# Wide-angle photoproduction of pions

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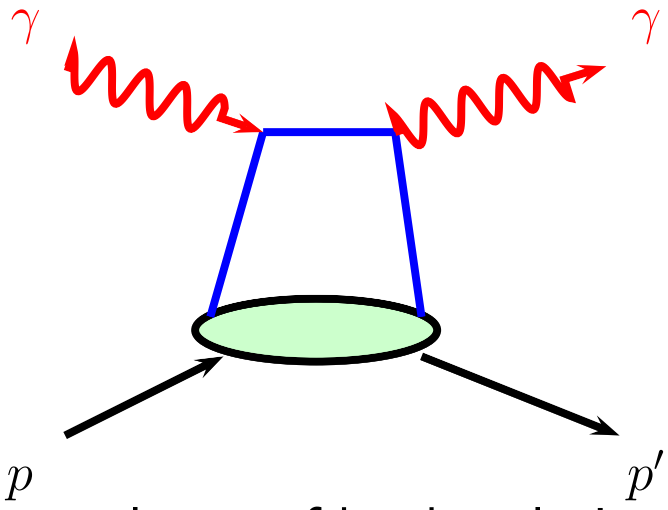
**Outline:**

- **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

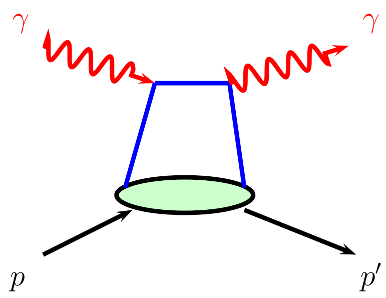
large $Q^2$ and $W$ but fixed $x_B$ and $-t/Q^2 \ll 1$

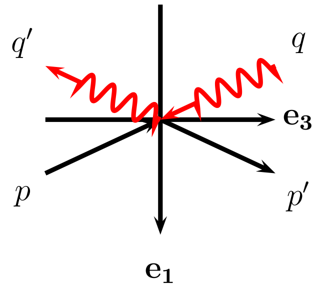
WIDE-ANGLE e.g. RCS or photoproduction of mesons

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: $R^{\gamma}_{i}(t) = \sum_a e_a^2 R^a_i(t)$

$$R^a_V = \int_0^1 \frac{dx}{x} H^{a_v}(x,\xi=0,t) \qquad E^{a_v} \to R^a_T \qquad \widetilde{H}^{a_v} \to R^a_A$$

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

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

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

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

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

axial form factor: $\widetilde{H}$ ($\kappa$ 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 $H:\ \ q(x)$ $\widetilde{H}:\ \ \Delta q(x)$

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

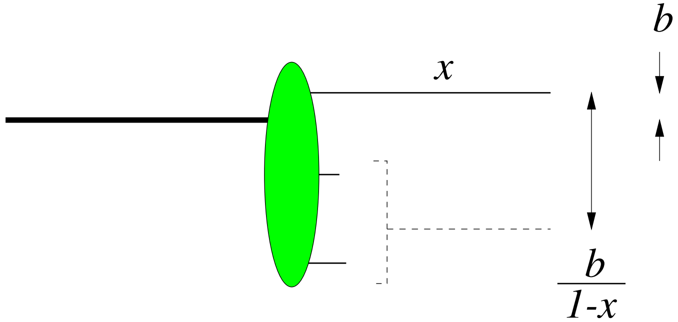
Approx: distance between active parton and cluster of spectators

work in hadron's center of momentum frame

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

Fourier transform of $H$

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



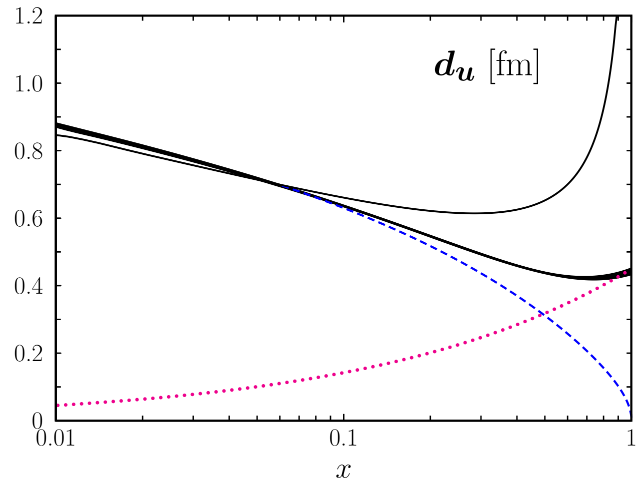

$$d_a(x) = \frac{\sqrt{\langle b^2 \rangle_x^a}}{1-x} = \frac{2\sqrt{f_q^a(x)}}{1-x} \to 2\sqrt{A_a}$$

