Wide-angle exclusive scattering

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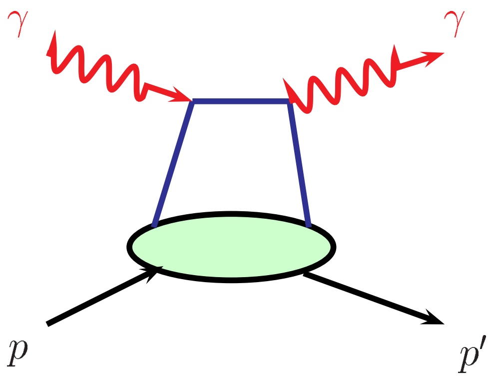
Outline:

- Factorization schemes
- The handbag contribution to WACS
- Extracting the GPDs from nucleon form factors
- Results on Compton scattering
- Summary

based on work done in collaboration with: M. Diehl, T. Feldmann, R. Jakob

Handbag factorization in excl. reactions

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



only one active parton (others are spectators)
occur in
DVES ($\gamma^* p \to \gamma p\,,\, Mp$) Q^2 large, t small
WAES ($\gamma p \to \gamma p\,,\, Mp$) Q^2 small, t large

hard process: $\gamma^{(*)} q \to \gamma q$

soft physics: GPDs $H^q(x,\xi,t)$, $\widetilde{H}^q$, E^q, $\widetilde{E}^q$ (skewness: $\xi = \frac{p^+ - p'^+}{p^+ + p'^+}$)

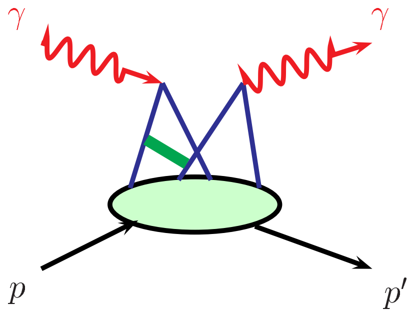
- reduction formulas: $H^q(x,0;0) = q(x)$; $\widetilde{H}^q(x,0;0) = \Delta q(x)$
- sum rules: $h^q_{10}(t) = \int_{-1}^{1} dx H^q(x,\xi,t)$; $F_1(t) = \sum_q e_q h^q_{10}(t)$;
  $E^q \to F_2^q$; $\widetilde{H}^q \to F_A^q$; $\widetilde{E}^q \to F_P^q$
- polynomiality: e.g. $\int_{-1}^{1} dx\, x^{n-1} H^q(x,\xi,t) = \sum_{i=0}^{[n/2]} h^q_{n,i}(t)\xi^i$

universality, evolution, positivity constraints, Ji's sum rule

Other topologies

Two active partons

cat's ears

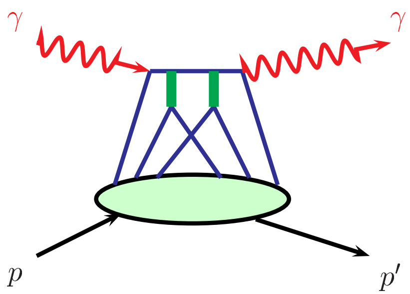


large virtualities or large intrinsic transverse momenta occur in diagram

at least one hard gluon is required

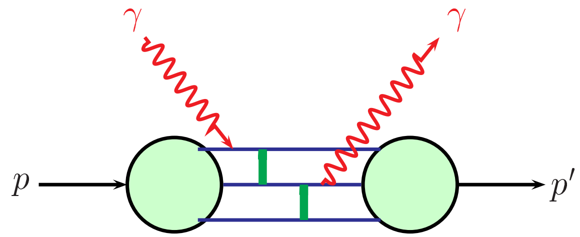
expected to be suppressed

Three active partons



two hard gluons required

valence quark appr. (blob decays into two)



at least

Brodsky-Lepage factorization (leading twist)

hard process: $\gamma qqq \to \gamma qqq$, soft physics: DA $\Phi_p = \Phi_p(x_1, x_2, x_3)$

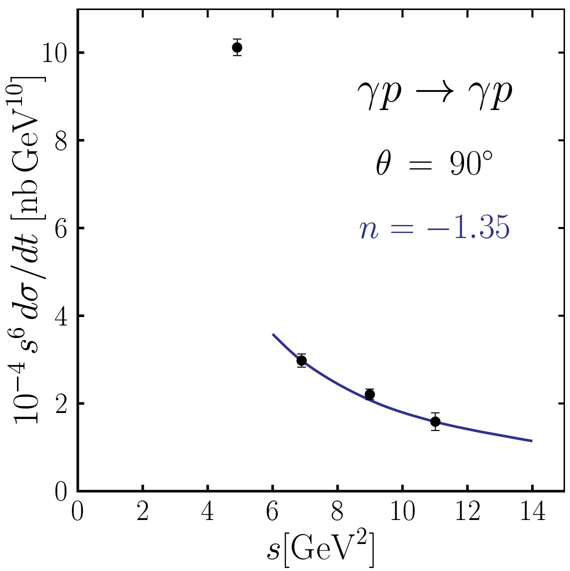
asymptotically dominant, handbag formally a power correction

