Hard Exclusive Scattering at JLab

P. Kroll

Fachbereich Physik, Universität Wuppertal

Newport News, May 2007

Outline:

- **The ERBL factorization scheme**
- **Handbag factorization**
- **Deeply virtual exclusive scattering**
- **GPD analyses**
- **Wide-angle exclusive scattering**
- **Outlook: Determination of GPDs**

Interest in large $p_\perp$ physics

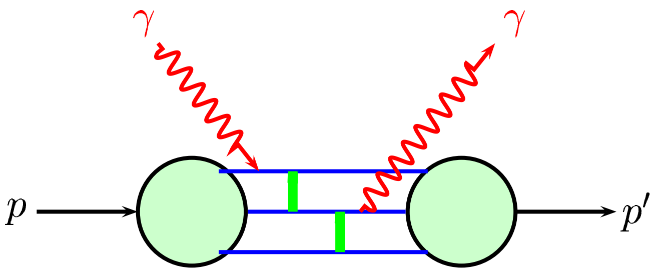
- scattering off constituents, i.e off quarks/partons
- scattering under control of QCD (and QED)
- question: are we able to calculate observables?
- decisive help from factorization properties of QCD:

  if a hard scale is available (e.g. large $p_\perp$)
  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)

rigorous proofs of factorization in some cases
hypothesis in others (often with good arguments)

The ERBL factorization scheme

Efremov-Radyushkin (80), Brodsky-Lepage (80)



hard process: e.g. $\gamma qqq \to \gamma qqq$

all partons participate in hard sc.

(in graphs: connections by hard gluons)

partons move collinearly with parent hadron

and are quasi on-shell

soft hadron-parton transitions:

Distr. Amplitudes $\Phi = \Phi(x_1, ...x_N)$

amplitudes/FFs: convolution of DAs and hard sc. amplitudes

$$\mathcal{M} \sim \Phi_p \otimes \mathcal{H} \otimes \Phi_p$$

lowest (valence) Fock state dominates at large scales

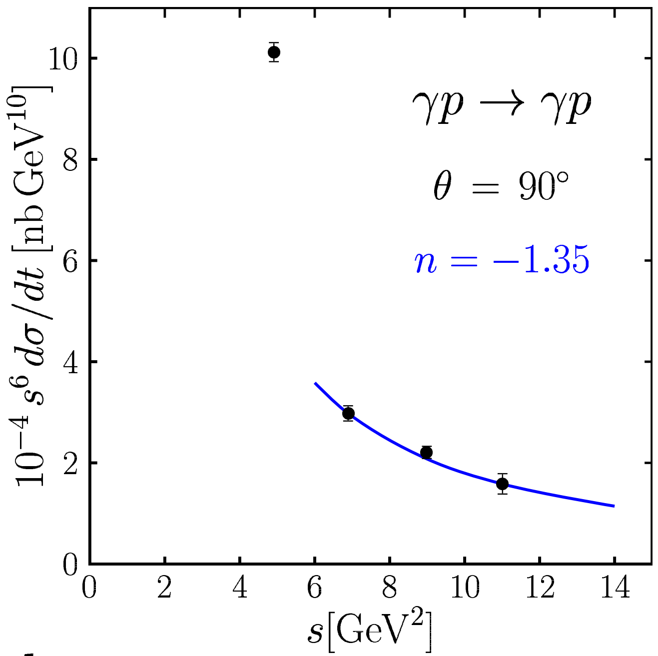
Dimensional counting

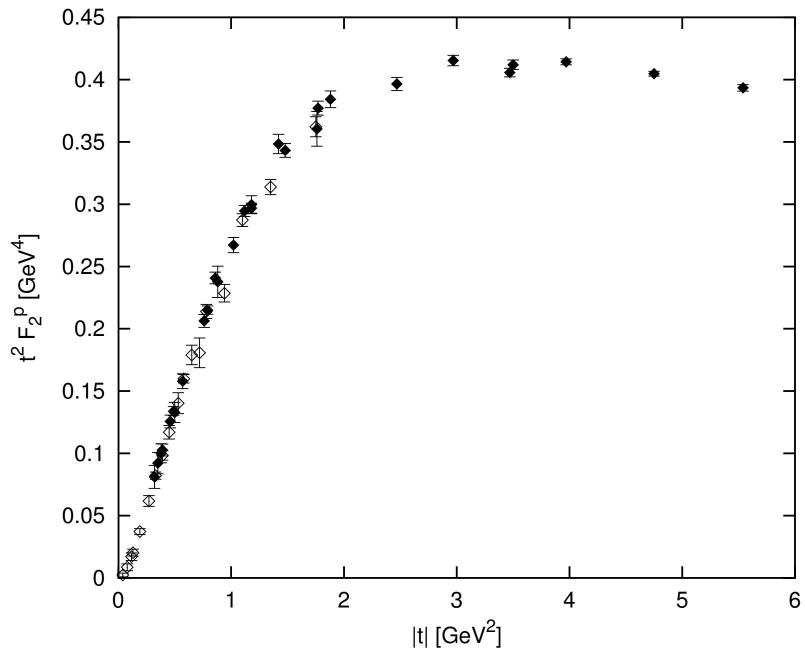
Matveev *et al* (73); Brodsky-Farrar (73)

at short distances/large Q^2: - observ. exhibit scaling (modified by pert. logs)

scaling often holds approximately but no evidence for logs

recent precise data are in conflict with scaling (Q^2 too low ?)





$$\frac{d\sigma}{dt}(\theta fixed) \sim s^{-(7\cdots 8)} \qquad (s^{-6}) \qquad\qquad F_2^p(t) \sim t^{-2} \qquad (t^{-3})$$

data: Hall A coll. (07) Hall A coll. (99,01,02) (large $-t$)

Applications of ERBL factorization scheme

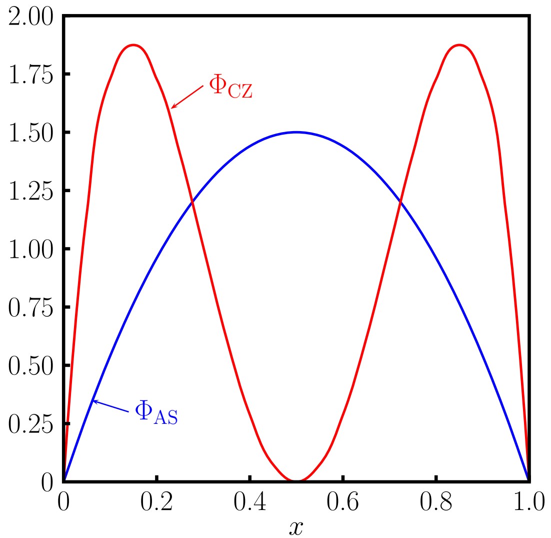
- elm. FFs (π, p, $p \to \Delta$, $\cdots$)
- wide-angle Compton scattering
- wide-angle photoproduction of mesons
- time-like processes
- $\cdots$

with very few exceptions - size of ERBL contribution too small

Ways out ?

more soft physics needed at scales of order $10\,\mathrm{GeV}^2$?

