Wide-angle photoproduction of pions

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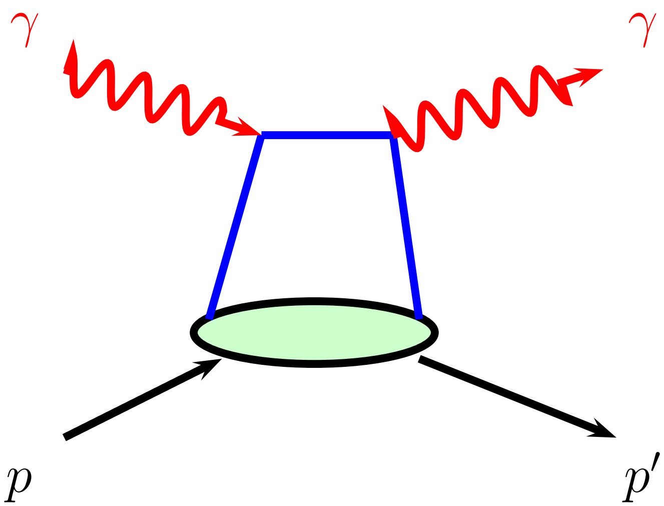
Outline:

- **The Handbag factorization for wide-angle processes**
- **Wide-angle Compton scattering**
- **Wide-angle photoproduction of pions**
- **The twist-3 contribution to photoproduction**
- **Results**
- **The 2-particle twist-3 DAs**
- **Summary**

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

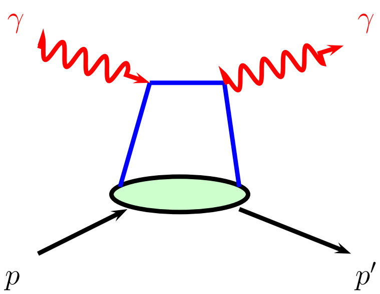
large Q^2 and W but fixed x_B and $-t/Q^2 \ll 1$

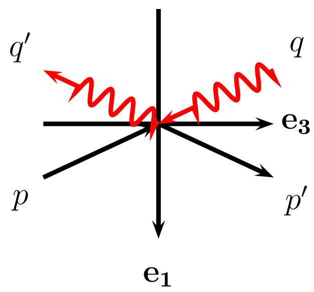
WIDE-ANGLE e.g. RCS or photoproduction of mesons

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

The handbag contribution to WACS (and WAPP)





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

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

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 — propagators poles avoided

  $\hat{s} = (k_j + q)^2 \simeq (p + q)^2 = s$ — active partons approximately on-shell

  $\hat{u} = (k_j' - q)^2 \simeq (p' - q)^2 = u$ — collinear with parent hadrons

  and $x_j, x_j' \simeq 1$

- 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

(light-cone helicities)

$$\mathcal{M}_{\mu'+,\mu+} = 2\pi\alpha_{\rm elm}\Big\{\mathcal{H}^{\gamma}_{\mu'+,\mu+}\big[R^{\gamma}_V + R^{\gamma}_A\big] + \mathcal{H}^{\gamma}_{\mu'-,\mu-}\big[R^{\gamma}_V - R^{\gamma}_A\big]\Big\}$$

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

form factors: $R^{\gamma}_i(t) = \sum_q e_q^2 R^q_i(t)$

$$R^q_V = \int_0^1 \frac{dx}{x} H^{q_v}(x,\xi=0,t) \qquad E^{q_v} \to R^q_T \qquad \widetilde{H}^{q_v} \to R^q_A$$

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

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

$\mathcal{H}_{-+-+} = 2\sqrt{-u/s} \qquad$ (+ NLO)

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

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

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

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

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

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

DFJK hep-ph/0408173; update: Diehl-K, 1302.4604; (see also Guidal et al, hep-ph/0410252)

fit to all data: $G_M^i, G_E^i/G_M^i$ $(i = p, n)$ and

use of ABM11, DSSV09 parton densities strong $x - t$ correlation

(see also de Teramond et al (1801.09154))

Estimate of proton radius

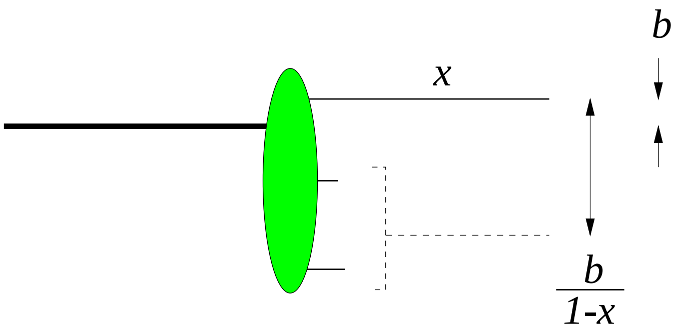
Approx: distance between active parton and cluster of spectators

work in hadron's center of momentum frame

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

Fourier transform of H

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



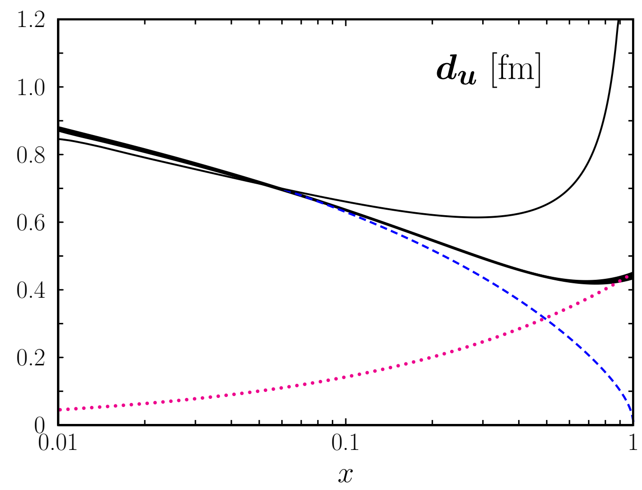
$$d_q(x) = \frac{\sqrt{\langle b^2 \rangle_x^q}}{1-x} = \frac{2\sqrt{f_q(x)}}{1-x} \to 2\sqrt{A_q}$$

