Deeply virtual Compton scattering off deuteron

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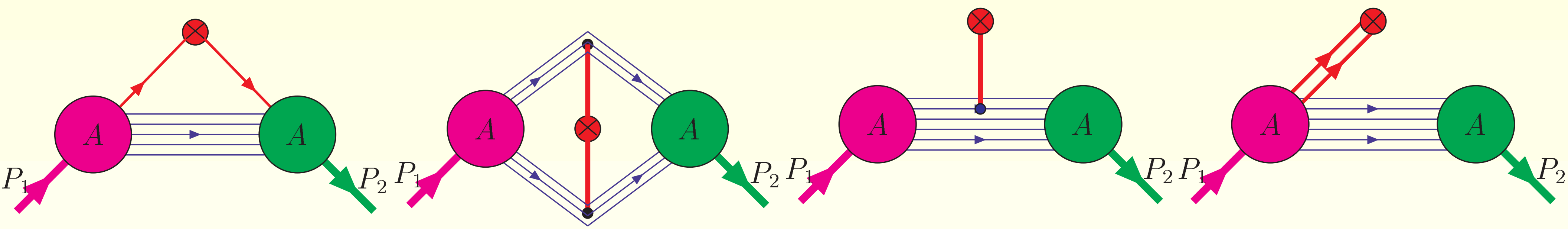
- Why we should study nuclei GPDs?
- Analytic results
- Estimates for several observables:
  - single beam spin asymmetry
  - charge beam asymmetry
  - single target spin asymmetries
  - tensor polarization
- Summary/conclusions

QCD Structure of the Nucleon, Rom 13^{th} June 2006

Why we should study nuclei GPDs?

- Resolution of nuclei in terms of partonic degrees of freedom:
  - *Holographic* 3D distribution of quarks and gluons.
  - Nucleus *spin* in terms of fundamental degrees of freedom.
- A *new window* to study the *nuclear* degrees of freedom:



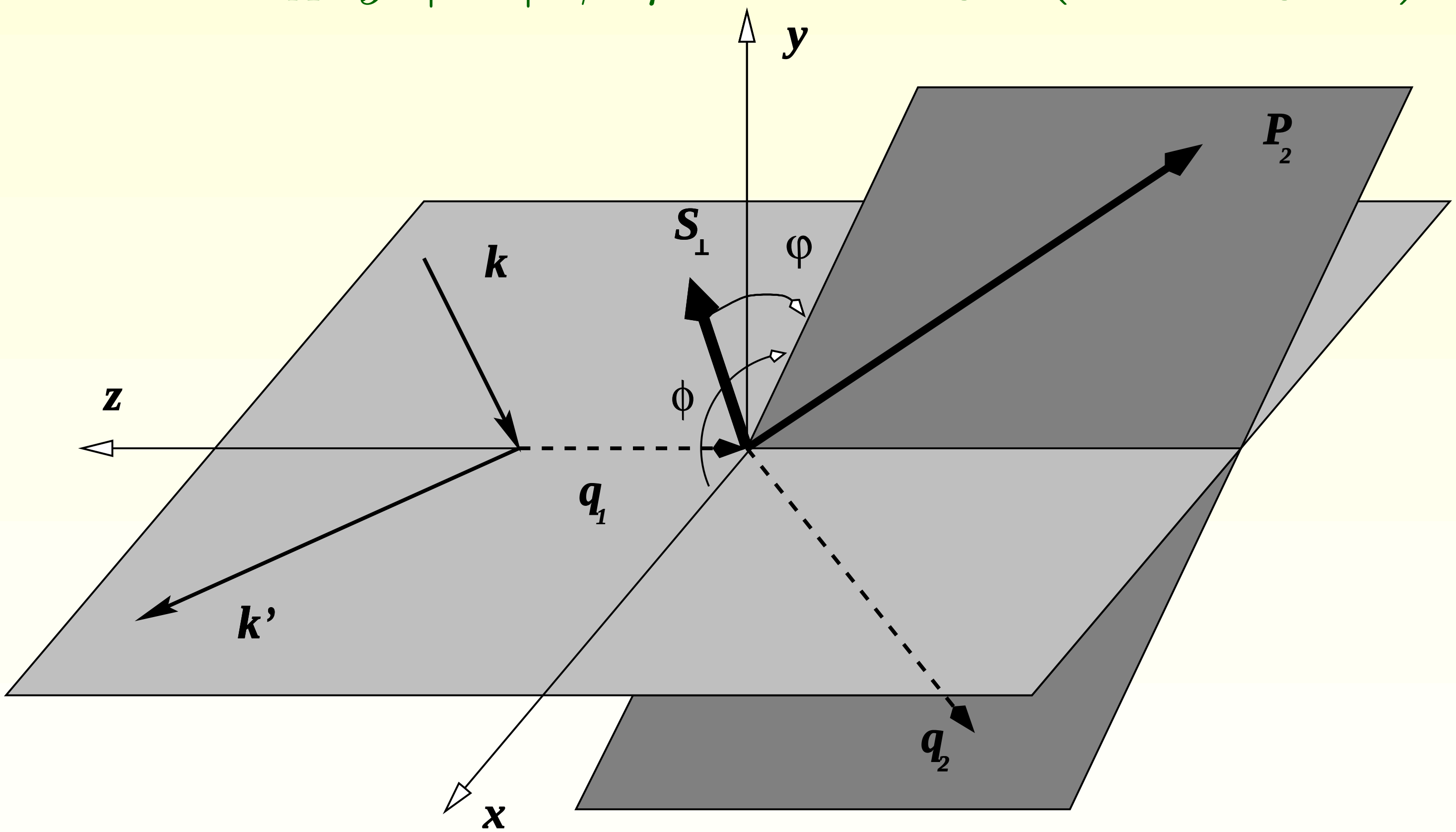
- To study *binding effects* in nuclei from a new perspective.
- Provides new constraints on the *nucleus wave function*.
- Links *fundamental* and *nuclear* degrees of freedom.

