Generalized parton distributions for non-experts

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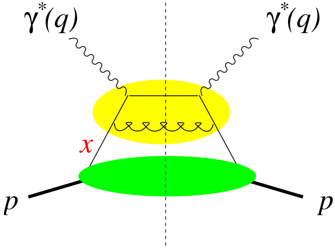
Reminder: short-distance factorization

- example: inclusive DIS
  (deep inelastic scattering)
- optical theorem:

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



- Bjorken limit: $Q^2 = -q^2 \to \infty$ at fixed $x_B = \frac{Q^2}{2p\cdot q} = \frac{Q^2}{2\nu m_p}$
- $\text{Im}\mathcal{A}$ = hard scattering $\otimes_x$ parton distribution
- factorization scale $\mu \;\rightsquigarrow$ DGLAP evolution equations

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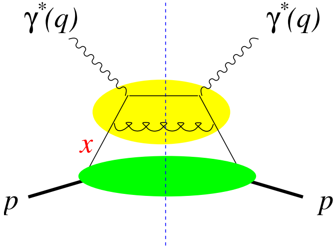

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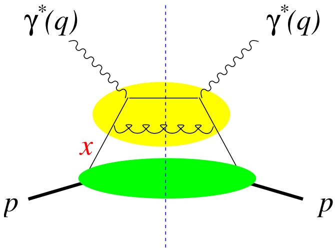
- $\mathrm{Im}\mathcal{A}$ = hard scattering $\otimes_x$ parton distribution
- factorization scale μ $\rightsquigarrow$ DGLAP evolution equations
- parton distributions also appear in other hard processes
  e.g. $\gamma^* p \to \text{jets} + X$, $p\bar{p} \to \gamma^* + X$, ...
  process independent quantities $\rightsquigarrow$ global parton analyses

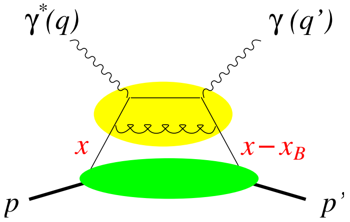
From inclusive ...

- Inclusive DIS
  cross section $\sigma_{\text{tot}}(\gamma^* p \to X)$
  $\xrightarrow{\text{opt. theor.}}$ $\text{Im}\mathcal{A}(\gamma^* p \to \gamma^* p)$
  forward amplitude
- measure in $ep \to eX$



From inclusive ... to exclusive factorization

- Deeply virtual Compton scatt. (DVCS) cross section
  $= $ square of amplitude
  $\mathcal{A}(\gamma^* p \to \gamma p)$
- measure in $ep \to ep\gamma$



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- μ dependence $\rightsquigarrow$ generalization of DGLAP evolution

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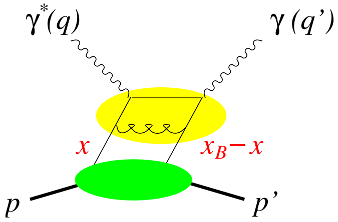

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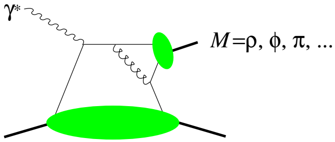
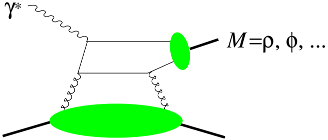
- μ dependence $\rightsquigarrow$ generalization of DGLAP evolution
- another space-time structure (included in $\int dx$)

- factorization also in meson production
  - $\gamma^* p \to \rho\, p,\ \pi\, n,\ \ldots$ light mesons
  - $\gamma p \to J/\Psi\, p,\ \Upsilon p,\ \ldots$ heavy quarkonium
- meson distribution amplitude (wave function) appears





⊕ access to different spin and flavor combinations of GPDs
for vector mesons quark and gluon distrib's at same $O(\alpha_s)$

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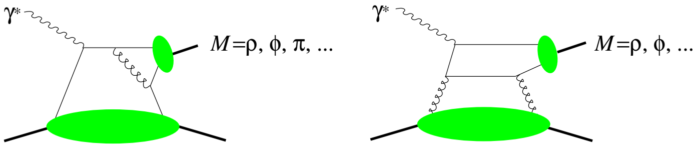

⊕ access to different spin and flavor combinations of GPDs
for vector mesons quark and gluon distrib's at same $O(\alpha_s)$

⊖ at moderate Q^2 can have large power corrections, e.g.

