Exclusive Drell-Yan processes

P. Kroll

Fachbereich Physik, Univ. Wuppertal and Univ. Regensburg

Trento, November 2017

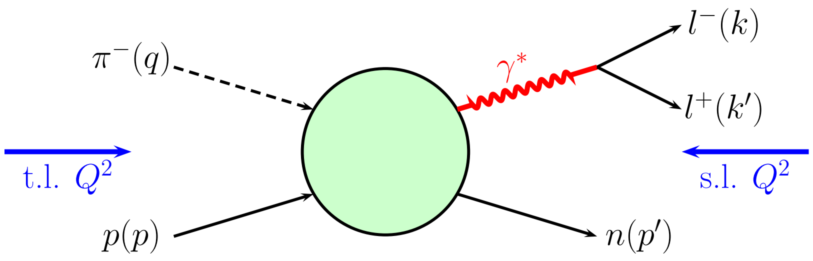
Outline:

- **Introduction: handbag approach and GPDs**
- **Analysis of pion leptoproduction**

  (the pion pole, transversity, subprocess amplitudes, results)
- **The exclusive DY process with a pion beam -** $\pi^- p \to l^+ l^- n$
- **with a kaon beam -** $K^- p \to l^+ l^- \Lambda(\Sigma^0)$
- **Lepton-pair production in exclusive hadron-hadron collisions**
- **Summary**

$lp \to l\pi^+ n$ and $\pi^- p \to l^- l^+ n$

in handbag approach:



exclusive Drell-Yan process

directly related to pion electroproduction:

- same GPDs
- $\hat{s} - \hat{u}$ $(l - \pi)$ crossed subprocess

$$\mathcal{H}^{\pi^- \to \gamma^*}(\hat{u}, \hat{s}) = -\mathcal{H}^{\gamma^* \to \pi^+}(\hat{s}, \hat{u})$$

equivalent to $Q^2 \to -Q'^2$

Idea: Study hard π^+ electroproduction first

plenty of data from Jlab and HERMES, more will come (Jlab12 and COMPASS)

learn about relevant GPDs and treatment of subprocesses

apply what has been learned there in a calculation of the Drell-Yan process

GPDs – a reminder

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

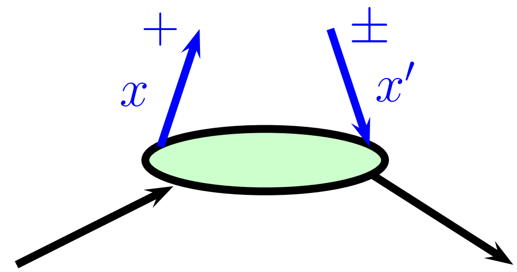
GPDs: $\sim \langle p'|\overline{\Psi}(-z/2)\Gamma\Psi(z/2)|p\rangle \qquad \Gamma = \gamma^+, \gamma^+\gamma_5, \sigma^{+j}$ (encode soft physics)

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

$$x = \frac{\bar{x}+\xi}{1+\xi} \quad x' = \frac{\bar{x}-\xi}{1-\xi} \quad \xi = \frac{(p-p')^+}{(p+p')^+} \simeq \frac{x_B}{2-x_B}$$

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 $\qquad J_q = \frac{1}{2}\int_{-1}^{1} d\bar{x}\, \bar{x}\, [H^q(\bar{x},\xi,t=0) + E^q(\bar{x},\xi,t=0)]$

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

Leptoproduction of pions

Rigorous proofs of collinear factorization in hard subprocesses and GPDs in generalized Bjorken regime of large Q^2, large W but fixed x_B (small $-t$)

Collins-Frankfurt-Strikman (96)

leading-twist amplitudes for longitudinally polarized photons

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

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

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

many leading-twist predictions for pion production

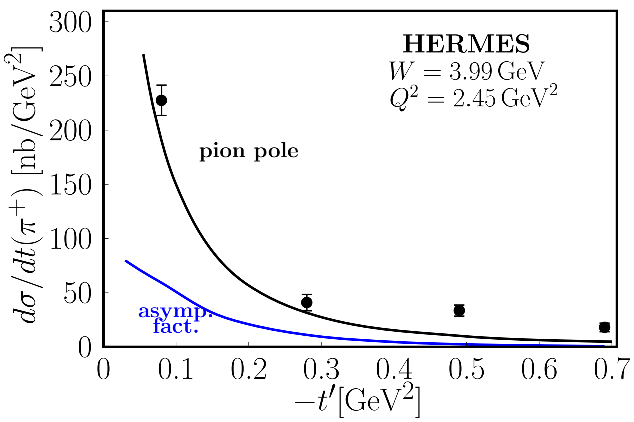
e.g. Mankiewicz et al (98), Frankfurt et al(99), Diehl al et(01), ...

all fail by order of magnitude in comparison with experiment

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

The pion pole

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



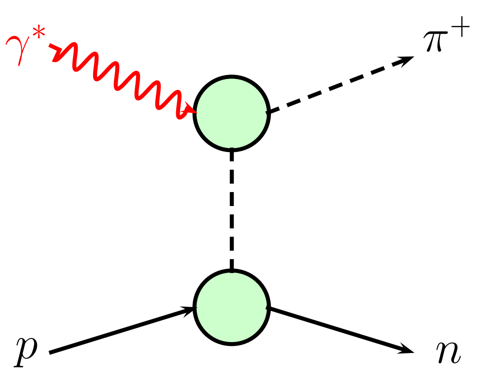
$$\widetilde{E}^u_{\rm pole} = -\widetilde{E}^d_{\rm pole} = \Theta(|x| \leq \xi)\,\frac{m f_\pi g_{\pi NN}}{\sqrt{2}\xi}\,\frac{F_{\pi NN}(t)}{m_\pi^2 - t}\,\Phi_\pi\Big(\frac{x+\xi}{2\xi}\Big)$$

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

understimates cross ssection (blue line)

$F_\pi^{\rm pert.} \simeq 0.3 - 0.5 F_\pi^{\rm exp.}$

(note: F_π measured in π^+ electroproduction at Jlab)