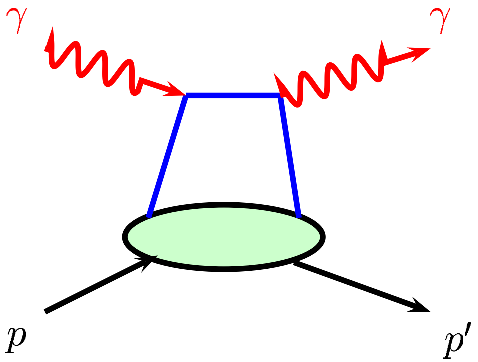
- use DAs concentrated in end-point regions Chernyak-Zhitnitsky (82) Isgur *et al* (84,89), Radyushkin (84): theor. inconsistent
  pert. theory breaks down in end-point regions
  (typical gluon virtuality $\langle x\rangle^2 Q^2$)
- large soft overlap contributions -Feynman mechanism (mimic dim. scaling)



or more pert. physics?
higher orders, resummation
NLO not sufficient

pion DA

The new idea - handbag factorization scheme



only one active parton (others are spectators)

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

soft, non-perturbative physics: GPDs

two classes of hard exclusive reactions:

DEEP VIRTUAL Q^2 large $-t/Q^2 \ll 1$
(DVCS, DVLM, $\gamma^*\gamma \to H\overline{H}$, $\gamma^* p \to \pi^+\pi^- p$, $\gamma p \to \gamma^* p$, $\gamma^*\gamma^* \to M\overline{M}$)

WIDE-ANGLE $-t(-u)$ large $Q^2/(-t) < 1$ complementary
(RCS, VCS, $\gamma p \to MB$, $\gamma\gamma \to H\overline{H}$, $p\overline{p} \to \gamma\gamma$, $p\overline{p} \to \gamma M$)
GPDs link inclusive and exclusive physics
same type of partons appear in both types of processes

Generalized Parton Distributions

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

GPDs $H^q(x,\xi,t)$, $\widetilde{H}^q$, E^q, $\widetilde{E}^q$ (skewness: $\xi = \frac{p^+ - p'^+}{p^+ + p'^+}$)
(for parton helicity non-flip)

- reduction formulas: $H^q(x,0;0) = q(x)$; $\widetilde{H}^q(x,0;0) = \Delta q(x)$
- sum rules: $h_{10}^q(t) = \int_{-1}^{1} dx H^q(x,\xi,t)$; $F_1 = \sum_q e_q h_{10}^q$;
  $E^q \to F_2^q$; $\widetilde{H}^q \to F_A^q$; $\widetilde{E}^q \to F_P^q$

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

for parton helicity flip: 4 more GPDs H_T, $\widetilde{H}_T$, E_T, $\widetilde{E}_T$
practically unknown
hard to access since in general helicity flip subpressed in subprocesses

Moments

define $H_v^q = H^q - H^{\bar{q}}$ ($\xi = 0$ for simplicity)

$$F_{1v}^u(t) = h_{10v}^u(t) = \int_0^1 dx[H^u - H^{\bar{u}}] = 2F_1^p(t) + F_1^n(t)$$

$$F_{1v}^d(t) = h_{10v}^d(t) = \int_0^1 dx[H^d - H^{\bar{d}}] = 2F_1^n(t) + F_1^p(t)$$

analogously - Pauli FF measures first moment of $E_v^q = E^q - E^{\bar{q}}$

contribution from $s - \bar{s}$ neglected
moments known for a certain range of t from form factor data

At $t = 0$: $F_{1v}^u = 2\,, \quad F_{1v}^d = 1\,, \quad F_{2v}^u = \kappa_u = 1.67\,, \quad F_{2v}^d = \kappa_d = -2.03$
axial FF (from β decay): $\tilde{h}_{10v}^u = 0.926 \pm 0.014 \quad \tilde{h}_{10v}^d = -0.341 \pm 0.018$
at least for small $-t$ (for orientation):
$H_v^u > H_v^d > 0\,,\ \widetilde{H}_v^u > -\widetilde{H}_v^d > 0\,,\ E_v^u \simeq -E_v^d > 0$

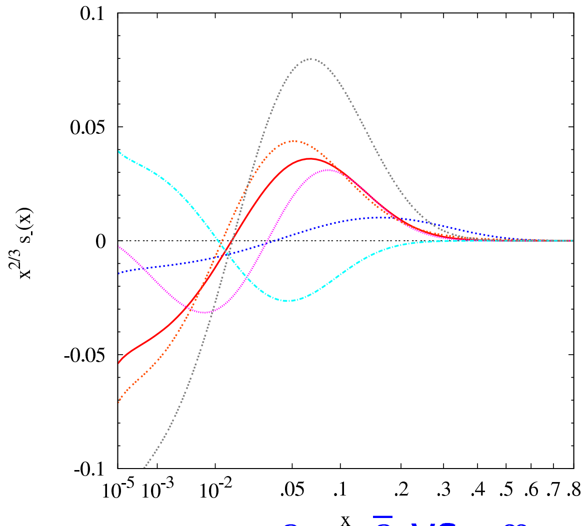
More moments

strangeness FF (g0, HAPPEX, A4, SAMPLE)

$-t \simeq 0.1 \cdots 1.0\,\mathrm{GeV}^2$

$F_1^s, F_2^s \longrightarrow h_{10}^s - h_{10}^{\bar{s}}, e_{10}^s - e_{10}^{\bar{s}}$ small?

errors of data are still large



$s - \bar{s}$ vs. x

CTEQ(07): weak indication for $s(x) \neq \bar{s}(x)$

important NuTeV $\nu/\bar{\nu}N \to \mu^{-/+}H_cX$

gluonic GPDs - information only from PDFs (combined with model t dep.)

H^g: very large at small $-t$ and small x ($\int_{x_0}^1 dx g(x) \to \infty$ for $x_0 \to 0$)

$\widetilde{H}^g$: related to Δg, not well determined but does not seem to be large

E^g: $\int_0^1 dx E^g(x,0,0) = -\sum_q \int_0^1 dx x E_v^q - 2\sum_q \int_0^1 dx x E^{\bar{q}}$