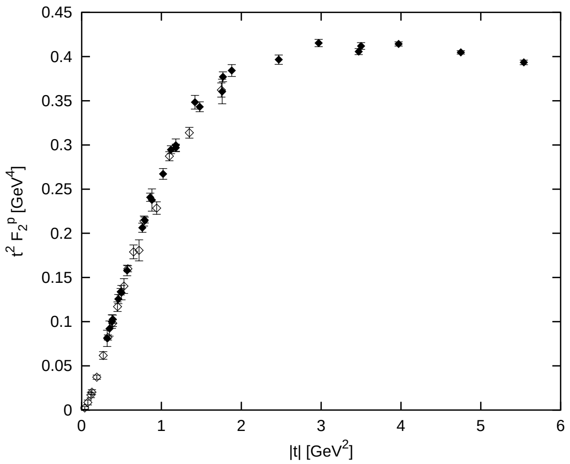
strongly suppressed for t of order of $10\mathrm{GeV}^2$ $(10^{-2} - 10^{-3})$

onset of leading-twist region probably above $-t(-u) > 100\,\mathrm{GeV}^2$

Dimensional counting

Matveev et al; Brodsky-Farrar $\mathcal{O} \propto \frac{\Psi_1 \cdots \Psi_m}{Q^{n(m)}}$ (+pert.logs) for $Q^2 \to \infty$





$d\sigma/dt(\gamma p \to \gamma p, \theta fixed) \sim s^{-(7\cdots 8)}$ s^{-6}

$F_2^p(t) \sim t^{-2}$ t^{-3}

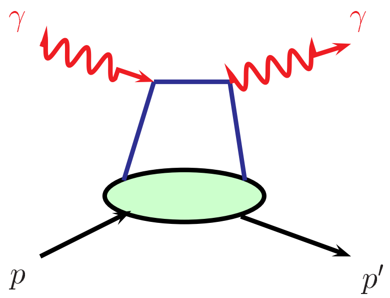
$F_1^d(t) \sim t^{-3}$ t^{-2}

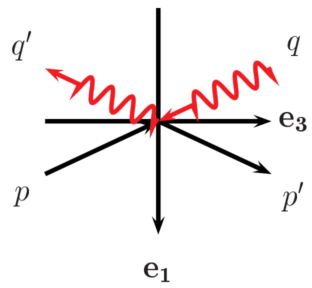
$\sigma(\gamma\gamma \to p\bar{p}) \sim s^{-7.2}$ s^{-5}

$\sigma(\gamma\gamma \to \pi^+\pi^-) \sim s^{-3.95}$ s^{-3}

$\sigma(\gamma\gamma \to K^+K^-) \sim s^{-3.65}$ s^{-3}

The handbag contribution to WACS





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

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

typical hadronic scale

- work in a symmetric frame:

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

- assumption of soft contribution:

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

- consequences

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

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

  collinear with parent hadrons

  and $x_j, x'_j \simeq 1$

- physical situation: hard photon-parton scattering and

  soft emission and reabsorbtion of partons by hadrons

The Compton amplitudes

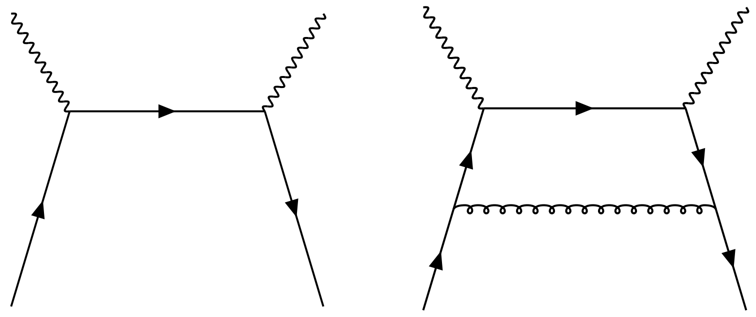
$$\mathcal{M}_{\mu'+,\mu+} = 2\pi\alpha_{elm}\Big\{\mathcal{H}_{\mu'+,\mu+}\big[R_V + R_A\big] + \mathcal{H}_{\mu'-,\mu-}\big[R_V - R_A\big]\Big\}$$

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

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

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

$\mathcal{H}(s,t)$: NLO $\gamma q \to \gamma q$ amplitudes $(+\ \gamma g \to \gamma g$, $R_i^g)$



Radyushkin hep-ph/9803316

DFJK hep-ph/9811253

Huang-K-Morii hep-ph/0110208

GPD analysis - what can be done?

DFJK hep-ph/0408173 (similar Guidal et al hep-ph/0410251)
analogue to PDF analyses

use all available data on $G_M^p\,, G_M^n\,, G_E^p\,, G_E^n\, (\Rightarrow F_1^p\,, F_1^n\,, F_2^p\,, F_2^n)\,, F_A$

exploit sum rules at $\xi = 0$

$$F_1^{p(n)}(t) = \int_0^1 dx \Big[e_{u(d)}\, H_v^u(x,t) + e_{d(u)}\, H_v^d(x,t) \Big] \qquad F_2 \Rightarrow E_v$$

$$F_A(t) = \int_0^1 dx \Big[\widetilde{H}_v^u(x,t) - \widetilde{H}_v^d(x,t) \Big] + 2\int_0^1 dx \Big[\widetilde{H}^{\bar{u}}(x,t) - \widetilde{H}^{\bar{d}}(x,t) \Big]$$