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

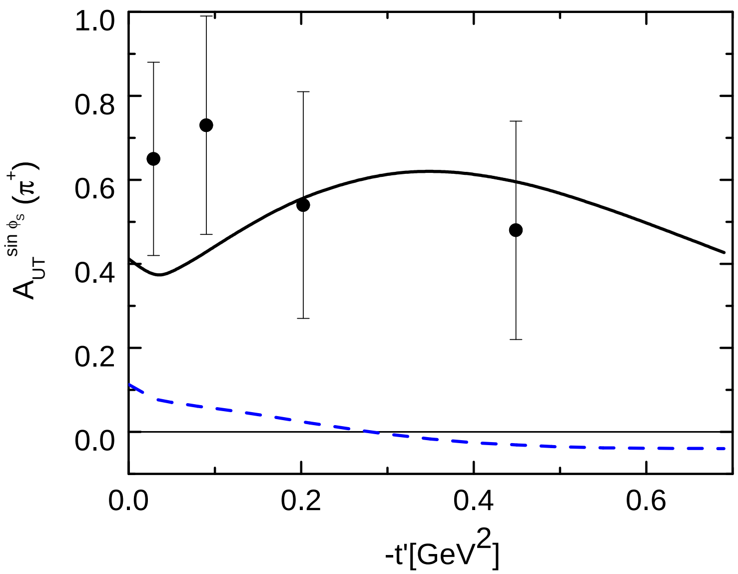
as one-pion-exchange contr.

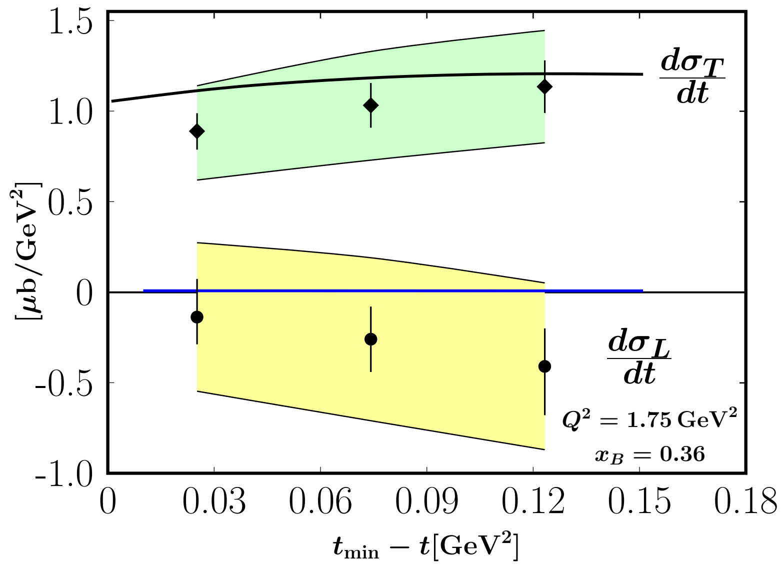
knowledge of the sixties suffices to explain

π^+ data at small $-t$

(detailed comparison Favart et al (16))

Evidence for contributions from transverse photons





HERMES(09)

$Q^2 \simeq 2.5\,\mathrm{GeV}^2, W = 3.99\,\mathrm{GeV}$

$\sin\phi_s$ modulation very large

does not vanish for $t' \to 0$

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

n-f. ampl. $\mathcal{M}_{0-,++}$ required

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

results from GK(11)

Hall A(16) π^0 production

$$\boxed{d\sigma_T \gg d\sigma_L \;(\; d\sigma \simeq d\sigma_T)}$$

like expectation for $Q^2 \to 0$

to be contrasted with QCD expectation for $Q^2 \to \infty$

$$\boxed{d\sigma_T \ll d\sigma_L \;(\; d\sigma \simeq d\sigma_L)}$$

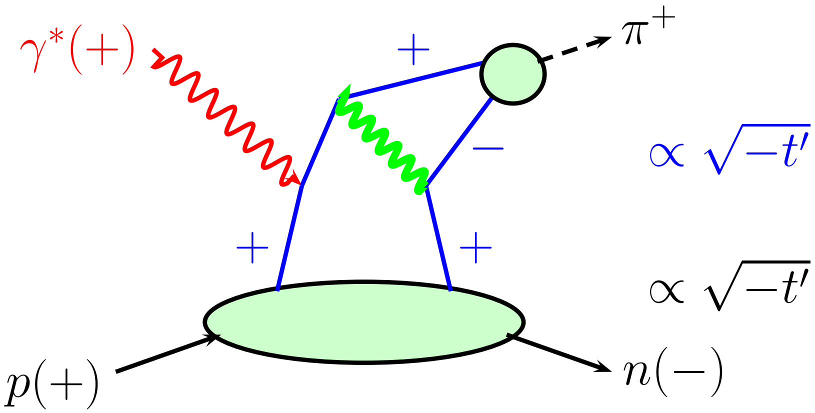
How can we model $\mathcal{M}_{0-,++}$ in the handbag?

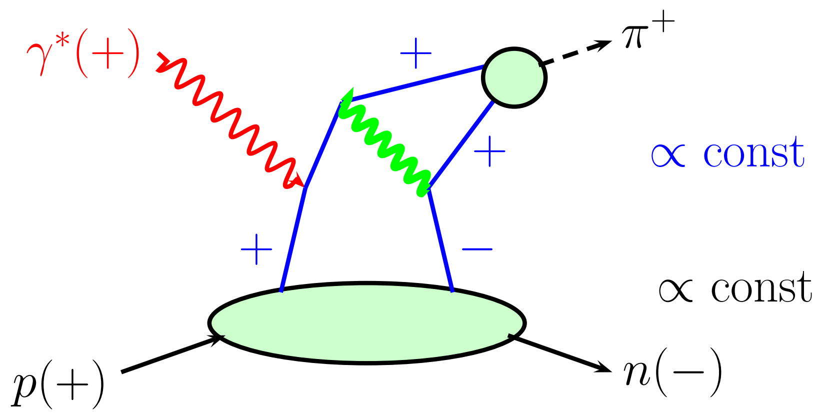
helicity-non-flip GPDs

$H, E, \widetilde{H}, \widetilde{E}$

helicity-flip (transv.) GPDs

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





lead. twist pion wave fct. $\propto q' \cdot \gamma\gamma_5$
(perhaps including $\mathbf{k}_\perp$)

transversity GPDs required
go along with twist-3 w.f.

