Generalized parton distributions at EIC

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EIC Collaboration Meeting
LBNL, 12 December 2008

1. Some reminders about GPDs
2. From processes to GPDs
3. Physics from GPDs: nucleon tomography
4. Spin and orbital angular momentum
5. Processes to measure GPDs
6. Conclusions

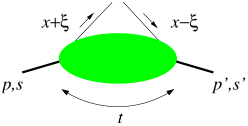
charge from the organizers:

- focus on issues that EIC will address
- what remains to be done to establish a scientific and facility case

Some brief reminders

- GPDs $\leftrightarrow$ matrix elements $\langle p' | \mathcal{O} | p \rangle$

  $\mathcal{O} =$ operator with quark or gluon
  fields along light cone
  same as for usual parton densities



  - for $p \neq p'$ have two mom. fractions x, ξ and $t = (p' - p)^2$
    at given ξ can trade t for transverse mom. transfer $\boldsymbol{\Delta} = \boldsymbol{p}' - \boldsymbol{p}$

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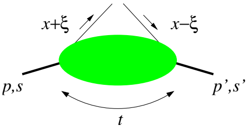

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    at given ξ can trade t for transverse mom. transfer $\boldsymbol{\Delta} = \boldsymbol{p}' - \boldsymbol{p}$
  - for unpolarized quarks two distributions:
    - H^q conserves proton helicity
      for $p = p'$ recover usual densities $q(x)$ and $\bar{q}(x)$
    - E^q responsible for proton helicity flip
      decouples for $p = p'$

  similar definitions for polarized quarks and for gluons

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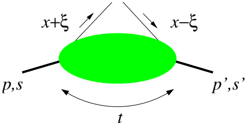

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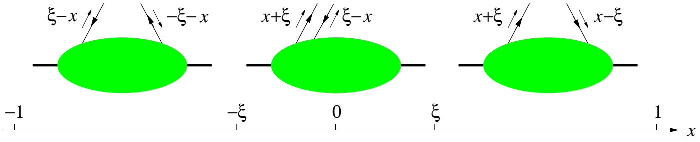
    at given ξ can trade t for transverse mom. transfer $\boldsymbol{\Delta} = \boldsymbol{p}' - \boldsymbol{p}$
  - $\int dx\, x^n\, \mathrm{GPD}(x, \xi, t) \rightarrow$ local operators $\rightarrow$ form factors
    calculations in lattice QCD
  - lowest moments: $\int dx\, H^q(x, \xi, t) = F_1^q(t)$ (Dirac)
    and $\int dx\, E^q(x, \xi, t) = F_2^q(t)$ (Pauli)

Partonic interpretation



- $|x| > \xi$ similar to parton densities
  correlation $\psi^*_{x-\xi}\,\psi_{x+\xi}$ instead of probability $|\psi_x|^2$
  $|x| < \xi$ coherent emission of $q\bar{q}$ pair
- regions related by Lorentz invariance
  spacelike partons incoming in some frames, outgoing in others

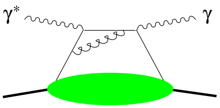
$$\rightsquigarrow \quad \int_{-1}^{1} dx\, x^n \,\mathsf{GPD}(x,\xi,t) = \text{polynomial in } \xi$$

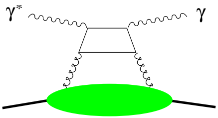
- not much known about relation $\mathsf{GPD}(x,\xi,t) \leftrightarrow \mathsf{GPD}(x,0,t)$
  (skewness effect)

Some more reminders

- Generalized parton distributions appear in description of hard exclusive processes
- for a number of cases have factorization theorems using collinear factorization

Collins, Frankfurt, Strikman '96; Collins, Freund '98





key processes:

- deeply virtual Compton scattering

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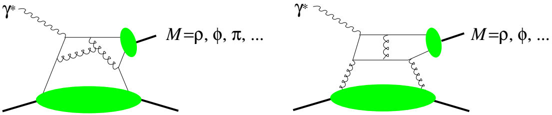

key processes:

- deeply virtual Compton scattering
- meson production: large Q^2 or heavy quarks $(J/\Psi, \Upsilon)$