$H_v = H^q - H^{\bar{q}}$

$s - \bar{s}$, $c - \bar{c}$ and sea quark contribution to F_A neglected, probably very small

in order to determine $H_v^{u,d}\,, \widetilde{H}_v^{u,d}\,, E_v^{u,d}$

in a strict mathematical sense an ill-posed problem BUT

Motivation of the ansatz for GPDs

ANSATZ: $H_v^q(x,t) \;=\; q_v(x)\,\exp\left[f_q(x)t\right]$

$$f_q = \left[\alpha' \log(1/x) + B_q\right](1-x)^{n+1} + A_q\, x(1-x)^n$$

$\alpha' = 0.9\,\mathrm{GeV}^{-2}$ (fixed) $\qquad n = 1, 2$ (favored, confinement)

$q_v(x)$ from CTEQ (INPUT)

Motivation:

for large $-t$ and x: overlaps of Gaussian LC wavefunctions

$$H_v^q(x,t) \;\rightarrow\; \exp\left[a^2 t \frac{1-x}{2x}\right] q_v(x)$$

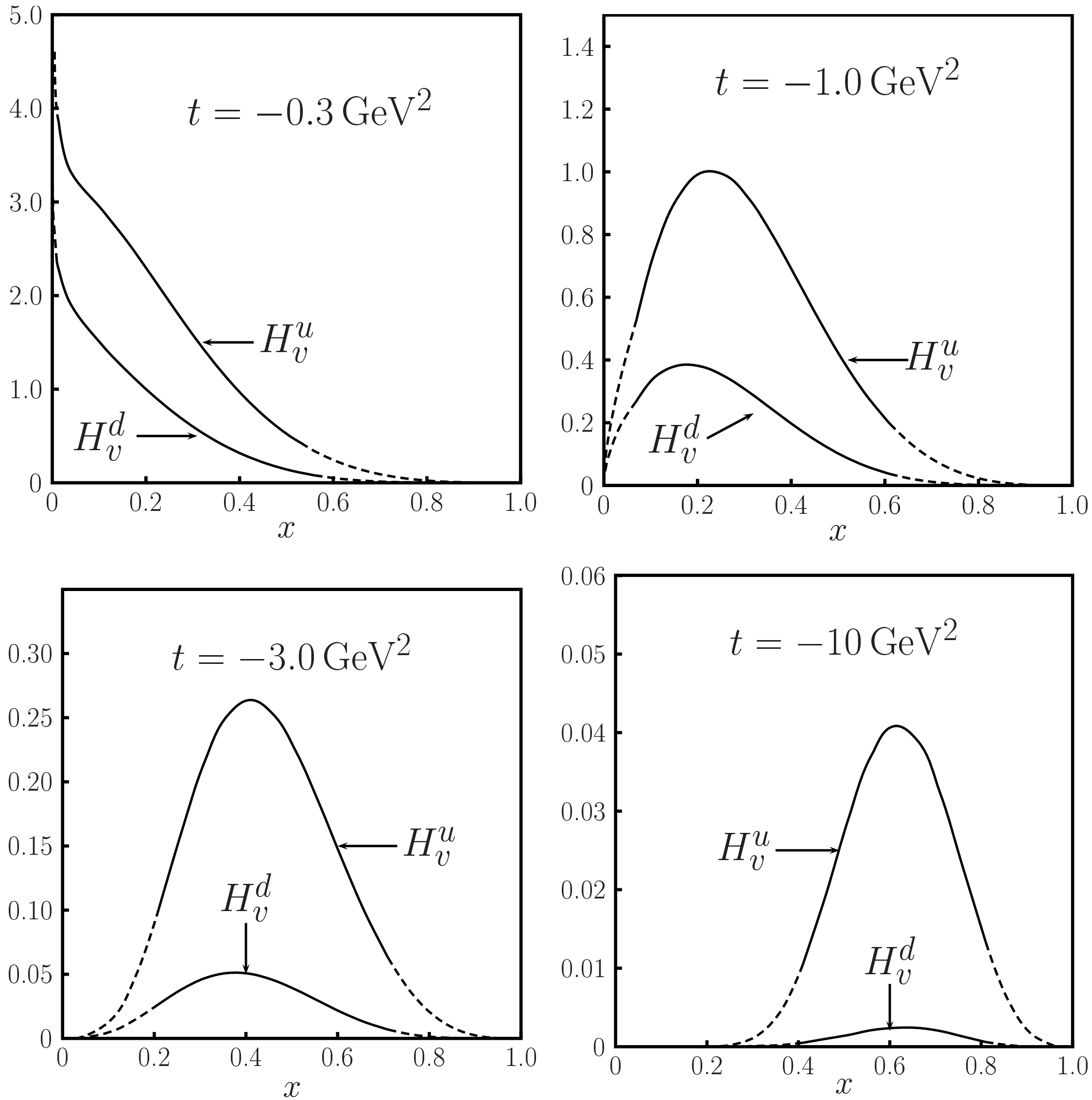
low $-t$, very small x: Regge behaviour expected

$$H_v^q(x,t) \;\rightarrow\; x^{-\alpha(0)} \exp\left[\alpha' t\, \log(1/x)\right]$$

criteria for good parameterization (met by ansatz):