γ leptoproduction on nucleus

$$e^{\pm}(k,\lambda)A(P_1,S_1) \to e^{\pm}(k',\lambda')A(P_2,S_2)\gamma(q_2,\Lambda)$$

The five-fold cross section reads

$$\frac{d\sigma}{dx_{\rm A}dyd|\Delta^2|d\phi d\varphi} = \frac{\alpha^3 x_{\rm A} y}{16\,\pi^2\,\mathcal{Q}^2}\left(1+\frac{4M_{\rm A}^2 x_{\rm A}^2}{\mathcal{Q}^2}\right)^{-1/2}\left|\frac{\mathcal{T}}{e^3}\right|^2,$$



$$\mathcal{Q}^2 = -q_1^2$$

$$x_{\rm A} = \frac{\mathcal{Q}^2}{2P_1\cdot q_1} \approx \frac{2\xi}{1+\xi}$$

$$y = \frac{P_1\cdot q_1}{P_1\cdot k}$$

$$\Delta^2 = t$$

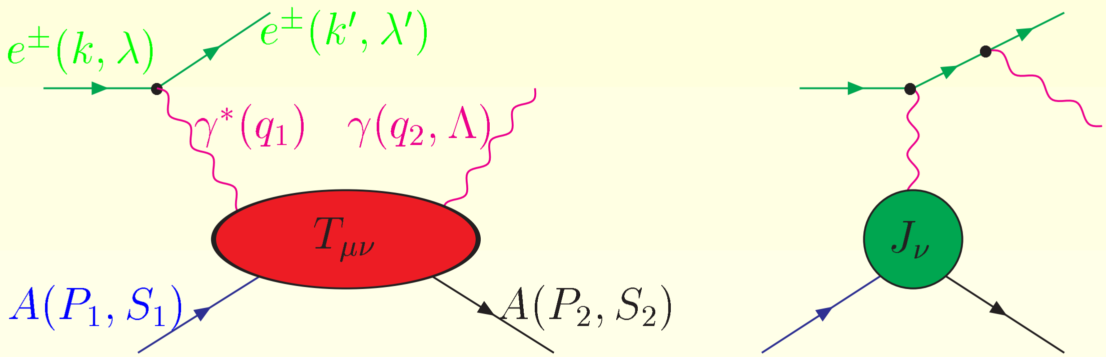
M_A - nucleus mass

NOTE: $0 \le x_{\rm B} \approx A\,x_A \le A$, $M_N \approx \frac{M_A}{A}$, $-\tau = \frac{-\Delta^2}{4M_A^2} \ll 1$

Analytic results for the amplitude square

[nucleon: A.V. Belitsky, D.M. A. Kirschner (01), deuteron: A.Kirschner, D.M. (03)]

γ Leptoproduction contains both *DVCS* and *Bethe-Heitler process*



The squared amplitude is decomposed in three parts

$$|\mathcal{T}|^2 = \sum_{\lambda',S_2,\Lambda} \left\{ |\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 \pm \mathcal{I} \right\} \quad \begin{cases} + \; e^-\text{-beam} \\ - \; e^+\text{-beam} \end{cases}$$

with the interference term $\mathcal{I} = \mathcal{T}_{DVCS}\mathcal{T}^*_{BH} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH}$.