for $x \to 1$

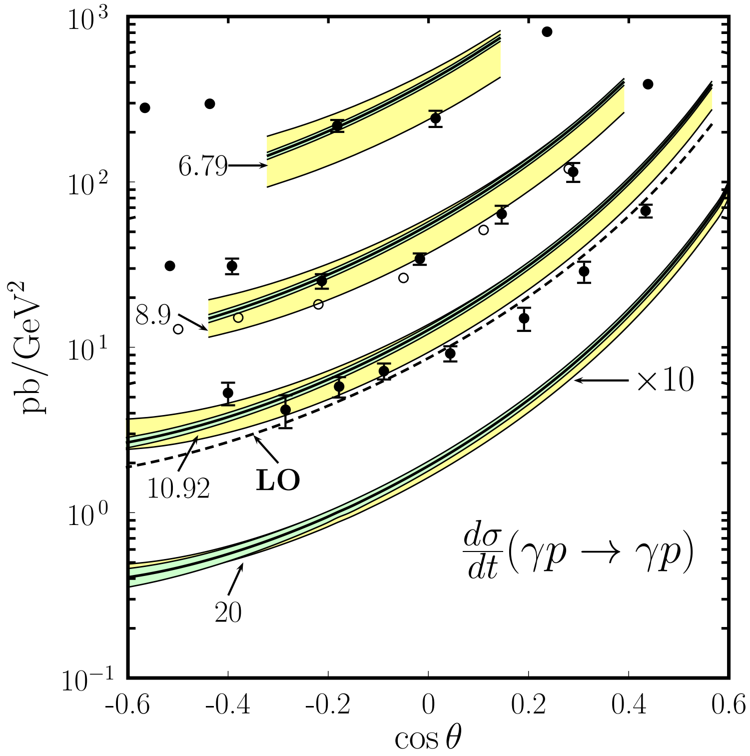
Regge-type term, A term, full profile fct

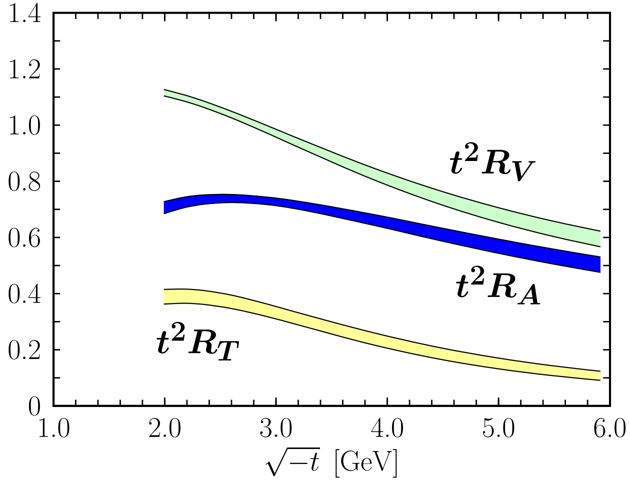
Regge-like profile fct can (only) be used at small $x$ (small $-t$)

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



# 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$^2$

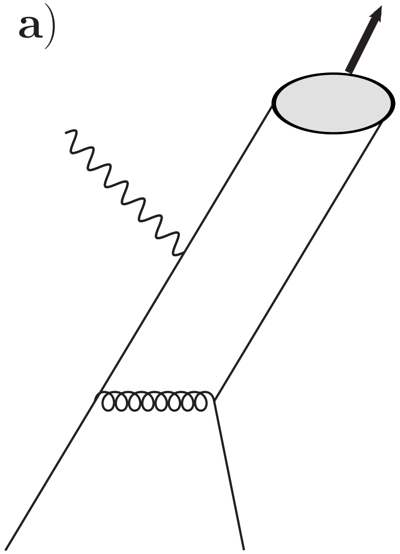
data: JLab E99-114

form factors from $\xi = 0$ anlaysis

# Photoproduction of pions

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

**a**)



leading-twist contribution

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

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

$$R_i^{\pi^0} = \frac{1}{\sqrt{2}}\left[e_u R_i^u - e_d R_i^d\right] \qquad R_i^{\pi^+} = R_i^{\pi^-} = R_i^u - R_i^d$$

