Hard Exclusive Processes

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Outline

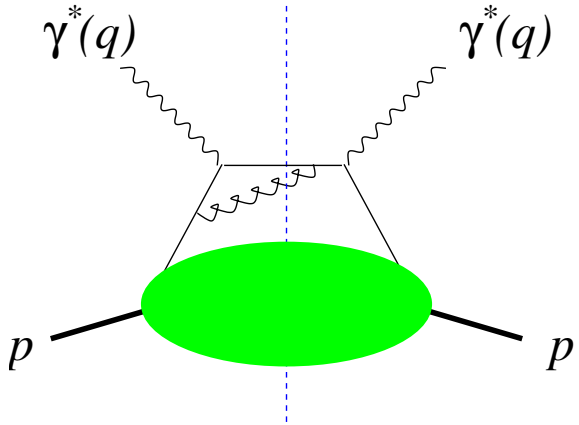
Overall aim

- investigate hadron structure at quark-gluon level
  $\rightsquigarrow$ QCD dynamics at large distances
- to probe this structure in controlled way use
  e.m. interactions + QCD dynamics at short distances
  $\longrightarrow$ factorization
  $\longrightarrow \langle \text{hadron} \,|\, \text{quark/gluon operator} \,|\, \text{hadron} \rangle$

Factorization: Deep inelastic scattering

- optical theorem:

  $\sigma_{\rm tot}(\gamma^* p \to X) \;\propto\; {\rm Im}\mathcal{A}(\gamma^* p \to \gamma^* p)$

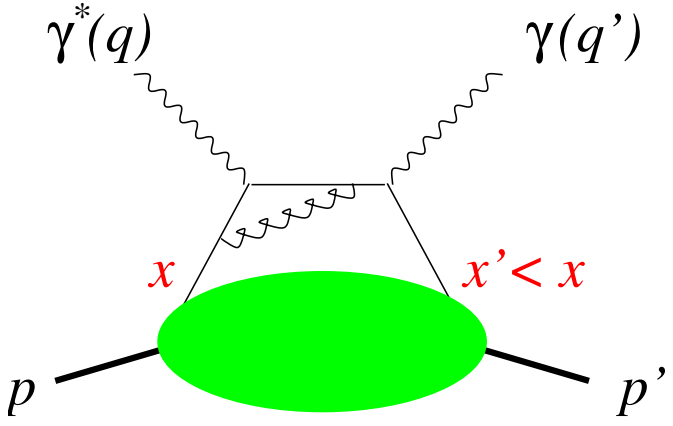


- Bjorken limit: $Q^2 = -q^2 \to \infty$, $\quad x_B = \dfrac{Q^2}{2p\cdot q}$ fixed

- ${\rm Im}\mathcal{A}(\gamma^* p \to \gamma^* p) \;\propto\; \int dx\, T(x, x_B, \log\frac{Q^2}{\mu^2})\, f(x, \mu^2)$

Factorization: Deeply virtual Compton scattering (DVCS)

- amplitude $\mathcal{A}(\gamma^* p \to \gamma p)$
  measure in $\ell p \to \ell p \gamma$

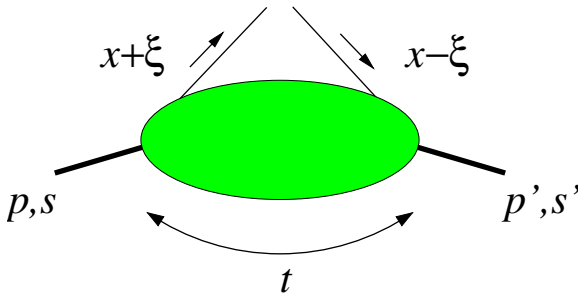


- Bjorken limit: $Q^2 = -q^2 \to \infty$, $x_B = \dfrac{Q^2}{2p \cdot q}$ fixed

  $t = (p - p')^2$ fixed

- $\mathcal{A}(\gamma^* p \to \gamma p) \;\propto\; \int dx\, \hat{T}(x, x_B, \log \frac{Q^2}{\mu^2})\, \hat{f}(x, x', t, \mu^2)$
- $\hat{f}$: generalized parton distribution (GPD)
  D. Müller et al. '94, X. Ji '96, J. Collins et al. '96,
  A. Radyushkin et al. '97

GPDs: definition and properties

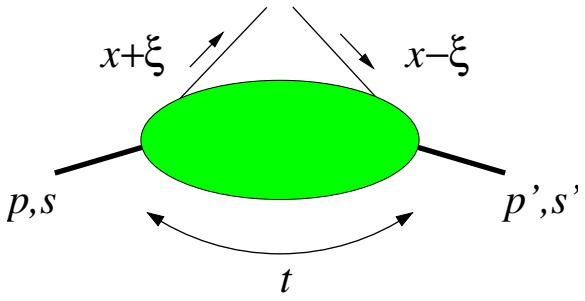


$$\int dz^- \, e^{ixP^+z^-} \langle p', s' | \, \bar{q}(-\tfrac{1}{2}z) \, \gamma^+ q(\tfrac{1}{2}z) \, | p, s \rangle \Big|_{z^+=0,\, z_T=0}$$

$$\propto \quad H^q \times \bar{u}(p', s')\gamma^+ u(p, s) + E^q \times \bar{u}(p', s') \frac{i\sigma^{+\alpha}(p' - p)_\alpha}{2m} u(p, s),$$