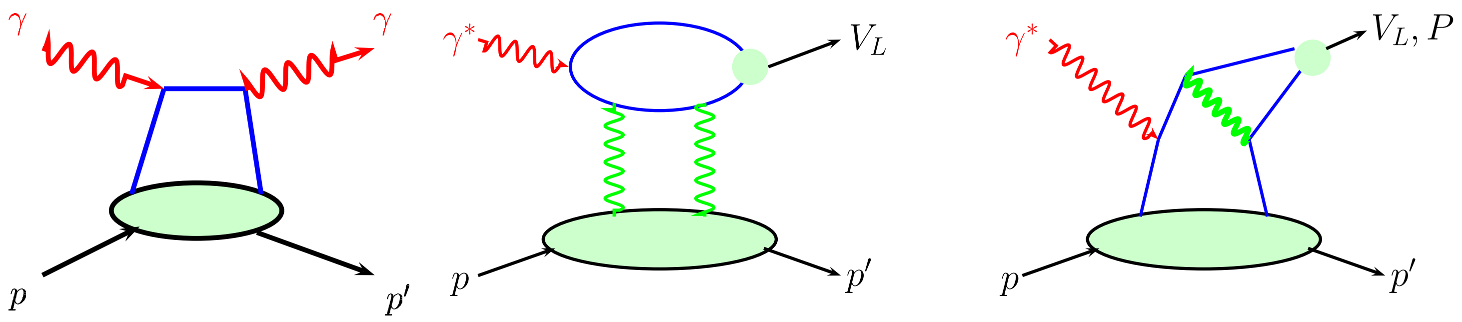
valence quark contribution small $\longrightarrow$ E^g probably less important than H^g

DVES

$ep \to e'p\gamma(V,P)$ to leading-twist (coll. appr.), LO pQCD accuracy

rigorous fact. proofs (Collins et al (97,98), Ji-Osborne (98), Radyushkin(96))

dominance of $L-L$ $(T-T)$ transitions in $\gamma^* \to VP$ $(\gamma^* \to \gamma)$



$$\mathcal{M}^{\gamma}_{+\nu',+\nu} \sim \sum_a e_a^2 \int_{-1}^{1} d\bar{x} \left[\frac{\mathcal{F}^a_{\nu'\nu} + \widetilde{\mathcal{F}}^a_{\nu'\nu}}{\bar{x} - \xi + i\epsilon} + \frac{\mathcal{F}^a_{\nu'\nu} - \widetilde{\mathcal{F}}^a_{\nu'\nu}}{\bar{x} + \xi - i\epsilon} \right]$$

$$\mathcal{M}^{M(q)}_{0\nu',0\nu} \sim \sum_a \mathcal{C}_V \int_{-1}^{1} d\bar{x} \left\{ \sum_\lambda \mathcal{H}^{M(q)}_{0\lambda,0\lambda}\, \mathcal{F}^a_{\nu'\nu} + \sum_\lambda \lambda \mathcal{H}^{M(q)}_{0\lambda,0\lambda}\, \widetilde{\mathcal{F}}^a_{\nu'\nu} \right\} + \text{gluon}$$

$$\mathcal{F}^a_{\nu\nu} = H^a - \frac{\xi^2}{1-\xi^2} E^a\,, \qquad \mathcal{F}^a_{-\nu\nu} = 2\nu \frac{\sqrt{t_0 - t}}{2m(1-\xi^2)} E^a\,, \quad \widetilde{\mathcal{F}} \to \widetilde{H}, \widetilde{E}$$

V_L: $\sum_\lambda \lambda \mathcal{H}_{0\lambda,0\lambda} = 0$, $P : \sum_\lambda \mathcal{H}_{0\lambda,0\lambda} = 0\,, \quad \xi \simeq x_{\rm Bj}/(2 - x_{\rm Bj})$

imaginary parts $\propto$ GPDs at $\xi = x$, real parts - convolutions

$\xi \simeq 10^{-3}$ HERA	$\simeq 10^{-2}$ COMPASS	$\simeq 10^{-1}$ HERMES	$\simeq 0.1 - 0.4$ JLab

gluon/sea $\cdots\cdots$ decreasing importance $\Longrightarrow$

valence $\cdots\cdots$ increasing importance $\Longrightarrow$

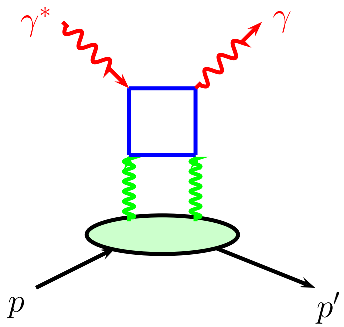
(based on GPDs constructed from PDFs through double distr. model)

γ production: valence + sea (to LO)
ρ^0, ω: gluon+sea+valence
ϕ: gluon +sea
J/Ψ: gluon
π^0: valence

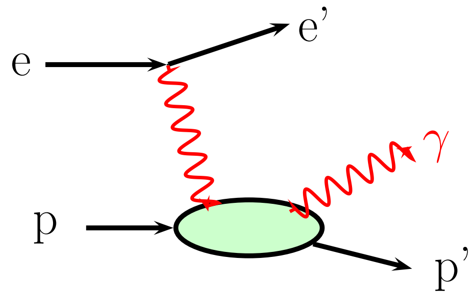
DVCS

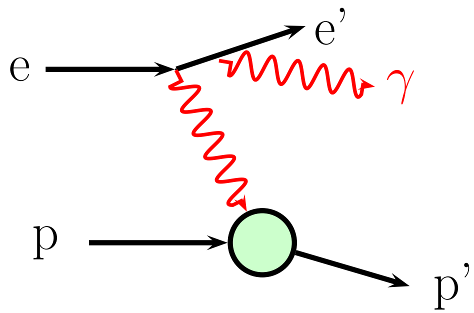
lot of exp. and theor. work devoted to this process, theor. cleanest process
for recent data - see following talks

- no photon helicity flip to LO, non-zero to NLO
  Diehl (01), Belitsky-Mueller (00), Hoodbhoy-Ji (98)
- in general all 4 quark GPDs contribute at LO in α_s
  unpol. DVCS at small ξ: mainly H
- all quarks contribute; neutron will help in flavor sep. (prel. data: E03-106)
- role of higher twist? (twist-3 Belitsky *et al* (01), Radyushkin-Weiss (00))
- a complication: enhanced NLO corr.
  gluonic GPD H contributes
  very large at low ξ, overcompensates α_s
  Belitsky-Müller (97,00), Ji-Osborn (98), ...



The Bethe-Heitler process





- BH calculable for given proton FF
- dominates in certain regions
- interf. region simplifies extraction of GPDs
- allows to study DVCS at amplitude level including phases
- lepton beams of both charges or a polarized beam/target: allow to filter out interference term

(CLAS(01,06), HERMES(01), HALL A(06))

Jlab Hall A coll. (06)

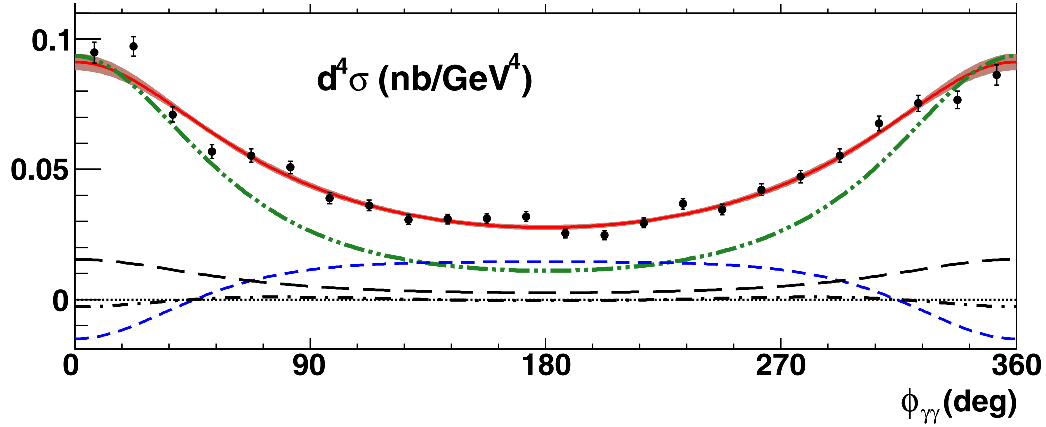
$\langle x_{\mathrm{Bj}} \rangle = 0.36$