for $x \to 1$

Regge-type term, A term, full profile fct

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

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

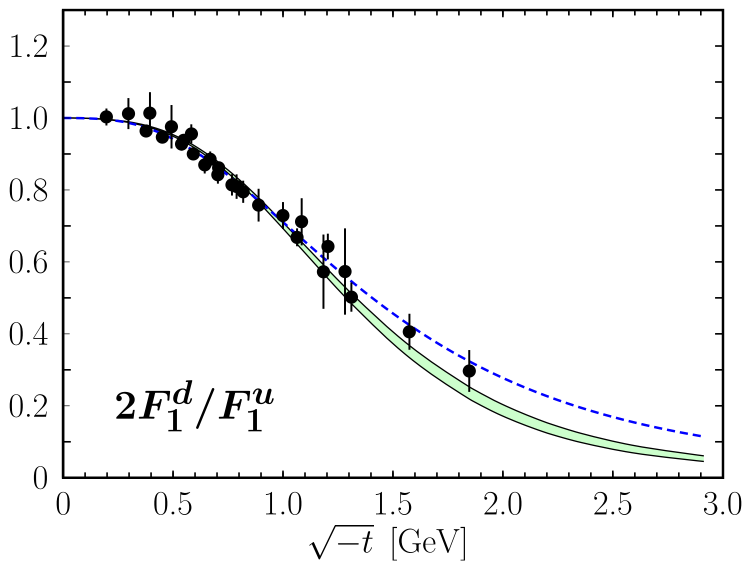


Large$-t$ behavior of flavor form factors

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

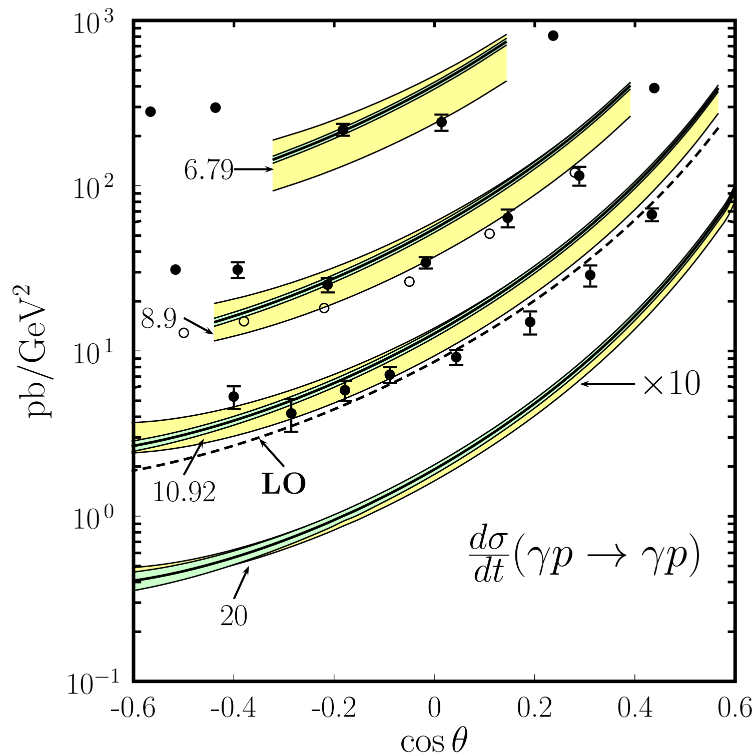


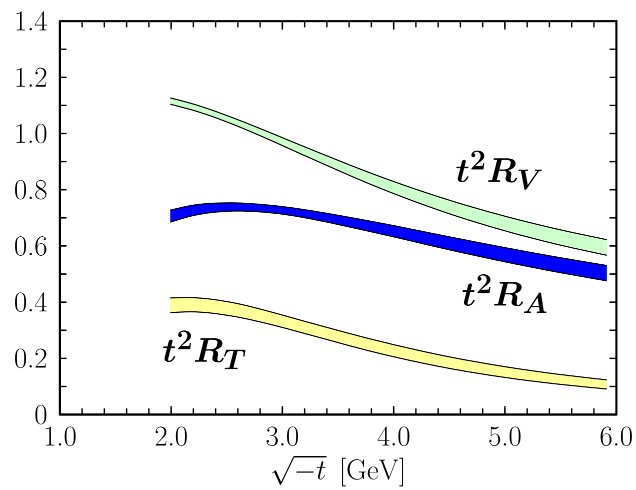
ABM PDFs: $\beta_u \simeq 3.4$, $\beta_d \simeq 5$,