- light-cone coordinates: $v^\pm = v^0 \pm v^3$

GPDs: definition and properties



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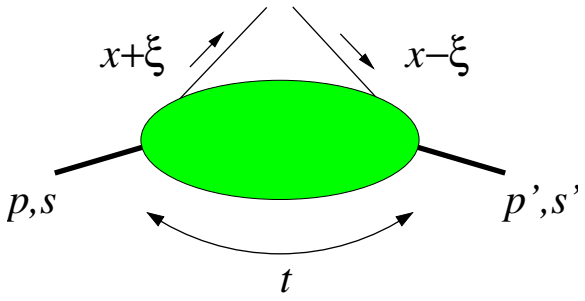
- variables in H^q, E^q:
  - x, ξ momentum fractions w.r.t. $P = \frac{1}{2}(p + p')$
    in amplitudes: $\xi = x_B/(2 - x_B)$, x integrated over
  - t can trade for transverse momentum transfer
  - μ^2 resolution scale $\rightarrow$ generalized DGLAP equations

GPDs: definition and properties



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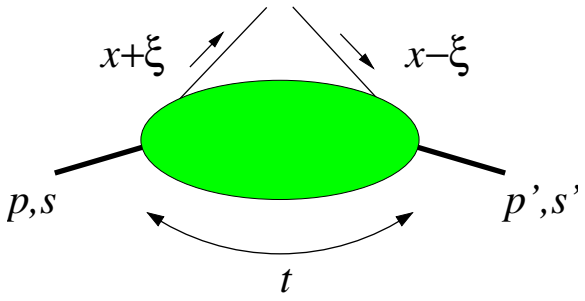
- proton spin structure:
  $H^q \leftrightarrow s = s'$ for $p = p'$ recover usual density:
  $$H^q(x, \xi = 0, t = 0) = q(x)$$
  $E^q \leftrightarrow s \neq s'$ decouples for $p = p'$
- similar definitions for polarized quarks and for gluons

GPDs: definition and properties



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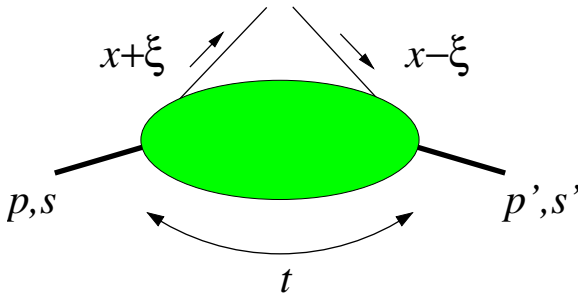
- Mellin moments: $\int dx \, x^n \;\rightarrow$ local operator $\rightarrow$ form factors
- $\int dx \;\rightarrow$ vector current
  $\sum_q e_q \int dx \, H^q(x, \xi, t) = F_1(t)$ Dirac f.f.
  $\sum_q e_q \int dx \, E^q(x, \xi, t) = F_2(t)$ Pauli f.f.

GPDs: definition and properties



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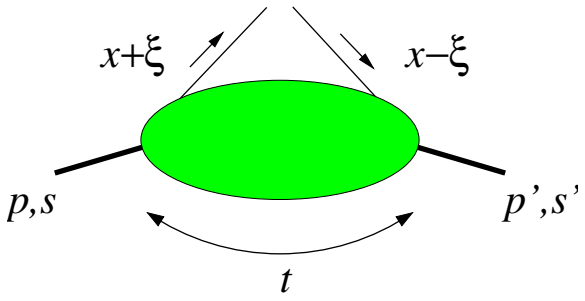
- Mellin moments: $\int dx \, x^n \;\rightarrow$ local operator $\rightarrow$ form factors
- can be evaluated in lattice QCD

  pioneering studies: QCDSF Collab. '03, LHPC Collab. '03

GPDs: definition and properties



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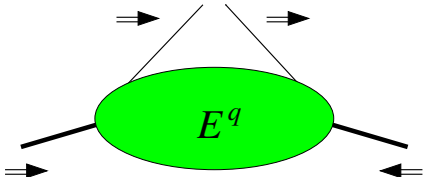
- $\int dx \, x \;\rightarrow$ energy-momentum tensor
  $\frac{1}{2} \int dx \, x (H^q + E^q) = J^q(t)$ X. Ji '96
  $J^q(0) =$ total angular momentum carried
  by quark flavor q (helicity and orbital part)

Physics information in GPDs: Spin



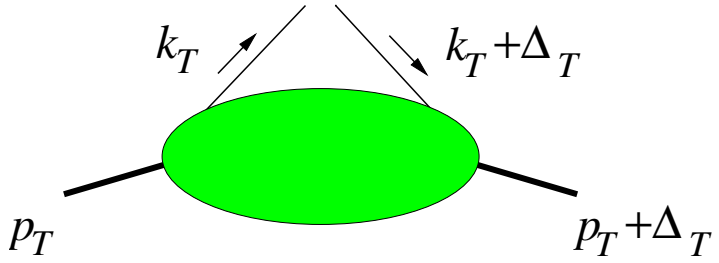
- $E^q \neq 0$ needs orbital angular momentum between partons

EXP: measurement of E^q (and E^g) requires transverse target polarization
otherwise E suppressed w.r.t. H by kinematical prefactors

- key observables: transverse target spin asymmetry in DVCS and production of vector mesons (ρ, ω, ϕ)
- nontrivial flavor structure:
  from magnetic moments know
  $$\int dx\, E^u > 0 \quad \text{but} \quad \int dx\, E^d < 0$$

More physics in GPDs

$\int d^2 k_T$



- different from k_T dependent GPDs
  (appear e.g. in semi-inclusice DIS)
  connection between two types of distributions:
  work in progress
- k_T is integrated over
  simplifies after Fourier transform to transverse space