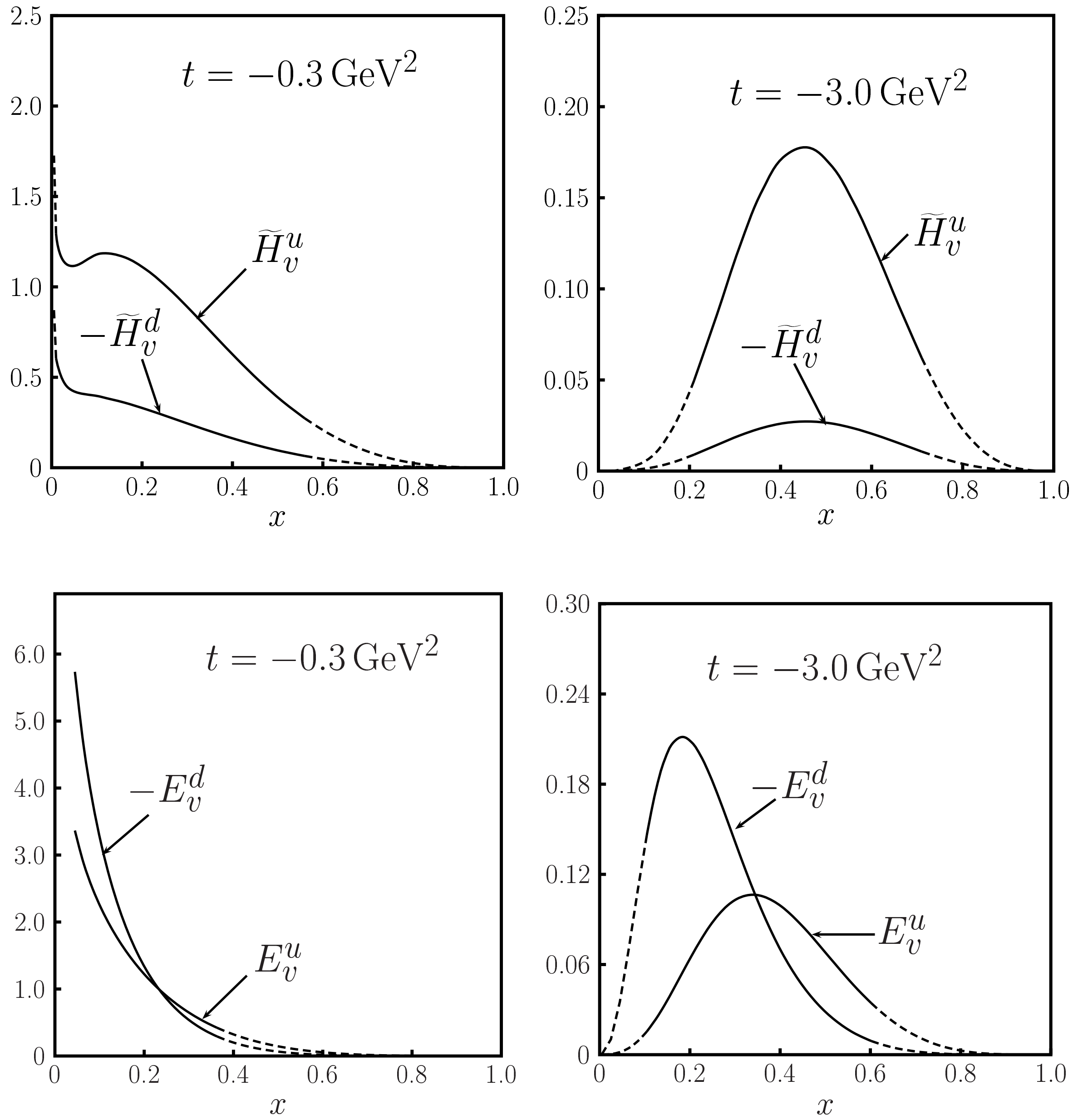
- simplicity
- consistency with theor. and phenom. constraints
- plausible interpretation of parameters (if possible)
- stability with respect to variation of PDFs
- stability under evolution (scale dependence of GPDs can be absorbed into parameters)

The GPD H ($\mu = 2\,\mathrm{GeV}$)



at large t only a narrow range of large x contributes to sum rule

The GPDs $\widetilde{H}$, E $(\mu = 2\,\mathrm{GeV})$

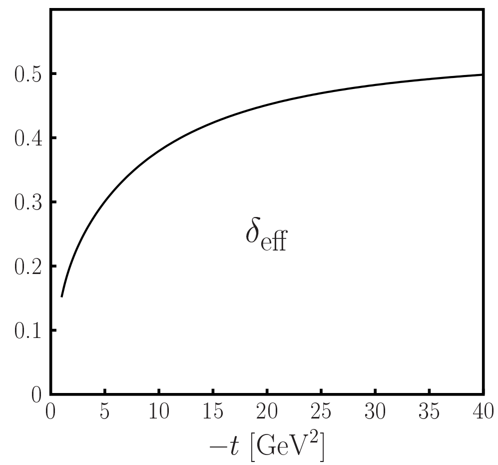


Feynman mechanism

k, k' momenta of active parton (before and after it is struck)
l momentum of spectator system; Λ typical hadronic scale
soft region: $1-x \sim \Lambda/\sqrt{|t|}$, $|k^2|, |k'^2| \sim \Lambda\sqrt{|t|}$ Feynman mechanism applies
ultrasoft: $1-x \sim \Lambda/|t|$, $|k^2|, |k'^2| \sim \Lambda^2$

large $t \Leftrightarrow$ large x: approx.: $q_v \sim (1-x)^{\beta_q}$, $f_q \sim A_q(1-x)^n$
Saddle point method: $1-x_s = \left(\frac{n}{\beta_q} A_q|t|\right)^{-1/n}$, $h^q_{1,0} \sim |t|^{-(1+\beta_q)/n}$
(similar to Drell-Yan)
$n=2$: x_s in soft region and in sensitive x-region $\Rightarrow$ early onset of power beh. ($t \simeq 5\,\mathrm{GeV}^2$)