$t = -0.27\,\mathrm{GeV}^2$

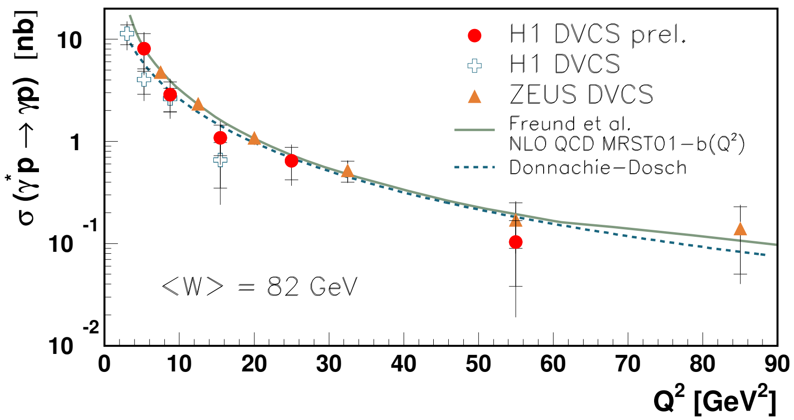
$Q^2 = 2.3\,\mathrm{GeV}^2$

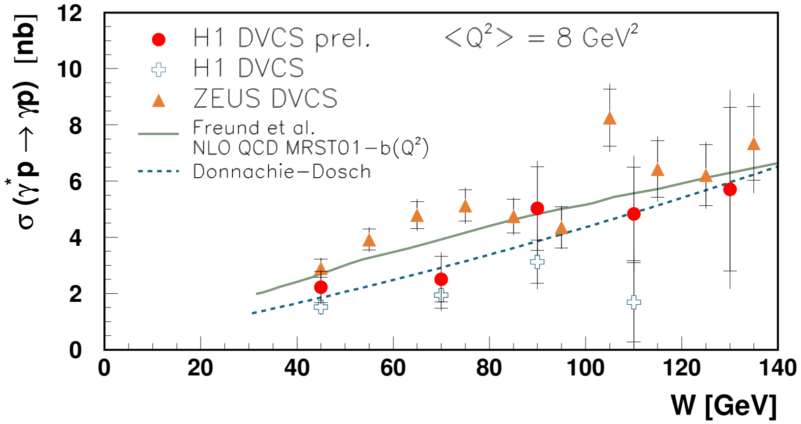
$|\mathrm{BH}|^2$ $|\mathrm{BH}+\mathrm{DVCS}|^2$

$\phi_{\gamma\gamma}$ azimithal angle



DVCS cross section





Freund *et al* (01)(02) NLO calculation

with H and $\widetilde{H}$ GPDs constructed via double distr. from MRST 01 PDFs

factorized t dependence with Q^2 dependent slopes

CTEQ6M doubles cross section

(but LO analyis with dual parameterization Guzey-Teckentrup (06))

for comparison:

color dipole model with soft and hard Pomeron Donnachie-Dosch (01)

alternative approaches not ruled out

DVEM

disadvantage - a second soft hadr. matrix element required (wave fct./DA)

advantage - V: only H, E P: only $\widetilde{H}$, $\widetilde{E}$

- mesons select their valence quarks from the proton
  important for flavor separation

large set of accurate data on V prod. available (HERA, HERMES, Jlab ...)

only preliminary data for π prod. (Jlab, HERMES)

mesons formed by one-gluon exchange to LO: $\mathcal{M} \propto \alpha_s$

(same graphs as for elm. FF of π - a bad omen)

warning: strong NLO corrections (Ivanov et al (04), DIS07: Diehl et al (07))

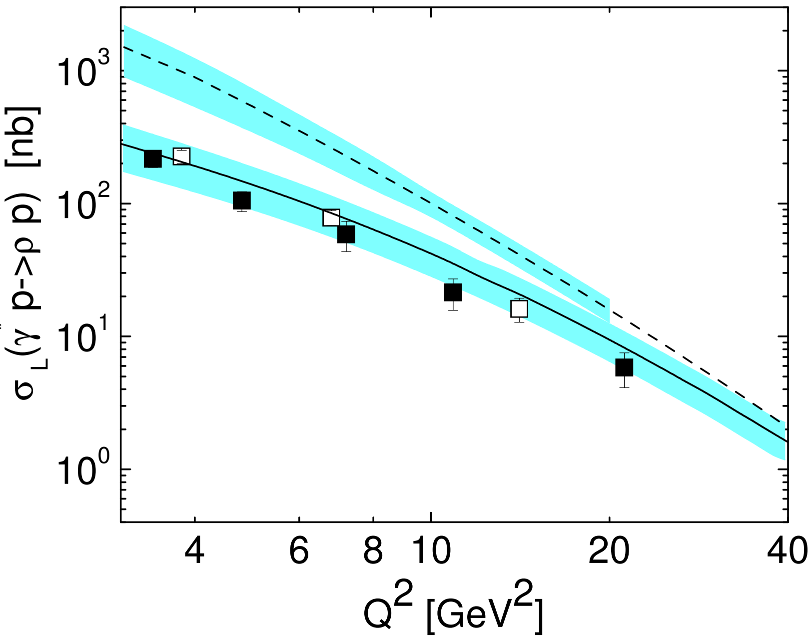
compensates LO contr. to large extent, NNLO and higher orders?