Hard exclusive processes $\xrightarrow{?}$ GPDs

amplitudes for DVCS and vector meson production at LO in α_s :

$$\mathcal{H}(\xi,t) = \int_{-1}^{1} dx\, H(x,\xi,t) \left[\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon} \right]$$

$$\mathrm{Im}\,\mathcal{H}(\xi,t) = \pi \big[H(\xi,\xi,t) - H(-\xi,\xi,t) \big]$$

$$\mathrm{Re}\,\mathcal{H}(\xi,t) = \mathrm{PV} \int_{-1}^{1} dx\, H(x,\xi,t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right]$$

for brevity suppress quark flavor labels
analogous eq's for mesons with other quantum numbers

$\xi = x_B/(2 - x_B)$ and t are measurable, x is loop variable

- Im part only involves GPDs at $x = \pm\xi$
- Re part sensitive to full x region
- dispersion relations: calculate Re from Im

up to an energy independent constant

Dispersion relations for hard exclusive processes

O.V. Teryaev '05, I.V. Anikin and O.V. Teryaev '07
K. Passek-Kumerički et al. '07; M.D. and D.Yu. Ivanov '07

- dispersion relation for amplitude at fixed t and Q^2

$$\mathrm{Re}\,\mathcal{H}(\xi,t) \overset{\text{LO}}{=} \mathrm{PV}\int_{-1}^{1} dx\, H(x,x,t)\left[\frac{1}{\xi-x}-\frac{1}{\xi+x}\right]+C(t)$$

- consistency with

$$\mathrm{Re}\,\mathcal{H}(\xi,t) \overset{\text{LO}}{=} \mathrm{PV}\int_{-1}^{1} dx\, H(x,\xi,t)\left[\frac{1}{\xi-x}-\frac{1}{\xi+x}\right]$$

  ensured by polynomiality, i.e. by Lorentz invariance

- subtraction constant
  - associated with pure spin-zero exchange in t-channel
  - related with Polyakov-Weiss D-term

Practical consequences

- at leading order in α_s

  $\mathrm{Im}\,\mathcal{H}(\xi,t,Q^2)$ from $H(\xi,\xi,t;Q^2)$

  $\mathrm{Re}\,\mathcal{H}(\xi,t,Q^2)$ from $H(x,x,t;Q^2)$ at all x and $C(t)$

  - amplitude determined by GPD(x,x) and subtraction constant
  - Re sensitive to x range around measured ξ

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- Q^2 dependence from evolution:

$$\frac{d}{d \ln Q^2} H(\xi, \xi, t; Q^2) = \text{kernel} \otimes \left\{ H(x, \xi, t; Q^2) \text{ for } |x| \geq \xi \right\}$$

  - sensitive to GPD in region $|x| \geq \xi$

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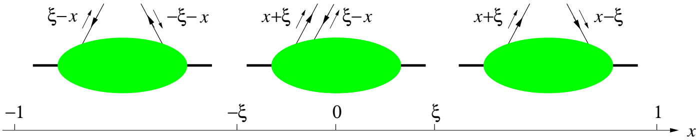
  - sensitive to GPD in region $|x| \geq \xi$

- beyond leading order in α_s find

  - amplitude determined by GPD in region $|x| \geq \xi$ and more complicated subtraction constant

Hard exclusive processes → GPDs



- at LO accuracy information about GPD(x, x)
  and subtraction constant
  ⇝ LO phenomenology relatively simple, but restricted
  cannot reconstruct GPD(x, ξ, t) as function of x
- sensitivity to $|x| \geq \xi$ from evolution/higher orders in α_s
  requires lever arm in Q^2 at given ξ, i.e. given x_B
- then can reconstruct region $|x| \leq \xi$ from polynomiality
  up to ambiguity corresponding to subtraction const.
  explicit construction: K. Passek-Kumerički, D. Müller, K. Kumerički '08