Impact parameter representation

- states with definite transverse position (impact parameter):
  $|p^+, \mathbf{b}\rangle = \int d^2\mathbf{p}\, e^{-i\mathbf{b}\mathbf{p}}\, |p^+, \mathbf{p}\rangle$
  formal: eigenstates of 2 dim. position operator
- can exacly localize proton in 2 dimensions
  (in 3 dim. only up to Compton wavelength)
- can stay in frame where proton moves fast
  (parton interpretation!)
- $\mathbf{b}$ is center of momentum of partons in proton D. Soper '77

$$\mathbf{b} = \frac{\sum_i k_i^+ \mathbf{b}_i}{\sum_i k_i^+} \qquad (i = q, \bar{q}, g)$$

non-relativistic analog: center of mass

Impact parameter GPDs

- for simplicity take $\xi = 0$ and $s = s'$
  (can generalize to $\xi \neq 0$ and to $s \neq s'$)

$$\int dz^- \, e^{ixP^+z^-} \langle p^+, \mathbf{b}, s | \, \bar{q}(-\tfrac{1}{2}z) \, \gamma^+ q(\tfrac{1}{2}z) \, | p^+, \mathbf{b}, s \rangle \Big|_{z^+=0,\, \mathbf{z}=\mathbf{0}}$$
$$\propto \int d^2\mathbf{\Delta} \, e^{i\mathbf{b}\mathbf{\Delta}} \, H^q(x, \xi = 0, t = -\mathbf{\Delta}^2)$$

- Fourier transformed GPD gives distribution of quarks with momentum fraction x and transverse distance $\mathbf{b}$ from proton center M. Burkardt '02

EXP: key observable: t dependence of cross sections at given x_B
need sufficient lever arm in t for Fourier transform

Dynamics correlates x and b distribution of partons

Examples:

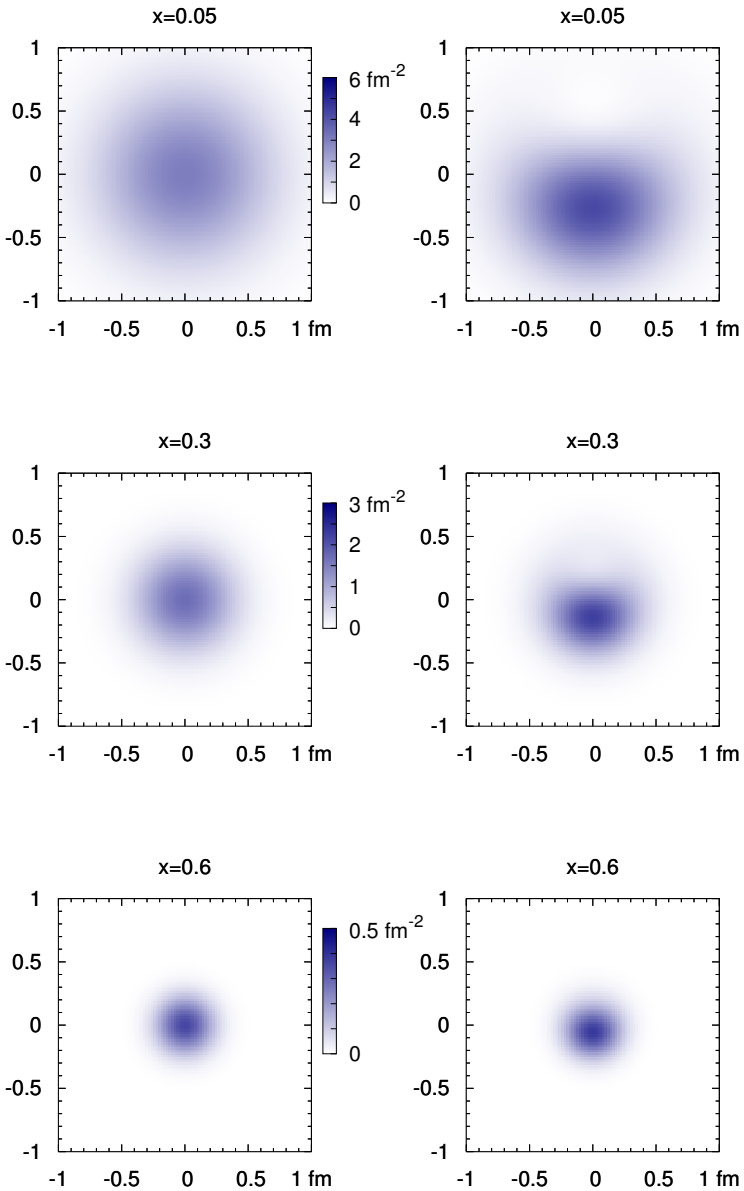
- chiral dynamics M. Strikman, C. Weiss '03
  partons at large b from pion cloud
  only possible for small enough x
  $\rightarrow$ find increase in average b^2 between $x \sim 0.2$ and $x \sim 0.05$

Dynamics correlates x and b distribution of partons

Examples:

- Gribov diffusion
  cascade of parton radiation $\longrightarrow$ smaller $x \leftrightharpoons$ larger b
  $$\langle b^2 \rangle = 4\alpha' \log \frac{1}{x}$$
  connection with confinement J. Bartels, H. Kowalski '01
  $\alpha' =$ shrinkage parameter, expect different for
  - hard vs. soft processes
    J/Ψ production at HERA: $\alpha'_{I\!P} \sim 0.1\ \mathrm{GeV}^{-2}$
    hadron-hadron scattering: $\alpha'_{I\!P} \approx 0.25\ \mathrm{GeV}^{-2}$
  - quark vs. gluon exchange
    meson exchange: $\alpha'_{I\!R} \approx 0.9\ \mathrm{GeV}^{-2}$
    mixing of quark singlet and gluons $\rightsquigarrow$???