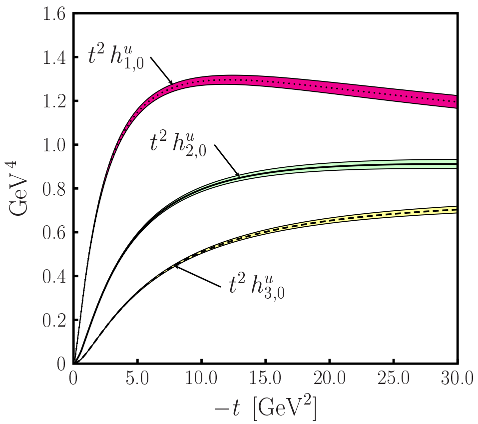
$n=1$: x_s in ultrasoft region (suspect - confinement!)
requires large t in order to have x_s in sensitive region
power behaviour of $h^q_{1,0}$ does not set in before
$-t \simeq 30\,\mathrm{GeV}^2$

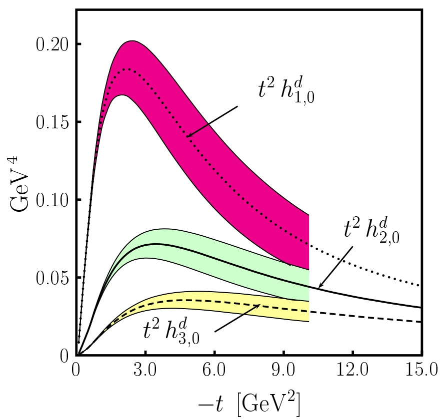


Testing the power laws:
eff. power $\delta_{\mathrm{eff}} = t\frac{d}{dt}\log[1-\langle x\rangle_t]$

soft region: $\delta_{\mathrm{eff}} = 1/2$ ultrasoft: $\delta_{\mathrm{eff}} = 1$ $n=1,2$ practically same δ_{eff} in fit
fit implies dominance of Feynman mechanism

Moments





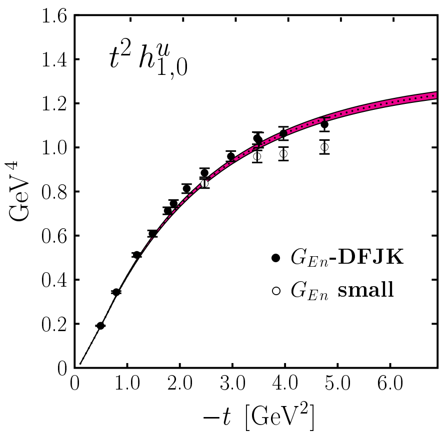
$h^q_{1,0} \sim |t|^{-(1+\beta_q)/n}$

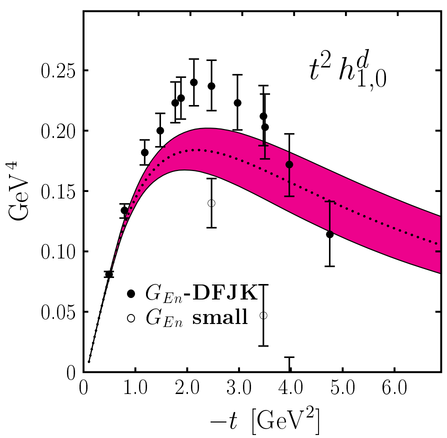
CTEQ PDFs:

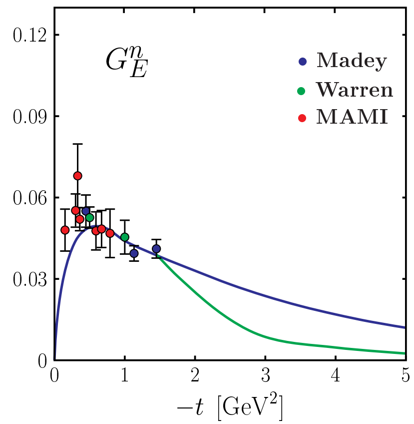
$\beta_u \simeq 3.4,\ \beta_d \simeq 5$

dimensional counting?

'pQCD'?