Observables in γ leptoproduction

Twist-3 result gives the general azimuthal angular dependence:

$$|\mathcal{T}_{\rm CS}|^2 = \frac{e^6}{y^2 \mathcal{Q}^2} \left\{ c_0^{\rm CS}(\varphi) + \sum_{n=1}^{2} \left[c_n^{\rm CS}(\varphi) \cos(n\phi) + s_n^{\rm CS}(\varphi) \sin(n\phi) \right] \right\},$$

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_A^2 y^2 \Delta^2 \, \mathcal{P}_1(\phi) \mathcal{P}_2(\phi)} \left\{ c_0^{\rm BH}(\varphi) + \sum_{n=1}^{2} c_n^{\rm BH}(\varphi) \cos(n\phi) \right\},$$

$$\mathcal{I} = \frac{\pm e^6}{x_A y^3 \Delta^2 \mathcal{P}_1(\phi) \mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}}(\varphi) + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}}(\varphi) \cos(n\phi) + s_n^{\mathcal{I}}(\varphi) \sin(n\phi) \right] \right\}.$$

- Fourier coefficients (FCs) $\leftrightarrow$ Compton form factors (CFFs):

$$c_0^{\mathcal{I}} \propto \frac{\Delta^2}{\mathcal{Q}^2}\text{tw-2}, \left\{ {c_1 \atop s_1} \right\}^{\mathcal{I}} \propto \frac{\Delta}{\mathcal{Q}}\text{tw-2}, \left\{ {c_2 \atop s_2} \right\}^{\mathcal{I}} \propto \frac{\Delta^2}{\mathcal{Q}^2}\ \text{tw-3}, \left\{ {c_3 \atop s_3} \right\}^{\mathcal{I}} \propto \frac{\Delta \alpha_s}{\mathcal{Q}}(\text{tw-2})^{\rm GT}$$

$$c_0^{\rm CS} \propto (\text{tw-2})^2, \left\{ {c_1 \atop s_1} \right\}^{\rm CS} \propto \frac{\Delta}{\mathcal{Q}}(\text{tw-2})(\text{tw-3}), \left\{ {c_2 \atop s_2} \right\}^{\rm CS} \propto \alpha_s(\text{tw-2})(\text{tw-2})^{\rm GT}$$

- The FCs are given by *'universal'* functions $\mathcal{C}$ of CFFs, e.g.,

$$\left\{ {c_1^{\mathcal{I}} \atop s_1^{\mathcal{I}}} \right\}(y, \xi, \Delta^2, \mathcal{Q}^2) = \left\{ {\mathcal{L}_1^{\mathcal{I}c} \atop \mathcal{L}_1^{\mathcal{I}s}} \right\}(y) \left\{ {\Re\mathrm{e} \atop \Im\mathrm{m}} \right\} \mathcal{C}^{\mathcal{I}}(\mathcal{F}(\xi, \Delta^2, \mathcal{Q}^2))$$

and $c/s_1^{\mathcal{I}} \to c/s_2^{\mathcal{I}}$, $\mathcal{L}_1 \to \mathcal{L}_2$, $\mathcal{F} \to \mathcal{F}^{\rm eff}$.

- Adjusting beam helicity $\Rightarrow$ separation of even/odd harmonics

  · target polarization $\Rightarrow$ new combinations of CFFs

Compton form factor (CFF) decomposition

Spin-1/2 target: $3 \times (2 \times 2)$ CFFs

$$V_\rho = \bar{U}\gamma_\rho U\,\mathcal{H} + \bar{U} i\sigma_{\rho\sigma}\frac{\Delta_\sigma}{2M}U\,\mathcal{E} + \text{twist-three contributions},$$

$$A_\rho = \bar{U}\gamma_\rho\gamma_5 U\,\widetilde{\mathcal{H}} + \frac{\Delta_\rho}{2M}\bar{U}\gamma_5 U\,\widetilde{\mathcal{E}} + \text{twist-three contributions},$$

CFFs $\mathcal{F} = \left\{\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}\right\}$ are given by GPDs $F = \left\{H, E, \widetilde{H}, \widetilde{E}\right\}$

$$\mathcal{F} = \sum_{i=u,d,s,G}\int_{-1}^{1} dx\, C_i^{\mp}\left(x, \xi, \alpha_s(\mathcal{Q})\right) F_i(x, \xi, \Delta^2, \mathcal{Q}^2)$$

At twist-three level four further ones appear

$$\mathcal{F}^3(F, F^{qGq}) = \left\{\mathcal{H}^3, \mathcal{E}^3, \widetilde{\mathcal{H}}^3, \widetilde{\mathcal{E}}^3\right\}$$
$$= \mathcal{F}^{\mathrm{WW}}(F) + \mathcal{F}^{qGq}(F^{qGq}).$$

Finally, there are four CFFs arising from gluon transversity

$$\mathcal{F}^T = \left\{\mathcal{H}^T, \mathcal{E}^T, \widetilde{\mathcal{H}}^T, \widetilde{\mathcal{E}}^T\right\}.$$