Proton tomography



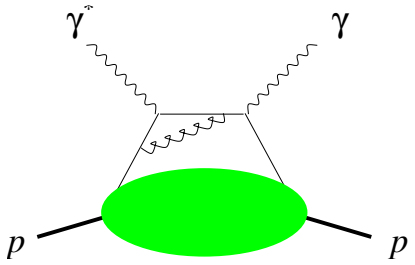
- plots: $d - \bar{d}$ in
  - unpolarized proton (left)
  - proton polarized in x-direction (right)

  M.D. et al. '04
- distribution of $q - \bar{q}$ from
  - data for e.m. nucleon form factors
  - assumptions on x and t dependence
- should
  - check these assumptions
  - investigate $\bar{q}$ and gluons

  $\longrightarrow$ exclusive processes

Principle of measurement

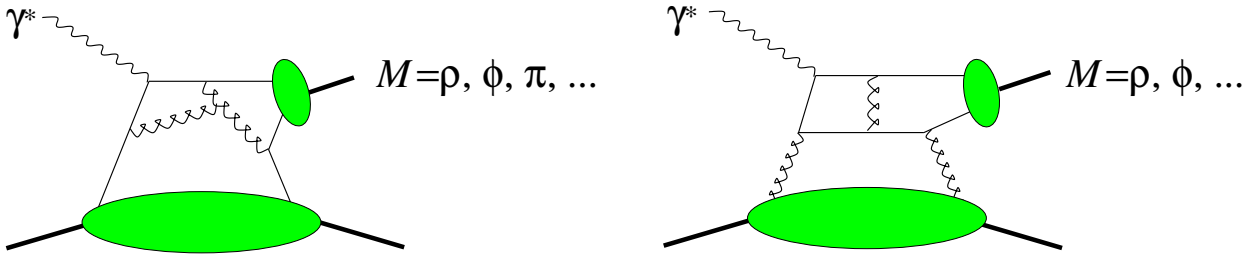
- factorization theorems J. Collins et al. '97, J. Collins, A. Freund '98
  very similar to those for deep inelastic scattering,
  Drell-Yan pair production, etc.
- processes: DVCS: $\gamma^* p \to \gamma p$



- best theory control:
  - leading twist: LO and NLO in α_s (NNLO: work in progress)
  - subleading twist ($1/Q$ suppressed): LO and partially NLO
    (very similar to spin structure function g_2)

Principle of measurement

- more processes: meson production: $\gamma^* p \to M p$



- leading twist: LO and NLO in α_s
- estimates of power corrections: can be substantial

EXP: $\to$ require larger Q^2 for quantitative interpretation

- different meson channels $\to$ select/separate
  - quark flavors, quarks vs. gluons
  - q vs. $\bar{q}$/valence vs. sea quarks
  - distributions with different spin dependence

Testing factorization

- kinematical limit in factorization theorems:
  $Q^2 \to \infty$, x_B and t fixed, i.e. $-t \ll Q^2$
- scaling predictions:

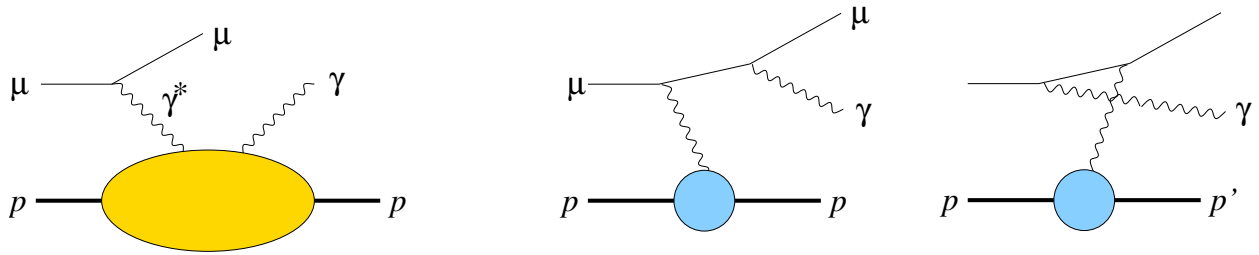
$$\left.\begin{array}{l} \mathcal{A}(\gamma_T^* p \to \gamma p) \sim Q^0 \\ \mathcal{A}(\gamma_L^* p \to M p) \sim Q^{-1} \end{array}\right\} \quad \text{at fixed } x_B \text{ and } t$$

up to effects $\sim \log Q^2$ from evolution/radiative corrections

EXP: to test scaling/use scaling violation
need lever arm in Q^2 at given x_B

DVCS is special:

- competes with Bethe-Heitler process at amplitude level

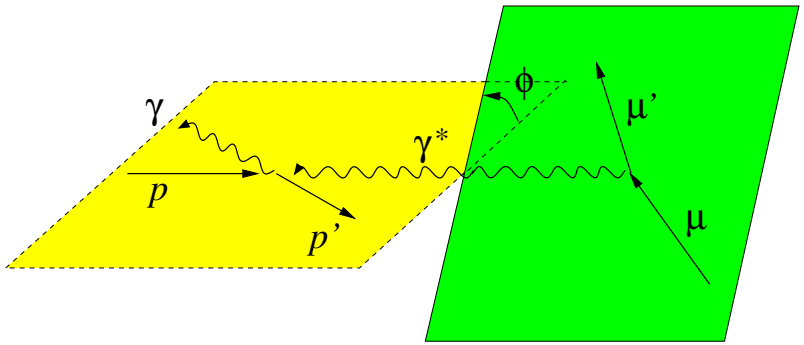


- cross section for $\ell p \to \ell \gamma p$

$$\frac{d\sigma_{\rm VCS}}{dx_B\, dQ^2\, dt} : \frac{d\sigma_{\rm BH}}{dx_B\, dQ^2\, dt} \sim \frac{1}{Q^2} : \frac{y^2}{t} \qquad\qquad y = \frac{Q^2}{x_B\, s_{\ell p}}$$

- small y: $\sigma_{\rm VCS}$ dominates
  moderate to large y: get VCS via interference with BH
  $\longrightarrow$ can measure phase of Compton amplitude
  great help in reconstructing GPDs from observables
- measurements at equal x_B, Q^2 but different $s_{\ell p}$ not equivalent

More on DVCS



- filter out interference term using cross section dependence on
  - beam charge e_ℓ
  - beam polarization P_ℓ
  - ϕ

- general structure:

$$d\sigma(\ell p \to \ell \gamma p) \sim d\sigma_{\rm BH} + e_\ell P_\ell \, d\tilde{\sigma}_{\rm INT} + d\sigma_{\rm VCS} + e_\ell \, d\sigma_{\rm INT} + P_\ell \, d\tilde{\sigma}_{\rm VCS}$$

  with $d\sigma$ even and $d\tilde{\sigma}$ odd in ϕ

- sufficient to reverse e_ℓ and P_ℓ simultaneously

More on DVCS

$$d\sigma(\ell p \to \ell\gamma p) \sim d\sigma_{\rm BH} + e_\ell P_\ell \, d\tilde{\sigma}_{\rm INT} + d\sigma_{\rm VCS} + e_\ell \, d\sigma_{\rm INT} + P_\ell \, d\tilde{\sigma}_{\rm VCS}$$

- from leading twist amplitudes:

$$\begin{aligned} d\sigma_{\rm INT} &\sim y \ \cos\phi \ \mathrm{Re}\mathcal{A}(\gamma^* p \to \gamma p) \\ d\tilde{\sigma}_{\rm INT} &\sim y^2 \sin\phi \ \mathrm{Im}\mathcal{A}(\gamma^* p \to \gamma p) \\ d\sigma_{\rm VCS} &\sim |\mathcal{A}(\gamma^* p \to \gamma p)|^2 \end{aligned}$$

- in principle can separate terms from ϕ dependence alone, but only if $1/Q$ suppressed terms small enough
  $\to$ much cleaner extraction with different beam charges
- quantitative interpretation easier for $d\sigma_{\mu^+} - d\sigma_{\mu^-}$ than for asymmetry $(d\sigma_{\mu^+} - d\sigma_{\mu^-})/(d\sigma_{\mu^+} + d\sigma_{\mu^-})$

Aside: GPDs and hadron-hadron collisions
(How not to measure GPDs)

- no factorization for exclusive processes in pp collisions
  $\leftarrow$ soft interactions between colliding hadrons/fragments
- phenomenological description of such reinteractions
  e.g. exclusive Higgs production $pp \to p + H + p$ at LHC
  A. Martin, V. Khoze, M. Ryskin et al.
- correlation between x and b distribution of partons is relevant for hadron-hadron collisions
  e.g. multiple parton interactions,
  selection of central collisions
  L. Frankfurt, M. Strikman, C. Weiss '03

Theory: status and prospects

Extracting GPDs from experiment

- solid basis: factorization theorems + QCD technology
  (profit from experience with inclusive processes)
  A. Belitsky et al. '02, M.D. '03
- work in progress:
  DVCS: precision tools
  meson production:
  - understand corrections to leading-order approximations
  - identify observables with small theory uncertainties (e.g. ratios)

Theory: status and prospects

Describing/understanding GPDs

- explored in a wide range of models
  $\rightsquigarrow$ test their underlying assumptions
- general properties/specific features from
  chiral perturbation theory, large-N_c limit
- extensive program to evaluate moments in lattice QCD
  main challenge: results for physical quark masses
  expect steady progress in coming years
- challenge: understand well enough to make functional ansatz
  for GPD(x, ξ, t)

EXP: requires input from data
we are just beginning to understand t dependence

Theory: status and prospects

Describing/understanding hadron structure

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Experiment: requirements

- identify final state $\ell p \gamma$, $\ell p \, \pi^+ \pi^-$ etc.
  (some measurements so far without detecting scattered p)
- large enough Q^2
- lever arm in Q^2 (scaling and evolution) and
  in t (impact parameter dependence) at given x_B
- lowish cross sections and multi-dimensional binning
  $\longrightarrow$ high luminosity
- for DVCS: polarized lepton beams of both charges
  $\longrightarrow$ cleanest access to GPDs
- to study polarization dependence: polarized protons