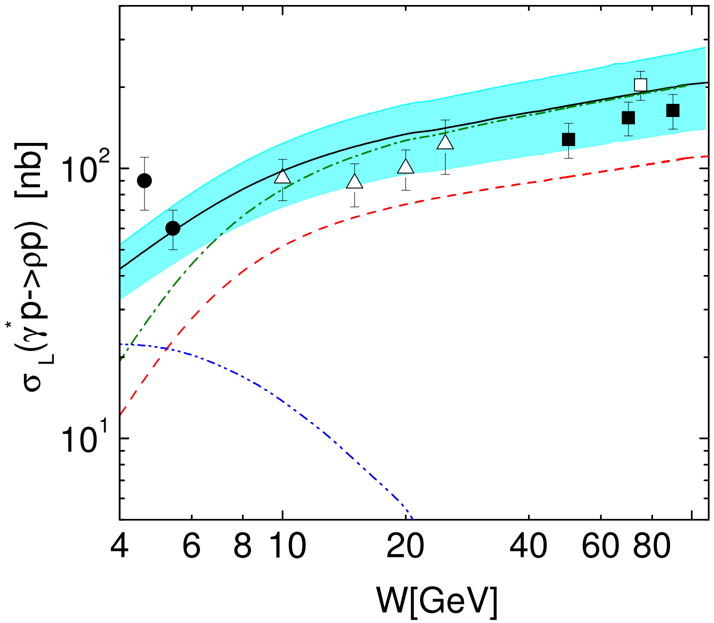
large $\ln(1/\xi)$ terms (BFKL type logs)

very small $x_{\rm Bj} \lesssim 10^{-3}$: huge NLO corrections even for $Q^2 \sim$ several GeV^2

moderate to large $x_{\rm Bj}$: moderate corrections as long as $Q^2 \gtrsim 4\,\mathrm{GeV}^2$

Example: $\sigma_L(\gamma^* p \to \rho p)$





$W = 75\,\mathrm{GeV}$ data: H1, ZEUS, $Q^2 = 4.0\,\mathrm{GeV}^2$ H1, ZEUS, E665, HERMES

double distr. model for GPDs (CTEQ6M) gluon+sea gluon val+(gluon+sea)-val

to leading-twist, LO pQCD accuracy: normalization fails

higher orders or power corrections (see also σ_T)?

power correction: suppression through quark transverse momentum

(modified pert. approach) Vanderhaeghen *et al* (98), Goloskokov *et al* (06)

GPD analysis - what can be done?

Diehl *et al* (04), Guidal *et al* (04), Ahmad *et al* (06)

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 $\xi = 0$ 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

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

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

$\alpha' = 0.9\,\mathrm{GeV}^{-2}$ (fixed); $n = 1, 2;$ $q_v(x)$ from CTEQ6 (INPUT)

(Guidal *et al*: $B_q = A_q = 0$, α' free, $n = 0$)

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

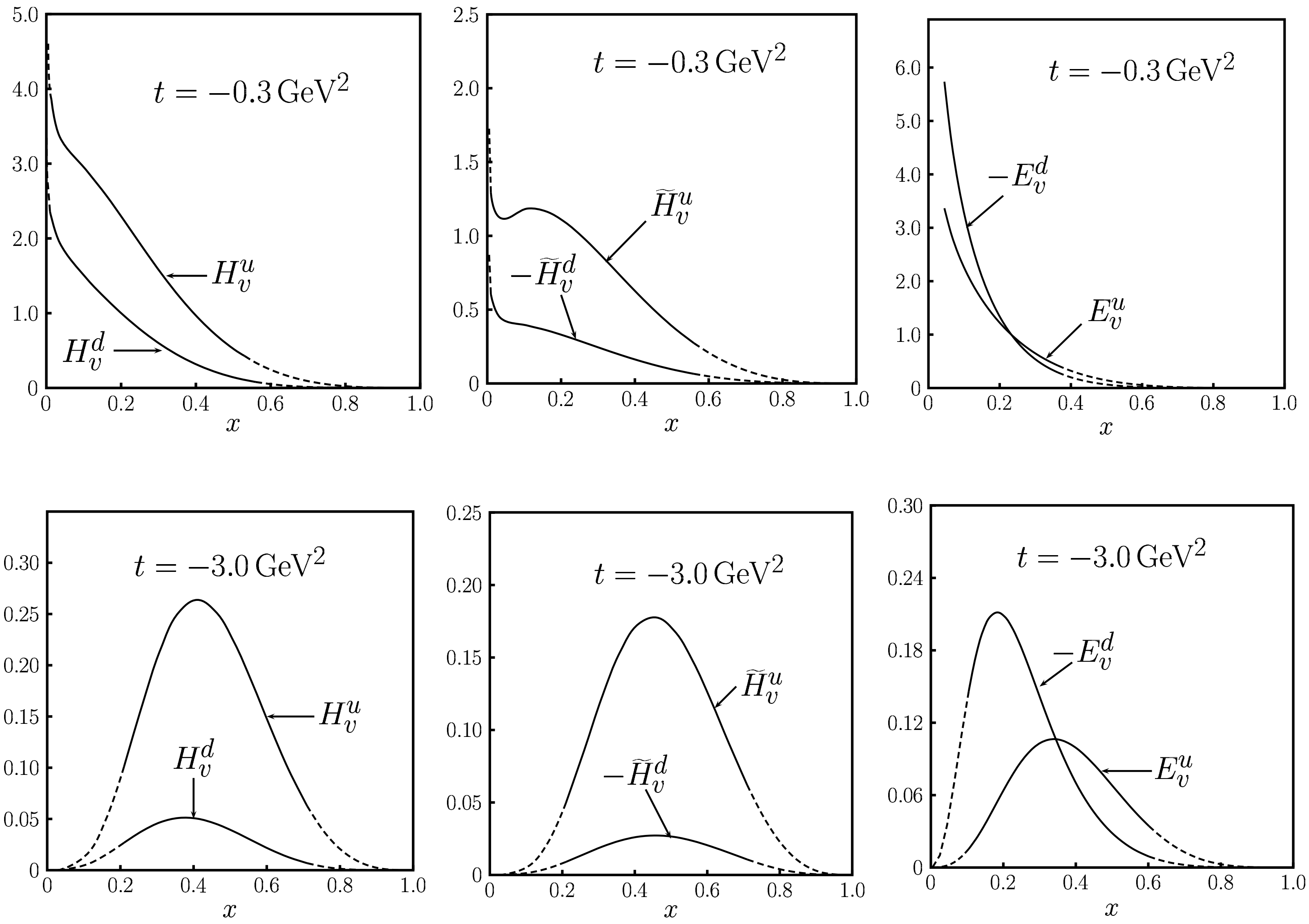
$H_v^q(x,t) \;\to\; \exp\left[a^2 t\,\frac{1-x}{2x}\right] q_v(x)$

low $-t$ and small x: double distr. ansatz for $\xi \to 0$

$H_v^q(x,t) \;\to\; q_v(x)\mathrm{e}^{[b+\alpha' \log(1/x)]t}\,, \quad q_v(x) \to x^{-\alpha(0)}$ for $x \to 0$

Regge behaviour (Landshoff *et al* (71), Feynman (72))

Results on the GPDs (at $\mu^2 = 4\,\text{GeV}^2$)



large $-t$: GPDs large in narrow region of large x

What do we learn about the proton from these GPDs?

take GPDs as examples

and show their physics potential

Ji's sum rule

valence quark contribution to sum rule for orbital angular momentum

$$\langle L_v^q \rangle = \frac{1}{2} \int_0^1 dx \Big[x E_v^q(x, \xi = 0, t = 0) + x q_v(x) - \Delta q_v(x) \Big]$$

$$\langle L_v^{u+d} \rangle = -(0.04 \div 0.12) \qquad \langle L_v^{u-d} \rangle = -(0.39 \div 0.46)$$

