Coherent DVCS on the deuteron

Wim Cosyn

Towards improved hadron femtography with hard exclusive reactions V
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Supported by

Deuteron GPD

- Requires **coherent** deuteron scattering
  $\rightarrow$ neutron, modified nucleon GPDs in **incoherent** deuteron scattering (next talk)

- 9 (5/4) chiral even, 9 chiral odd GPDs
  [Berger et al, PRL87 '01; Cosyn, Pire, PRD98 '18]
- Tomography of nuclear bound states
  $\rightarrow$ cfr. ^{4}He data (+ ALERT)
- New structures
  $\rightarrow$ tensor polarization, quadrupole
  $\rightarrow$ JLab tensor pol. deuteron target, EIC (upgraded)
- Cross section
  [Kirchner, Muller, EPJC32 ('04)]
- Phenomenology
  [Cano, Pire, EPJA19 ('04)]

This work

- Elucidate the full spin structure
- Reflect the spin 1/2 structure for the unpolarized / vector polarized
- Prioritize external kinematic variables (so avoid ξ)
- Avoid explicit frames, calculation can happen in **any frame**
  $\rightarrow$ everything is formulated in terms of invariants
  $\rightarrow$ interpretation L/T/ϕ happens in class of collinear frames
- Comment on role of choice of $n, \bar{n}$
  $\rightarrow$ $n \propto k$ is the obvious choice for the cross section
- A lot builds on previous works
  $\rightarrow$ Zhite Yu et al. SDHEP works for unification of BH, INT, DVCS

Kinematic Variables

- Separate
  - Hard: $e(k) + A^*(-\Delta) \rightarrow e'(k') + \gamma(q')$

    $\rightarrow \Delta^2 = t, \quad -(k-k')^2 = Q^2$

    $\rightarrow$ Bjorken-like variable $x_e = \frac{-\Delta^2}{-2\Delta\cdot k}; \quad 0 < x_e < 1$

    $\rightarrow$ related to invariant mass in eA^* system:

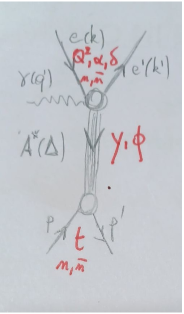
    $$W_e^2 = (k-\Delta)^2 = m_e^2 - t\left(\frac{1}{x_e} - 1\right)$$
  - For DVCS $x_e < \frac{-t}{Q^2} = \delta^2$

    $$\alpha \equiv \frac{x_e}{\delta^2}; \quad 0 < \alpha < 1$$
  - Soft: $d(p) \rightarrow d'(p') + A^*(-\Delta)$

    $\rightarrow \Delta^2 = t; \qquad \tau = -\frac{t}{4M^2}$
- Connect
  - Inelasticity variable (+Rosenbluth-like)

    $\rightarrow \mathrm{y} = -\frac{k\cdot\Delta}{k\cdot p} \quad 0 < \mathrm{y} < 1$ [Stricter limit for DVCS]

    $$\mathfrak{e} = \frac{1-\mathrm{y}-\frac{\mathrm{y}^2}{4\tau}}{1-\mathrm{y}+\frac{\mathrm{y}^2}{2}+\frac{\mathrm{y}^2}{4\tau}} = \frac{(\mathrm{P}_L^{\mu\nu}\mathrm{Q}_{T,\mu\nu})}{(\mathrm{P}_T^{\mu\nu}\mathrm{Q}_{T,\mu\nu})} = \frac{(\mathrm{Q}_L^{\mu\nu}\mathrm{P}_{T,\mu\nu})}{(\mathrm{Q}_T^{\mu\nu}\mathrm{P}_{T,\mu\nu})}$$
  - Angle ϕ between two planes



Covariant bases

$$d\sigma^{\mathrm{BH}} \propto \frac{1}{-t}\, \mathtt{H}^{\mathrm{B},\mu\nu}\mathtt{S}^{\mathrm{B}}_{\mu\nu}$$

$$d\sigma^{\mathrm{I}} \propto \frac{1}{-t}\, 2\,\mathrm{Re}\left[\mathtt{H}^{\mathrm{I},\mu}_{[V]}\mathtt{S}^{\mathrm{I}}_{[V],\mu} + \mathtt{H}^{\mathrm{I},\mu}_{[A]}\mathtt{S}^{\mathrm{I}}_{[A],\mu}\right]$$

$$d\sigma^{\mathrm{DVCS(LT)}} \propto \frac{1}{-t}\left(\mathtt{H}^{\mathrm{D}}_{U}\mathtt{S}^{\mathrm{D}}_{[V^2/A^2]} + \mathtt{H}^{\mathrm{D}}_{L}\mathtt{S}^{\mathrm{D}}_{[VA]}\right)$$