in following concentrate on DVCS

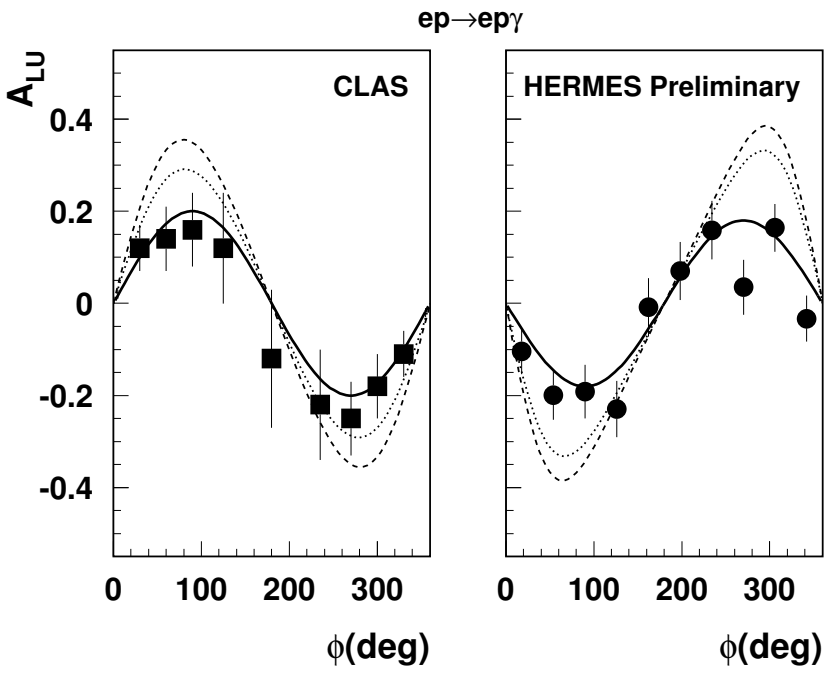
Measurements of DVCS (published or being analyzed)

experiment	$s_{\ell p}$ $[\mathrm{GeV}^2]$	$\mathcal{L}$(unpol.) $[\mathrm{cm}^2\mathrm{s}^{-1}]$	beam	pol. p
JLab CLAS	8.9		pol.	
"	11.7	$2 \cdot 10^{34}$	pol.	long.
JLab Hall A	11.7	10^{37}	pol.	
HERMES*	52.6		pol., $e^{\pm}$	long. (?)
H1, ZEUS*	10^5		σ_{VCS}	

* without detecting scattered proton

Measurements of DVCS (published or being analyzed)

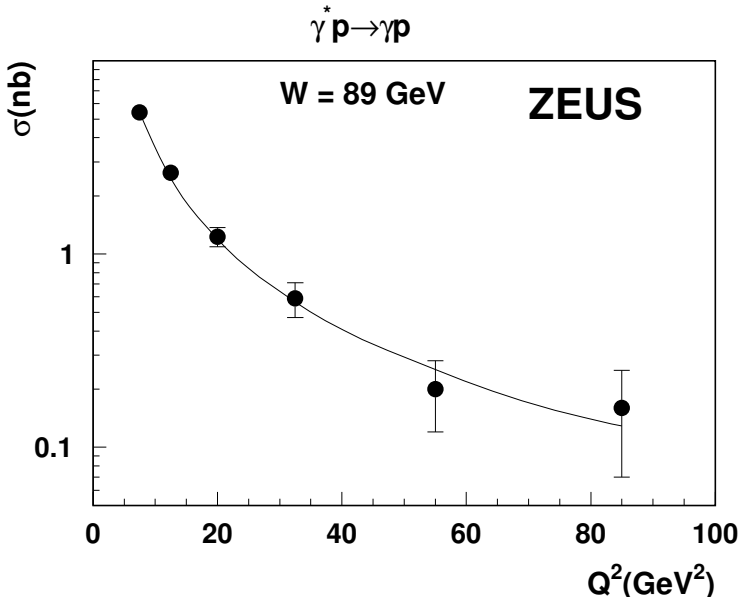
- beam polarization asymmetry $A_{LU} = \frac{d\sigma(e^{\uparrow}) - d\sigma(e^{\downarrow})}{d\sigma(e^{\uparrow}) + d\sigma(e^{\downarrow})}$



- average kinematics
  - $Q^2 = 1.25\ \mathrm{GeV}^2$, $x_B = 0.19$ (CLAS)
  - $Q^2 = 2.5\ \mathrm{GeV}^2$, $x_B = 0.12$ (HERMES)

Measurements of DVCS (published or being analyzed)

- cross section for $\gamma^* p \to \gamma p$



- $x_B \sim 5 \cdot 10^{-4}$ to 0.01
- at very small x_B and moderate Q^2 expect physics beyond leading-twist description
  $\longrightarrow$ color dipole description, parton saturation, ...

Measurements of DVCS (+ongoing and near future)