$\mathcal{M}_{0-,++} \propto t'$

$\mathcal{M}_{0-,++} \propto$ const

(forced by angular momentum conservation)

$\gamma_T^* \to \pi$ in the handbag approach

see Diehl01, GK10, GK11 $\qquad \bar{E}_T \equiv 2\widetilde{H}_T + E_T \qquad \mu = \pm 1$

$$\begin{aligned}
\mathcal{M}_{0+\mu+} &= e_0 \frac{\sqrt{-t'}}{4m} \int dx \Big\{ \big(H_{0+\mu-} - H_{0-\mu+}\big)\big(\bar{E}_T - \xi \widetilde{E}_T\big) \\
&+ \big(H_{0+\mu-} + H_{0-\mu+}\big)\big(\widetilde{E}_T - \xi E_T\big)\Big\} \\
\mathcal{M}_{0-\mu+} &= e_0 \sqrt{1-\xi^2} \int dx \Big\{ H_{0-\mu+} \Big[H_T + \frac{\xi}{1-\xi^2}\big(\widetilde{E}_T - \xi E_T\big)\Big] \\
&+ \big(H_{0+\mu-} - H_{0-\mu+}\big) \frac{t'}{4m^2} \widetilde{H}_T \Big\}
\end{aligned}$$

with parity conserv. ($H_{0+\pm-} = -H_{0-\mp+}$): $\qquad \mathcal{M}_{0+\pm+} = \mathcal{M}^N_{0+++} \pm \mathcal{M}^U_{0+++}$

time-reversal invariance: $\widetilde{E}_T$ is odd function of ξ

N: $\bar{E}_T$ with corrections of order ξ^2 $\qquad$ U: order ξ

small $-t'$: $\mathcal{M}_{0-++}$ mainly H_T with corrections of order ξ^2 (no definite parity)

$\mathcal{M}_{0--+}$ suppressed by t/Q^2 due to H_{0--+}

handbag explains structure of ampl. at least at small ξ and small $-t'$

The twist-3 pion distr. amplitude

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

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 $2\,\mathrm{GeV}$ (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)

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

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

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

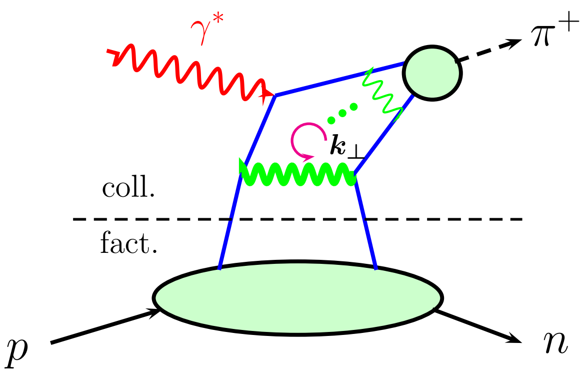
(suppressed by μ_π/Q as compared to $L \to L$ amplitudes) $\mathcal{M}_{0--+} \simeq 0$

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 $b_\perp = 1/\Lambda_{\rm QCD}$

$$\mathcal{H}_{0\pm0+} = \int d\tau d^2 b_\perp \, \hat{\Psi}^\pi_{\pm+}(\tau, -\mathbf{b}_\perp)\, e^{-S} \hat{\mathcal{F}}_{0\pm0+}(\bar{x}, \xi, \tau, Q^2, \mathbf{b}_\perp)$$

$\hat{\Psi}^\pi_{++} \sim \exp[\tau\bar{\tau} b_\perp^2/4a_M^2]$ 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)

(no D-term for $\widetilde{H}$, $\widetilde{E}$ and the transversity GPDs)

Details of the parametrization

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

$\widetilde{E}_{\rm non-pole}$: fit to π^+ data

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

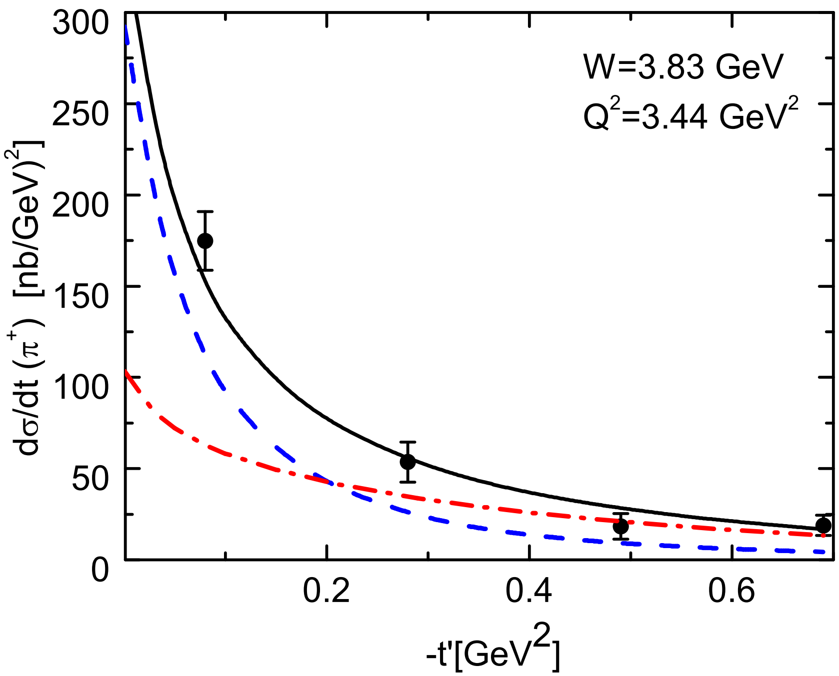
opposite sign for u and d quarks, normalized to lattice moments QCDSF-UKQCD(05)

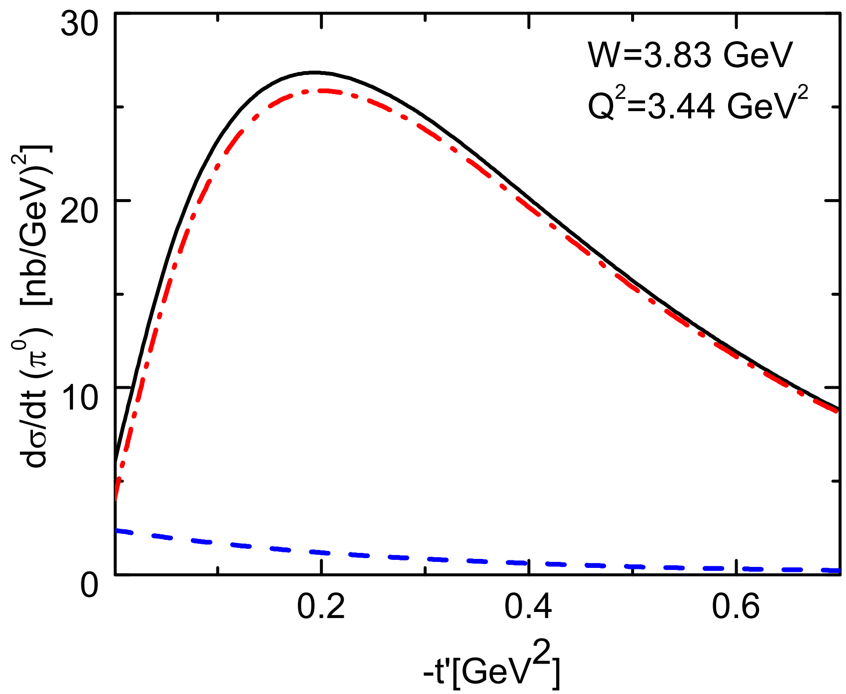
$\bar{E}_T$: adjusted to lattice results QCDSF-UKQCD(06)