$n \sim k$

$$\mathtt{H}^{\mathrm{B},\mu\nu} = \sum_i c_i(\alpha,\delta)\,\mathtt{Q}^{\mu\nu}_i$$

$$\mathtt{S}^{\mathrm{B}}_{\mu\nu} = \sum_{\lambda\lambda'} \rho_{\lambda\lambda'}\langle p\lambda'|J^{\dagger\mu}|p'\rangle\langle p'|J^{\nu}|p\lambda\rangle = \sum_i F_i(t)\,\mathtt{P}^{\mu\nu}_i$$

$$\mathtt{S}^{\mathrm{I}}_{[V],\mu} = \sum_{\lambda\lambda'} \rho_{\lambda\lambda'}\langle p\lambda'|J^{\dagger\mu}|p'\rangle\langle p'|\frac{V\cdot n}{P\cdot n}|p\lambda\rangle = \sum \mathcal{F}_i(\xi,t)\,\frac{\mathtt{P}^{\mu\nu}_i n_\nu}{P\cdot n}$$

$$\mathtt{S}^{\mathrm{D}}_{[V^2/A^2]} = \sum_{\lambda\lambda'} \rho_{\lambda\lambda'}\langle p\lambda'|\frac{V^\dagger\cdot n}{P\cdot n}|p'\rangle\langle p'|\frac{V\cdot n}{P\cdot n}|p\lambda\rangle = \text{bilinear GPDs}$$

Hard part

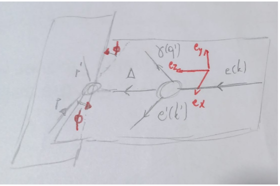
- L subspace k, Δ
  $\rightarrow e'_L, e_\Delta$
- T subspace k'
  $\rightarrow e_x, e_y$
- $e_x \cdot V = V_T \cos\phi$
  $e_y \cdot V = V_T \sin\phi$

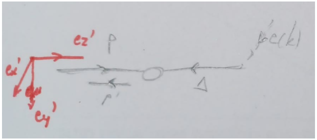
Soft part

- L subspace p, Δ
  $\rightarrow e_L, e_\Delta; e_p, e_{L*}$
- T subspace
  $\rightarrow g_{T'}, \epsilon_{T'}$
- $k \cdot g_{T'} \cdot V = -V_{T'}k_{T'}\cos\omega$
  $k \cdot \epsilon_{T'} \cdot V = -V_{T'}k_{T'}\sin\omega$

Overall $(\mathtt{H}\,\mathtt{S}) \rightarrow \sum_{ij} c_i(\alpha,\delta)\, d_{ij}(\mathfrak{e}, \mathrm{Pol.}, \phi)\, F_j(t,\xi)$

Covariant bases





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Overall $(\mathtt{H}\,\mathtt{S}) \rightarrow \sum_{ij} c_i(\alpha,\delta)\, d_{ij}(\mathfrak{e}, \mathrm{Pol.}, \phi)\, F_j(t,\xi)$

Hard part expansion

- Determines power counting of each contribution $\delta = \sqrt{\frac{-t}{Q^2}}$
- BH