- propagator denominators in hard scattering $\sim zQ^2 + \boldsymbol{k}^2$
  z = momentum fraction of quark in meson
  $\rightsquigarrow$ k_t dependent meson wave functions/parton distributions

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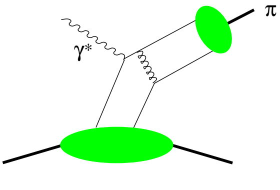
- note similarity with pion form factor at large Q^2

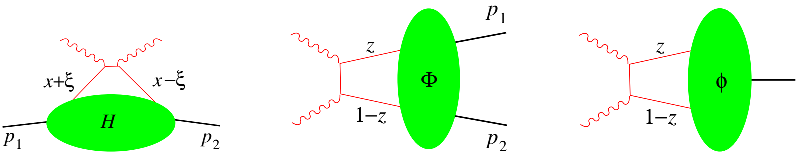


⊖ at moderate Q^2 can have large power corrections, e.g.

- end point regions of wave functions $(z \sim 0, 1)$

Two-pion distribution amplitudes

- matrix element $\langle \pi\pi | \mathcal{O}_x | 0 \rangle$
  $\mathcal{O}_x$ = Fourier transformed light-cone separated $q\bar{q}$ operator
- same as in nucleon GPD matrix element $\langle p | \mathcal{O}_x | p \rangle$
  and in meson distribution amplitude $\langle \rho | \mathcal{O}_x | 0 \rangle$
- related to pion GPD $\langle \pi | \mathcal{O}_x | \pi \rangle$ by crossing
  (at level of moments = form factors of local operators)
- appears in $\gamma^*\gamma \to \pi\pi$ for $Q^2 \gg s = (p_1 + p_2)^2$
  crossed channel to DVCS $\gamma^*\pi \to \gamma\pi$, analog of $\gamma^*\gamma \to \pi$



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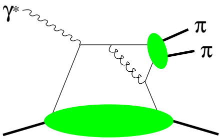

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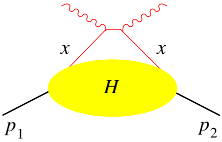
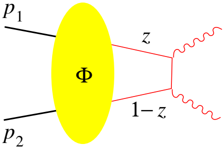
  (at level of moments = form factors of local operators)
- connections with chiral symmetry — M. Polyakov '98
- generalized distribution amplitudes also for other hadron pairs: $\rho\rho$, $p\bar{p}$, ...
- data: $\gamma^*\gamma \to \rho^0\rho^0$, $\rho^+\rho^-$ — L3 Collab. '05
  $ep \to ep\,\pi^+\pi^-$ — HERMES Collab. '04

Handbag approach to wide-angle scattering

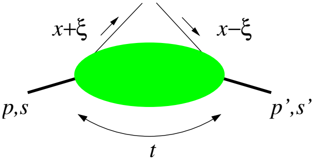
- handbag graphs and GPDs/GDAs also appear in wide-angle scattering (all invariants s, t, u large)
- integrals over GPDs at $\xi = 0$
- $\gamma p \to \gamma p,\ \ \gamma\gamma \to p\bar{p},\ \ p\bar{p} \to \gamma\gamma$, etc.