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

The role of H_T and $\bar{E}_T$





unseparated (longitudinal, transverse) cross sections

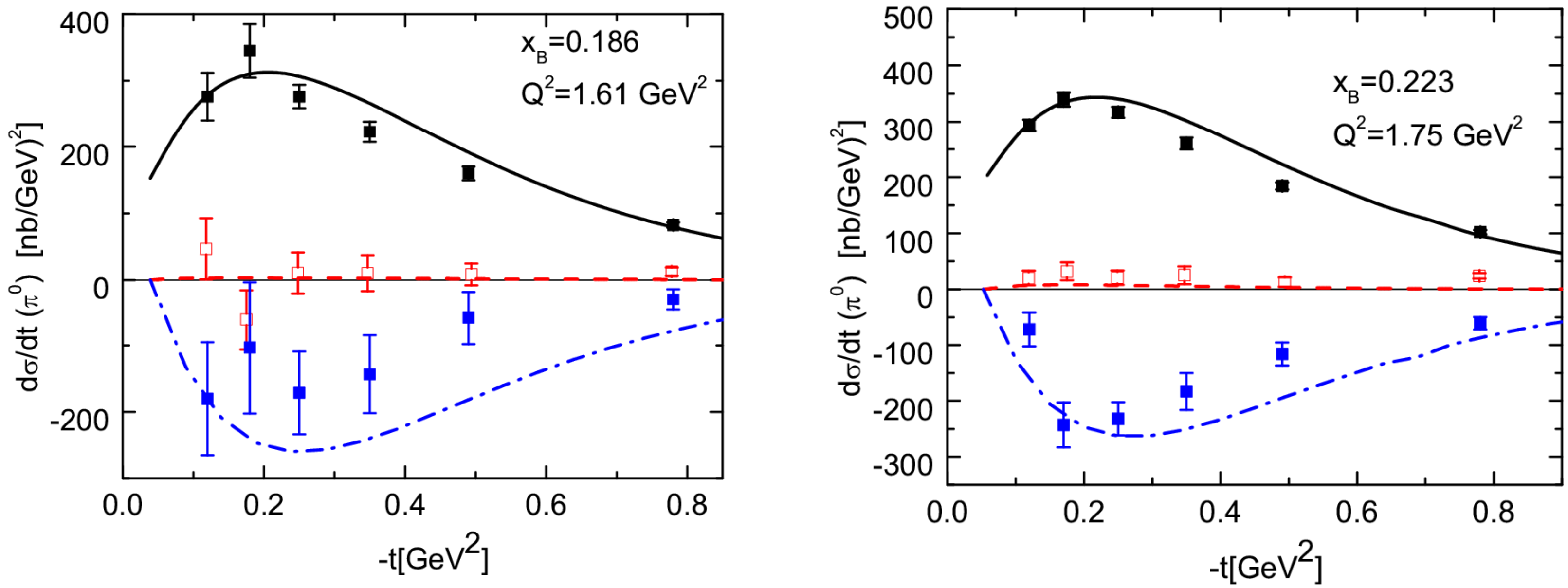
π^+: pion pole and $\propto K^u - K^d$ $\qquad$ π^0: no pion pole and $\propto e_u K^u - e_d K^d$

consider $u-d$ signs: $\widetilde{E}$, $\bar{E}_T$ same, $\widetilde{H}, H_T$ opposite sign

$\Longrightarrow$ $\widetilde{H}$ and H_T large for π^+, small for π^0

$\widetilde{E}$ and $\bar{E}_T$ small for π^+, large for π^0 $\qquad$ confirmed by preliminary COMPASS data