(at $\mu^2 = 4\,\mathrm{GeV}^2$)
opposite signs of u and d due to $E_v^u \simeq -E_v^d$

fair agreement with lattice results (Schierholz *et al* (05))

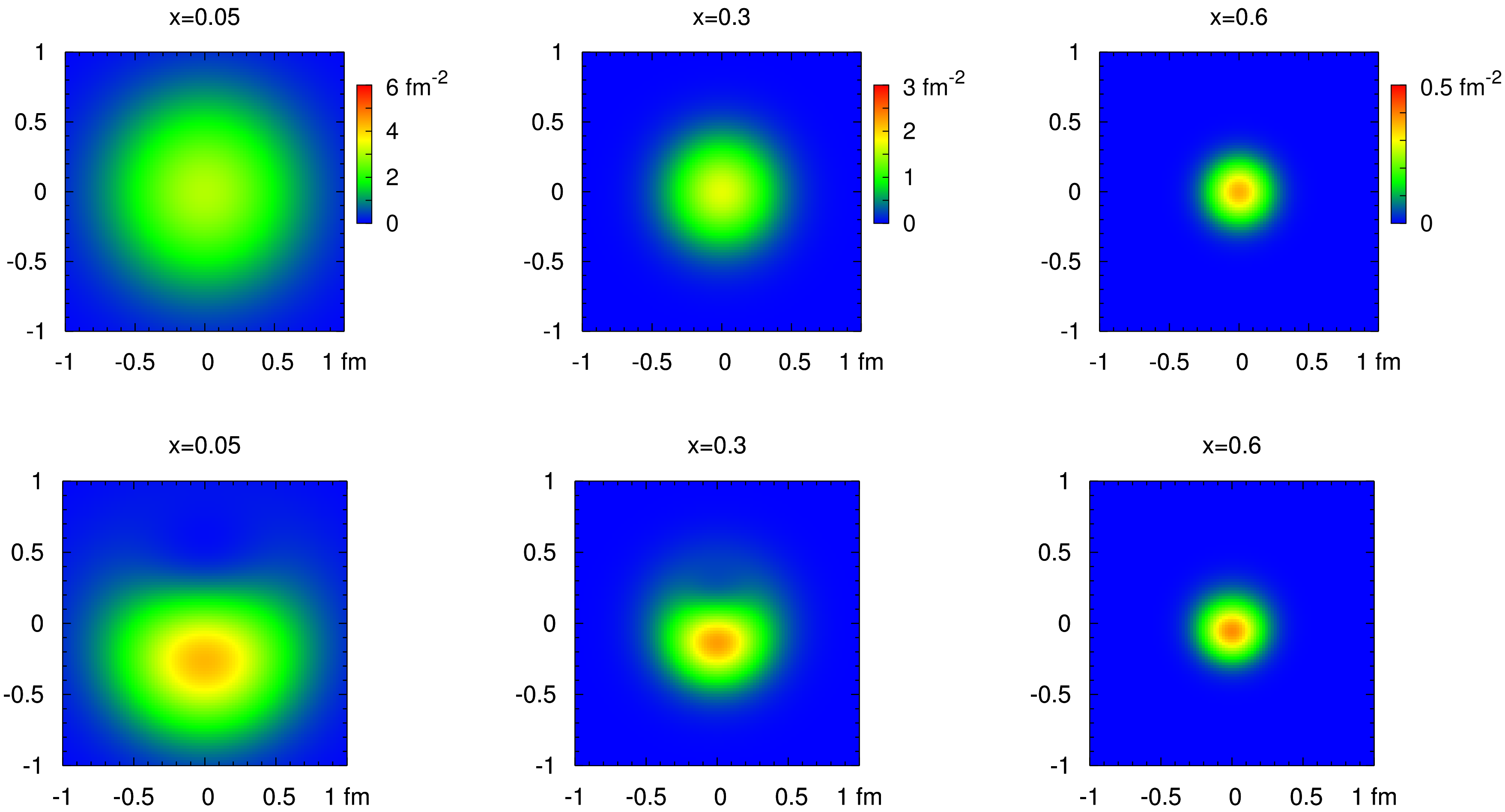
Fourier transform

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

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

Burkhardt (00),(03)

Density of d_v quarks



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

e_v contains non-zero orbital ang. mom.

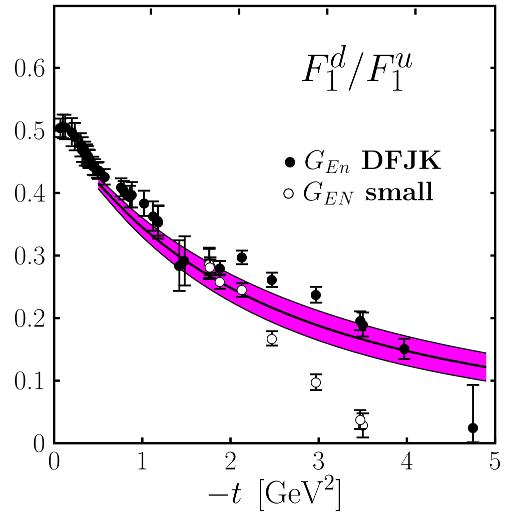
(remember $E_v^u \simeq -E_v^d$)

u_v pushed upwards

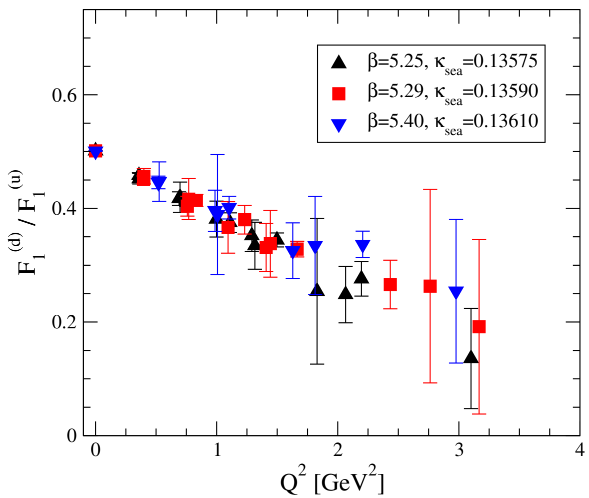
flavor segregation in trans. pol. proton

related to Sivers eff.?