c_i	exact (x_e, t, Q^2)	exact (α, δ)	LP coeff.
$\mathcal{A}^{\mathrm{B}}_{T}$	$2\,\frac{2Q^4x_e^4+2t\left(Q^2-t\right)x_e+\left(Q^4-4Q^2t+t^2\right)x_e^2-2\left(Q^4-Q^2t\right)x_e^3+2t^2}{t^2(1-x_e)\left(-t-Q^2x_e\right)}$	$2\,\frac{2-\alpha\left((2(1-\alpha)\alpha-1)\alpha\delta^4+2(1-\alpha)^2\delta^2-\alpha+2\right)}{(1-\alpha)\left(1-\alpha\delta^2\right)}$	$2\,\frac{2-(2-\alpha)\alpha}{(1-\alpha)}+\mathcal{O}(\delta^2)$
$\mathcal{C}^{\mathrm{B}}_{L}$	$8\,\frac{Q^2x_e^2}{-t}$	$8\alpha^2\delta^2$	$=$
$\mathcal{B}^{\mathrm{B}}_{LT}$	$4\,\frac{\left(-t-\left(Q^2-t\right)x_e+2Q^2x_e^2\right)}{(-t)\sqrt{(1-x_e)\left(-t-Q^2x_e\right)}}\,Qx_e$	$4\alpha\,\frac{1-\alpha+(2\alpha-1)\alpha\delta^2}{\sqrt{(1-\alpha)\left(1-\alpha\delta^2\right)}}\,\delta$	$4\alpha\sqrt{1-\alpha}\,\delta+\mathcal{O}(\delta^3)$
$\mathcal{C}^{\mathrm{B}}_{TT}$	$-4\,\frac{Q^2x_e^2}{t}$	$4\alpha^2\delta^2$	$=$
$\mathcal{A}^{\mathrm{B}}_{TT'}$	$2\,\frac{\left(\left(Q^4-4Q^2t+t^2\right)x_e-2\left(Q^4-Q^2t\right)x_e^2+2t\left(Q^2-t\right)\right)}{t(1-x_e)\left(-t-Q^2x_e\right)}\,x_e$	$2\alpha\,\frac{2-\alpha+2(\alpha-1)^2\delta^2+\left((2\alpha-1)\alpha\delta^4\right)}{(1-\alpha)\left(1-\alpha\delta^2\right)}$	$2\,\frac{(2-\alpha)\alpha}{1-\alpha}+\mathcal{O}(\delta^2)$
$\mathcal{B}^{\mathrm{B}}_{LT'}$	$-4\,\frac{Qx_e\left(-t-\left(Q^2-t\right)x_e\right)}{(-t)\sqrt{(1-x_e)\left(-t-Q^2x_e\right)}}$	$-4\alpha\,\frac{1-\alpha-\alpha\delta^2}{\sqrt{(1-\alpha)\left(1-\alpha\delta^2\right)}}\,\delta$	$-4\alpha\sqrt{1-\alpha}\,\delta+\mathcal{O}(\delta^3$

- Similar expressions for
  - Interference: 6 coefficients (4 NLP δ, 2 NNLP δ^2): 3 independent at LP
  - DVCS: 2 coefficients (NNLP δ^2)

Soft part: covariant density matrices

$$\sum_{\lambda\lambda'} \rho_{\lambda\lambda'} u(p,\lambda)\bar{u}(p,\lambda') = (\not{p} + M)\,\tfrac{1}{2}(1 + \not{S}\gamma_5)$$

$$\sum_{\lambda\lambda'} \rho_{\lambda\lambda'} \epsilon^{\mu}(p,\lambda)\epsilon^{*\nu}(p,\lambda') = \frac{1}{3}\left(-g^{\alpha\beta} + \frac{p^{\alpha}p^{\beta}}{M^2}\right) + \frac{i}{2M}\epsilon^{\alpha\beta\gamma\delta}p_{\gamma}S_{\delta} - T^{\alpha\beta}$$

- Expand covariant S^{μ}, $T^{\mu\nu}$ on the basis used in Soft part

  $\rightarrow$ **Invariants** $S_L, S_T, \omega_S; T_{LL}, T_{LT}, \omega_{T_L}, T_{TT}, \omega_{T_T}$
  (Different from SDHEP papers!)
- Polarization $||, \perp$ to electron beam? $\rightarrow$ **effective polarizations**

$||$

$$S_L = \Lambda_d \frac{(2\tau + y)}{2\sqrt{\tau(\tau+1)}}$$

$$S_T \cos\omega_S = -\Lambda_d \frac{\sqrt{4\tau - 4\tau y + y^2}}{2\sqrt{\tau(\tau+1)}}$$

$$S_L \sin\omega_S = 0$$

$\perp$ (ψ_N)

$$S_L = \Lambda_d \frac{(2\tau + y)}{2\sqrt{\tau(\tau+1)}} \cos\psi_N$$

$$S_T \cos\omega_S = \Lambda_d \frac{(2\tau + y)}{2\sqrt{\tau(\tau+1)}} \cos\psi_N$$