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

power laws are a necessary but not sufficient signal of perturbative physics

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

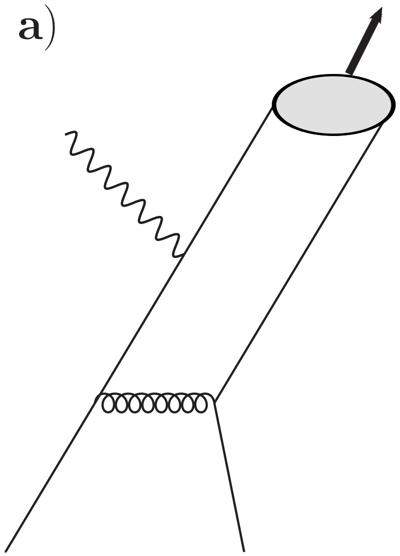
$-t, -u > 2.5$ GeV^2

data: JLab E99-114

form factors from $\xi = 0$ anlaysis

Photoproduction of pions

arguments for handbag factorization as for WACS $\qquad s, -t, -u \ll \Lambda^2$



leading-twist contribution

$$\mathcal{M}^{\pi}_{0+\mu+} = \frac{e_0}{2}\sum_{\lambda}\mathcal{H}^{\pi}_{0\lambda\mu\lambda}\left[R^{\pi}_{V} + 2\lambda R^{\pi}_{A}\right]$$

$$\mathcal{M}^{\pi}_{0-\mu+} = \frac{e_0}{2}\sum_{\lambda}\frac{\sqrt{-t'}}{2m}\mathcal{H}^{\pi}_{0+\mu+}R^{\pi}_{T}$$

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

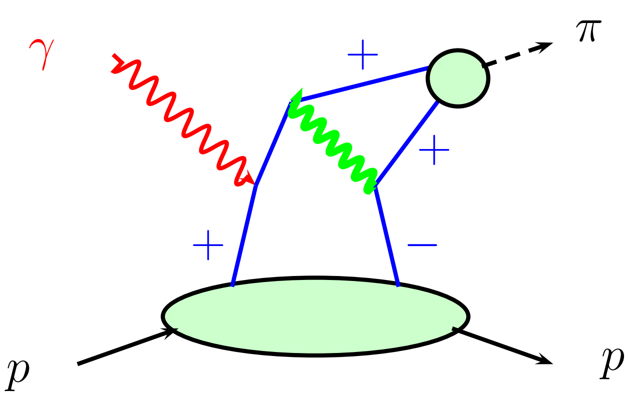
same flavor form factors as for WACS $\qquad$ known, universality

twist-2 subprocess amplitude $\qquad (\langle 1/\tau\rangle_\pi = \int d\tau/\tau\Phi_\pi(\tau))$

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

cross section too small by factor 50 - 100 $\qquad$ 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: $\langle \pi^+(q') \mid \bar{d}(x)\gamma_5 u(-x) \mid 0 \rangle = i f_\pi \mu_\pi \int d\tau \mathrm{e}^{iq'x\tau} \Phi_P(\tau)$

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 $2\,\mathrm{GeV}$ $\quad (\int d\tau \Phi_P(\tau) = 1)$

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)

(WW approx.)

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

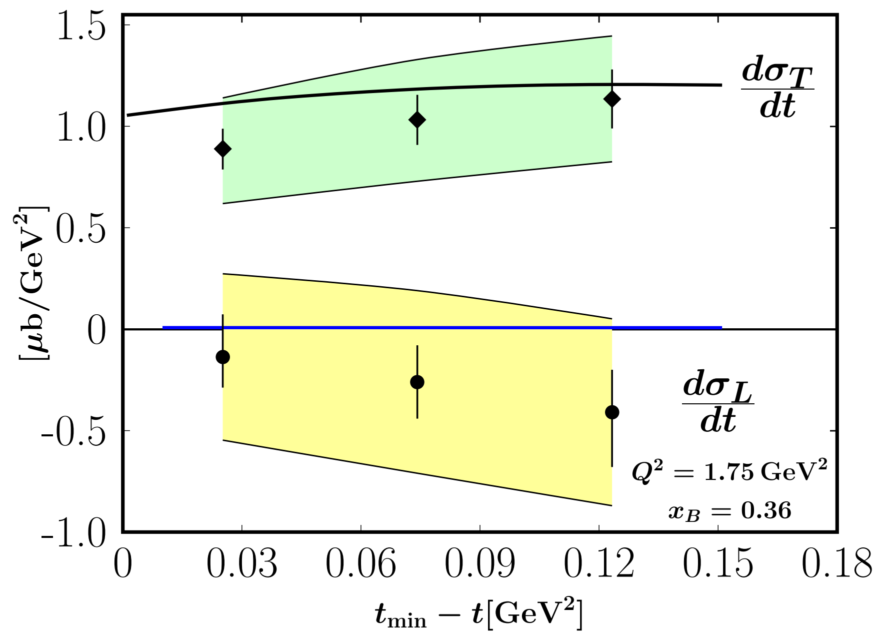
to be contrasted with electroproduction of pions:

– the subprocess amplitudes in WW appr. are non-zero

– contribute to transversely polarized photons

– dominate the cross section for π^0 production

– in agreement with experiment



Defurne et al (1608.01003)

π^0 production off protons

curves: Goloskokov-K (1106.4897)

$Q^2 \to \infty : d\sigma_L \gg d\sigma_T$

Pion photoproduction again

K.-Passek-Kumericki, (1802.06597)

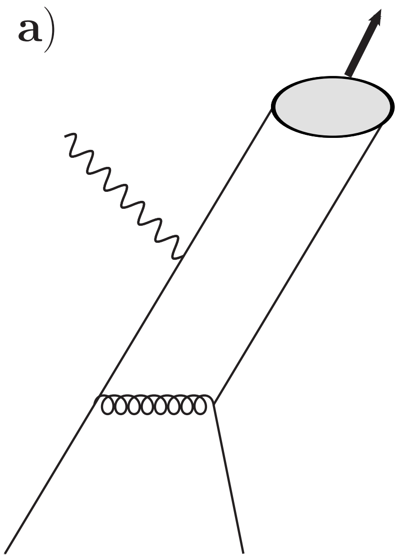
In view of situation in electroproduction:
include full twist-3 contribution ($q\bar{q}$ + $q\bar{q}g$ Fock components of the pion)
both are needed in order to achieve gauge invariance
they are related by eq. of motion (with light-cone gauge $A^+ = 0$):