Results for π^0

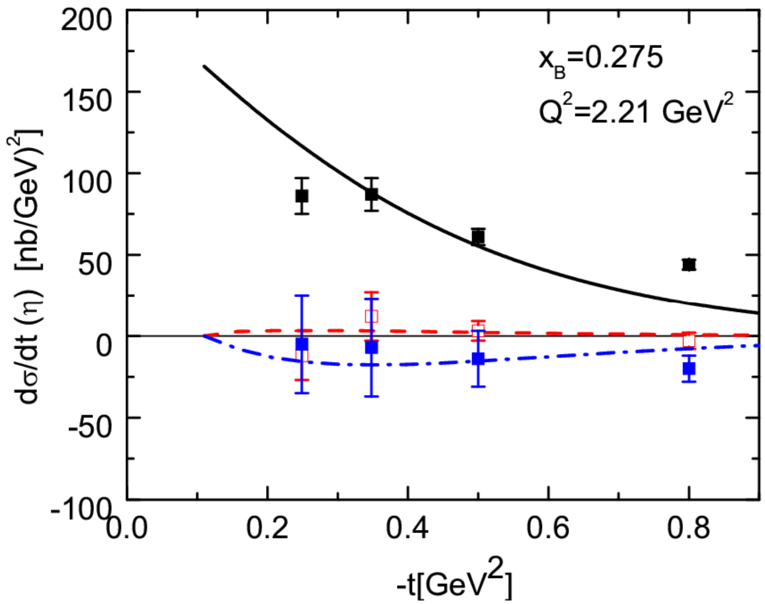


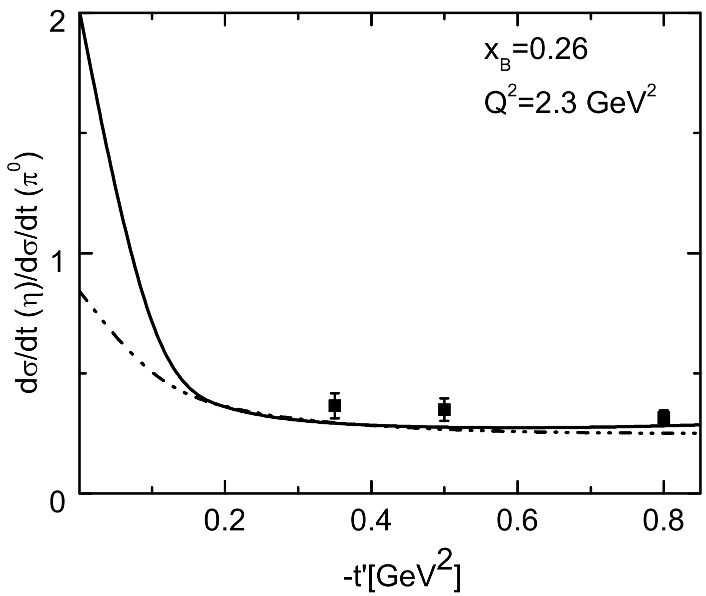
data: CLAS (12) $d\sigma$, $d\sigma_{LT}$, $d\sigma_{TT}$

curves: Goloskokov-K(11)

transversity GPDs in pion production also studied by Goldstein et al (12)

η production





data CLAS (17) unseparated (TT, LT) cross sections

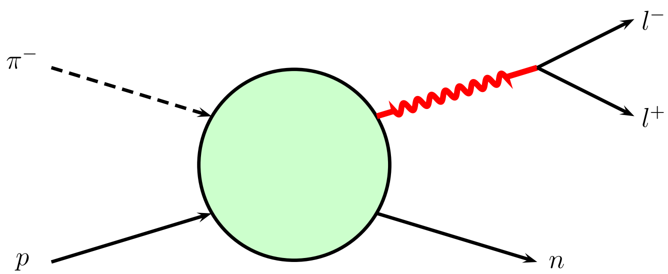
$$\frac{d\sigma(\eta)}{d\sigma(\pi^0)} \simeq \left(\frac{f_\eta}{f_\pi}\right)^2 \frac{1}{3}\left|\frac{e_u\langle K^u\rangle + e_d\langle K^d\rangle}{e_u\langle K^u\rangle - e_d\langle K^d\rangle}\right|^2 \qquad (f_\eta \simeq 1.26 f_\pi \text{ FKS(98)})$$

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

$t' \simeq 0$ $\widetilde{H}, H_T$ dominant (see also Eides et al(98) assuming dominance of $\widetilde{H}$ for all t')

$t' \neq 0$ $\bar{E}_T$ dominant

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)

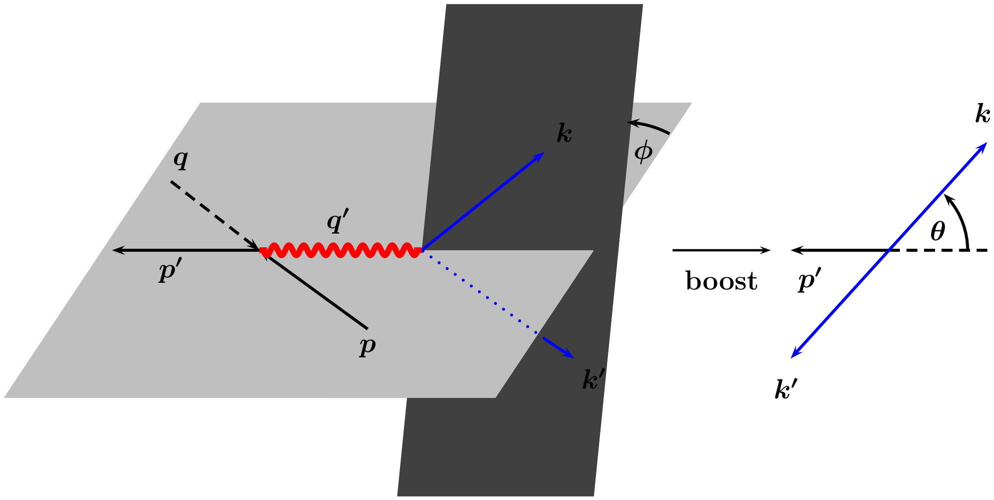
we know that leading-twist analysis of π^+ production fails with JLAB, HERMES data by order of magnitude

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

- treating pion-pole contribution as an OPE term
- take into account transverse photons and transversity GPDs
- retaining quark transverse momenta in the subprocess (the MPA)

Cross section



k momentum of l^-

$\tau = Q'^2/(s-m^2)$

the time-like analogue

of x_B

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

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

partial cross sections analogous to pion production

Time-like pion form factor

only new element:

CLEO(12), BaBar(13):