$$S_L \sin\omega_S = \Lambda_d \sin\psi_N$$

- All $\mathcal{O}(1)$ $\leftrightarrow$ **contrary** to DIS case

BH contractions

	$F^{\mathrm{el}}_{[UT_{LT}]} = -4\sqrt{\tau}(1+\tau)G_M(t)G_Q(t)$	$F^{\mathrm{el}}_{[UT_{TT}]} = -(1+\tau)G_M^2(t)$
$\mathcal{A}^{\mathrm{B}}_{T}$	$\mathtt{Q}^{\mu\nu}_{T}\mathtt{P}\,T_{LT,\mu\nu} = T_{LT}\cos\omega_{T_L}\,\frac{\sqrt{2\varepsilon(1+\varepsilon)}}{1-\varepsilon}$	$\mathtt{Q}^{\mu\nu}_{T}\mathtt{P}\,T_{TT,\mu\nu} = T_{TT}\cos 2\omega_{T_T}\,\frac{\varepsilon}{1-\varepsilon}$
$\mathcal{C}^{\mathrm{B}}_{L}$	$\mathtt{Q}^{\mu\nu}_{L}\mathtt{P}\,T_{LT,\mu\nu} = T_{LT}\cos\omega_{T_L}\,\frac{\sqrt{2\varepsilon(1+\varepsilon)}}{1-\varepsilon}$	$\mathtt{Q}^{\mu\nu}_{L}\mathtt{P}\,T_{TT,\mu\nu} = T_{TT}\cos 2\omega_{T_T}\,\frac{\varepsilon}{1-\varepsilon}$
$\mathcal{B}^{\mathrm{B}}_{LT}$	$\mathtt{Q}^{\mu\nu}_{LT}\mathtt{P}\,T_{LT,\mu\nu} = T_{LT}\cos\omega_{T_L}\cos\phi\,\frac{1+3\varepsilon}{1-\varepsilon}$	$\mathtt{Q}^{\mu\nu}_{LT}\mathtt{P}\,T_{TT,\mu\nu} = T_{TT}\cos 2\omega_{T_T}\cos\phi\,\frac{\sqrt{2\varepsilon(1+\varepsilon)}}{1-\varepsilon}$
	$-T_{LT}\sin\omega_{T_L}\sin\phi\,\frac{\sqrt{1-\varepsilon^2}}{1-\varepsilon}$	$-T_{TT}\sin 2\omega_{T_T}\sin\phi\,\frac{\sqrt{2\varepsilon(1-\varepsilon)}}{1-\varepsilon}$
$\mathcal{C}^{\mathrm{B}}_{TT}$	$\mathtt{Q}^{\mu\nu}_{TT}\mathtt{P}\,T_{LT,\mu\nu} = T_{LT}\cos\omega_{T_L}\cos 2\phi\,\frac{\sqrt{2\varepsilon(1+\varepsilon)}}{1-\varepsilon}$	$\mathtt{Q}^{\mu\nu}_{TT}\mathtt{P}\,T_{TT,\mu\nu} = T_{TT}\cos 2\omega_{T_T}\cos 2\phi\,\frac{1}{1-\varepsilon}$
	$+T_{LT}\sin\omega_{T_L}\sin 2\phi\,\frac{\sqrt{2\varepsilon(1-\varepsilon)}}{1-\varepsilon}$	$-T_{TT}\sin 2\omega_{T_T}\sin 2\phi\,\frac{\sqrt{1-\varepsilon^2}}{1-\varepsilon}$

- Invariant coefficients combine in many different ways to build up cross section