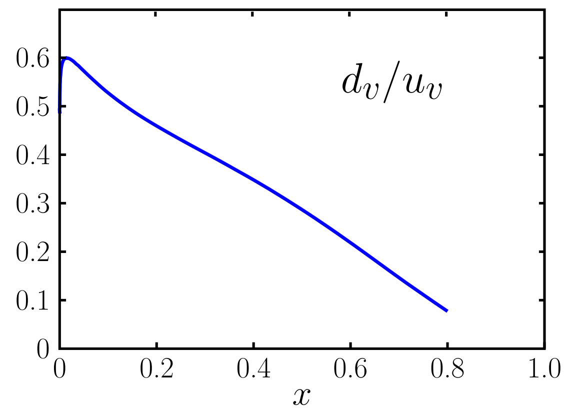
Ratio of d and u quark contributions to Dirac FF



form factor data



lattice (Göckeler et al (06))
$N_F = 2$, $m_\pi = 340\,\mathrm{MeV}$



CTEQ6M pdfs
at $Q^2 = 4\mathrm{GeV}^2$

behaviour of FF in Diehl *et al* (04) analyis: $h^q_{1,0} \sim |t|^{-(1+\beta_q)/2}$
CTEQ PDFs: $\beta_u \simeq 3.4$, $\beta_d \simeq 5$ $x \Longleftrightarrow t$ correlation
dominance of u over d in FF at large t corresponds to that in PDFs at large x
except G_E^n is much larger than expected (wait for E02-013 data)

The handbag contribution to WACS

work in frame where $\xi = 0$:

if $s, -t, -u \gg \Lambda^2$ (i.e. for c.m.s. scattering angles near 90°)

($\Lambda \sim \mathcal{O}(1\mathrm{GeV})$ is a typical hadronic scale)

Compton amplitudes factorize into
- subprocess amplitudes $\gamma q \to \gamma q$

and
- $1/x$ moments of GPDs (Compton FFs)

$$R_V(t) \simeq e_u^2 \int_0^1 \frac{dx}{x} H_v^u(x, \xi = 0, t) + e_d^2 \int_0^1 \frac{dx}{x} H_v^d(x, \xi = 0, t)$$

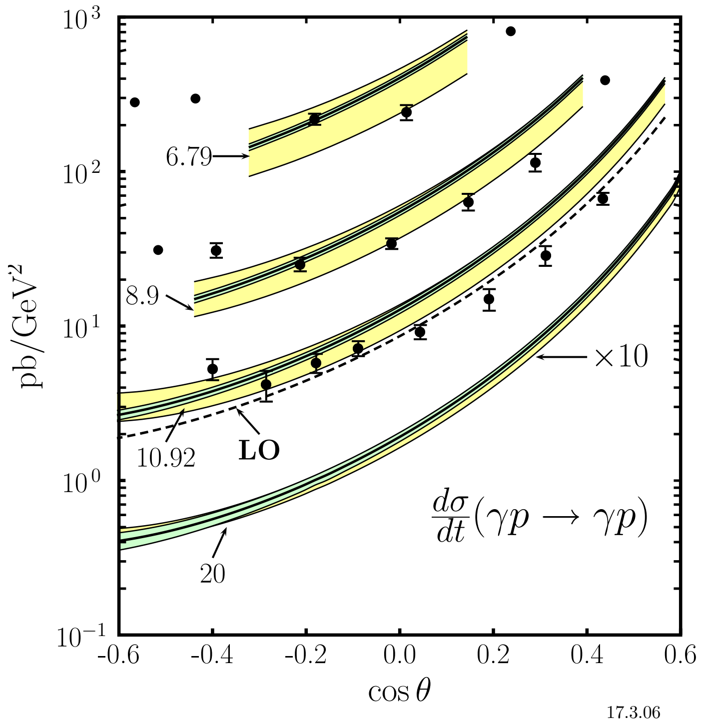
and analogously $\widetilde{H} \to R_A$, $E \to R_T$

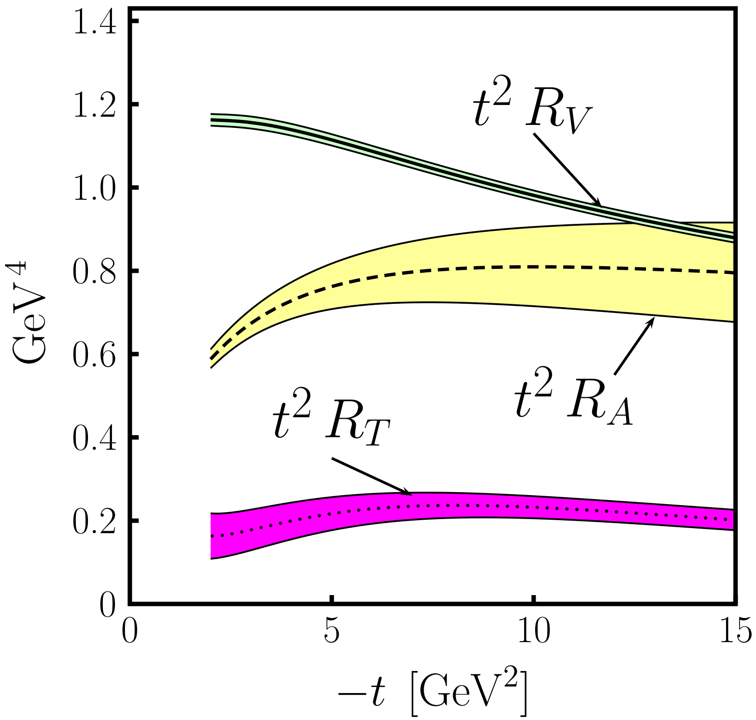
sea quarks neglected

Radyushkin (98), Diehl *et al* (99), Huang *el al* (01)

work out Compton FFs from GPDs and ....

The Compton cross section



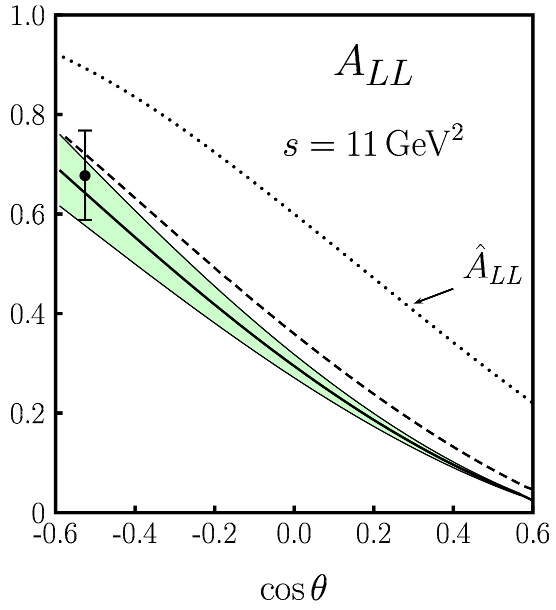


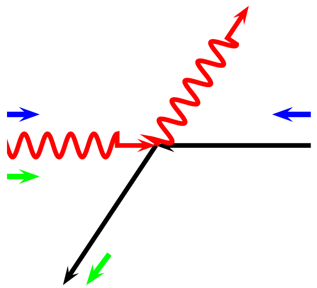
$$\frac{d\sigma}{dt} = \frac{d\hat{\sigma}}{dt}\left\{\frac{1}{2}\,\frac{(s-u)^2}{s^2+u^2}\left[R_V^2(t) + \frac{-t}{4m^2}\,R_T^2(t)\right] + \frac{1}{2}\,\frac{(s+u)^2}{s^2+u^2}R_A^2(t)\right\} + \mathcal{O}(\alpha_s)$$

$\frac{d\hat{\sigma}}{dt}(s,t) = 2\pi\alpha_{\rm elm}^2/s^2[-u/s - s/u]$ Klein-Nishina cross section

data: JLab E99-114 (07) form factors from $\xi = 0$ anlaysis

Helicity correlation A_{LL}, K_{LL}





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

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

JLab E99-114 (05): at $E_\gamma = 3.23\mathrm{GeV}$: $\cos\theta = -0.5$, $t(u) = -4\,(-1.14)\,\mathrm{GeV}^2$

Miller (04): constituent quark model with massive quarks
$A_{LL} \neq K_{LL}$ for $\theta \gtrsim 90^\circ$

measure helicity corr. at higher energies and set of scattering angles

Alternatives

since a complete and consistent analysis of hard excl reaction within a given factorization scheme does not exist (as yet), use of alternative approaches is justified and needed for comparison

Examples:

DVCS: color dipole and Regge poles Donnachie-Dosch (01), Laget (w.i.p.)

