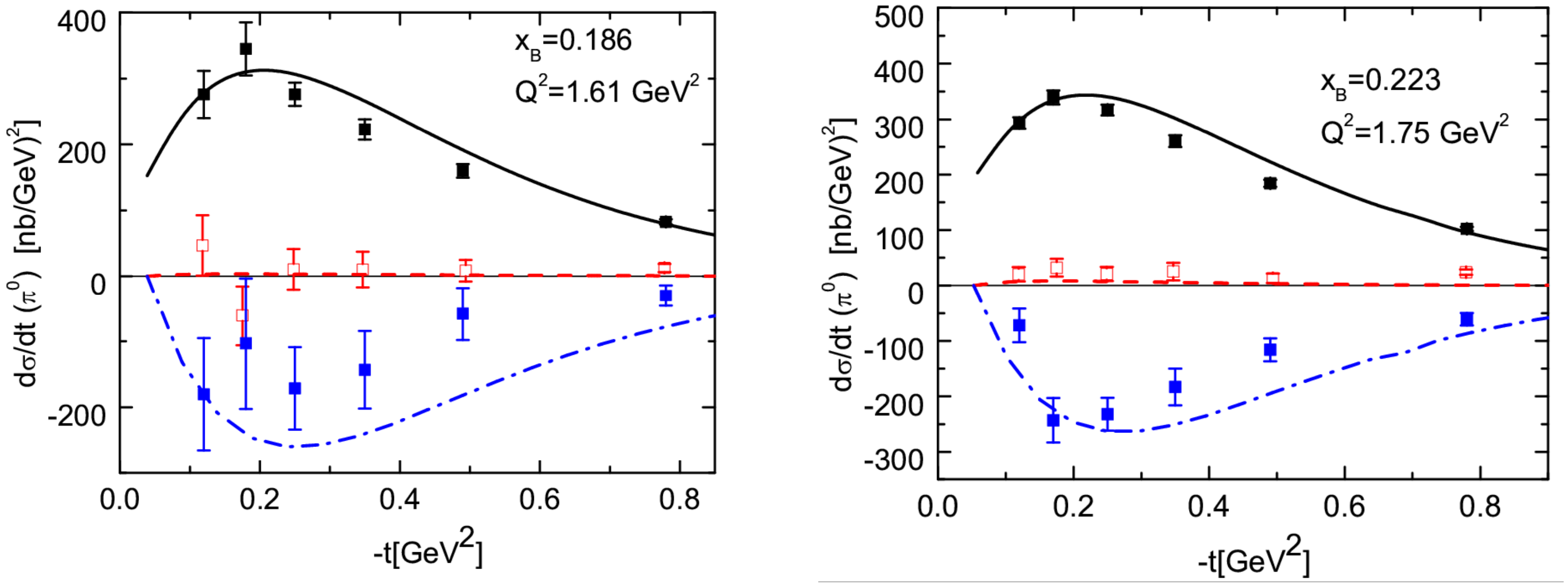
opposite sign for u and d quarks, normalized to lattice moments QCDSF-UKQCD(05)

$\bar{E}_T$: adjusted to lattice results QCDSF-UKQCD(06)

Large, same sign and almost same size for u and d quarks

Burkardt: related to Boer-Mulders fct $\langle\cos(2\phi)\rangle$ in SIDIS $-$ same pattern