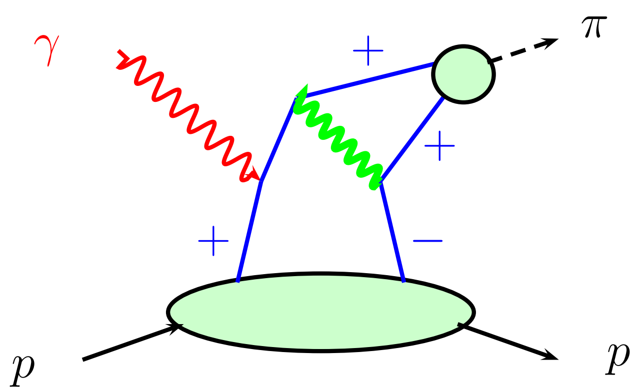
same flavor form factors as for WACS $\quad$ known, universality

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

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

cross section too small by factor 50 - 100 $\quad$ Huang-K., hep-ph/0005318

# Photoproduction: Transversity GPDs?




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

$H_T, E_T, \widetilde{H}_T, \tilde{E}_T \qquad (\bar{E}_T = 2\widetilde{H}_T + E_T)$

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)

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

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

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

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

(WW approx.)

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

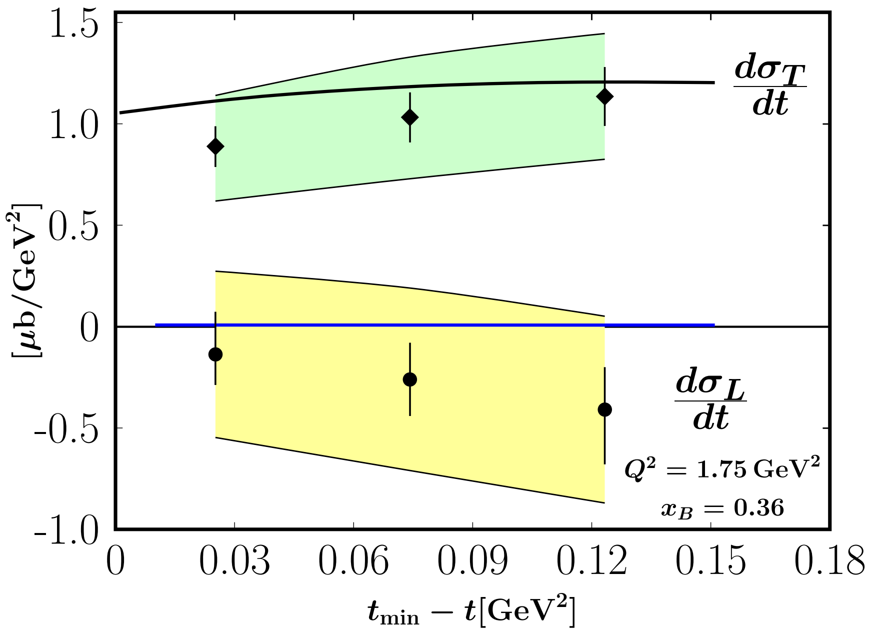
# to be contrasted with electroproduction of pions:

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

– contribute to transversely polarized photons

– dominate the cross section for $\pi^0$ production

– in agreement with experiment




Defurne et al (1608.01003)

$\pi^0$ 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 $A^+ = 0$):

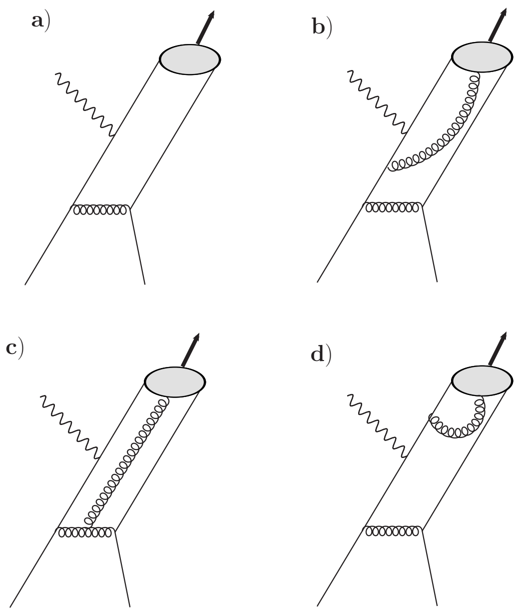
$$\bar{\tau}\Phi_p - \frac{1}{6}\bar{\tau}\Phi'_\sigma - \frac{1}{3}\Phi_\sigma = 2\frac{f_{3\pi}}{f_\pi\mu_\pi}\int_0^\tau \frac{d\tau_g}{\tau_g}\,\Phi_{3\pi}(\tau-\tau_g,\bar{\tau},\tau_g) = \Phi_1^{EOM}(\tau)$$