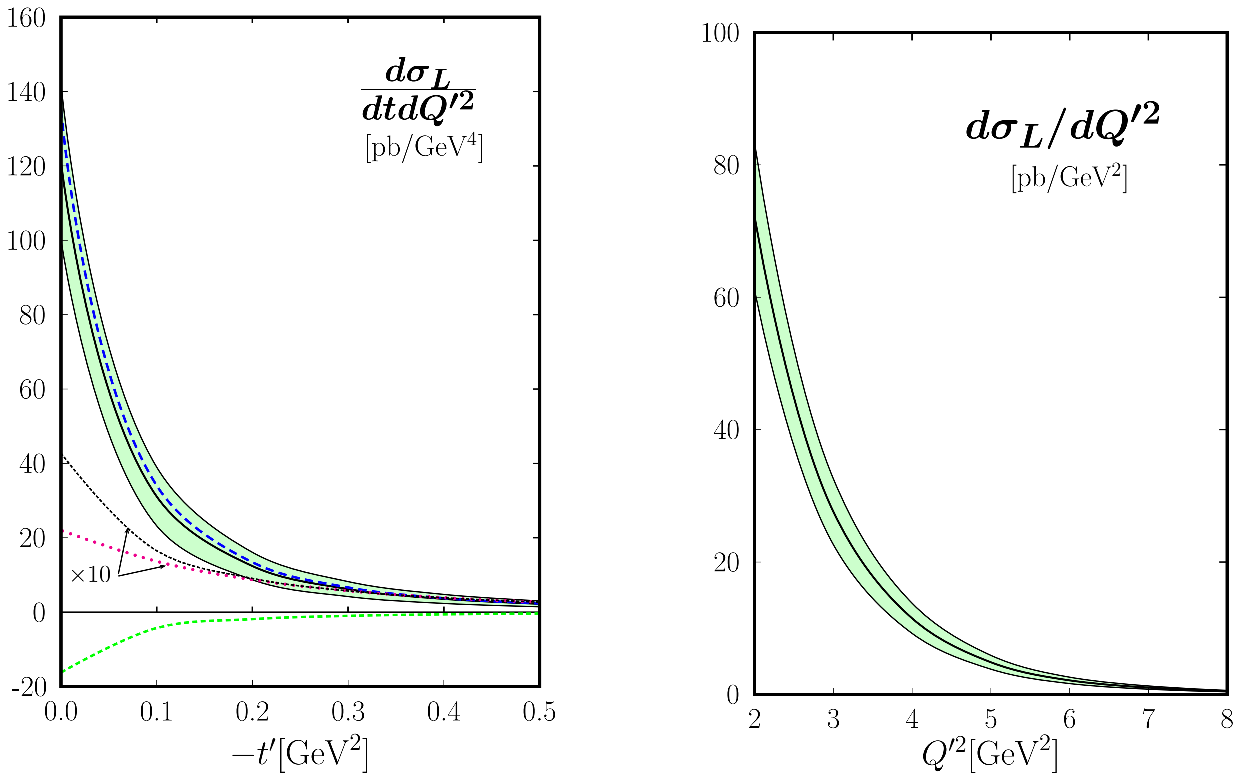
$Q'^2|F_\pi(Q'^2)| = 0.88 \pm 0.04\,\mathrm{GeV}^2$ for $Q'^2 \gtrsim 2\,\mathrm{GeV}^2$

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

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

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

Results on the longitudinal cross section

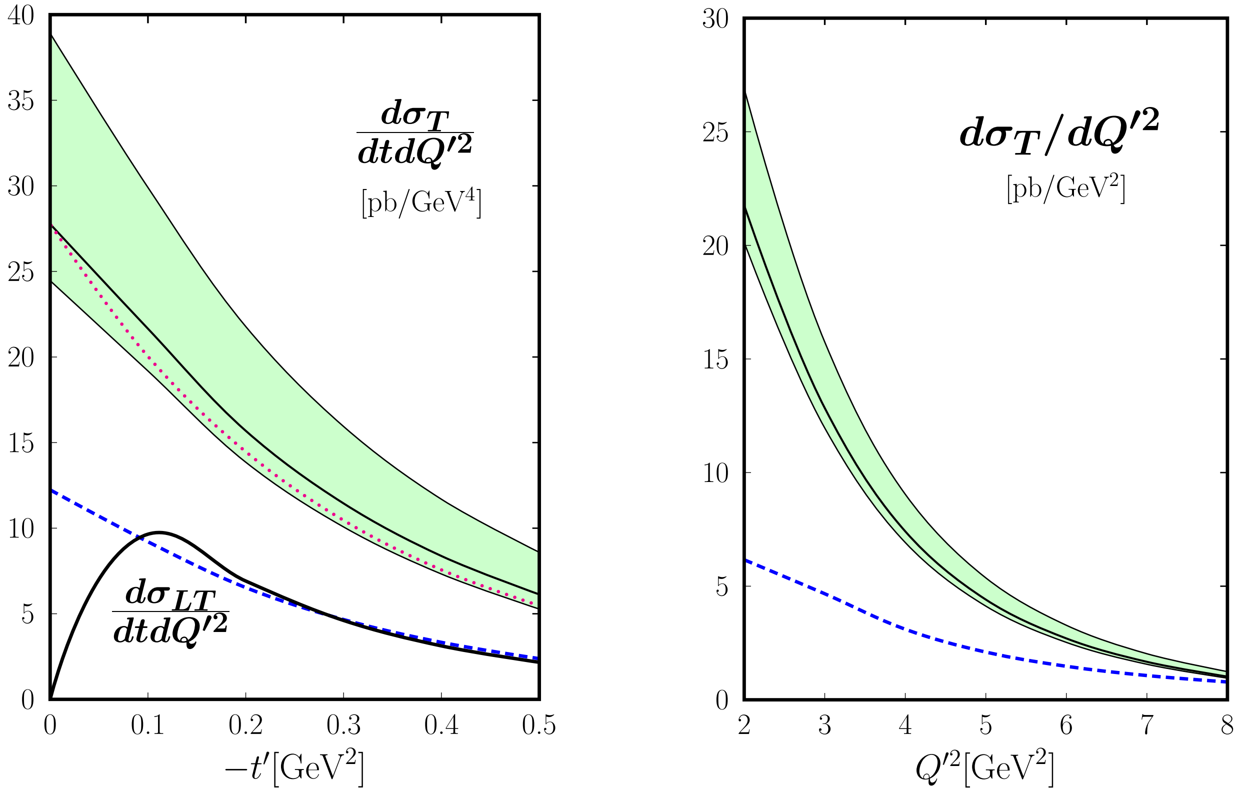


$Q'^2 = 4\,\mathrm{GeV}^2$ and $s = 20\,\mathrm{GeV}^2$

solid lines with error bands: full result, pion pole, $|\langle \widetilde{H}^{(3)} \rangle|^2$, interference,

short dashed: leading-twist contribution

Results on the transversal cross section



$Q'^2 = 4\,\mathrm{GeV}^2$ and $s = 20\,\mathrm{GeV}^2$
dominated by H_T (dotted l.)
blue dashed line: $s = 30\,\mathrm{GeV}^2$
(COMPASS: $s = 360\,\mathrm{GeV}^2$ pb $\to$ fb)

$\bar{E}_T^u - \bar{E}_T^d$ small
$d\sigma_{TT}$ very small

The Drell-Yan process with a kaon beam

similar to case of pions

kaon pole: coupling constants: $g_{KN\Lambda} = -13.3\,;\qquad g_{KN\Sigma^0} = 3.5$

in agreement with SU(3) predictions   Chiang et al (04)

KpY form factors: $F_{KpY} = \frac{\Lambda_N^2 - m_K^2}{\Lambda_N^2 - t}\qquad \Lambda_N = 0.64 \pm 0.03$

time-like elm. form factor: $|F_{K^+}| = c_{\rm pole}/Q'^2$ Babar(13), CLEO(12)