Results for π^0

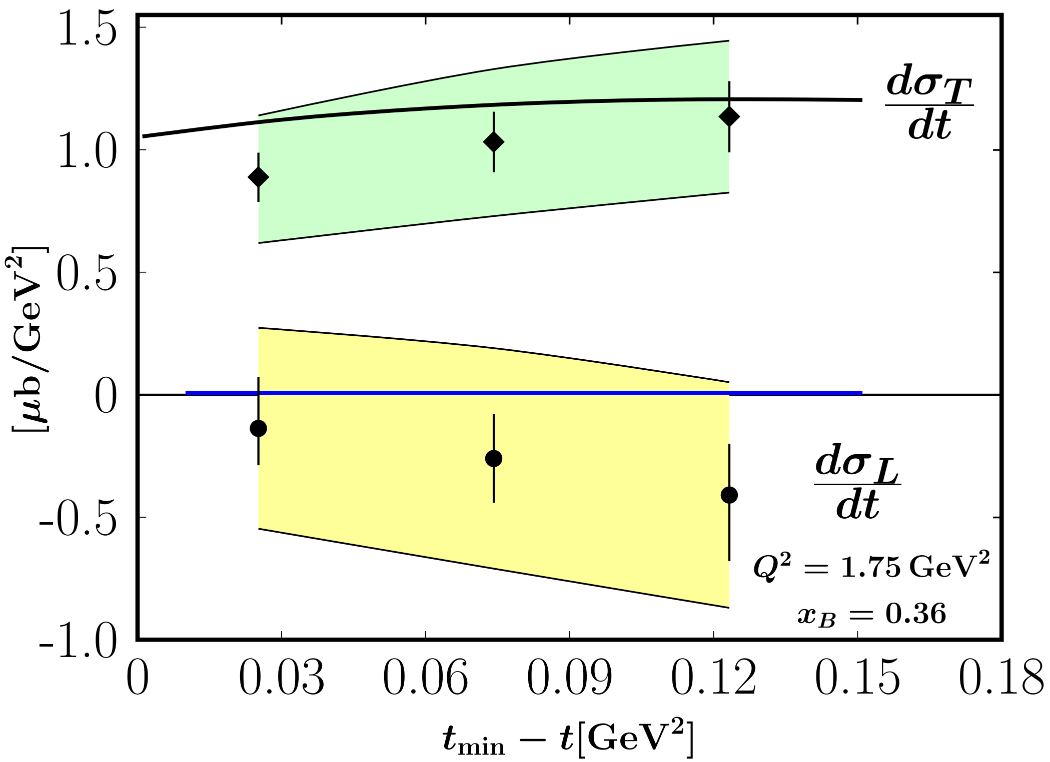


data: CLAS (12) $d\sigma$, $d\sigma_{LT}$, $d\sigma_{TT}$

curves: Goloskokov-K(11)

similar results from COMPASS (preliminary) $Q^2 \simeq 2\,\mathrm{GeV}^2$, $x_B \simeq 0.05$

Hall A results on π^0 production



Hall A (16)

π^0 production off protons

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

to be contrasted with

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

Pion photoproduction again

In view of situation in electroproduction

K.-Passek-Kumericki in progress, preliminary results

include full twist-3 contribution $(q\bar{q} + q\bar{q}g)$

both are needed in order to achieve gauge invariance

they are related by eq. of motion:

with light-cone gauge:

$$f_\pi \mu_\pi \Big(\bar{\tau}\Phi_p - \frac{1}{6}\bar{\tau}\Phi'_\sigma - \frac{1}{3}\Phi_\sigma\Big) = 2 f_{3\pi} \int_0^{\bar{\tau}} \frac{d\tau_g}{\tau_g}\, \Phi_{3\pi}(\tau, \bar{\tau} - \tau_g, \tau_g)$$

$$f_\pi \mu_\pi \Big(\tau\Phi_p + \frac{1}{6}\tau\Phi'_\sigma - \frac{1}{3}\Phi_\sigma\Big) = 2 f_{3\pi} \int_0^{\tau} \frac{d\tau_g}{\tau_g}\, \Phi_{3\pi}(\bar{\tau}, \tau - \tau_g, \tau_g)$$