- theory more complicated than for processes where have factorization theorems
- quite successful phenomenology

GPDs: definition and properties

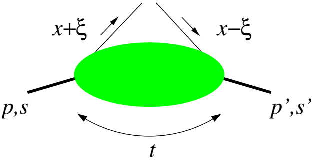


$$\int dz^- \, e^{ixP^+z^-} \langle p', s' | \, \bar{q}(-\tfrac{1}{2}z) \, W[-\tfrac{1}{2}z, \tfrac{1}{2}z] \, \gamma^+ q(\tfrac{1}{2}z) \, |p, s\rangle \Big|_{z^+=0,\, \boldsymbol{z}=\boldsymbol{0}}$$

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

- light-cone coordinates: $l^\pm = \frac{1}{\sqrt{2}}(l^0 \pm l^3) \qquad \boldsymbol{l} = (l^1, l^2)$
- kinematic variables in H^q, E^q:
  x, ξ momentum fractions w.r.t. $P = \frac{1}{2}(p + p')$
  in DVCS: $\xi = x_B/(2 - x_B)$, x integrated over
  t can trade for transverse momentum transfer $\boldsymbol{\Delta} = \boldsymbol{p}' - \boldsymbol{p}$

GPDs: definition and properties



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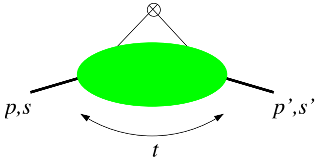
- proton spin structure:
  $H^q \leftrightarrow s = s'$ for $p = p'$ recover usual densities:
  $$H^q(x, \xi = 0, t = 0) = \begin{cases} q(x) & x > 0 \\ -\bar{q}(-x) & x < 0 \end{cases}$$
  $E^q \leftrightarrow s \neq s'$ decouples for $p = p'$
- similar definitions for quark helicity distributions $\tilde{H}^q$ and $\tilde{E}^q$ and for gluons

GPDs: definition and properties



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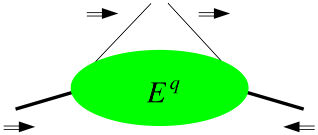
- Mellin moments: $\int dx \, x^n \;\rightarrow\;$ local operator $\;\rightarrow\;$ form factors
- can be calculated in lattice QCD
- $\int dx \;\rightarrow\;$ vector current

  $\sum_q e_q \int dx \, H^q(x, \xi, t) = F_1(t)$ 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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- $\int dx \, x \;\; \rightarrow$ energy-momentum tensor

  Ji's sum rule $\frac{1}{2} \int dx \, x(H^q + E^q) = J^q(t)$

  $J^q(0)$ = total angular momentum carried by quark flavor q (helicity and orbital part)

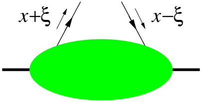
- $E^q \neq 0$ needs orbital angular momentum between partons

Evolution

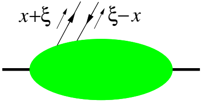
- dependence on factorization/resolution scale μ

$$\mu^2 \frac{d}{d\mu^2} GPD(x,\xi,t) = \int dx' \, K(x',x,\xi) \, GPD(x'\xi,t)$$

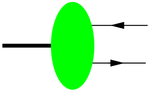
- kernel K calculable in perturbation theory
- evolution local in t



generalization of DGLAP
evolution to $\xi \neq 0$



ERBL evolution as for
meson distribution amplitudes



Impact parameter

- states with definite light-cone momentum p^+ and transverse position (impact parameter):

$$|p^+, \boldsymbol{b}\rangle = \int d^2\boldsymbol{p}\, e^{-i\boldsymbol{b}\boldsymbol{p}}\, |p^+, \boldsymbol{p}\rangle$$

formal: eigenstates of 2 dim. position operator D. Soper '77

- can exactly localize proton in 2 dimensions
  no limitation by Compton wavelength
- and stay in frame where proton moves fast
  $\rightsquigarrow$ parton interpretation
- different from localization in 3 spatial dimensions
  well-known for form factors; also for GPDs Belitsky, Ji, Yuan '03