Nucleon tomography: impact parameter

- at fixed longitudinal momentum fractions x, ξ:
  t dependence of GPD $\rightarrow$ transverse mom. transfer $\boldsymbol{\Delta}$
  $\rightarrow$ Fourier transform to position $\boldsymbol{b}$ of struck parton
- no relativistic corrections; consistent with uncertainty principle
- for $\xi = 0$ have joint density
  in long. momentum fraction x and transv. position b

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

M. Burkardt '00, '02

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- $q(x, \boldsymbol{b}^2)$ not Fourier conjugate to $q(x, \boldsymbol{k}^2)$

  transverse mom. dependent density

  both generated by higher-level function

$$q(x, \boldsymbol{k}^2) \quad \overset{\boldsymbol{\Delta}=\boldsymbol{0}}{\longleftarrow} \quad H(x, \xi = 0, \boldsymbol{\Delta}, \boldsymbol{k}) \quad \xrightarrow{\int d^2\boldsymbol{k}\, d^2\boldsymbol{\Delta}\, e^{-i\boldsymbol{b}\boldsymbol{\Delta}}} \quad q(x, \boldsymbol{b}^2)$$

$\rightsquigarrow$ complementary information about transverse structure

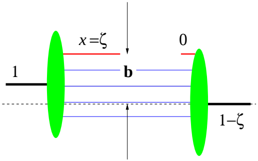
Nucleon tomography: impact parameter

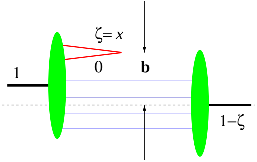
- for $\xi \neq 0$ get distance of quark to "average" positions of initial and final proton M. Diehl '02
- situation again simple for $x = \xi$

  $\boldsymbol{\Delta} \to \boldsymbol{b}$ with $t = \frac{\zeta^2 m_p^2 + \boldsymbol{\Delta}^2}{1-\zeta}$ $\xi = \frac{\zeta}{2-\zeta}$

  distance of struck parton from spectator system

  M. Burkardt '07





- measure t dependence at given $\zeta = x_B$

  handy quantity: $\frac{\partial}{\partial t} \ln \mathrm{GPD}(x,x,t)\Big|_{t=0}$

Interest of nucleon tomography

- for $x < m_\pi/m_p$: effects from pion cloud
  $\rightsquigarrow$ chiral dynamics M. Strikman, Ch. Weiss '03-'08
- small x: shrinkage use as approx. parameterization

$$H(x,0,t) \sim H(x,x,t) \sim x^{-\alpha-\alpha' t}$$
$$\langle b^2 \rangle \sim \alpha' \log(1/x)$$

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  - meson trajectories $\rightsquigarrow$ $\alpha' \sim 1\,\mathrm{GeV}^{-2}$
    if taken for valence quarks → good description of $F_1(t)$ data
    M.D. et al. '04, M. Guidal et al. '04
  - vector meson prod'n $\rightsquigarrow$ gluons
    HERA data → small but nonzero $\alpha' \sim 0.1 \ldots 0.2\,\mathrm{GeV}^{-2}$
  - DVCS $\rightsquigarrow$ gluons and sea quarks
    current errors at HERA too large for α' determ'n

- transition from soft to hard dynamics?
- interplay between gluons and sea quarks?

Interest of nucleon tomography

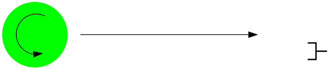
- impact parameter transform of $E(x, \xi, t)$
  $\rightsquigarrow$ spin-orbit correlations

  - parton distribution in nucleon polarized along x-axis
    is shifted in y direction M. Burkardt '02

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

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

  - semi-classical picture: rotating matter distribution



  gives alternative view on Ji's sum rule $L^x = b^y p^z$
  M. Burkardt '05

Interest of nucleon tomography

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  - parton distribution in nucleon polarized along x-axis is shifted in y direction — M. Burkardt '02

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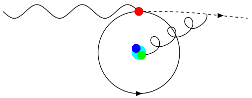
    where $e^q(x, b)$ is Fourier transform of $E^q(x, \xi = 0, t)$
  - explanation of Sivers effect by chromodynamic lensing

$$\left.\begin{array}{l}\text{struck quark interacts with spectators}\\ \text{anisotropic spectator distribution}\end{array}\right\} \Rightarrow \begin{array}{l}\text{anisotropic } \boldsymbol{p}_T \text{ distrib.}\\ \text{of struck quark}\end{array}$$