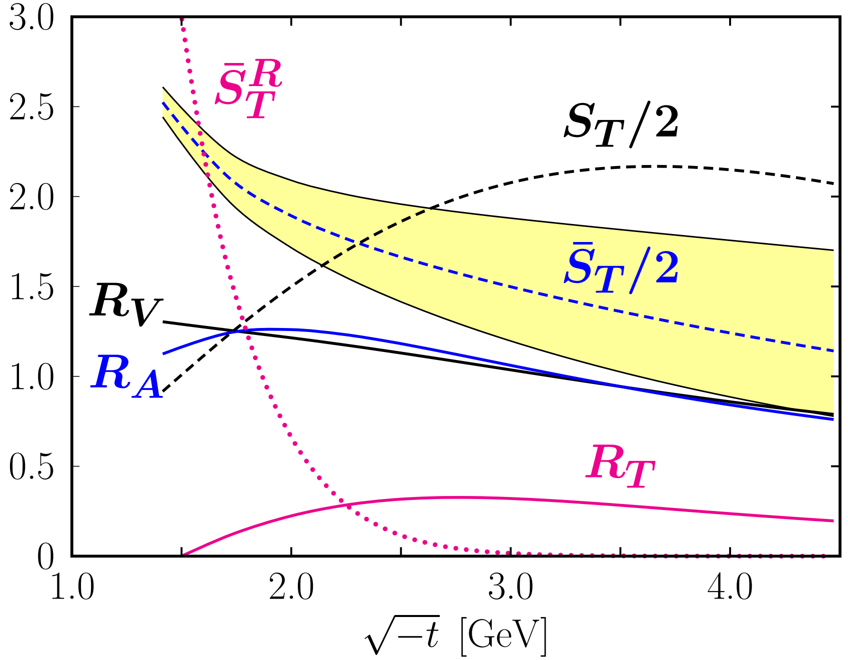
Handbag amplitudes

$$\begin{aligned}
\mathcal{M}^{\pi}_{0+,\mu+} &= \frac{e_0}{2}\sum_{\lambda}\Big[\mathcal{H}^{\pi}_{0\lambda,+\lambda}\,R^{\pi}_{V}(t) + 2\lambda\mathcal{H}^{\pi}_{0\lambda,+\lambda}\,R^{\pi}_{A}(t) \\
&\quad -2\lambda\frac{\sqrt{-t}}{2m}\mathcal{H}^{\pi}_{0-\lambda,+\lambda}\,\bar{S}^{\pi}_{T}(t)\Big]\,, \\
\mathcal{M}^{\pi}_{0-,\mu+} &= \frac{e_0}{2}\sum_{\lambda}\Big[\frac{\sqrt{-t}}{2m}\mathcal{H}^{\pi}_{0\lambda,+\lambda}\,R^{\pi}_{T}(t) \\
&\quad -2\lambda\frac{t}{2m^2}\mathcal{H}^{\pi}_{0-\lambda,+\lambda}\,S^{\pi}_{S}(t)\Big] + e_0\mathcal{H}^{\pi}_{0-,\mu+}\,S^{\pi}_{T}(t)\,,
\end{aligned}$$

Form factors

in addition to R_V, R_A, R_T: transversity FFs (skewness=0)

$$S_T^a(t) = \int_{-1}^{1} \frac{dx}{x} \operatorname{sign}(x) H_T^a(x,t)\,, \quad \bar{S}_T^a(t) \to \bar{E}_T^a(x,t)\,, \quad S_S^a(t) \to \widetilde{H}_T^a(x,t)\,,$$

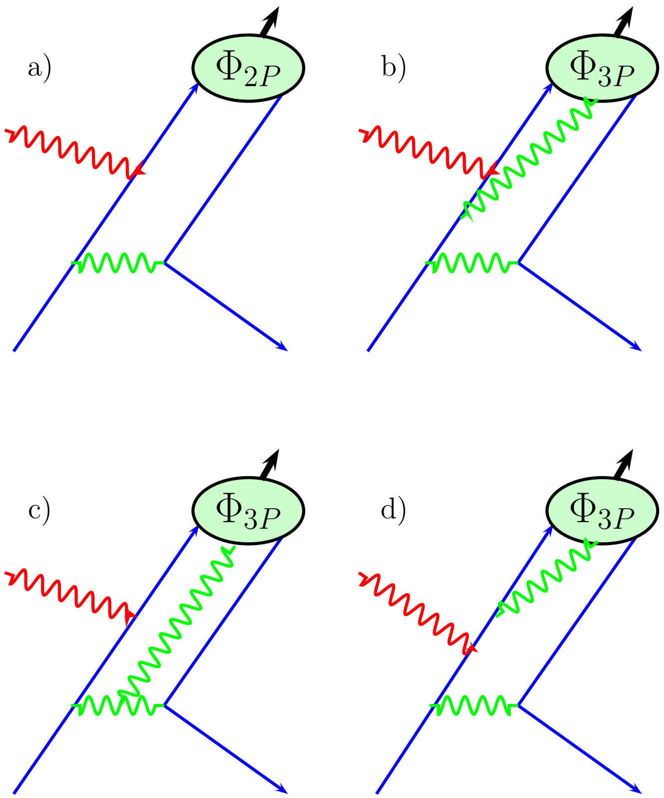


only valence quarks contribute
(charge conjugation symmetry)
$F_i^{\pi^0} = (e_u F_i^a - e_d F_i^d)/\sqrt{2}$