Impact parameter GPDs

- from $\langle p^+, \boldsymbol{p}' \,|\, \mathcal{O} \,|\, p^+, \boldsymbol{p} \,\rangle$ to $\langle p^+, \boldsymbol{b} \,|\, \mathcal{O} \,|\, p^+, \boldsymbol{b} \rangle$
- impact parameter distribution

$$q(x, b^2) = (2\pi)^{-2} \int d^2\boldsymbol{\Delta}\, e^{-i\boldsymbol{\Delta b}}\, H^q(x, \xi = 0, t = -\boldsymbol{\Delta}^2)$$

gives distribution of quarks with
- longitudinal momentum fraction x
- transverse distance b from proton center — M. Burkardt '00

- average impact parameter

$$\langle b^2 \rangle_x = \frac{\int d^2b\, b^2\, q(x, b^2)}{\int d^2b\, q(x, b^2)} = 4\, \frac{\partial}{\partial t} \log H(x, \xi = 0, t) \Big|_{t=0}$$

- $q(x, b^2)$, $\langle b^2 \rangle_x$ depend on resolution scale μ^2
  $\rightsquigarrow$ evolution equations — Diehl, Feldmann, Jakob, Kroll '04

Impact parameter GPDs

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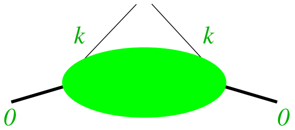
- can generalize to $\xi \neq 0$ — M.D. '02

t dependence of hard exclusive processes
$\rightsquigarrow$ spatial distribution of partons
e.g. from $ep \to ep\, \rho$, $ep \to ep\, \phi$, $ep \to ep\, J/\Psi$, DVCS

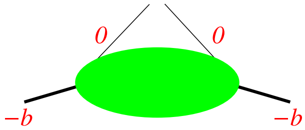
Note the difference

k_T dependent distributions



$\int d^2 z \, e^{-izk} \langle \mathbf{0} | \bar{q}(-\tfrac{1}{2} z) \ldots q(\tfrac{1}{2} z) | \mathbf{0} \rangle$

impact parameter distributions



$\int d^2 \boldsymbol{\Delta} \, e^{-ib\Delta} \langle -\tfrac{1}{2} \boldsymbol{\Delta} | \bar{q}(\mathbf{0}) \ldots q(\mathbf{0}) | \tfrac{1}{2} \boldsymbol{\Delta} \rangle$

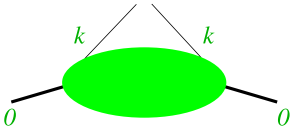
longitudinal variables not shown for simplicity

Fourier conjugates:

average transv. momentum	$\leftrightarrow$	difference of transv. positions
difference of transv. momenta	$\leftrightarrow$	average transv. position

Note the difference

k_T dependent distributions



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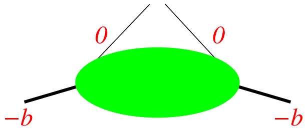

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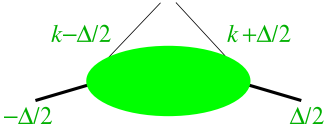
more general:

k_T dependent GPDs



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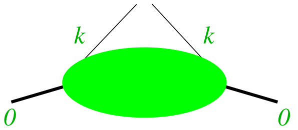
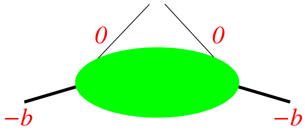


$$\int d^2 \boldsymbol{z}\, e^{-i\boldsymbol{z}\boldsymbol{k}} \langle \mathbf{0}|\bar{q}(-\tfrac{1}{2}\boldsymbol{z}) \ldots q(\tfrac{1}{2}\boldsymbol{z})|\mathbf{0}\rangle$$

impact parameter distributions



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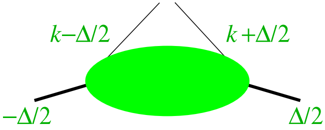
more general:

k_T dependent GPDs



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Fourier transf. from $\boldsymbol{\Delta}$ to $\boldsymbol{b}$

$\rightsquigarrow$ Wigner functions

Belitsky, Ji, Yuan '03

parton momentum and position
within limits of uncertainty rel'n

Helicity flip and transverse spin

- $E \leftrightarrow$ nucleon helicity flip $\langle\downarrow|\mathcal{O}|\uparrow\rangle$