M. Burkardt '04
figure from arXiv:0807.2599

The proton spin budget

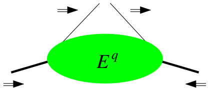
- sum rule X. Ji '06,'07

$$J^q = \frac{1}{2}\int dx\, x(H^q + E^q)\Big|_{\substack{t=0\\ \xi=0}} \qquad J^g = \frac{1}{2}\int dx\,(H^g + E^g)\Big|_{\substack{t=0\\ \xi=0}}$$

with $\frac{1}{2} = J^g + \sum_q J^q$

- further decomposition $L^q = J^q - \frac{1}{2}\Sigma$
  with Σ from ordinary parton densities
- $E^{q,g} \;\leftrightarrow\; \Delta L^3 = 1$ from helicity imbalance

M. Burkardt, G. Schnell '05



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  with Σ from ordinary parton densities

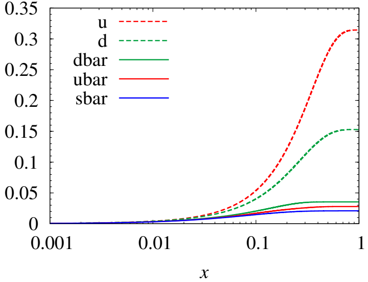
- lattice $\rightsquigarrow$ Σ and J^q
  - directly get integrals over x at $\xi = 0$
- exclusive processes $\rightsquigarrow$ GPDs $\rightsquigarrow$ J^q and (more difficult) J^g
  - exclusive (and inclusive) processes: $\int dx$ difficult
  - measure at $\xi \neq 0$
  - but get access at x dependence of $E^{q,g}(x, x, t)$

Small and large x in Ji's sum rule

- in $\int_0^1 dx\, xq(x)$ only little contrib'n from $x < 10^{-2}$ or $x > 0.5$

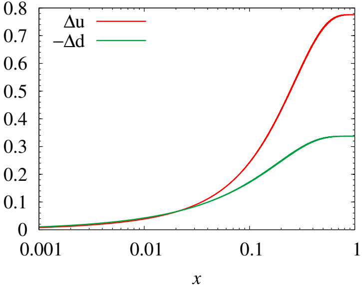
quite different for helicity integrals $\int_0^1 dx\, \Delta q(x)$

$\int_0^x dz\, zq(z)$



CTEQ6.6

$\int_0^x dz\, \Delta q(z)$



DSSV

all distributions at $\mu = 2\,\mathrm{GeV}$

Constraints from positivity

M.D., in preparation

- positivity of $q^X(x, \boldsymbol{b})$ ensured by M. Burkardt '03

$$\big|E(x,0,0)\big|^2 \le \big[q(x) + \Delta q(x)\big]\,\big[q(x) - \Delta q(x)\big]\; m^2 \langle b^2 \rangle_{q \pm \Delta q}$$

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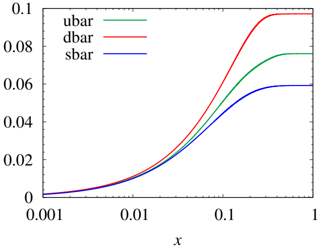
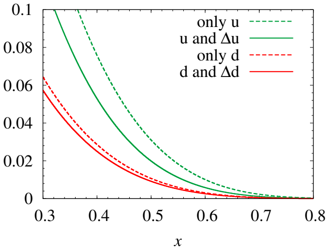
bound on $\left| \int_0^x dz\, zE(z) \right|$



CTEQ6.6

$\langle b^2\rangle$ estimated from HERA DVCS and J/Ψ data

bound on $\left| \int_x^1 dz\, zE(z) \right|$



MRST 2002/DSSV

$\langle b^2\rangle$ taken from fit to $F_1(t)$

There is more to a function than its integral . . .

constraints on E:

- at $t = 0$ have $\int_{-1}^{1} dx\, E^u > 0$ and $\int_{-1}^{1} dx\, E^d < 0$ from magnetic moments
- at $t = 0$, $\xi = 0$ have $\int_{-1}^{1} dx\, x \sum_q E^q + \int_0^1 dx\, E^g = 0$ from momentum conservation
  lattice finds small $\int_{-1}^{1} dx\, x \sum_q E^q \;\Rightarrow\; \int_0^1 dx\, E^g$ small

$\rightsquigarrow$ E^g small unless has a node in x

very different from situation for H^g

There is more to a function than its integral ...