$$\bar{\tau}\Phi_p - \frac{1}{6}\bar{\tau}\Phi'_\sigma - \frac{1}{3}\Phi_\sigma = 2\frac{f_{3\pi}}{f_\pi\mu_\pi}\int_0^\tau \frac{d\tau_g}{\tau_g}\,\Phi_{3\pi}(\tau-\tau_g,\bar{\tau},\tau_g) = \Phi_1^{EOM}(\tau)$$

$$\tau\Phi_p + \frac{1}{6}\tau\Phi'_\sigma - \frac{1}{3}\Phi_\sigma = 2\frac{f_{3\pi}}{f_\pi\mu_\pi}\int_0^{\bar{\tau}} \frac{d\tau_g}{\tau_g}\,\Phi_{3\pi}(\tau,\bar{\tau}-\tau_g,\tau_g) = \Phi_2^{EOM}(\tau)$$

for pions: $\Phi_1^{EOM}(\tau) = \Phi_2^{EOM}(\bar{\tau})$
$f_{3\pi} = f_{3\pi}(\mu_R^2) \qquad \mu_\pi = \mu_\pi(\mu_R^2)$

The 2-particle twist-3 contribution



amplitude for $\gamma q \to \pi^0 q$

$$\mathcal{H}^{twist-3,2-particle}_{0-\lambda,\,\mu\lambda} = 4\pi\alpha_s\, f_\pi\, \mu_\pi \frac{C_F}{N_C} \times \frac{\sqrt{-us}}{\sqrt{2}s^2u^2}\int_0^1 d\tau\, \phi_2^{\rm EOM}(\tau)\left[\mu\,\frac{ts}{\tau(1-\tau)} + \left(\frac{2\lambda-\mu}{2(1-\tau)^2}+\frac{2\lambda+\mu}{2\tau(1-\tau)}\right)(s^2+u^2)\right]$$

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

(Φ_P and Φ_σ always appear in combinations Φ_i^{EOM})

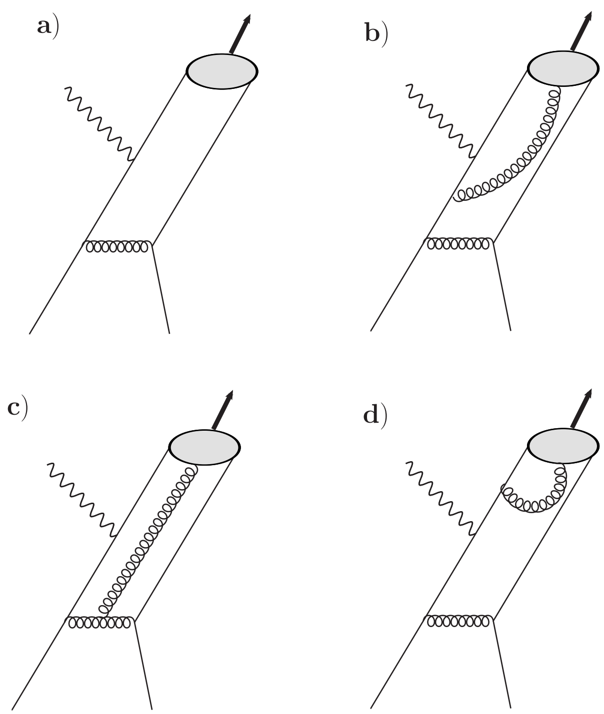
gauge invariant in QCD but not in QED

violates $s-u$ crossing symmetry

(Chew-Goldberger-Low-Nambu (57)

need also 3-particle twist-3 contribution

The 3-particle twist-3 contribution



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

d) soft, part of DA

gauge invariant in QCD but not in QED

$s-u$ crossing symmetry violated

twist-3 3-particle projector ($q\bar{q}g\to\pi$)

$$\mathcal{P}^{\beta,c}_{3,fg} = \frac{i}{g}\,\frac{f_{3\pi}}{2\sqrt{2N_C}}\,\frac{(t^c)_{fg}}{C_F\sqrt{N_C}}\,\frac{\gamma_5}{\sqrt{2}}\,\sigma_{\mu\nu}q'^{\mu}g_\perp^{\nu\beta}\,\frac{\Phi_{3\pi}(\tau_a,\tau_b,\tau_g)}{\tau_g} \qquad g_\perp^{\nu\beta} = g^{\nu\beta} - \frac{k'^{\nu}_j q'^{\beta} + q'^{\nu}k'^{\beta}_j}{k'_j\cdot q'}$$

π^0 subprocess amplitudes

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

$\mathcal{H}^{twist-3} = 0$ if $\Phi_{3\pi} = 0$ (WW appr.)

sum is gauge invariant (QCD and QED) and $s \leftrightarrow u$ crossing symmetric

generalization to other pseudoscalar mesons straightforward

The photoproduction amplitudes

$$\mathcal{M}^{\pi}_{0+\mu+} \;=\; \frac{e_0}{2}\sum_{\lambda}\Big\{\mathcal{H}^{\pi}_{0\lambda\mu\lambda}\,[R^{\pi}_V + 2\lambda R^{\pi}_A] - 2\lambda\frac{\sqrt{-t}}{2m}\mathcal{H}^{\pi}_{0-\lambda\mu\lambda}\,\bar{S}^{\pi}_T\Big\}$$

$$\mathcal{M}^{\pi}_{0-\mu+} \;=\; \frac{e_0}{2}\sum_{\lambda}\Big\{\frac{\sqrt{-t}}{2m}\mathcal{H}^{\pi}_{0\lambda\mu\lambda}R^{\pi}_T - 2\lambda\frac{t}{2m^2}\mathcal{H}^{\pi}_{0-\lambda\mu\lambda}S^{\pi}_S\Big\} + e_0\mathcal{H}^{\pi}_{0-,\mu+}S^{\pi}_T$$

form factors S_i are $1/x$ moments of transversity GPDs

light-cone helicities, transform to ordinary helicities Diehl(01)