from electroproduction:
H_T, $\bar{E}_T$ known at small $-t$
$\widetilde{H}_T$ unknown, suppressed by $-t/(4m^2)$

extrapolation to large $-t$:
by term $Ax(1-x)^2$ in profile fct.
with $A \simeq 0.5\,\mathrm{GeV}^{-2}$ and $S_S^{\pi^0} \simeq \bar{S}_T^{\pi^0}/2$

Subprocess amplitudes



d) soft, part of DA

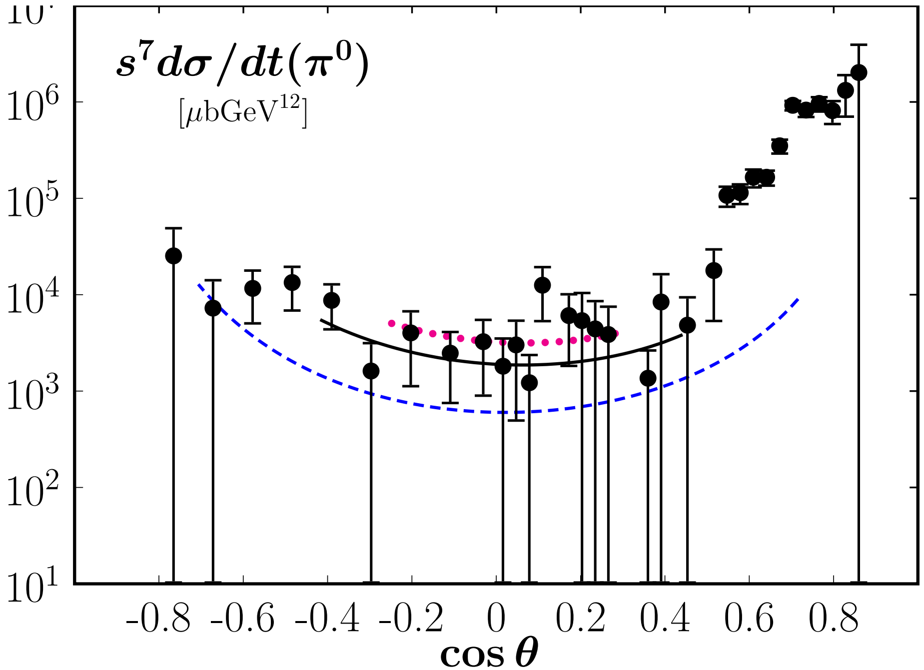
$$
\begin{aligned}
\mathcal{H}^{\pi^0,twist-3}_{0-\lambda,\mu\lambda} &= 4\pi\alpha_s(\mu_R)\,\frac{f_{3\pi}}{N_C}\,\frac{2\lambda-\mu}{s^2u^2}\sqrt{-\frac{us}{2}} \\
&\times \int_0^1 d\tau \int_0^{\bar\tau} \frac{d\tau_g}{\tau_g}\,\Phi_{3\pi}(\tau,\bar\tau-\tau_g,\tau_g) \\
&\times \Bigg[C_F\left(\frac{1}{\bar\tau^2}-\frac{1}{\bar\tau(\bar\tau-\tau_g)}\right)\left(s^2+u^2\right) \\
&+ \left(C_F-\frac{1}{2}C_A\right)\left(\frac{1}{\tau}+\frac{1}{\bar\tau-\tau_g}\right)\frac{t^2}{\tau_g}\Bigg]
\end{aligned}
$$

$\mathcal{H}^{\pi^0,twist-3} = 0$ if $\Phi_{3\pi} = 0$

$$
\begin{aligned}
\Phi_{3\pi} &= 360\tau_a\tau_b\tau_g^2\Big[1+\omega_{10}(7\tau_g-3)/2 \\
&+ \omega_{20}(2-4\tau_a\tau_b-8\tau_g+8\tau_g^2) \\
&+ \omega_{11}(3\tau_a\tau_b-2\tau_g+3\tau_g^2)\Big]
\end{aligned}
$$