Spin-1 target: $3 \times (3 \times 3)$ CFFs

Only twist-two LO sector is known [E.R.Berger, F.Cano, M.Diehl, B.Pire]

$$V_\mu = -\epsilon_2^* \cdot \epsilon_1 P_\mu \mathcal{H}_1 + \left(\epsilon_2^* \cdot P \epsilon_{1\mu} + \epsilon_1 \cdot P \epsilon_{2\mu}^*\right) \mathcal{H}_2$$

$$-\epsilon_2^* \cdot P\, \epsilon_1 \cdot P \frac{P_\mu}{2M_A^2} \mathcal{H}_3 + \left(\epsilon_2^* \cdot P \epsilon_{1\mu} - \epsilon_1 \cdot P \epsilon_{2\mu}^*\right) \mathcal{H}_4$$

$$+ \left(\frac{2M_A^2 \left\{\epsilon_2^* \cdot q \epsilon_{1\mu} + \epsilon_1 \cdot q \epsilon_{2\mu}^*\right\}}{P \cdot q} + \frac{\epsilon_2^* \cdot \epsilon_1}{3} P_\mu \right) \mathcal{H}_5,$$

$$A_\mu = i\epsilon_{\mu\epsilon_2^*\epsilon_1 P} \widetilde{\mathcal{H}}_1 - \frac{i\epsilon_{\mu\Delta P\epsilon_1}\, \epsilon_2^* \cdot P + i\epsilon_{\mu\Delta P\epsilon_2^*}\, \epsilon_1 \cdot P}{M_A^2} \widetilde{\mathcal{H}}_2$$

$$- \frac{i\epsilon_{\mu\Delta P\epsilon_1}\, \epsilon_2^* \cdot P - \{\epsilon_1 \leftrightarrow \epsilon_2^*\}}{M_A^2} \widetilde{\mathcal{H}}_3 - \frac{i\epsilon_{\mu\Delta P\epsilon_1}\, \epsilon_2^* \cdot q + \{\epsilon_1 \leftrightarrow \epsilon_2^*\}}{q \cdot P} \widetilde{\mathcal{H}}_4,$$

The Compton form factors are given as convolution of nine GPDs:

$$\mathcal{H}_k = \sum_{i=u,\dots} \int_{-1}^{1} dx\, C_i^{(-)}(\xi, x, \mathcal{Q}^2) H_k^i(x, \xi, \Delta^2, \mathcal{Q}^2), \quad k = \{1, \dots, 5\},$$

$$\widetilde{\mathcal{H}}_k = \sum_{i=u,\dots} \int_{-1}^{1} dx\, C_i^{(+)}(\xi, x, \mathcal{Q}^2) \widetilde{H}_k^i(x, \xi, \Delta^2, \mathcal{Q}^2), \quad k = \{1, \dots, 4\},$$

What can be measured in fixed target experiments?

- *Assuming* $H(\xi,\xi,\Delta^2) \sim \xi^{-1} F(\Delta^2) \;\Rightarrow\; \boxed{\frac{|\mathcal{T}^{\rm DVCS}|}{|\mathcal{T}^{\rm BH}|} \sim \frac{A}{Z}\sqrt{\frac{1-y}{y^2}}\sqrt{\frac{-\Delta^2}{\mathcal{Q}^2}}}$

- For larger value of y, i.e., $|\mathcal{T}^{\rm BH}| \gg |\mathcal{T}^{\rm DVCS}|$:

  - *beam spin* and *single target spin* asymmetries :

$$\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \Im\mathrm{m}\mathcal{I} + \cdots \propto H(\xi,\xi,\Delta^2,\mathcal{Q}^2) + \cdots .$$

  - *charge* asymmetries

$$\frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}} \propto \Re\mathrm{e}\mathcal{I} \propto \mathrm{PV}\int_{-1}^{1} dx \frac{H(x,\xi,\Delta^2,\mathcal{Q}^2) - \{x \to -x\}}{x-\xi}.$$

  - *tensor polarization* for spin-1 target
  - *double spin* asymmetries

$$\frac{d\sigma^{\uparrow\Uparrow} - d\sigma^{\uparrow\Downarrow} - d\sigma^{\downarrow\Uparrow} + d\sigma^{\downarrow\Downarrow}}{d\sigma^{\uparrow\Uparrow} + d\sigma^{\uparrow\Downarrow} + d\sigma^{\downarrow\Uparrow} + d\sigma^{\downarrow\Downarrow}} \propto \Re\mathrm{e}\left\{\text{contribution of } \left|\mathcal{T}^{\rm BH}\right|^2 + \mathcal{I} + \cdots\right\}.$$

Spin-1 target: deuteron (A=d)

For unpolarized or longitudinally polarized target one can access

$$-\tau = \frac{-\Delta^2}{4M_A^2} \ll 1 : \quad \{H_1^d, \cdots, H_5^d, \widetilde{H}_1^d \cdots \widetilde{H}_4^d\} \quad \Rightarrow \quad \{H_1^d,\ H_3^d,\ H_5^d, \widetilde{H}_1^d\},$$

related to

$$H_1^d \to q^d, \quad \widetilde{H}_1^d \to \Delta q^d, \quad H_5^d \to \delta q^d = q^0 - \frac{1}{2}\left(q^{+1} + q^{-1}\right),$$

$$\int_{-1}^{1} dx\, H_1^d = G_1, \quad \int_{-1}^{1} dx\, H_3^d = G_3, \quad \int_{-1}^{1} dx\, \widetilde{H}_1^d = \widetilde{G}_1.$$

Are bound state effects small? (S- and D-wave overlap):

- $G_1(\Delta^2 = 0) = 1\,, G_2(\Delta^2 = 0) = 1.714\,, G_3(\Delta^2 = 0) = 25.989$

- Measurement of the tensor polarization (HERMES coll.):

$$A_{zz} = -\frac{2}{3}\frac{b_1}{F_1} \propto \sum_{i=u,d,s} Q_i^2\, \delta q_i^d$$

suggests a rather *small value* for $x_{\rm B} \sim 0.1$, however, a *large one* for small or large values of $x_{\rm B}$.