DV electropr. of vector mesons: Regge poles, color dipole, lead. log. appr.
Donnachie *et al* (98,01), Ivanov *et al* (06), Martin *et al* (00), ...

wide-angle photoproduction of mesons: Regge poles, diquarks
Laget (00), Berger *et al* (00)

WACS: constituent quark model Miller (04)

Form factors: disp. relations and/or VDM, Meissner *et al* (96,06), Iachello (03)
constituent quark models with overlaps of LCWF, de Melo *et al* (06), ...

How to improve the $\xi = 0$ GPD analysis?

More data on form factors

JLab:	G_M^n up to $\simeq 5.0\,\mathrm{GeV}^2$	preliminary data from CLAS (05)
	G_E^p up to $\simeq 9\quad \mathrm{GeV}^2$	E01-109, run in 2007
	G_E^n up to $\simeq 3.5\,\mathrm{GeV}^2$	E02-013, data taken

upgraded JLab - further extension of t range

axial vector form factor?

More moments (to become independent of parameterization)

from lattice calculations (provided reliable chiral extrapolation is made)

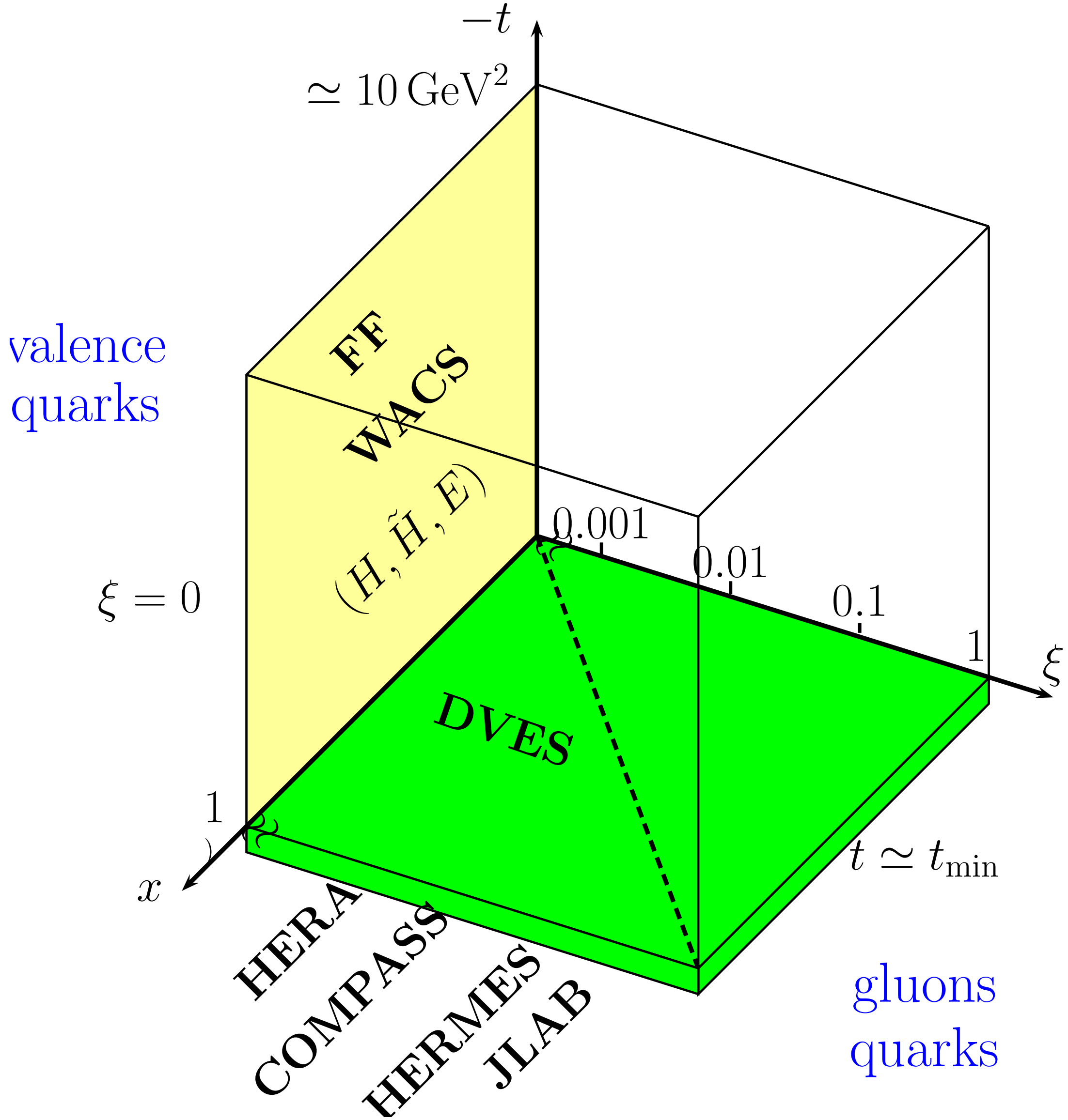
$1/x$ moments from Compton scattering

(provided power corr. have been died out, wait for upgraded Jlab?)

Determination of the GPDs at $\xi \neq 0$?

extension of $\xi = 0$ analysis: more complicated ansatz
but no idea of the ξ dependence as yet
constrain ansatz for GPDs by PDFs and form factors
and fit parameters to DVCS (and perhaps to meson prod.) data:
cross section and BH-interference and beam and target polarizations
CLAS, Hall A, HERMES, COMPASS, HERA

or use model GPDs, e.g. double distribution model
or expansions of GPDs ('partial wave decompositions')
- conformal GPD moments Kumerički *et al* (07)
- dual parameterizations of GPDs Polyakov *et al* (02)
coefficients fitted to data



$-t$
$\simeq 10\,\mathrm{GeV}^2$
valence
quarks
FF
WACS
$(H, \tilde{H}, E)$
$\xi = 0$
0.001
0.01
0.1
1
ξ
DVES
1
x
$t \simeq t_{\mathrm{min}}$
HERA
COMPASS
HERMES
JLAB
gluons
quarks