$c_{\rm pole} = 0.79 \pm 0.04$ phase assumed to be equal to phase of pion form factor

kaon pole substantially smaller than that from the pion pole since kaon pole farther away from physical region

relative suppression factor $\left(\frac{t-m_\pi^2}{t-m_K^2}\right)^2 \simeq 0.1$ at small $-t$

GPD: $K_{ip\to Y}$ related to $K_{ip\to p}$ by flavor symmetry   Frankfurt et al(99)

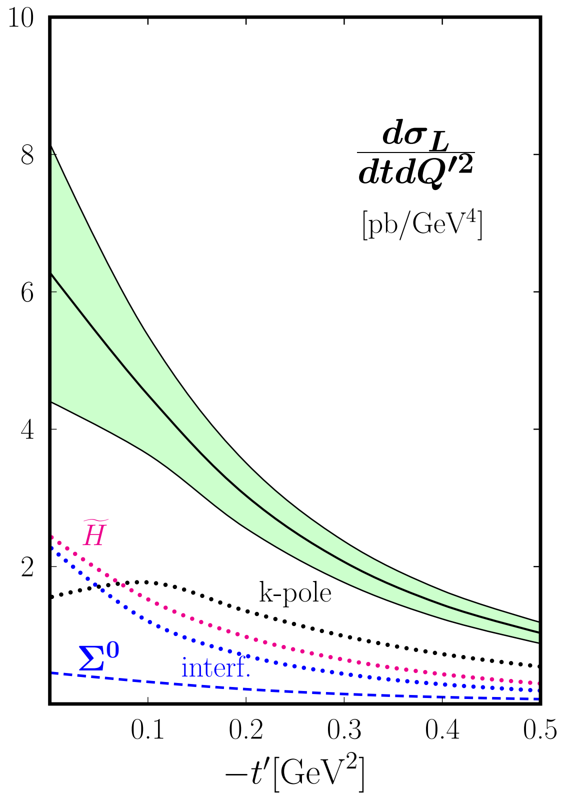
assuming a flavor symmetric sea

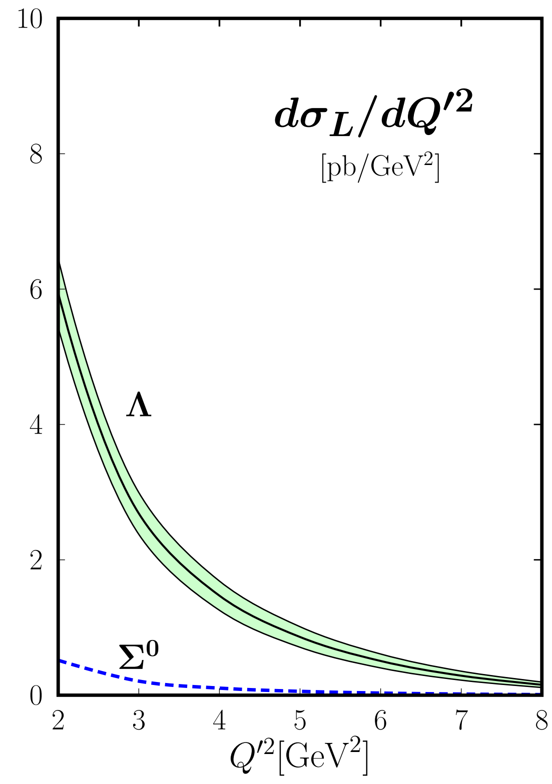
$$K_{ip\to\Lambda} \simeq \frac{1}{\sqrt{6}}\Big[2K_i^{u_v} - K_i^{d_v}\Big] \qquad K_{ip\to\Sigma^0} \simeq -\frac{1}{\sqrt{2}}K_i^{d_v}$$

kaon DA: $(a_1 = -a_2 = 0.05)$

$$\Phi_K = 6\tau(1-\tau)\Big[1 + a_1(\mu_R)C_1^{3/2}(2\tau-1) + a_2(\mu_R)C_2^{3/2}(2\tau-1)\Big]$$