Interference

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$$
\begin{aligned}
2\,\mathrm{Re}\left[\mathbb{H}^{\mathrm{I},\mu}_{[V]}\mathbb{S}^{\mathrm{I}}_{[V],\mu}+\mathbb{H}^{\mathrm{I},\mu}_{[A]}\mathbb{S}^{\mathrm{I}}_{[A],\mu}\right] = \cos\phi\,&\left(\mathcal{B}^{\mathrm{I}}_{TV}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[UV]L}+\mathcal{F}^{I}_{[UV]T}\right]+\mathcal{B}^{\mathrm{I}}_{T'A}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[UA]}\right]\right)\\
&+\mathcal{C}^{\mathrm{I}}_{LV}\left(\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[UV]L}\right]+\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[UV]T}\right]\right)\\
&+(2\Lambda_e)\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'V}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[UV]L}+\mathcal{F}^{I}_{[UV]T}\right]+\mathcal{B}^{\mathrm{I}}_{TA}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[UA]}\right]\right)\\
&+S_L\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'A}\left[\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_LA]L}\right]+\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_LA]T}\right]\right]-\mathcal{B}^{\mathrm{I}}_{TV}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_LV]}\right]\right)\\
&+(2\Lambda_e)S_L\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TA}\left[\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_LA]L}\right]+\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_LA]T}\right]\right]-\mathcal{B}^{\mathrm{I}}_{T'V}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_LV]}\right]\right)\\
&+(2\Lambda_e)S_L\,\mathcal{C}^{\mathrm{I}}_{LA}\left(2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_LA]L}\right]+\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_LA]T}\right]\right)\\
&+S_T\sin\omega_S\,\mathcal{C}^{\mathrm{I}}_{LV}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Im}\left[-\mathcal{F}^{I}_{[S_TV]L}+\mathcal{F}^{I}_{[S_TV]T}\right]\\
&+S_T\sin\omega_S\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TV}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_TV]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_TV]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{T'A}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_TA]N}\right]\right)\\
&-(2\Lambda_e)S_T\sin\omega_S\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'V}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TV]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TV]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{TA}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TA]N}\right]\right)\\
&+(2\Lambda_e)S_T\cos\omega_S\,\mathcal{C}^{\mathrm{I}}_{LA}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}\left[-2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TA]L}\right]+2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TA]T}\right]\right]\\
&+S_T\cos\omega_S\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'A}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_TA]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_TA]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{TV}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[S_TV]N}\right]\right)\\
&+(2\Lambda_e)S_T\cos\omega_S\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TA}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TA]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TA]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{T'V}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[S_TV]N}\right]\right)\\
&+T_{LL}\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TV}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LL}V]L}+\mathcal{F}^{I}_{[T_{LL}V]T}\right]+\mathcal{B}^{\mathrm{I}}_{T'A}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LL}A]}\right]\right)\\
&+T_{LL}\mathcal{C}^{\mathrm{I}}_{LV}\left(\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LL}V]L}\right]+\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LL}V]T}\right]\right)\\
&+(2\Lambda_e)T_{LL}\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'V}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LL}V]L}+\mathcal{F}^{I}_{[T_{LL}V]T}\right]+\mathcal{B}^{\mathrm{I}}_{TA}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LL}A]}\right]\right)\\
&+T_{LT}\cos\omega_{T_L}\,\mathcal{C}^{\mathrm{I}}_{LV}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Re}\left[-\mathcal{F}^{I}_{[T_{LT}V]L}+\mathcal{F}^{I}_{[T_{LT}V]T}\right]\\
&+T_{LT}\cos\omega_{T_L}\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TV}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}V]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}V]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{T'A}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}A]N}\right]\right)\\
&-(2\Lambda_e)T_{LT}\cos\omega_{T_L}\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'V}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}V]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}V]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{TA}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}A]N}\right]\right)\\
&+(2\Lambda_e)T_{LT}\sin\omega_{T_L}\,\mathcal{C}^{\mathrm{I}}_{LA}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}\left[-2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}A]L}\right]+2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}A]T}\right]\right]\\
&+T_{LT}\sin\omega_{T_L}\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'A}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}A]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}A]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{TV}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}V]N}\right]\right)
\end{aligned}
$$

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$$
\begin{aligned}
&+(2\Lambda_e)T_{LT}\sin\omega_{T_L}\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TA}\left(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}A]L}\right]+\frac{\sqrt{1-\epsilon^2}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}A]T}\right]\right)+\mathcal{B}^{\mathrm{I}}_{T'V}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{LT}V]N}\right]\right)\\
&+T_{TT}\cos 2\omega_{T_T}\,\mathcal{C}^{\mathrm{I}}_{LV}\frac{2\epsilon}{\sqrt{1-\epsilon^2}}2\,\mathrm{Re}\left[-\mathcal{F}^{I}_{[T_{TT}V]L}+\mathcal{F}^{I}_{[T_{TT}V]T}\right]\\
&+T_{TT}\cos 2\omega_{T_T}\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TV}\left(-\frac{2\epsilon\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon^2}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{TT}V]L}\right]+\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{TT}V]T}\right]\right)\right.\\
&\qquad\left.+\mathcal{B}^{\mathrm{I}}_{T'A}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{TT}A]N}\right]\right)\\
&+(2\Lambda_e)T_{TT}\cos 2\omega_{T_T}\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'V}\left(-\frac{2\epsilon\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon^2}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}V]L}\right]+\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}V]T}\right]\right)\right.\\
&\qquad\left.+\mathcal{B}^{\mathrm{I}}_{TA}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}A]N}\right]\right)\\
&+(2\Lambda_e)T_{TT}\sin 2\omega_{T_T}\,\mathcal{C}^{\mathrm{I}}_{LA}\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}\left[-2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}A]L}\right]+2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}A]T}\right]\right]\\
&-T_{TT}\sin 2\omega_{T_T}\sin\phi\left(\mathcal{B}^{\mathrm{I}}_{T'A}\left(-\frac{2\epsilon\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon^2}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{TT}A]L}\right]+\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{TT}A]T}\right]\right)\right.\\
&\qquad\left.+\mathcal{B}^{\mathrm{I}}_{TV}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{TT}V]N}\right]\right)\\
&+(2\Lambda_e)T_{TT}\sin 2\omega_{T_T}\cos\phi\left(\mathcal{B}^{\mathrm{I}}_{TA}\left(-\frac{2\epsilon\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon^2}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}A]L}\right]+\frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}A]T}\right]\right)\right.\\
&\qquad\left.+\mathcal{B}^{\mathrm{I}}_{T'V}\frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon}2\,\mathrm{Im}\left[\mathcal{F}^{I}_{[T_{TT}V]N}\right]\right)
\end{aligned}
\tag{108}
$$