  $\leftrightarrow$ transverse pol. difference $|X\pm\rangle = \frac{1}{\sqrt{2}}(\,|\uparrow\rangle \pm |\downarrow\rangle\,)$

  $$\langle X{+}|\mathcal{O}|X{+}\rangle - \langle X{-}|\mathcal{O}|X{-}\rangle = \langle\uparrow|\mathcal{O}|\downarrow\rangle + \langle\downarrow|\mathcal{O}|\uparrow\rangle$$

  note: helicity states here refer to infinite momentum frame
  related to standard (Bjorken-Drell) spin basis by Melosh transform

- quark density in proton state $|X{+}\rangle$

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

  is shifted in y direction — M. Burkardt '02

  $e^q(x,b) =$ Fourier transform of $E^q(x,\xi=0,t)$

- density representation

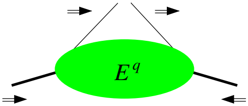
$$q^X(x,\boldsymbol{b}) = q(x,\boldsymbol{b}^2) - \frac{b^y}{m}\frac{\partial}{\partial \boldsymbol{b}^2}\, e^q(x,\boldsymbol{b}^2)$$

gives positivity bound M. Burkardt '03

$$\Big| E^q(x,\xi=0,t=0) \Big| \;\; \leq \;\; q(x)\, m \sqrt{\langle \boldsymbol{b}^2 \rangle_x}$$

have more restrictive bounds involving polarized distributions

$\Rightarrow$ E^q must fall faster than H^q at large x



- $E \;\leftrightarrow$ orbital angular momentum
  $\Rightarrow$ carried by partons with smaller x

GPDs for transverse quark polarization

$$\int dz^- \, e^{ixP^+z^-} \langle p', s' | \, \bar{q}(-\tfrac{1}{2}z) \, \ldots \sigma^{+i}\gamma_5 \, q(\tfrac{1}{2}z) \, |p, s\rangle \Big|_{z^+=0,\, \boldsymbol{z}=\boldsymbol{0}}$$

$$\propto \quad \bar{u}(p', s')\sigma^{+i}\gamma_5 \, u(p, s) \, H_T^q + \ldots \bar{E}_T^q + \ldots \tilde{H}_T^q + \ldots \tilde{E}_T^q$$

- in forward limit $p = p'$
  - $H_T^q \rightsquigarrow$ transversity distribution $h_1(x) = \delta q(x)$
  - $\bar{E}_T^q$, $\tilde{H}_T^q$, $\tilde{E}_T^q$ decouple
- $\xi = 0 \;\rightsquigarrow\;$ density interpretation in impact parameter space

  M.D., P. Hägler '05
- in particular find

  $\bar{E}_T \leftrightarrow$ shifted $\boldsymbol{b}$ distribution of $q^{\rightarrow}$ in unpolarized p

  had: $E \leftrightarrow$ shifted $\boldsymbol{b}$ distribution of unpolarized q in $p^{\rightarrow}$

Longitudinal vs. transverse quark polarization

- axial vs. tensor charge

$$\Delta q = \int_0^1 dx \, [\Delta q(x) + \Delta \bar{q}(x)] \qquad \delta q = \int_0^1 dx \, [\delta q(x) - \delta \bar{q}(x)]$$

$\Delta q(x)$ helicity distribution, $\delta q(x)$ transversity distribution

- in nucleon rest frame (s = spin vector)

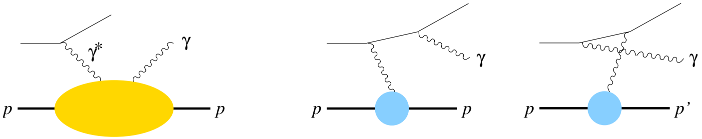
$$\langle p, s | \bar{q} \, \gamma^j \gamma_5 \, q | p, s \rangle = 2m s^j \, \Delta q$$
$$\langle p, s | \bar{q} \, i\sigma^{j0} \gamma_5 \, q | p, s \rangle = 2m s^j \, \delta q$$

$$\gamma^j \gamma_5 = \begin{pmatrix} \sigma^j & 0 \\ 0 & -\sigma^j \end{pmatrix} \qquad i\sigma^{j0}\gamma_5 = \begin{pmatrix} \sigma^j & 0 \\ 0 & \sigma^j \end{pmatrix}$$

differ in small components of quark spinor
and large components of antiquark spinor