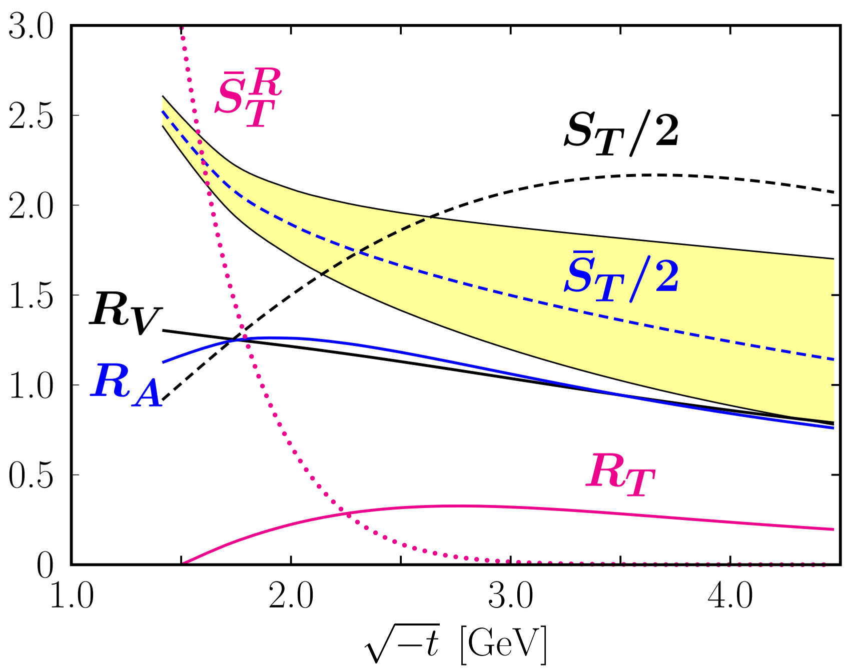
$$\Phi_{0\nu',\mu\nu} = \mathcal{M}_{0\nu',\mu\nu} + \frac{1}{2}\kappa\Big[(-1)^{1/2-\nu'}\mathcal{M}_{0-\nu',\mu\nu} + (-1)^{1/2+\nu}\mathcal{M}_{0\nu',\mu-\nu}\Big] + \mathcal{O}(m^2/s)$$

$\kappa = \frac{2m}{\sqrt{s}}\,\frac{\sqrt{-t}}{\sqrt{s}+\sqrt{-u}}$ relevant for spin effects

Form factors

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

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



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

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 $A \simeq 0.5\,\text{GeV}^{-2}$ and $S_S^{\pi^0} \simeq \bar{S}_T^{\pi^0}/2$

Large $-t$ behavior of form factors

the power law behavior of the elm. FF also holds for the $1/x$ moments

$$F_i \sim 1/(-t)^{d_i}$$

d_i determined by the powers β_i in $K_i(x, t=0) \to (1-x)^{\beta_i}$ for $x \to 1$

$$d_i = (1 + \beta_i)/2$$

	R_V	R_A	R_T	S_T	$\bar{S}_T$
u	2.25	2.22	2.83	2.5	2.5
d	3.0	2.61	3.12	3.5	3.0

The 3-particle twist-3 pion DA

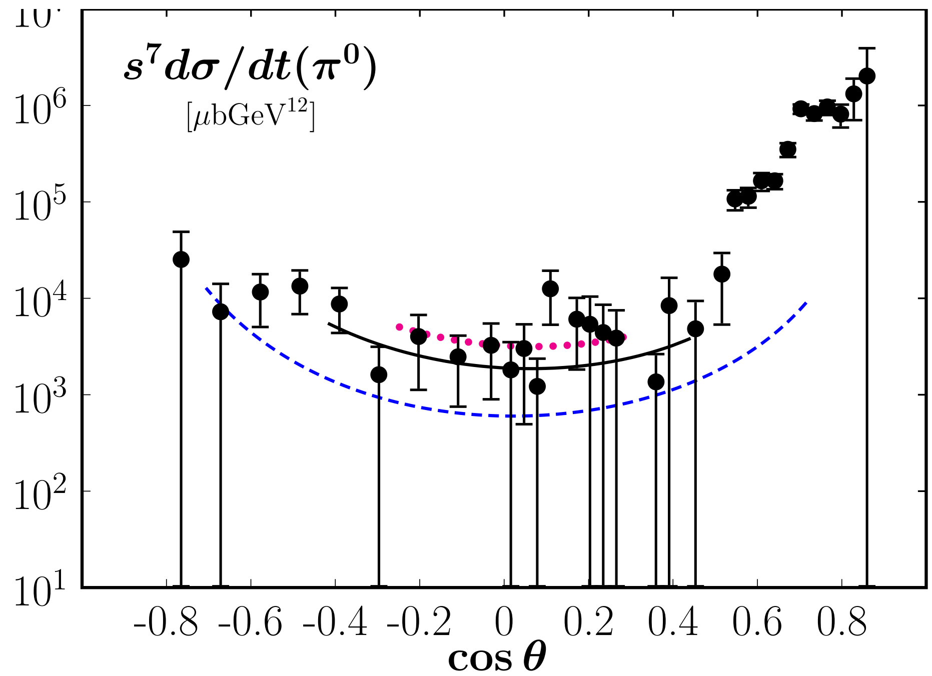
$$\Phi_{3\pi} = 360\tau_a\tau_b\tau_g^2\Big[1+\omega_{10}(\mu_R^2)(7\tau_g-3)/2 + \omega_{20}(\mu_R^2)(2-4\tau_a\tau_b-8\tau_g+8\tau_g^2) + \omega_{11}(\mu_R^2)(3\tau_a\tau_b-2\tau_g+3\tau_g^2)+\ldots\Big]$$