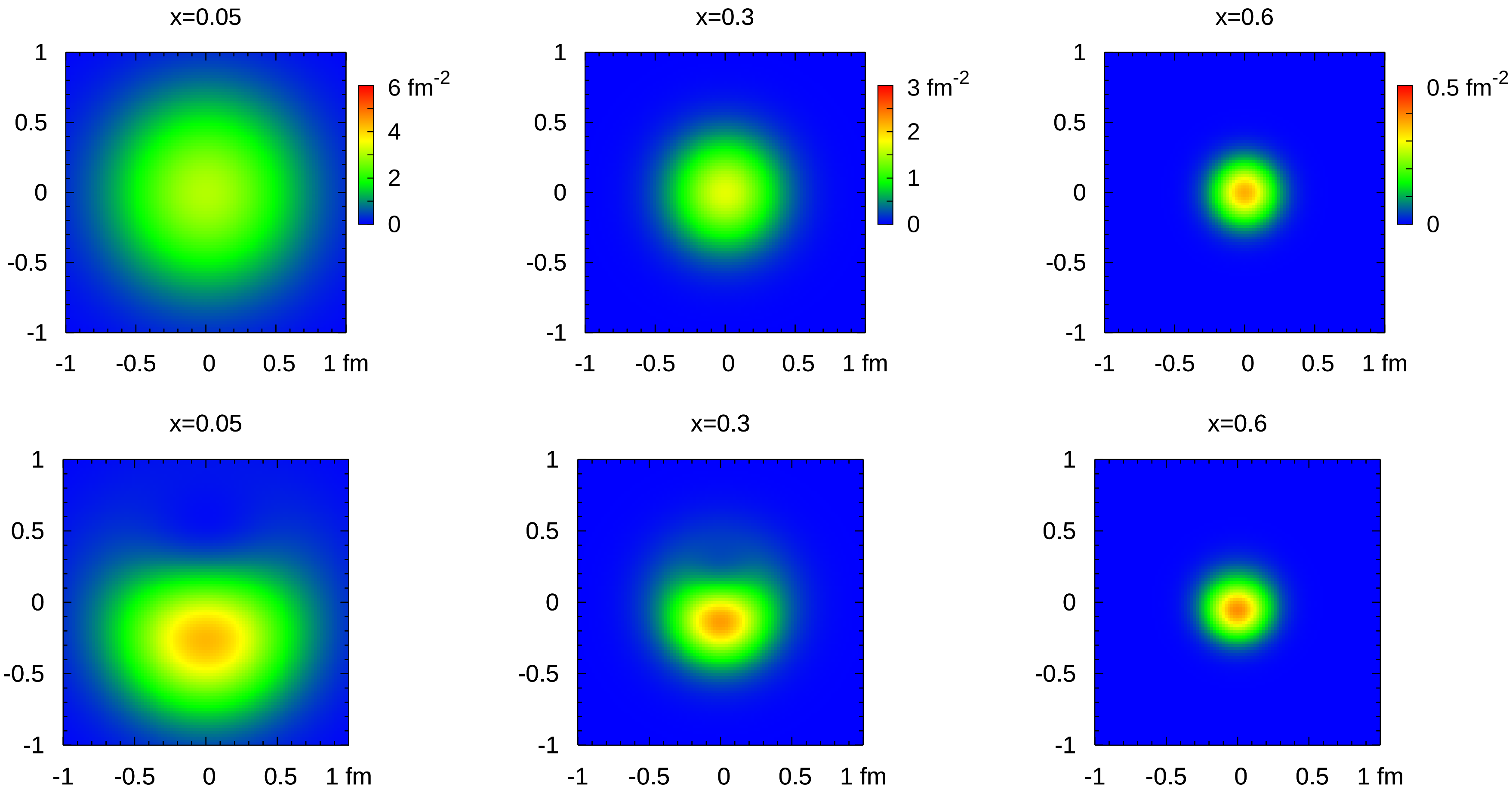


(preliminary CLAS data on G^n_M used)

dominance of u over d in FF at large t corresponds to that in PDFs at large x

except G^n_E is much larger than expected wait for JLab

Tomography of d_v quarks



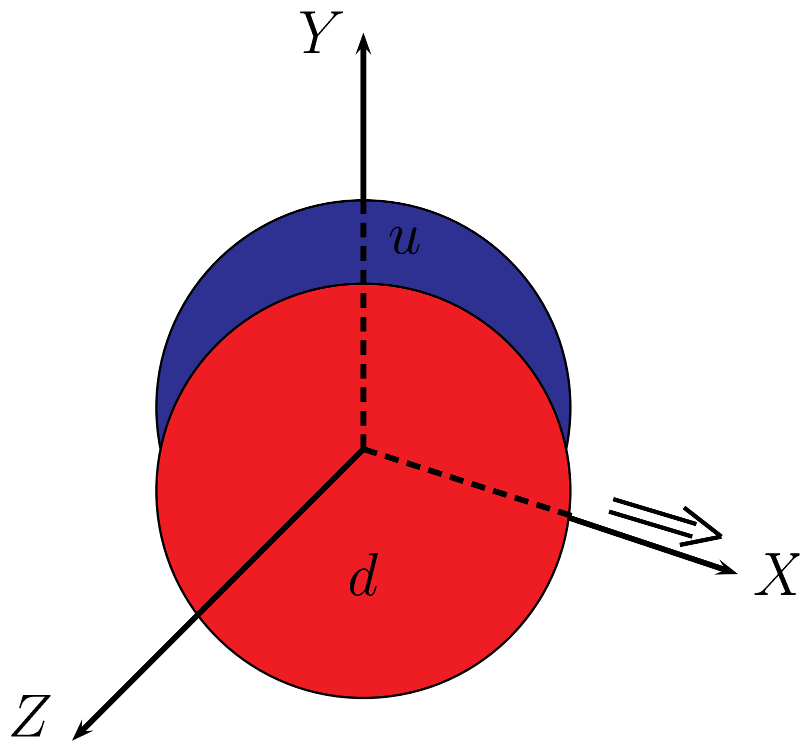
Fourier transform, e.g.: $q(x,\xi,\mathbf{b}) = \int \frac{d^2\mathbf{\Delta}}{(2\pi)^2}\, e^{-i\mathbf{b}\cdot\mathbf{\Delta}}\, H^q(x,\xi,t=-\Delta^2)$