experiment	$s_{\ell p}$ [GeV^2]	$\mathcal{L}$(unpol.) [cm^{2}s^{-1}]	beam	pol. p
JLab CLAS	8.9		pol.	
"	11.7	$2 \cdot 10^{34}$	pol.	long.
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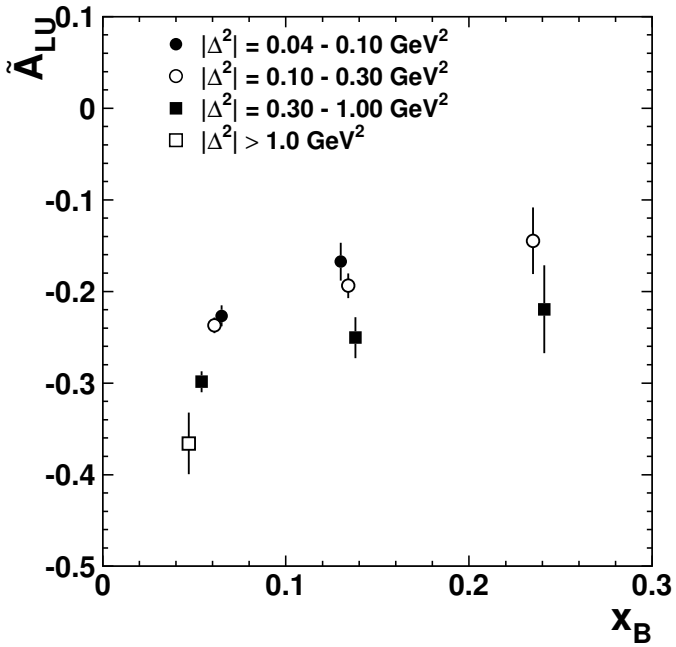
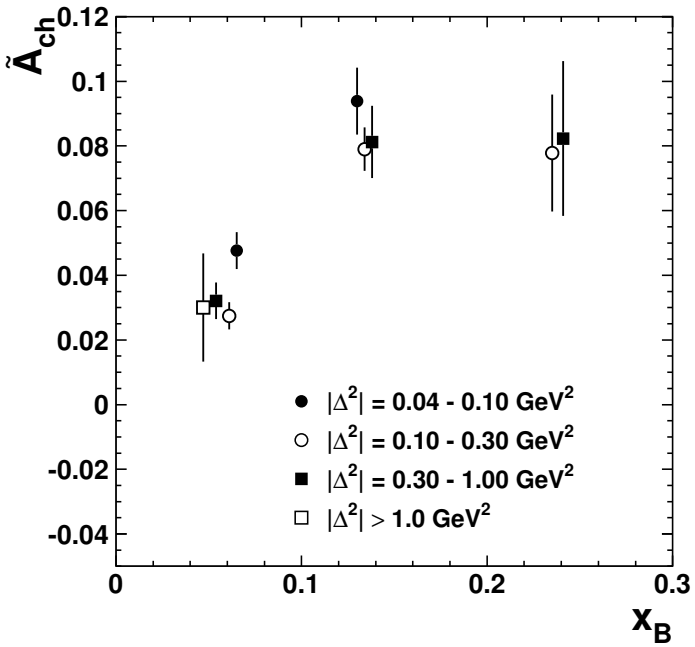
HERMES*	52.6		pol., $e^{\pm}$	long. (?)
" *	52.6			transv.
"	52.6	$3 \cdot 10^{32}$	pol., $e^{\pm}$	
H1, ZEUS*	10^5		$\sigma_{\rm VCS}$	
"	10^5	$4.5 \cdot 10^{31}$	pol., $e^{\pm}$	

* without detecting scattered proton

Measurements of DVCS (projected errors)

- projections for HERMES recoil detector run 2006-07 beam polarization and beam charge asymmetries
  V. Korotkov, W.-D. Nowak, hep-ph/0108077

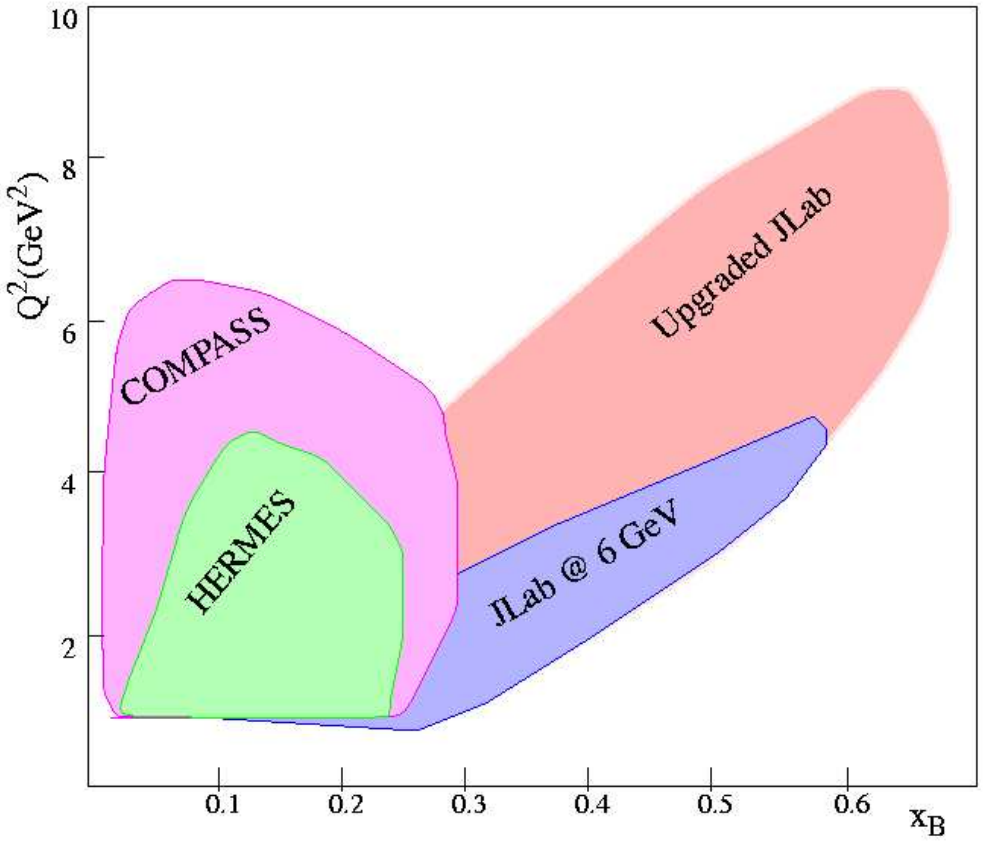




$\tilde{A}$ = amplitude of $\sin\phi$ or $\cos\phi$, cut $Q^2 > 1\ \mathrm{GeV}^2$