(expansion in a series of Jacobi polynomials; coeff. evolve with scale)

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

choice: $\mu_R^2 = \mu_F^2 = tu/s$

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)

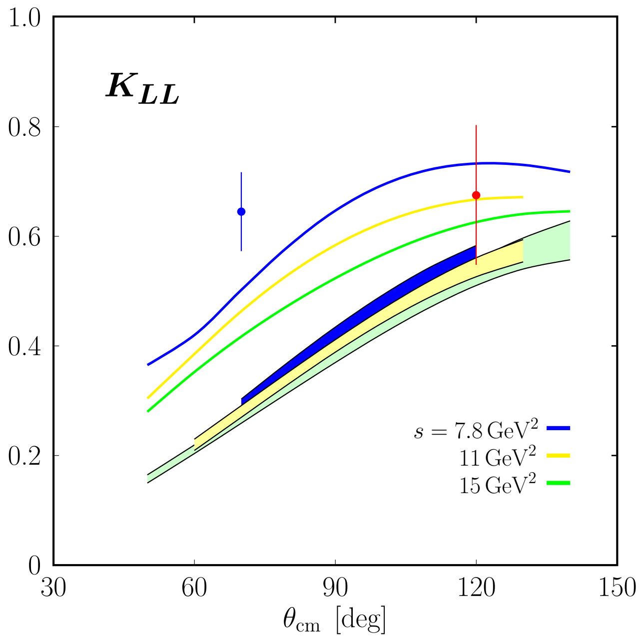
fit to data: $\omega_{20} = 8.0$ $\quad \omega_{11} = 0$

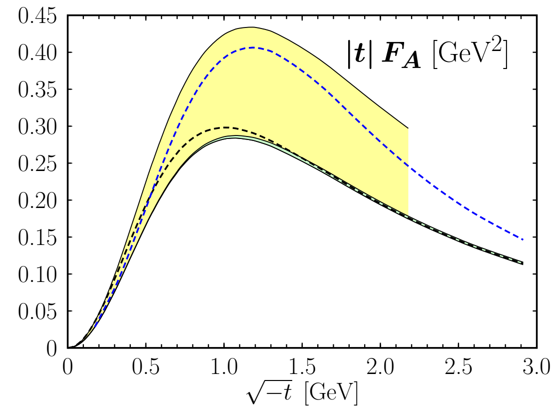
close to values quoted in

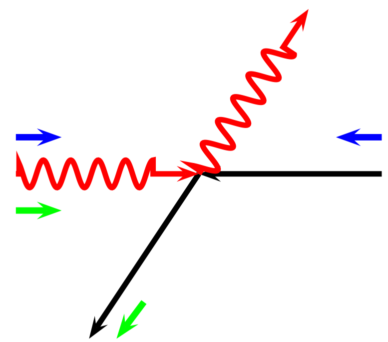
Braun-Filyanov (90),Chernyak-Zhit.(84)

energy dependence: $s^{-7\frac{\mu_\pi^2}{s}}$ $\times$ logs from evolution $\times$ t dependence of form factors

Helicity correlation A_{LL} and K_{LL} in WACS







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 ($s = 6.9$GeV^2 $\quad u = -1.04$GeV^2)

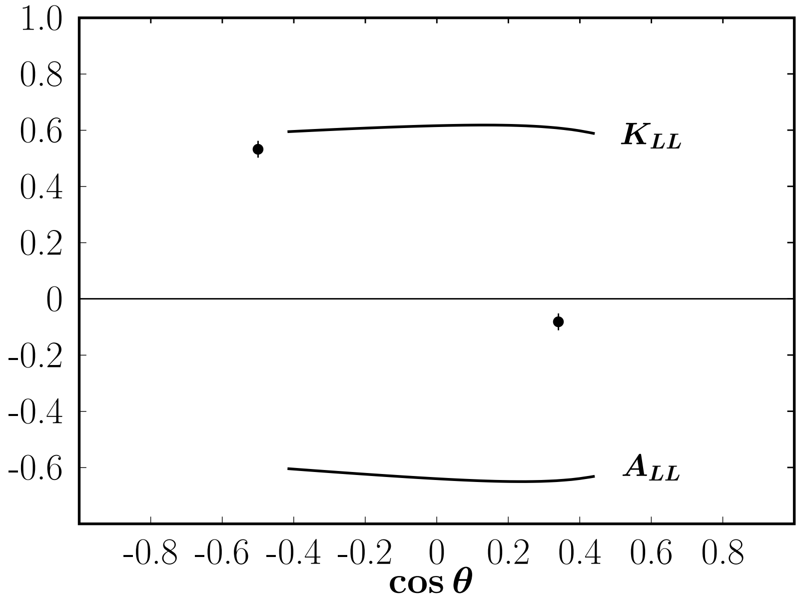
JLab E07-002 ($s = 7.8$GeV^2 $\quad t = -2.1$GeV^2)

application of handbag mechanism is at the limits

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

MINERvA? or K_{LL} from Jlab?