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- at $t = 0$ have $\int_{-1}^{1} dx\, E^u > 0$ and $\int_{-1}^{1} dx\, E^d < 0$
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very different from situation for H^g

- what about sea quark contribution?
  - mainly generated from E^g by evolution?
  - same sign for $\bar{u}$ and $\bar{d}$? nodes in x?

  $\rightsquigarrow$ dynamical origin of sea quarks
- whether E^g and/or E^q have nodes in x
  hard or impossible to infer from a few x moments

The key process: DVCS

- good theoretical control:
  - NLO and NNLO corrections (at twist two) typically small
    except for scaling violation at very small x_B,
    where evolution effects analogous to inclusive DIS

    D. Müller et al. '05–'07
  - close connection to inclusive DIS
    $\rightsquigarrow$ may reach Bjorken regime at moderately large Q^2
- large number of observables accessible to GPD approach
  - both twist two and twist three amplitudes
  - using interference with Bethe-Heitler can
    separate Im and Re of Compton amplitude
    $\rightsquigarrow$ most direct connection with GPDs

for more information wait a few slides

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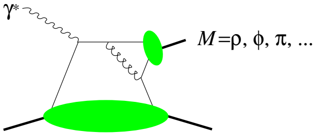
  - close connection to inclusive DIS
    $\rightsquigarrow$ may reach Bjorken regime at moderately large Q^2
- but: DVCS provides limited information
  - on quark flavor separation
    at LO get $4u + d + s$ with proton target
    in addition $u + 4d + s$ with neutron target
  - gluon distributions only through scaling violation and NLO

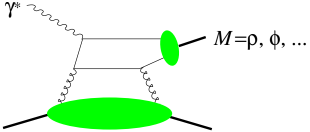
. . . just as inclusive DIS

Meson production

- vector mesons ρ, ω, ϕ and J/Ψ, Υ $\rightsquigarrow$ sensitivity to gluon
  gluon already visible in HERMES kinematics
  follows from comparing ϕ with ρ production

M.D. and A.V.Vinnikov '04





- may complement DVCS for quark flavor separation
  interesting non-singlet channels, e.g.

$$\gamma^* p \to \rho^+ n \quad \leftrightarrow \quad u - d$$
$$\gamma^* p \to K^* \Sigma \quad \leftrightarrow \quad d - s$$

if use SU(3) flavor symm.

however, typically small cross sections at small x

Meson production

- but: corrections larger than for DVCS at moderate Q^2
- power corrections in $1/Q^2$

  inclusion of intrinsic quark k_T in hard scattering

  $\rightsquigarrow$ successful phenomenology P. Kroll, S. Goloskokov '06 – '08

  based on modified hard scattering formalism of Sterman et al.

  gives estimate but no systematic evaluation of power corrections
- NLO corrections in hard scattering
  - moderate to large x: typical K-factors ~ 2 in cross section
  - NLO corrections tend to cancel in some ratios but not in all

    D.Yu. Ivanov et al. '04, M.D. and W. Kugler '07
  - at small x huge NLO corrections

    ongoing work on resummation of BFKL logs

    D.Yu. Ivanov and A. Papa '07

$\rightsquigarrow$ for quantitative analysis of meson production want

largest possible Q^2

The cherry on the cake: double DVCS

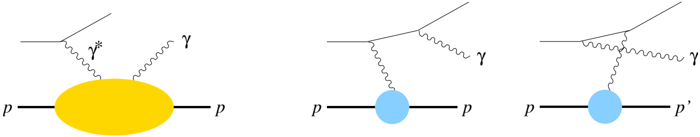
- subprocess $\gamma^*{}_{\text{spacelike}}\, p \to \gamma^*{}_{\text{timelike}}\, p$
- at LO have $\mathrm{Im}\,\mathcal{A} \propto \text{GPD}(\xi, \eta, t)$

  with $\xi < \eta$ fixed by photon virtualities

  $\rightsquigarrow$ direct access to region of $q\bar{q}$ emission
- measure in $ep \to ep\,\gamma^* \to ep\,\mu^+\mu^-$
  using angular distrib. and spin asymmetries similar to DVCS
  not possible for $ep \to ep + \gamma^* \to ep\,e^+e^-$