Deeply virtual Compton scattering

- competes with Bethe-Heitler process at amplitude level

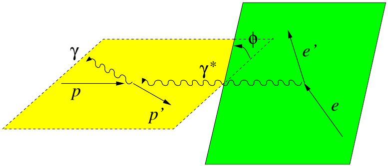


- cross section for $\ell p \to \ell \gamma p$

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

- small y: σ_{VCS} dominates
  moderate to large y: get VCS via interference with BH
  $\rightsquigarrow$ separate Re $\mathcal{A}(\gamma^* p \to \gamma p)$ and Im $\mathcal{A}(\gamma^* p \to \gamma p)$
  great help in reconstructing GPDs from observables

More on DVCS



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

- general structure:

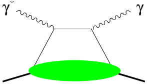
$$d\sigma(\ell p \to \ell\gamma p) \quad \sim \quad d\sigma_{\text{BH}} + e_\ell P_\ell \, d\tilde{\sigma}_{\text{INT}} + d\sigma_{\text{VCS}} \\ + e_\ell \, d\sigma_{\text{INT}} + P_\ell \, d\tilde{\sigma}_{\text{VCS}}$$

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

Access to GPDs

- DVCS and meson production at LO in α_s : GPDs appear as

$$\mathcal{F} \propto \int dx \, \frac{F(x,\xi,t)}{x-\xi+i\epsilon} \pm \{\xi \to -\xi\}$$



- DVCS: many independent observables at leading twist (γ_T^*) in interference term:

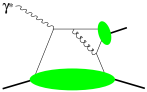
target pol.	GPD combination
U	$F_1 \mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + \frac{t}{4m^2} F_2 \, \mathcal{E}$
L	$F_1 \tilde{\mathcal{H}} + \xi(F_1+F_2)\mathcal{H} - \frac{\xi}{1+\xi} F_1 \, \xi\tilde{\mathcal{E}} + \dots$
$T_{\cos(\phi-\phi_S)}$	$F_2 \tilde{\mathcal{H}} - F_1 \, \xi\tilde{\mathcal{E}} + \dots$
$T_{\sin(\phi-\phi_S)}$	$F_2 \mathcal{H} - F_1 \, \mathcal{E} + \dots$

with unpolarized or polarized lepton beam

Access to GPDs

- DVCS and meson production at LO in α_s: GPDs appear as

$$\mathcal{F} \propto \int dx \, \frac{F(x,\xi,t)}{x-\xi+i\epsilon} \pm \{\xi \to -\xi\}$$



- meson production: two leading-twist observables (γ_L^*)

target pol.	GPD combination
U	$\lvert\mathcal{H}\rvert^2 - \frac{t}{4m^2}\lvert\mathcal{E}\rvert^2 - \xi^2\,\lvert\mathcal{H}+\mathcal{E}\rvert^2$
$T_{\sin(\phi-\phi_S)}$	$\mathrm{Im}\,(\mathcal{E}^*\mathcal{H})$
U	$(1-\xi^2)\,\lvert\tilde{\mathcal{H}}\rvert^2 - \frac{t}{4m^2}\,\xi^2\lvert\tilde{\mathcal{E}}\rvert^2 - 2\xi^2\mathrm{Re}\,(\tilde{\mathcal{E}}^*\tilde{\mathcal{H}})$
$T_{\sin(\phi-\phi_S)}$	$\mathrm{Im}\,(\xi\tilde{\mathcal{E}}^*\tilde{\mathcal{H}})$

with unpolarized lepton beam