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

for pions: $\Phi_1^{EOM}(\tau) = \Phi_2^{EOM}(\bar{\tau})$ $\qquad$ $(\bar{\tau} = 1-\tau)$

$f_{3\pi} \;=\; f_{3\pi}(\mu_R^2) \qquad \mu_\pi \;=\; \mu_\pi(\mu_R^2)$

# $\pi^0$ subprocess amplitudes




$$\mathcal{H}^{twist-3}_{0-\lambda,\mu\lambda} = \mathcal{H}^{twist-3,2-particle} + \mathcal{H}^{twist-3,3-particle}$$

$$= 4\pi\alpha_s\, f_{3\pi}\frac{C_F}{N_C}\,\frac{2\lambda-\mu}{2}\,\frac{\sqrt{-us}}{s^2u^2}\int_0^1 d\tau\int_0^{\bar\tau}\frac{d\tau_g}{\tau_g}\Phi_{3\pi}(\tau,\bar\tau-\tau_g,\tau_g)$$

$$\times\left[\left(\frac{1}{\bar\tau^2}-\frac{1}{\bar\tau(\bar\tau-\tau_g)}\right)\left(s^2+u^2\right)+\left(1-\frac{1}{2}\frac{C_A}{C_F}\right)\left(\frac{1}{\tau}+\frac{1}{\bar\tau-\tau_g}\right)\frac{t^2}{\tau_g}\right]$$

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

sum is gauge invariant (QCD and QED) and

$s\leftrightarrow u$ crossing symmetric CGLN(57)

d) soft, part of 2-part. DA

Qiu(90) DIS

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

$$\mathcal{P}^{\beta,c}_{3,fg}=\frac{i}{g}\,\frac{f_{3\pi}}{2\sqrt{2N_C}}\,\frac{(t^c)_{fg}}{C_F\sqrt{N_C}}\,\frac{\gamma_5}{\sqrt2}\,\sigma_{\mu\nu}q'^{\mu}g_\perp^{\nu\beta}\,\frac{\Phi_{3\pi}(\tau_a,\tau_b,\tau_g)}{\tau_g}\qquad g_\perp^{\nu\beta}=g^{\nu\beta}-\frac{k'^{\nu}_j q'^{\beta}+q'^{\nu}k'^{\beta}_j}{k'_j\cdot q'}$$

# 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)

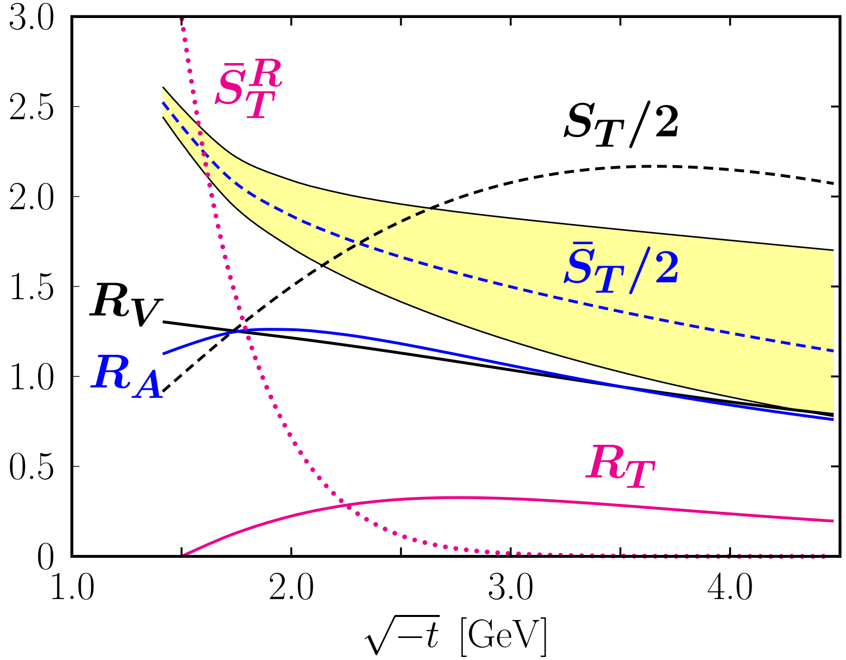
$$\Phi_{0\nu',\mu\nu} = \mathcal{M}_{0\nu',\mu\nu} + \frac{1}{2}\kappa\Big[(-1)^{1/2-\nu'}\mathcal{M}_{0-\nu',\mu\nu} + (-1)^{1/2+\nu}\mathcal{M}_{0\nu',\mu-\nu}\Big] + \mathcal{O}(m^2/s)$$