Helicity correlation in photoproduction



$s = 11.06\,\mathrm{GeV}^2$

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

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

characteristic signature for dominance of twist-3

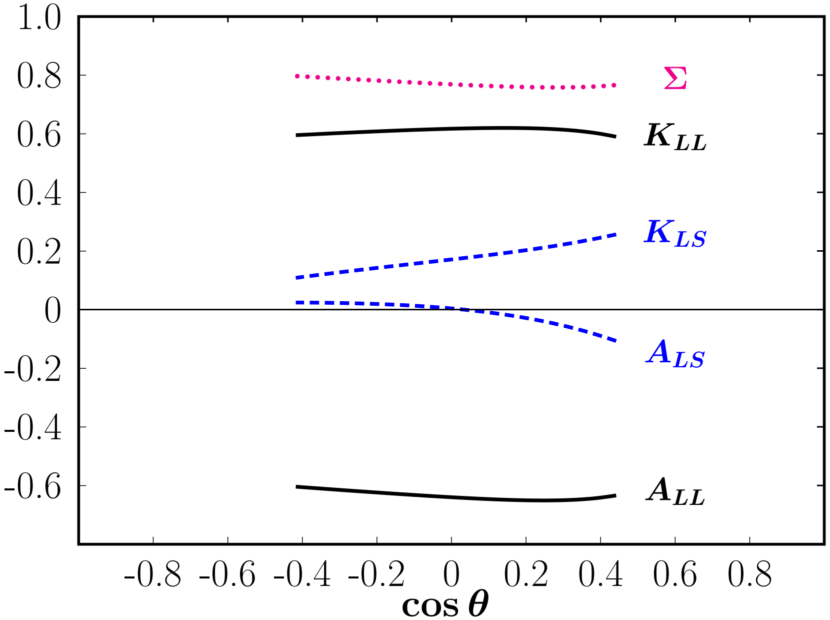
like $\sigma_T \gg \sigma_L$ in pion electroprod.

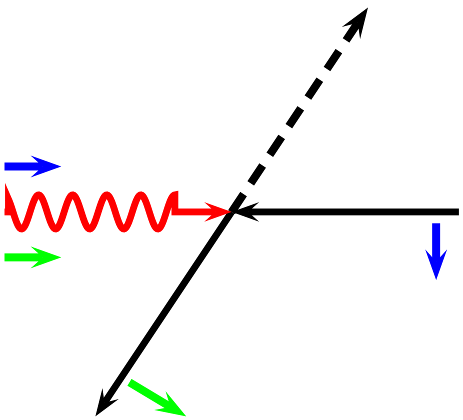
$$A_{LL}^{twist-3} = -K_{LL}^{twist-3} = -4\frac{S_T^{\pi^0}}{F^{\pi^0}}\Big[S_T^{\pi^0} - \frac{t}{2m^2}S_S^{\pi^0} + \kappa\frac{\sqrt{-t}}{2m}\bar{S}_T^{\pi^0}\Big]$$

$$F^{\pi^0} = \frac{-t}{2m^2}\Big[(\bar{S}_T^{\pi^0})^2 - \frac{t}{m^2}(S_S^{\pi^0})^2 + 4S_S^{\pi^0}S_T^{\pi^0} - 8\frac{m^2}{t}(S_T^{\pi^0})^2\Big]$$

K_{LL} data: Fanelli(15)(Hall A(05)) $s = 7.8(6.9)\,\mathrm{GeV}^2$, $t = -2.1(u = -1.04)\,\mathrm{GeV}^2$

Other observables





$$A_{LS}^{twist-3} \quad = \quad -K_{LS}^{twist-3}$$

$$= -2\frac{S_T^{\pi^0}}{F^{\pi^0}}\left[\frac{\sqrt{-t}}{m}\bar{S}_T^{\pi^0} - 2\kappa\Big(S_T^{\pi^0} - \frac{t}{4m^2}S_S^{\pi^0}\Big)\right]$$

$$A_{LS}^{twist-2} = K_{LS}^{twist-2}$$

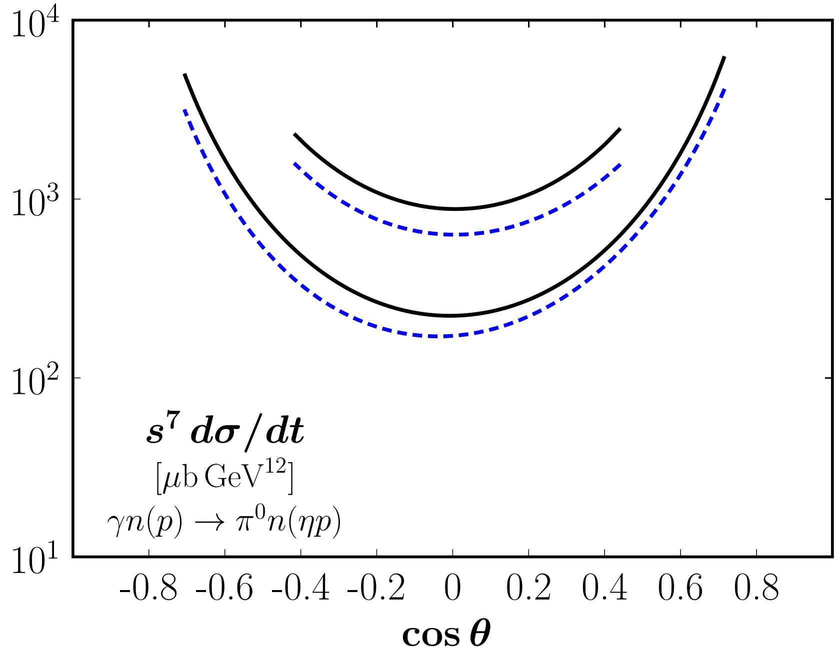
$$\Sigma^{twist-3} = 1 - 4\frac{(S_T^{\pi^0})^2}{F^{\pi^0}}$$

asymmetry for linearly polarized photons

data: Fanelli(15)(Hall A(05)) $s = 7.8(6.9)\,\mathrm{GeV}^2$, $t = -2.1(u = -1.04)\,\mathrm{GeV}^2$