$q(x,\xi=0,\mathbf{b})$ probability to find a quark q with long. momentum fraction x at transverse position $\mathbf{b}$ (Burkardt)

$$q_v^X(x,\mathbf{b}) = q_v(x,\mathbf{b}) - \frac{b^y}{m}\frac{\partial}{\partial\mathbf{b}^2} e_v^q(x,\mathbf{b})$$

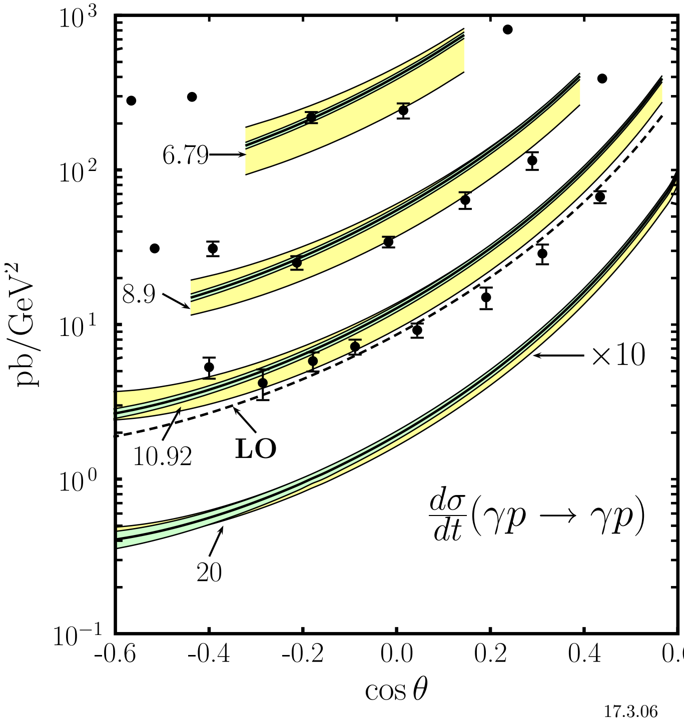
flavor segregation

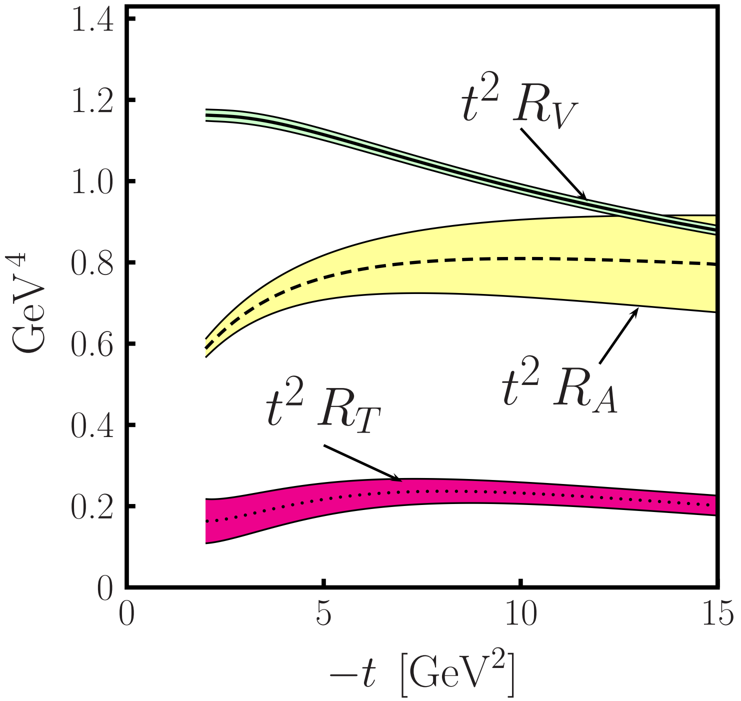
in transversely polarized proton



responsible for asymmetries in e.g. $p \uparrow p \longrightarrow \pi^{\pm}$?