Estimates for several observables

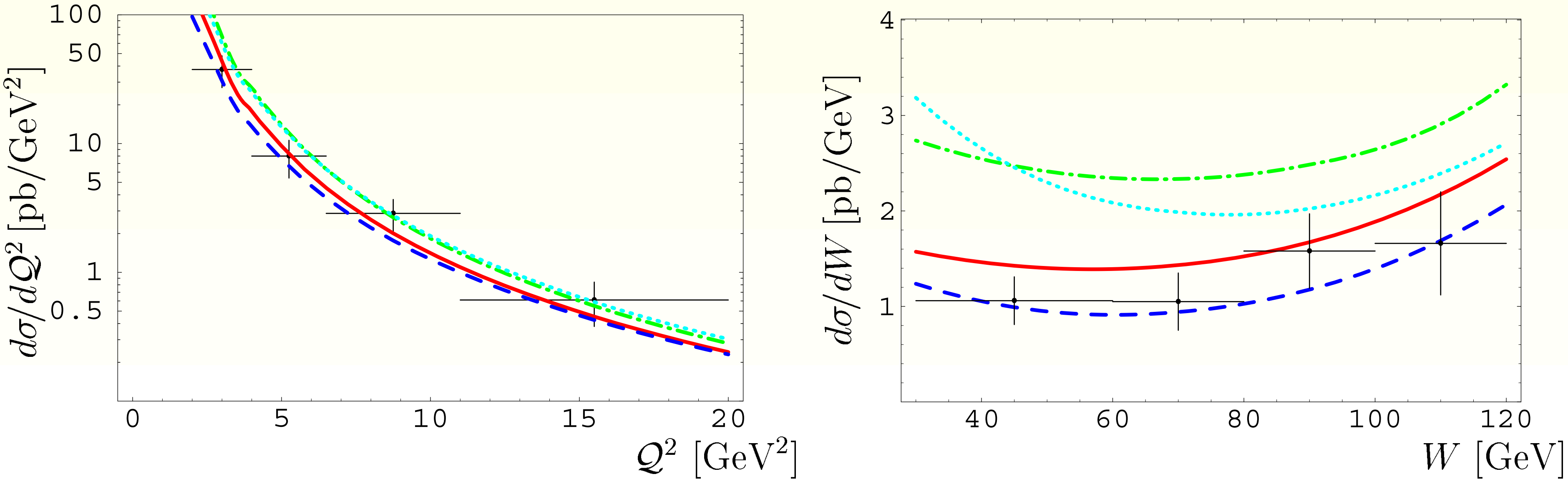
- For the kinematics of present fixed target experiments, i.e.,

$$y \geq 0.5, \quad |\Delta^2_{\rm min}| \ll |\Delta^2| \ll \mathcal{Q}^2 \qquad \text{(BH dominates DVCS)}$$

  the predictions for observables can be drastically simplified.

- Taking leading order approximations in α_s and $1/\mathcal{Q}$.
- The 'model' $H_i(x,\xi,\Delta^2) = F_i(\Delta^2) q_i(x, \mathcal{Q}_0^2)$
  allows a simple quantitative estimate on the level of $\lesssim 100\%$.

- Sea quarks are somehow suppressed (H1& ZEUS).



Beam spin asymmetry

$$A_{\mathrm{LU}}(\phi) = \frac{d\sigma^{\uparrow}(\phi) - d\sigma^{\downarrow}(\phi)}{d\sigma^{\uparrow}(\phi) + d\sigma^{\downarrow}(\phi)}$$

contains both *twist-two* and *twist-three* contributions.