Interference

- Looks long and very wieldy....BUT
- Only 6 hard coefficients (2 indep at NLP)
- 1/9/27 independent $\mathcal{F}$ for spin $0/\frac{1}{2}/1$
- Compact expressions: Spin 1/2

$$\mathcal{F}^I_{[UV]L} = \frac{G_E(\mathcal{H} - \tau\mathcal{E})}{\sqrt{\tau(1+\tau)}},$$

$$\mathcal{F}^I_{[UA]} = -\frac{1}{2} G_M \widetilde{\mathcal{H}},$$

$$\mathcal{F}^I_{[S_L A]T} = G_M \widetilde{\mathcal{H}}$$

$$\mathcal{F}^I_{[S_T V]T} = G_M \frac{(\mathcal{H} - \tau\mathcal{E})}{\sqrt{1+\tau}}$$

$$\mathcal{F}^I_{[S_T A]T} = \frac{\xi}{\tau} G_M \frac{(\widetilde{\mathcal{H}} - \tau\widetilde{\mathcal{E}})}{\sqrt{1+\tau}}$$

$$\mathcal{F}^I_{[UV]T} = \mathcal{F}^I_{[S_L V]} = \tau \frac{G_M(\mathcal{H} + \mathcal{E})}{\sqrt{\tau(1+\tau)}},$$

$$\mathcal{F}^I_{[S_L A]L} = G_E(\widetilde{\mathcal{H}} - \tau\widetilde{\mathcal{E}}),$$

$$\mathcal{F}^I_{[S_T V]L} = \frac{G_E(\mathcal{H} + \mathcal{E})}{\sqrt{1+\tau}},$$

$$\mathcal{F}^I_{[S_T A]L} = \frac{G_E \widetilde{\mathcal{H}}}{\sqrt{\tau}}$$

- Spin 1: Similar pattern G_M vs G_C, G_Q $\times$ { more CFFs }

Choice of $n, \bar{n}$–vector

- Leads to different ξ (GPD/CFF evaluated at different point), different expansion coefficients in cross section
  $\rightarrow$ everything will agree after including everything (higher twist etc.)
- (Good / Greatest): For preservation of azimuthal structure of cross section $n \sim k$ is the only valid choice
  - $\mathrm{y} = \frac{2\xi}{2+\xi}$
  - No approximations needed (can be done of course)
- (Bad / A bit less great): vectors from within the Span$\{k, k', q'\}$ [includes BMP $n\ q'$].
  - Hard coefficients change, but still $c_i(\alpha, \delta)$
  - ξ gets ϕ dependence: alters modulations
- (Worst / Less great): vectors from Span$\{p, q\}$.
  - Hard coefficients get ϕ–dependence
  - ξ gets y, ϕ dependence

Choice of n, $\bar{n}$–vector

- **BUT…all** differences are power corrections
  $\rightarrow$ choices agree when doing LP approximation of coefficients/ξ

  $\rightarrow$ DVCS hard coefficient with n from (p, q)

```
DeltaExpand[bb, MaxOrder → 2, Assumptions → {τ > 0}]
```

Substitution:Q->Sqrt[$-\frac{t}{\delta^2}$], $x_e \to \alpha\delta^2$

Substituted expression:

Out[◦]=

$$
\begin{aligned}
&\Big(2\,\delta^2\Big(4\,\tau\Big(\alpha\Big(\alpha\big(6(\alpha-1)\alpha+1\big)\delta^4-2(\alpha-1)(3\alpha-1)\delta^2+\alpha-2\Big)+2\Big)+y_h^2\Big(2\alpha^3\delta^2\big(-\alpha\delta^2+\delta^2+1\big)-2(\alpha-1)\alpha^2\delta^2\big(\alpha\delta^2-1\big)\cos(2\phi)+\tau\Big(\alpha\Big((1-2\alpha)^2\alpha\delta^4-2\big(2(\alpha-2)\alpha+1\big)\delta^2+\alpha-2\Big)+2\Big)\Big)+\\
&\quad 8\,\alpha\,\delta\Big((\alpha-1)\alpha\,\delta\,\tau\big(\alpha\delta^2-1\big)\cos(2\phi)+\big(\alpha(2\alpha-1)\delta^2-\alpha+1\big)\cos(\phi)\sqrt{-\big((\alpha-1)\tau\big(\alpha\delta^2-1\big)\big(4\tau y_h+y_h^2-4\tau\big)\big)}\Big)+\\
&\quad 4\,y_h\Big(\alpha\,\delta\Big(\big((1-2\alpha)\alpha\delta^2+\alpha-1\big)\cos(\phi)\sqrt{-\big((\alpha-1)\tau\big(\alpha\delta^2-1\big)\big(4\tau y_h+y_h^2-4\tau\big)\big)}-2(\alpha-1)\alpha\,\delta\,\tau\big(\alpha\delta^2-1\big)\cos(2\phi)\Big)-\tau\Big(\alpha\Big(\alpha\big(6(\alpha-1)\alpha+1\big)\delta^4-2(\alpha-1)(3\alpha-1)\delta^2+\alpha-2\Big)+2\Big)\Big)\Big)\Big)\Big/\\
&\Big(\alpha^2\Big(8(\alpha-1)\delta^2\tau\big(\alpha\delta^2-1\big)\cos(2\phi)+4\,\tau\Big(\big(6(\alpha-1)\alpha+1\big)\delta^4+(4-6\alpha)\delta^2+1\Big)+8\,\delta\Big((2\alpha-1)\delta^2-1\Big)\cos(\phi)\sqrt{-\big((\alpha-1)\tau\big(\alpha\delta^2-1\big)\big(4\tau y_h+y_h^2-4\tau\big)\big)}-\\
&\quad 4\,y_h\Big(2(\alpha-1)\delta^2\tau\big(\alpha\delta^2-1\big)\cos(2\phi)+\delta^2\tau\Big(6\alpha\big((\alpha-1)\delta^2-1\big)+\delta^2+4\Big)+\delta\Big((2\alpha-1)\delta^2-1\Big)\cos(\phi)\sqrt{-\big((\alpha-1)\tau\big(\alpha\delta^2-1\big)\big(4\tau y_h+y_h^2-4\tau\big)\big)}+\tau\Big)+\\
&\quad y_h^2\Big(\delta^4\big(2(\alpha-1)\alpha(2\tau-1)+\tau\big)+2\delta^2\big(-2\alpha\tau+\alpha+3\tau+1\big)-2(\alpha-1)\delta^2\big(\alpha\delta^2-1\big)\cos(2\phi)+\tau\Big)\Big)
\end{aligned}
$$

Expansion in δ:

δ^2 : $\frac{2(\alpha-2)\alpha+4}{\alpha^2}$

High level cross section summary

Polarization	LP	NLP	NNLP
UU / UT_{LL}	1: BH	$\cos\phi$: BH, INT	1: BH, INT, DVCS(V^2/A^2) $\cos 2\phi$: BH
LU / LT_{LL}	$\times$	$\sin\phi$: INT	$\times$
US_L	$\times$	$\sin\phi$: INT	$\times$
LS_L	1: BH	$\cos\phi$: BH, INT	1: INT, DVCS(VA)
US_T	$\times$	$\cos\phi$: INT $\sin\phi$: INT	1: INT, DVCS(V^2/A^2)
LS_T	1: BH	$\cos\phi$: BH, INT $\sin\phi$: BH, INT	1: INT, DVCS(VA)
UT_{LT}	1: BH	$\cos\phi$: BH, INT $\sin\phi$: BH, INT	1: BH, INT, DVCS(V^2/A^2) $\cos 2\phi, \sin 2\phi$: BH
LT_{LT}	$\times$	$\cos\phi$: INT $\sin\phi$: INT	1: INT, DVCS(VA)
UT_{TT}	1: BH	$\cos\phi$: BH, INT $\sin\phi$: BH, INT	1: BH, INT, DVCS(V^2/A^2) $\cos 2\phi, \sin 2\phi$: BH
LT_{TT}	$\times$	$\cos\phi$: INT $\sin\phi$: INT	1: INT, DVCS(VA)