Braun-Filyanov (90), Chernyak-Zhitnitsky(84)

Results on π^0 cross section



data: CLAS (17) at $s = 11.06\,\mathrm{GeV}^2$

$s = 11.06(9, 20)\mathrm{GeV}^2$

solid(dotted, dashed)

$-t, -u \geq 2.5\,\mathrm{GeV}^2$

dominance of twist-3

large parametric uncertainty (about 70%)

parameters of $\Phi_{3\pi}$ at $\mu_0 = 2\,\mathrm{GeV}$:

$f_{3\pi} = 0.004\,\mathrm{GeV}^2 \quad \omega_{10} = -2.55$

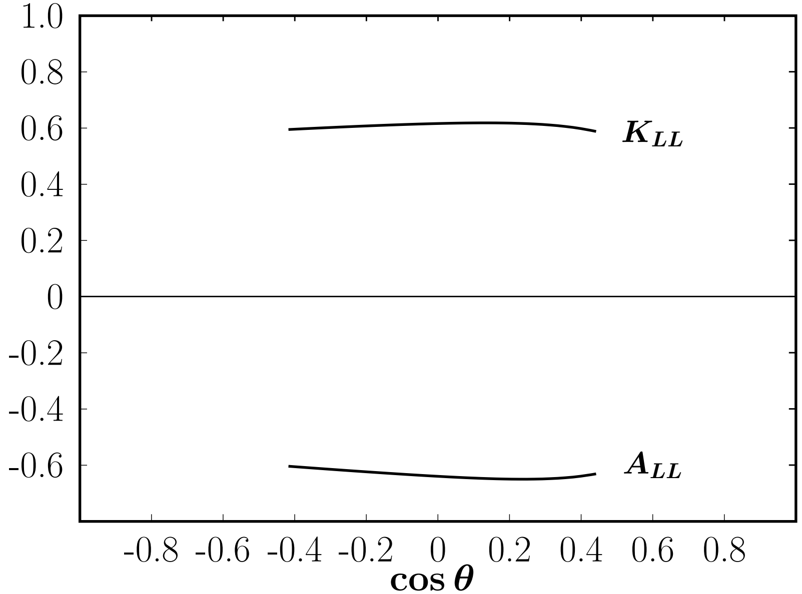
from Ball (98)

fit to data: $\omega_{20} = 8.0 \quad \omega_{11} = 0$

close to values quoted in

Braun-Filyanov (90),Chernyak-Zhit.(84)

Helicity correlation



$A_{LL}^{twist-2} = K_{LL}^{twist-2}$ as for WACS

$A_{LL}^{twist-3} = -K_{LL}^{twist-3}$

characteristic signature for dominance of twist-3

like $\sigma_T \gg \sigma_L$ in electroproduction

$$A_{LL}^{twist-3} = -K_{LL}^{twist-3} = \frac{8m^2}{t} \frac{S_T^{\pi^0}(S_T^{\pi^0} - t/(2m^2)S_S^{\pi^0})}{\left[\bar{S}_T^{\pi^0 2} - \frac{t}{m^2} S_S^{\pi^0 2} + 4S_S^{\pi^0} S_T^{\pi^0} - 8\frac{m^2}{t} S_T^{\pi^0 2}\right]}$$

Summary

handbag approach applied to deep virtual and wide-angle exclusive processes

- WACS: gold-plated wide-angle process
  (almost) parameter-free predictions, in fair agreement with experiment

- extension to WA photoproduction of pions fails badly with twist-2 DA
  inclusion of transversity GPDs/twist-3 DAs ($q\bar{q}g$ neglected) does not help

- deep virtual electroproduction of pions:
  experimental evidence for strong contributions from transverse photons
  explained by transversity GPDs with twist-3 DAs (under neglect of $q\bar{q}g$)
  signature for twist-3: $\sigma_T \gg \sigma_L$ (experimentally confirmed)

- look again to WA photoproduction with full twist-3 DAs($q\bar{q}$ and $q\bar{q}g$)
  strong enhancement of cross section, fair agreement with experiment
  signature for twist-3: $A_{LL} = -K_{LL}$