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

# Form factors

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

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




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

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

# The 3-particle twist-3 pion DA

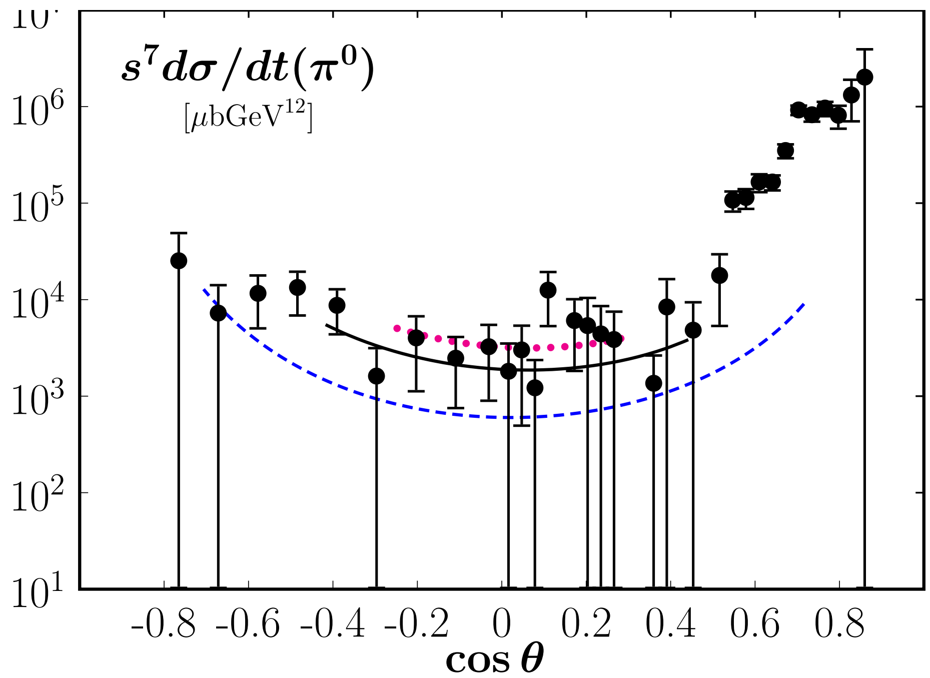
$$
\begin{aligned}
\Phi_{3\pi} &= 360\tau_a\tau_b\tau_g^2\Big[1+\omega_{10}(\mu_R^2)(7\tau_g-3)/2 \\
&+ \omega_{20}(\mu_R^2)(2-4\tau_a\tau_b-8\tau_g+8\tau_g^2) + \omega_{11}(\mu_R^2)(3\tau_a\tau_b-2\tau_g+3\tau_g^2)+\ldots\Big]
\end{aligned}
$$

( 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 $\pi^0$ 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)

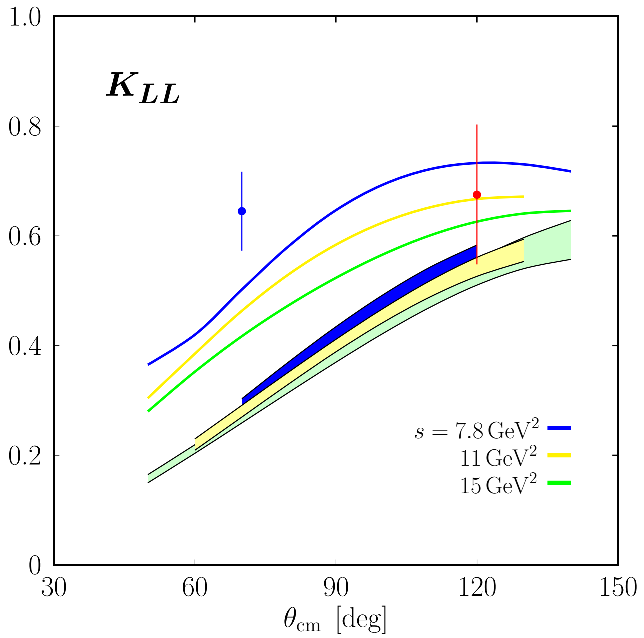
fit to data: $\omega_{20} = 8.0 \quad \omega_{11} = 0$