Interference twist 3 GPD, kinematic power corrections enter at NNLP

Example :UT_{LT}

$$
\begin{aligned}
d\sigma_{[UT_L T]} \propto T_{LT} \Bigg\{ & \cos\omega_{T_L} \left(\mathcal{A}^{\mathrm{B}}_{T} + \mathcal{C}^{\mathrm{B}}_{L}\right) \frac{\sqrt{2\epsilon(1+\epsilon)}}{1-\epsilon} F^{\mathrm{el}}_{[UT_{LT}]} \\
& + \cos\omega_{T_L} \cos\phi \Bigg[\mathcal{B}^{\mathrm{B}}_{LT} \frac{1+3\epsilon}{1-\epsilon} F^{\mathrm{el}}_{[UT_{LT}]} + \mathcal{B}^{\mathrm{I}}_{TV} \Bigg(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}} 2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}V]L}\right] \\
& \qquad + \frac{\sqrt{1-\epsilon^2}}{1-\epsilon} 2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}V]T}\right] \Bigg) + \mathcal{B}^{\mathrm{I}}_{T'A} 2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}A]N}\right] \Bigg] \\
& + \sin\omega_{T_L} \sin\phi \Bigg[\mathcal{B}^{\mathrm{B}}_{LT} \frac{\sqrt{1-\epsilon^2}}{1-\epsilon} F^{\mathrm{el}}_{[UT_{LT}]} + \mathcal{B}^{\mathrm{I}}_{T'A} \Bigg(-\frac{2\epsilon}{\sqrt{1-\epsilon^2}} 2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}A]L}\right] \\
& \qquad + \frac{\sqrt{1-\epsilon^2}}{1-\epsilon} 2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}A]T}\right] \Bigg) + \mathcal{B}^{\mathrm{I}}_{TV} 2\,\mathrm{Re}\left[\mathcal{F}^{I}_{[T_{LT}V]N}\right] \Bigg] \\
& + \cos\omega_{T_L} \cos 2\phi\, \mathcal{C}^{\mathrm{B}}_{TT} \frac{\sqrt{2\epsilon(1+\epsilon)}}{1-\epsilon} F^{\mathrm{el}}_{[UT_{LT}]} + \sin\omega_{T_L} \sin 2\phi\, \mathcal{C}^{\mathrm{B}}_{TT} \frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon} F^{\mathrm{el}}_{[UT_{LT}]} \\
& + \cos\omega_{T_L} \mathcal{C}^{\mathrm{I}}_{LV} \frac{\sqrt{2\epsilon(1-\epsilon)}}{1-\epsilon} 2\,\mathrm{Re}\left[-\mathcal{F}^{I}_{[T_{LT}V]L} + \mathcal{F}^{I}_{[T_{LT}V]T}\right] \\
& + \cos\omega_{T_L} \mathcal{C}^{\mathrm{D}}_{U} \frac{\sqrt{2\epsilon(1+\epsilon)}}{1+\epsilon} F^{\mathrm{D}}_{[UT_{LT}]} \Bigg\}
\end{aligned}
$$

- Isolate tensor pol. from $2\sigma^0 - \sigma^+ - \sigma^-$
- Modulations can be disentangled
- Separation within by variation of ϵ.

Conclusions

- Decomposition of spin-1 DVCS cross section in true invariant building blocks
  $\rightarrow$ direct connection to external kinematic variables / polarization
- Unpolarized/Vector pol. like spin 1/2
- Many additional tensor pol. structures
- Choice $n \sim k$ obvious choice for cross section expressions (SDHEP)
- Pheno study next (straightforward part)
- Convenient combinations of spin-1 GPDS? $\rightarrow$ multipoles
- How do kinematic power corrections a la BMP fit in?
- Inclusion higher twist / NLO obvious extension
- Methodology applicable/advantageous to any hard exclusive / diffractive process where spin plays an important role