$K_{LS} = -0.296 \pm 0.007(0.480 \pm 0.007)$

π^0 production off neutrons and η production



$$F_{in}^{\pi^0} = \frac{1}{\sqrt{2}}\left[e_u F_i^d - e_d F_i^u\right] \qquad F_i^{(8)} \simeq F_i^{(1)} \simeq \frac{1}{\sqrt{6}}\left[e_u F_i^u + e_d F_i^d\right]$$

$$\mathcal{M}_i^\eta = \cos\theta_8 \mathcal{M}_i^{(8)} - \sin\theta_1 \mathcal{M}_i^{(1)}$$

solid: neutron dashed: η $s = 11.06\,\mathrm{GeV}^2$

The 2-particle twist-3 DAs

a combination of EOM is linear first order diff. equation for Φ_σ solution:

$$\Phi_\sigma = 6\tau\bar\tau\left(\int d\tau \frac{\bar\tau\Phi_1^{EOM} - \tau\Phi_2^{EOM}}{2\tau^2\bar\tau^2} + C\right)$$

$$\Phi_P = \frac{\Phi_\sigma}{6\tau\bar\tau} + \frac{\Phi_1^{EOM}}{2\tau} + \frac{\Phi_2^{EOM}}{2\bar\tau}$$

local limit: $\langle\pi^+(q') \mid \bar d(0)\gamma_5 u(0) \mid 0\rangle = i f_\pi \mu_\pi$ $\left(\int_0^1 d\tau \Phi_P(\tau) = 1\right)$

$\Longrightarrow$ fixes constant of integration:

$$C = 1 + \eta_3(7\omega_{1,0} - 2\omega_{2,0} - \omega_{1,1}) \qquad (\eta_3 = f_{3\pi}/(f_\pi\mu_\pi))$$

$$\Phi_P = 1 + \sum_{n=2,4,\dots} a_n^P C_n^{(1/2)}(2\tau - 1) \qquad a_2^P = -\tfrac{10}{3}a_4^P = \tfrac{10}{7}\eta_3(7\omega_{1,0} - 2\omega_{2,0} - \omega_{1,1})$$

$$\Phi_\sigma = \eta_\sigma\tilde\Phi_\sigma \qquad \tilde\Phi_\sigma = 6\tau\bar\tau\left[1 + \sum_{n=2,4,\dots} a_n^\sigma C_n^{(3/2)}(2\tau - 1)\right]$$

$$a_2^\sigma = \tfrac{1}{6}\tfrac{\eta_3}{\eta_\sigma}(12 + 3\omega_{1,0} - 4\omega_{2,0}) \qquad a_4^\sigma = \tfrac{1}{105}\tfrac{\eta_3}{\eta_\sigma}(22\omega_{2,0} - 3\omega_{1,1})$$

$$\eta_\sigma = 1 - \eta_3(12 - 4\omega_{1,0} + \tfrac{8}{7}\omega_{2,0} + \tfrac{4}{7}\omega_{1,1})$$ may be absorbed in μ_π

for $\eta_3 \to 0$: $\Phi_P \to 1$, $\Phi_\sigma \to 2\tau\bar\tau$ WW approx.

The Gegenbauer coefficients

at scale $\mu_0 = 2\,\mathrm{GeV}$:

$$a_2^P = -0.56\,, \qquad a_4^P = 0.17\,,$$
$$a_2^\sigma = -0.084\,, \qquad a_4^\sigma = 0.031\,, \qquad \eta_\sigma = 0.64\,.$$

$a_n^P = a_n^\sigma = 0$ for $n \geq 6$

values of $a_2^{P,\sigma}$ compatible with other results
values of $a_4^{P,\sigma}$ have opposite sign

Dyson-Schwinger approach Shi et al (15)
light-cone quark model Choi-Ji (17)
chiral quark model Nam-Kim (06)

An alternative

Braun-Filyanov (90), Ball (98)

instead of $A^+ = 0$ the contour (Fock-Schwinger) gauge $x^\mu A_\mu(x) = 0$ is used

EOM more complicated but a recursion formula for the moments of the twist-3 DAs has been derived, allows also to calculate Φ_P and Φ_σ for given $\Phi_{3\pi}$

they differ from our ones for the same $\Phi_{3\pi}$

With these DAs the result for the subprocess amplitude is not gauge invariant

Reason: the Wilson lines ($\neq 1$) in the vacuum-pion matrix elements affect the calculation of the amplitudes

At least for electroproduction of ρ_T the equivalence of the two methods has been shown Anikin et al (10)

Summary

handbag factorization applied to wide-angle photoproduction of pions

- In contrast to WACS, the leading-twist analysis (with helicity non-flip GPDs) fails by order of magnitude
- we calculated the full (2- and 3-particle) twist-3 contribution;
  in contrast to electroproduction the subprocess amplitude is regular in collinear approximation
- together with the transversity form factors ($1/x$ moments of transversity GPDs) which are known from pion electroproduction at small $-t$ and are extrapolated to large $-t$ and a 3-particle twist-3 DA taken (partially) from literature we are able to fit the CLAS data at $s = 11.06\,\mathrm{GeV}^2$
- there are interesting spin effects, e.g. $A_{LL}^{twist-3} = -K_{LL}^{twist-3}$ but $A_{LL}^{twist-2} = K_{LL}^{twist-2}$ as for WACS