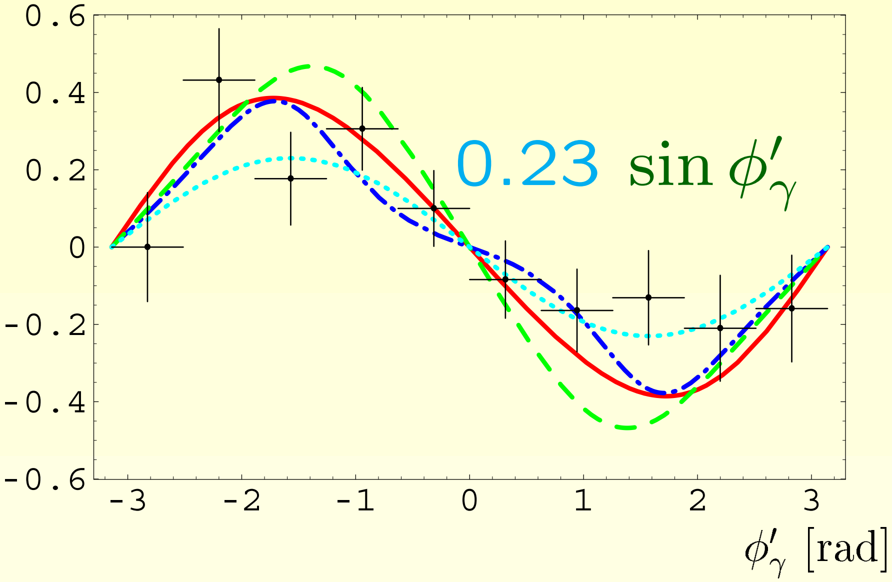
Proton target

$$A_{\mathrm{LU}} \sim \pm \frac{x_{\mathrm{B}}}{y} \frac{s^{\mathcal{I}}_{1,\mathrm{unp}}}{c^{\mathrm{BH}}_{0,\mathrm{unp}}} \sin(\phi) + \mathcal{O}\left(\frac{1}{\mathcal{Q}}\right)$$

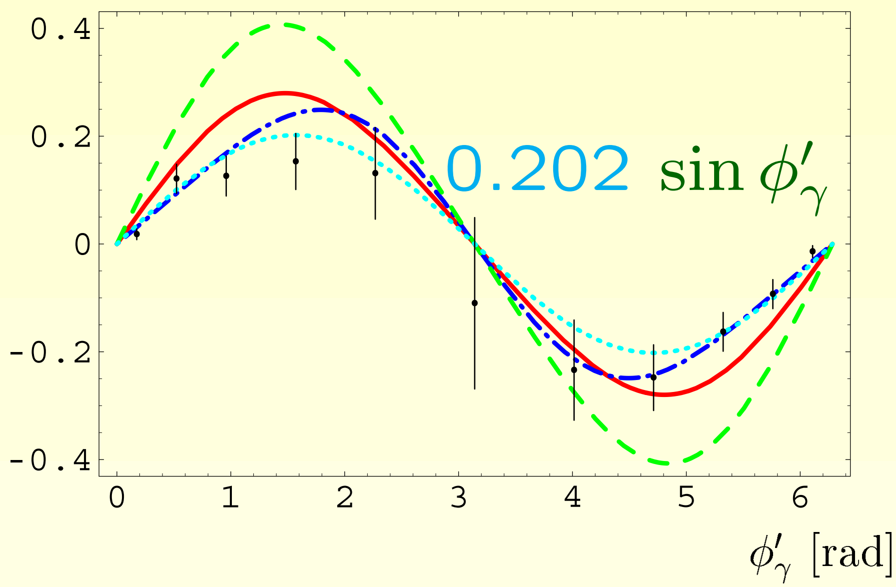
$$\sim \pm x_{\mathrm{B}} \sqrt{\frac{-\Delta^2(1-y)}{\mathcal{Q}^2}} \Im\mathrm{m} \left\{ \frac{\mathcal{H}}{F_1} + \frac{x_{\mathrm{B}}(F_1+F_2)\widetilde{\mathcal{H}}}{(2-x_{\mathrm{B}})F_1^2} - \frac{\Delta^2}{4M^2}\frac{F_2 \mathcal{E}}{F_1^2} \right\} \sin(\phi)$$

experiment	x_{B}	$\mathcal{Q}^2$[GeV^2]	$-\Delta^2$[GeV^2]
HERMES 96/97	$\langle 0.11 \rangle$	$\langle 2.6 \rangle$	$\langle 0.27 \rangle$
CLAS	$0.13 \cdots 0.35$	$1 \cdots 1.75$	$0.1 \cdots 0.3$

HERMES



CLAS



model	b^{val}	b^{sea}	B_{sea} [GeV^{-2}]	approximation
A: solid	1	∞	9	WW + D-term
B: dashdotted	∞	∞	9	toy qGq + D-term
C: dashed	1	1	5	WW + D-term

Simplification of Compton form factors

Neglecting skewness effects and sea quarks provides:

$$H_A \sim F_A(\Delta^2) q_A^{\mathrm{val}}(x) \qquad \Rightarrow$$

$$\Im\mathrm{m}\mathcal{H} \propto F_A(\Delta^2) \left[\left(Z Q_u^2 + N Q_d^2 \right) q^{u_{\mathrm{val}}} + \left(N Q_u^2 + Z Q_d^2 \right) q^{d_{\mathrm{val}}} \right] (\xi_N)$$