Making the most of DVCS

- competes with Bethe-Heitler process at amplitude level



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

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

- visible interference term unless y is very small
- key variable: azimuth ϕ between lepton and hadron planes
- following slides:
  - how to extract the interference, relevance of e^+ beam
  - possibilities with lepton and nucleon polarization

GPD combinations in interference term made simple

$$r = \frac{t_0 - t}{4m^2}$$

target pol.	interference $\propto$	
Unpolarized	$\sqrt{r}\left[F_1 H + \xi(F_1+F_2)\widetilde{H} + rF_2 E\right]$	
Longitudinal	$\sqrt{r}\left[F_1 \widetilde{H} + \xi(F_1+F_2) H + (rF_2 - \xi F_1)\,\xi\widetilde{E}\right]$	$+\sqrt{r}\,\xi^2\,\mathcal{O}(E,\xi\widetilde{E})$
Normal	$r\left[F_2 H - F_1 E + \xi(F_1+F_2)\,\xi\widetilde{E}\right]$	$+\,\xi^2\,\mathcal{O}(H,E,\widetilde{H})$
Sideways	$r\left[F_2 \widetilde{H} - F_1\,\xi\widetilde{E} + \xi(F_1+F_2) E - \xi F_2\,\xi\widetilde{E}\right]$	$+\,\xi^2\,\mathcal{O}(H,E,\widetilde{H},\xi\widetilde{E})$

count $\xi\widetilde{E}$ since pion exchange gives $\widetilde{E} \propto 1/\xi$

- neglecting F_1 for neutron (small t) get

target pol.	interference $\propto$
U	$\sqrt{r}\left[\xi\widetilde{H} + rE\right] F_2$
L	$\sqrt{r}\left[\xi H + r\xi\widetilde{E}\right] F_2$
N	$r\left[H + \xi^2\widetilde{E}\right] F_2$
S	$r\left[\widetilde{H} + \xi E - \xi^2\widetilde{E}\right] F_2$

- with long. and transv. target pol. can separate all four GPDs

Structure of differential cross section (unpolarized target)

$$\sigma_{ep\to e\gamma p} = \sigma_{\mathrm{BH}} + e_\ell\,\sigma_{\mathrm{INT}} + P_\ell e_\ell\,\tilde{\sigma}_{\mathrm{INT}} + \sigma_{\mathrm{VCS}} + P_\ell\,\tilde{\sigma}_{\mathrm{VCS}}$$

where σ even in ϕ $\qquad \sigma_{\mathrm{INT}} \propto \mathrm{Re}\,\mathcal{A}_{\gamma^* N\to\gamma N}$

$\tilde{\sigma}$ odd in ϕ $\qquad \tilde{\sigma}_{\mathrm{INT}} \propto \mathrm{Im}\,\mathcal{A}_{\gamma^* N\to\gamma N}$

beam charge	beam pol.	combination
e^-	difference	$-\tilde{\sigma}_{\mathrm{INT}} + \tilde{\sigma}_{\mathrm{VCS}}$
difference	none	σ_{INT}
difference	fixed	$P_\ell\,(\tilde{\sigma}_{\mathrm{INT}} + \sigma_{\mathrm{INT}})$

so that with

only pol. e^- — need Rosenbluth to separate $\tilde{\sigma}_{\mathrm{INT}}$ from $\tilde{\sigma}_{\mathrm{VCS}}$ (different y at same x_B and Q^2)

unpol. e^- and e^+ — get σ_{INT}

pol. e^- and pol. e^+ — get σ_{INT} and separate $\tilde{\sigma}_{\mathrm{INT}}$ from $\tilde{\sigma}_{\mathrm{VCS}}$