The Compton cross section

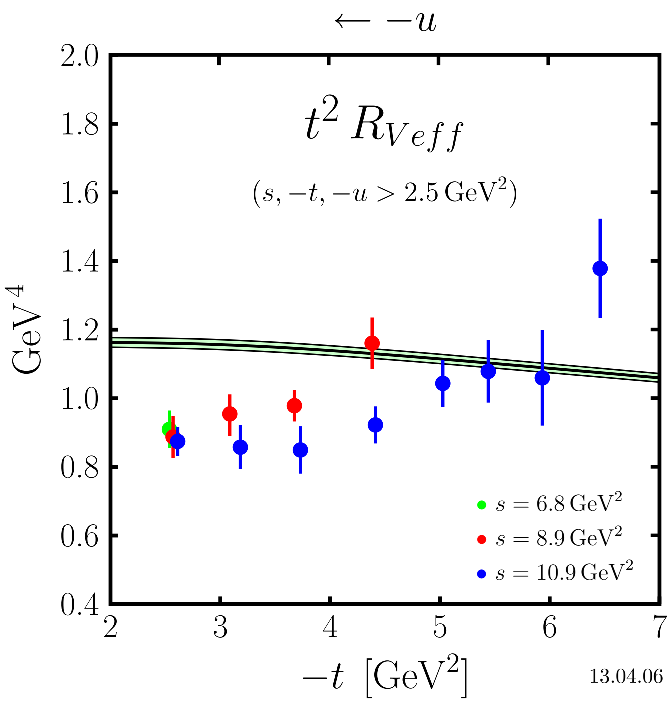




$$\frac{d\sigma}{dt} = \frac{d\hat{\sigma}}{dt}\left\{\frac{1}{2}\,\frac{(s-u)^2}{s^2+u^2}\left[R_V^2(t) + \frac{-t}{4m^2}\,R_T^2(t)\right] + \frac{1}{2}\,\frac{(s+u)^2}{s^2+u^2}\,R_A^2(t)\right\} + \mathcal{O}(\alpha_s)$$

$\frac{d\hat{\sigma}}{dt}(s,t)$ Klein-Nishina cross section data: JLab E99-114

The onset of factorization



extract from Jlab E99-114 data

$$R_V^{\text{eff}} = R_V \sqrt{1 + \frac{-t}{4m^2} \frac{R_T^2}{R_V^2}}$$

FACTORIZATION:

R_V^{eff} should not depend on s

provided $-t, -u$ are sufficiently large

seems to hold for $\lesssim 2.5\,\mathrm{GeV}^2$

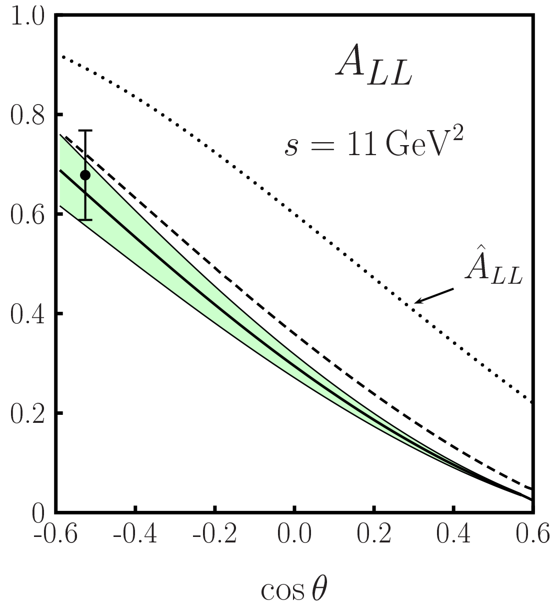
target mass corr. not shown

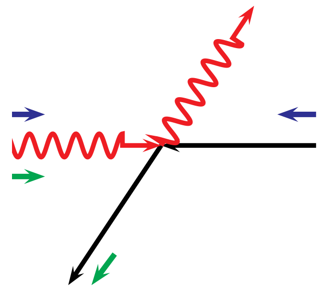
Comparison with result from GPD analysis - not too good at small $-t$

possible reasons: $\langle x \rangle$ too small, power corrections?

Feynman mechanism (exponential t dependence) seems to be favored

Spin correlation $A_{LL}, K_{LL}, A_{LS}, K_{LS}$





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

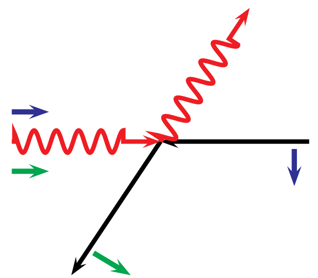
$$A_{LL} = K_{LL} \simeq \hat{A}_{LL}\,\frac{R_A}{R_V}$$

JLab E99-114 data at $E_\gamma = 3.23\mathrm{GeV}$: $\cos\theta = -0.5,\ t = -4\,\mathrm{GeV}^2,\ u = -1.14\,\mathrm{GeV}^2$

$$\hat{A}_{LS} = 0$$

$$A_{LS} = -K_{LS} \simeq \frac{R_A}{R_V}\,\hat{A}_{LL}\,\Big(\frac{\sqrt{-t}}{2m}\,\frac{R_T}{R_V} - \beta\Big)$$

$$\beta = \frac{2m}{\sqrt{s}}\,\frac{\sqrt{-t}}{\sqrt{s}+\sqrt{-u}}$$



$$K_{LS} = 0.111 \pm 0.078 \pm 0.04 \quad \text{(exp)}$$

$$= 0.10 \pm 0.02 \qquad \text{(theory)}$$

Summary

- There are many applications of the handbag approach to space- and time-like wide-angle exclusive process; seems to work reasonable well for momentum transfers of the order of 10 GeV^2
- First attempt to extract GPDs from form factor data ($F_1^{p,n}$, $F_2^{p,n}$, F_A) in analogy to analyses of PDFs
- On the basis of a physically motivated parameterization information on $H, \widetilde{H}, E$ for valence quarks and at $\xi = 0$ has been extracted
- Improvements required: need F_1^n, F_2^n (CLAS prel)
  F_2^p at larger t (present, upgraded Jlab)
  other moments as input: WACS at upgraded Jlab
  lattice QCD (reliable extrapol. to chiral limit required)
- predictions for WACS with soft form factors known from recent GPD analysis in good agreement with experiment
- the handbag approach also applies to time-like processes
  $\gamma\gamma \to B\overline{B}, M\overline{M}$, $p\bar{p} \to \gamma\gamma, \gamma M$