Measurements of DVCS (x_B and Q^2)

- kinematics for DVCS (taking into account event statistics)



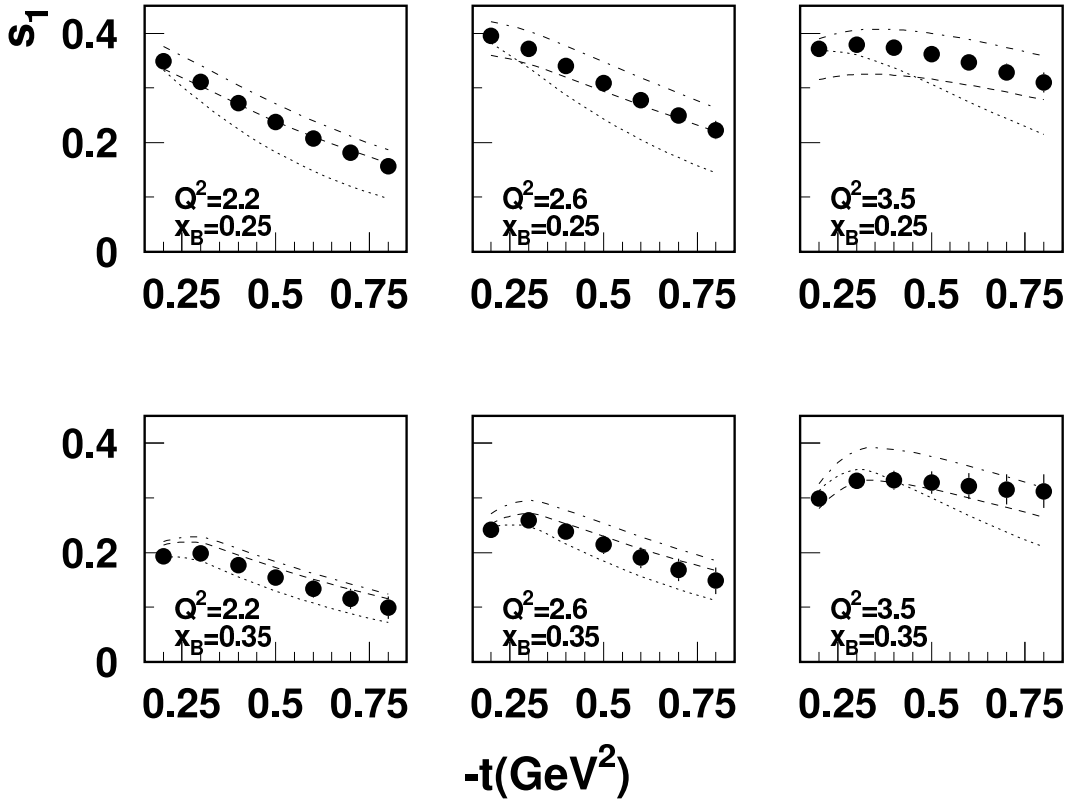
Measurements of DVCS (Future plans)

- JLab at 12 GeV (11 GeV for e^-p): pre-CDR
- eRHIC: Zeroth Design Report
  BNL proton (and heavy ion) ring + $e^\pm$ ring (or e^- linac)
- ELIC
  CEBAF e^- linac + proton (and light ion) ring
  see talks at EIC workshop, JLab, May 2004

Measurements of DVCS (more projected errors)

- projections for upgraded CLAS with $E_e = 11$ GeV beam polarization asymmetry s_1 = amplitude of $\sin\phi$

  V. Burkert, priv. comm.



Measurements of DVCS (+future plans)

experiment	$s_{\ell p}$ [GeV^2]	$\mathcal{L}$(unpol.) [cm^{2}s^{-1}]	beam	pol. p
JLab CLAS	8.9		pol.	
"	11.7	$2 \cdot 10^{34}$	pol.	long.
JLab Hall A	11.7	10^{37}	pol.	
JLab at 12 GeV	21.6	10^{35} to 10^{38}	pol.	?
HERMES*	52.6		pol., $e^{\pm}$	long. (?)
" *	52.6			transv.
"	52.6	$3 \cdot 10^{32}$	pol., $e^{\pm}$	
Compass (100 GeV)	189	$1.3 \cdot 10^{32}$	$\mu^{\pm}$ pol.	
ELIC	360 to 4200	$10^{34 \text{ to } 35}$	pol.	yes
eRHIC (ring)	2000 to 10^4	$\leq 4.4 \cdot 10^{32}$	pol., e^+	yes
eRHIC (linac)	4000 to 10^4	1 to $2 \cdot 10^{33}$	pol.	yes
H1, ZEUS*	10^5		σ_{VCS}	
"	10^5	$4.5 \cdot 10^{31}$	pol., $e^{\pm}$	

* without detecting scattered proton

Conclusions: hard exclusive processes and Compass

- access to fundamental (and unknown) features of proton structure:
  - transverse profile of q, $\bar{q}$, g as a function of their longitudinal momentum fraction (proton structure in 3d)
  - orbital angular momentum: requires transverse target
- essential need to cover large kinematical region: $Q^2 \gg -t$
  at given x_B, want lever arm in both Q^2 and t
  Compass: x_B typical of sea quarks/gluons
- range in $s_{\ell p}$ not covered by any existing or planned facility
- DVCS: beams with both charges essential asset for in-depth studies