Structure of differential cross section (polarized target)

$$\sigma_{ep\to e\gamma p} = \sigma_{\mathrm{BH}} + e_\ell\, \sigma_{\mathrm{INT}} + P_\ell e_\ell\, \tilde{\sigma}_{\mathrm{INT}} + \sigma_{\mathrm{VCS}} + P_\ell\, \tilde{\sigma}_{\mathrm{VCS}}$$

$$+ S\big[P_\ell\, \Delta\sigma_{\mathrm{BH}} + e_\ell\, \Delta\tilde{\sigma}_{\mathrm{INT}} + P_\ell e_\ell\, \Delta\sigma_{\mathrm{INT}} + \Delta\tilde{\sigma}_{\mathrm{VCS}} + P_\ell\, \Delta\sigma_{\mathrm{VCS}}\big]$$

where polarization S can be longitudinal or transverse

beam charge	beam pol.	target pol.	combination
e^-	difference	none	$-\tilde{\sigma}_{\mathrm{INT}} + \tilde{\sigma}_{\mathrm{VCS}}$
difference	none	none	σ_{INT}
difference	fixed	none	$P_\ell\,(\tilde{\sigma}_{\mathrm{INT}} + \sigma_{\mathrm{INT}})$
e^-	none	difference	$-\Delta\tilde{\sigma}_{\mathrm{INT}} + \Delta\tilde{\sigma}_{\mathrm{VCS}}$
difference	none	fixed	$S\,\Delta\tilde{\sigma}_{\mathrm{INT}} + \sigma_{\mathrm{INT}}$
difference	fixed	fixed	$S\,\Delta\tilde{\sigma}_{\mathrm{INT}} + P_\ell\,\tilde{\sigma}_{\mathrm{INT}} + SP_\ell\,\Delta\sigma_{\mathrm{INT}} + \sigma_{\mathrm{INT}}$

so that with pol. target and

only pol. e^-	need Rosenbluth to separate $\Delta\tilde{\sigma}_{\mathrm{INT}}$ from $\Delta\tilde{\sigma}_{\mathrm{VCS}}$
unpol. e^- and e^+	can separate $\Delta\tilde{\sigma}_{\mathrm{INT}}$ from $\Delta\tilde{\sigma}_{\mathrm{VCS}}$
pol. e^- and pol. e^+	can separate $\Delta\tilde{\sigma}_{\mathrm{INT}}$ from $\Delta\tilde{\sigma}_{\mathrm{VCS}}$ and get $\Delta\sigma_{\mathrm{INT}}$

Conclusions

what remains to be done to establish a scientific and facility case?

- my feeling is that we have good elements for a physics case:
  - identified quantities to reveal aspects of QCD dynamics
  - solid theory to extract such quantities from observables
    we cannot presently promise to fully deconvolute functions GPD(x, ξ, t), but I think a physics case need not rely on this

Conclusions

what remains to be done to establish a scientific and facility case?

- it remains to see and show what can be quantitatively achieved with a given EIC design
  - DVCS
    - extraction of azimuthal and polarization asymmetries or (better) cross section differences
    - two-dimensional spectra in (t, x_B) $\longrightarrow$ nucleon tomography
    - two-dimensional spectra and kinematic reach in (x_B, Q^2) $\longrightarrow$ information beyond GPD(x, x, t)
    - change of t dependence with Q^2 $\longrightarrow$ scale evolution of $\langle b^2 \rangle$
  - meson production: kinematic reach and rates for high Q^2
    possibilities for non-singlet channels, e.g. ρ^+, K^*
  - possibility to measure azimuthal asymmetries in double DVCS $(ep \to ep + \mu^+\mu^-)$

Conclusions

requirements on machine (in order of priority)

1. clean measurement and kin. reconstruction of DVCS *
2. polarized e^- beam
3. polarized proton beam
4. (if possible polarized) e^+ beam **
5. (if possible polarized) deuteron beam
   and tagging of spectator nucleon

* an oxymoron

** without polarized e^+ beam may need different collision energies