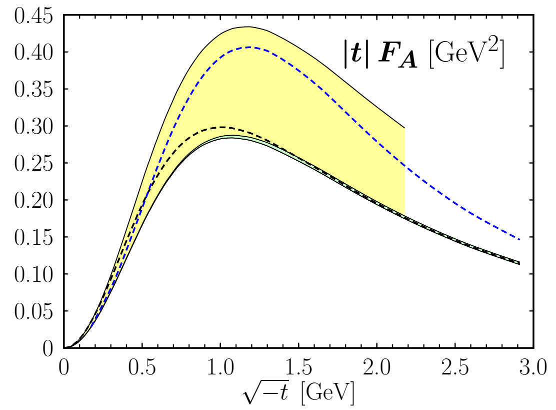
close to values quoted in

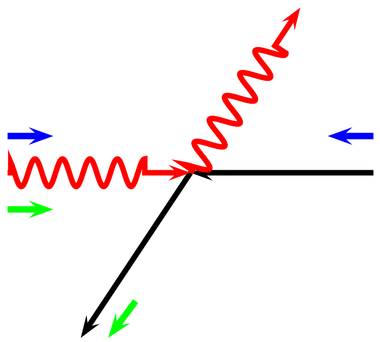
Braun-Filyanov (90),Chernyak-Zhit.(84)

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

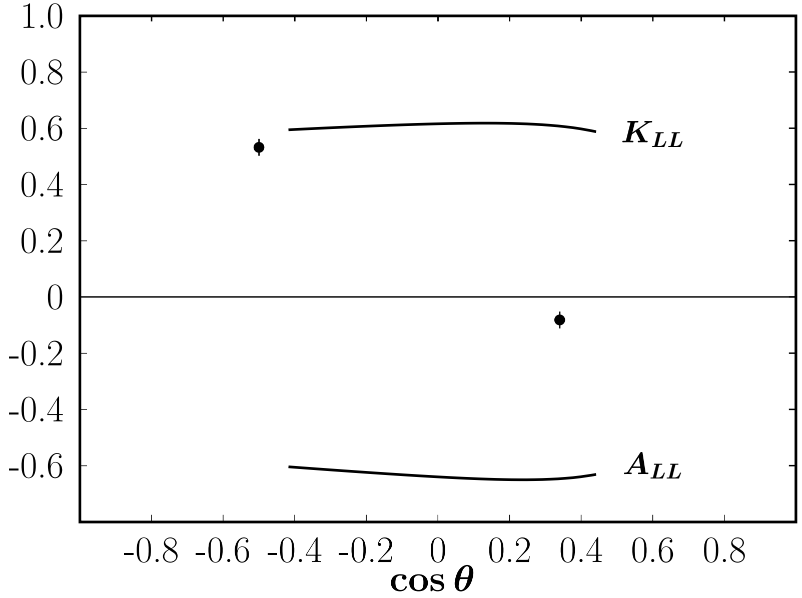
JLab E07-002 ($s = 7.8{\rm GeV}^2$ $\quad t = -2.1{\rm GeV}^2$)

application of handbag mechanism is at the limits

$R_A$ badly known since $F_A$ badly known, old data for $-t \lesssim 2\,{\rm GeV}^2$ 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.

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

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

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

# The 2-particle twist-3 DAs

a combination of EOM is linear first order diff. equation for $\Phi_\sigma$ 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: $\langle\pi^+(q')\mid\bar d(0)\gamma_5 u(0)\mid 0\rangle = i f_\pi\mu_\pi$ $\quad(\int_0^1 d\tau\Phi_P(\tau)=1)$

$\Longrightarrow$ fixes constant of integration:

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

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

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

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

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

for $\eta_3\to 0$: $\Phi_P\to 1$, $\Phi_\sigma\to 6\tau\bar\tau$ 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 $\Phi_P$ and $\Phi_\sigma$ 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 $\rho_T$ 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