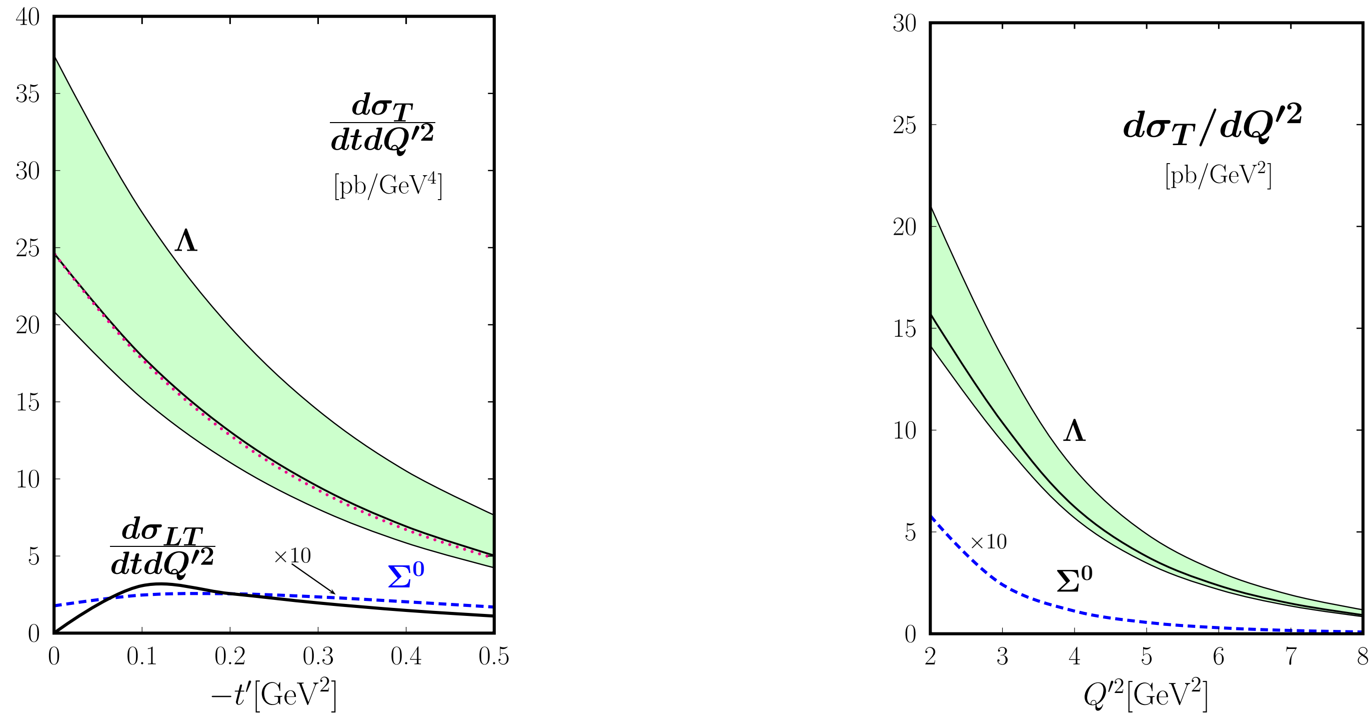
Kaon: predictions for long. photons





$Q^2 = 4\,\mathrm{GeV}^2 \qquad s = 20\,\mathrm{GeV}^2$

Kaon: predictions for trans. photons



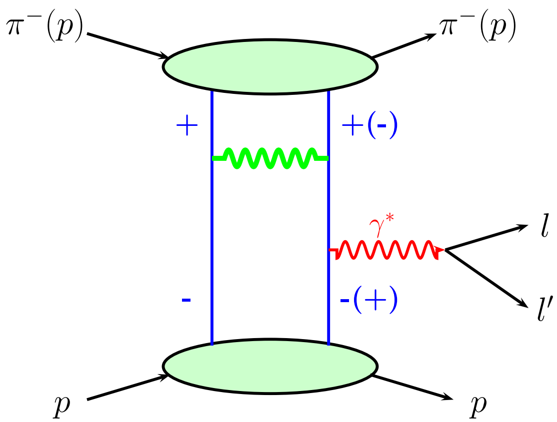
$Q^2 = 4\,\mathrm{GeV}^2 \qquad s = 20\,\mathrm{GeV}^2$

transverse cross sections about 10% smaller than the pion one

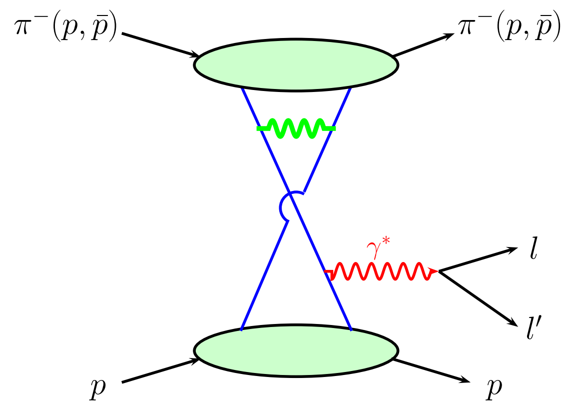
Lepton-pair production in exclusive hadron-hadron collisions

Pivovarov-Teryaev (14), Goloskokov-K-Teryaev (in progress)

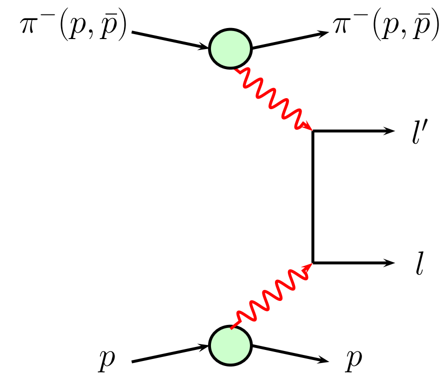
double handbag   measurable at J-PARC, LHC, FAIR, NICA



$q\bar{q} \to q\bar{q}\gamma$



$qq \to qq\gamma$



elm. contribution
$\sim F_{\text{elm}}^{\pi(p,\bar{p})} F_{\text{elm}}^{p}$

access to pion GPDs   subprocesses:

$q(\lambda)\bar{q}(-\lambda) \to q(\lambda')\bar{q}(-\lambda')$: $\quad \lambda = \lambda'$: $\quad H_\pi^q \times K^{\bar{q}} \quad \lambda = -\lambda'$: $\quad H_{T\pi}^q \times K_T^{\bar{q}}$

$q(\lambda)q(\lambda') \to q(\lambda)q(\lambda')$: $\quad \lambda = \lambda'$: $\quad H_\pi^q \times K^q \quad \lambda = -\lambda'$: $\quad H_{T\pi}^q \times K_T^q$

leading-twist contr. from transversity GPDs

$q(\lambda)g(\lambda') \to q(\lambda)g(\lambda')\ H_\pi^q \times K^g$

(bears resemblance to constituent interchange model) for pp and $\bar{p}p$ processes:

only long. polarized photons contribute dominant contribution from H

with $H^{\bar{q}}_{\bar{p}} = H^q_p \equiv H^q$ and

$$H^q(x) = \begin{cases} H^q(x) & x > 0 \\ -H^{\bar{q}}(-x) & x < 0 \end{cases}$$

combinations with definite $x \to -x$ symmetry and charge conj. $(C_\gamma = -1)$

$H^{q(\mu)} = H^q(x) - \mu H^q(-x) \qquad H^{q(\mu)}(x) = -\mu H^{q(\mu)}(-x) \qquad C = \mu$

typical contribution

$$M_L \sim \int_0^1 dx_1 \int_0^1 dx_2 \frac{H^{q(-)}(x_1) H^{q(+)}(x_2)}{(x_1 \pm \xi_1)(x_2 \pm \xi_2) - i\epsilon}$$

how to regularize?

real part can be calculated as a principal value

and can be measured from the interference with real elm. contribution

Summary

- asymptotia is far away
  interpretation of data on pion leptoproduction requires strong power corrections from the pion pole and from transverse photons
- within handbag approach $\gamma_T^* \to \pi$ transitions are related to transversity (helicity-flip) GPDs accompanied by a twist-3 pion wave fct.
- making use of what we have learned from pion leptoproduction we evaluated the long. and transverse cross sections for exclusive Drell-Yan processes for pion and kaon beams
- case of pions: long. cross section dominated by the pion pole (not subject to evolution and pert. corrections)
  transverse cross section fed by H_T ($\bar{E}_T$ small)
- case of kaons: pole less important, $d\sigma_T > d\sigma_L$
- t.l. π FF: $l^+l^- \to \pi^+\pi^-$ (CLEO, BaBar) versus $\pi^-\pi^{+*} \to l^+l^-$
- imortant to measure the exclusive DY processes: time-like reactions often provide surprising results (e.g. inclusive DY, time–like FF,...)