Isoscalar spin-0 or spin-1/2 nucleus target

$$\frac{A_{\mathrm{LU}}^{\mathrm{A}}(\phi)}{A_{\mathrm{LU}}(\phi)} \sim \left. \frac{(Q_u^2 + Q_d^2) \left\{ q^{u_{\mathrm{val}}}(\xi_N) + q^{d_{\mathrm{val}}}(\xi_N) \right\}}{Q_u^2 q^{u_{\mathrm{val}}}(\xi_N) + Q_d^2 q^{d_{\mathrm{val}}}(\xi_N)} \right|_{\xi_N \simeq \frac{x_{\mathrm{B}}}{2}}$$

For $q_u \sim 2 q_d$ the ratio is roughly estimated

$$\frac{A_{\mathrm{LU}}^{\mathrm{A}}(\phi)}{A_{\mathrm{LU}}(\phi)} \sim \frac{5}{3} \sim \mathcal{O}(1)$$

Spin-1 target (deuteron)

$$A^d_{\rm LU} \propto \Im\mathrm{m} \frac{2G_1\mathcal{H}_1 + (G_1 - 2\tau G_3)(\mathcal{H}_1 - 2\tau\mathcal{H}_3) + \frac{2}{3}\tau G_3\mathcal{H}_5}{2G_1^2 + (G_1 - 2\tau G_3)^2},$$

$$A^d_{\rm L\pm} \propto \Im\mathrm{m} \frac{2G_1\left(\mathcal{H}_1 - \frac{1}{3}\mathcal{H}_5\right) + 2(G_1 - 2\tau G_3)(\mathcal{H}_1 - 2\tau\mathcal{H}_3 - \frac{1}{3}\mathcal{H}_5)}{2G_1^2 + 2(G_1 - 2\tau G_3)^2},$$

where $-\tau = -\Delta^2/4M_d^2 \ll 1.$

Assuming that H_3 and H_5 are *small* for $x_{\rm B} \sim 0.1$, i.e,

$$\frac{A^d_{\rm LU}}{A_{\rm LU}} \sim \frac{3 - 2\tau G_3/G_1}{2 + (1 - 2\tau G_3/G_1)^2} \frac{(Q_u^2 + Q_d^2)\left\{q^{u_{\rm val}}(\xi_N) + q^{d_{\rm val}}(\xi_N)\right\}}{Q_u^2 q^{u_{\rm val}}(\xi_N) + Q_d^2 q^{d_{\rm val}}(\xi_N)}$$

$$\frac{A^d_{L\pm}}{A_{\rm LU}} \sim \frac{3 - 3\tau G_3/G_1}{2 + 2(1 - 2\tau G_3/G_1)^2} \frac{(Q_u^2 + Q_d^2)\left\{q^{u_{\rm val}}(\xi_N) + q^{d_{\rm val}}(\xi_N)\right\}}{Q_u^2 q^{u_{\rm val}}(\xi_N) + Q_d^2 q^{d_{\rm val}}(\xi_N)}$$

Comparison with 2000 run data from HERMES

$$A_{\rm LU} = -0.18 \pm 0.03 \pm 0.03, \; {}_{\langle x_{\rm B}\rangle = 0.12, \langle -\Delta^2\rangle = 0.18 \text{ GeV}^2, \langle \mathcal{Q}^2\rangle = 2.5 \text{ GeV}^2},$$

$$A^{Ne}_{\rm LU} = -0.22 \pm 0.03 \pm 0.03, \; {}_{\langle x_{\rm B}\rangle = 0.09, \langle -\Delta^2\rangle = 0.13 \text{ GeV}^2, \langle \mathcal{Q}^2\rangle = 2.2 \text{ GeV}^2},$$

$$A^{d}_{\rm L\pm} = -0.15 \pm 0.03 \pm 0.03, \; {}_{\langle x_{\rm B}\rangle = 0.1, \langle -\Delta^2\rangle = 0.2 \text{ GeV}^2, \langle \mathcal{Q}^2\rangle = 2.5 \text{ GeV}^2},$$

Our naive estimates are

$$A_{\rm LU} = -0.27\,, \quad A^{Ne}_{\rm LU} = -0.34\,, \quad A^{d}_{\rm L\pm} = -0.25\,.$$

Numerical estimates

$$A_{\rm LU} = \left\{ \begin{matrix} [-0.29, -0.25, -0.41] \\ [-0.29, -0.20, -0.37] \end{matrix} \right\} \quad \text{for} \quad \left\{ \begin{matrix} \text{twist-two} \\ \text{twist-three} \end{matrix} \right\} \quad \& \quad [\rm A, B, C]$$

$$A^{\rm Ne}_{\rm LU} = \left\{ \begin{matrix} [-0.30, -0.28, -0.54] \\ [-0.34, -0.24, -0.49] \end{matrix} \right\} \quad \text{for} \quad \left\{ \begin{matrix} \text{twist-two} \\ \text{twist-three} \end{matrix} \right\} \quad \& \quad [\rm A, B, C]$$

$$\left\{ \begin{matrix} A^{d}_{\rm LU} \\ A^{d}_{\rm L\pm} \end{matrix} \right\} = \left\{ \begin{matrix} [-0.37, -0.26, -0.23, -0.34] \\ [-0.34, -0.24, -0.16, -0.34] \end{matrix} \right\} \quad \text{for} \quad [\rm A, B, \hat{B}, B']$$

Unpolarized charge asymmetry

$$A_{\rm C}(\phi) = \frac{d\sigma^{+}(\phi) - d\sigma^{-}(\phi)}{d\sigma^{+}(\phi) + d\sigma^{-}(\phi)}$$

contains a *twist-two* and *a measurable* *twist-three* contribution:

$$A_{\rm C} = A_{\rm C}^{(0)} + A_{\rm C}^{(1)} \cos(\phi) + \dots .$$

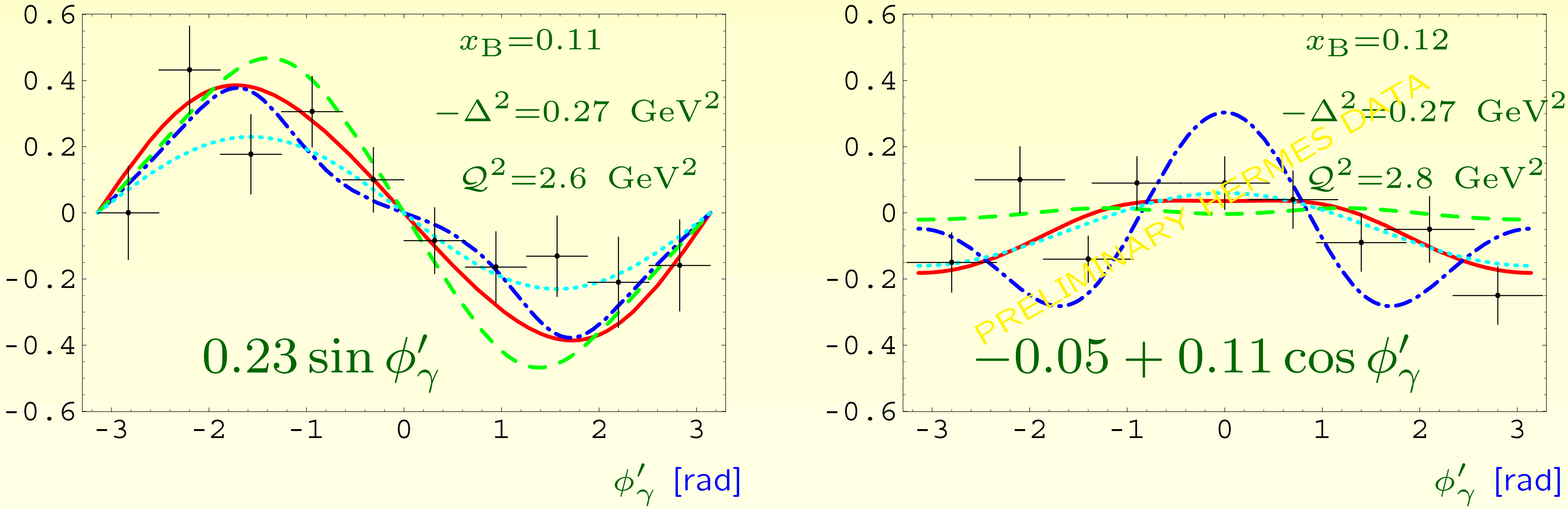
- The ratio is [nearly] GPD independent for spin-0 [1/2]:

$$\frac{A_{\rm C}^{(0)}}{A_{\rm C}^{(1)}} \simeq \frac{2-y}{\sqrt{1-y}} \sqrt{\frac{-\Delta^2}{\mathcal{Q}^2}} .$$

- The size of the twist-two harmonic depends on the ratio of

$$R^i = \frac{\Re{\rm e}\ \mathcal{H}^i}{\Im{\rm m}\ \mathcal{H}^i} = \left\{ \begin{matrix} < 0 \\ > 0 \end{matrix} \right\} \quad \text{for} \quad \left\{ \begin{matrix} \text{valence quarks} \\ \text{sea quarks} \end{matrix} \right. .$$

? D-term "significance" for sign & magnitude is questionable



- Neglecting *sea quarks* and *D-term* contribution implies:
  - proton target (consistent with HERMES measurement)

$$\frac{A_{\mathrm{C}}^{(1)}}{A_{\mathrm{LU}}} \sim \frac{2-2y+y^2}{(2-y)y} \frac{Q_u^2 R^{u_{\mathrm{val}}} q^{u_{\mathrm{val}}} + Q_d^2 R^{d_{\mathrm{val}}} q^{d_{\mathrm{val}}}}{Q_u^2 q^{u_{\mathrm{val}}} + Q_d^2 q^{d_{\mathrm{val}}}} \sim -0.8\,,$$

  - isoscalar nucleus target

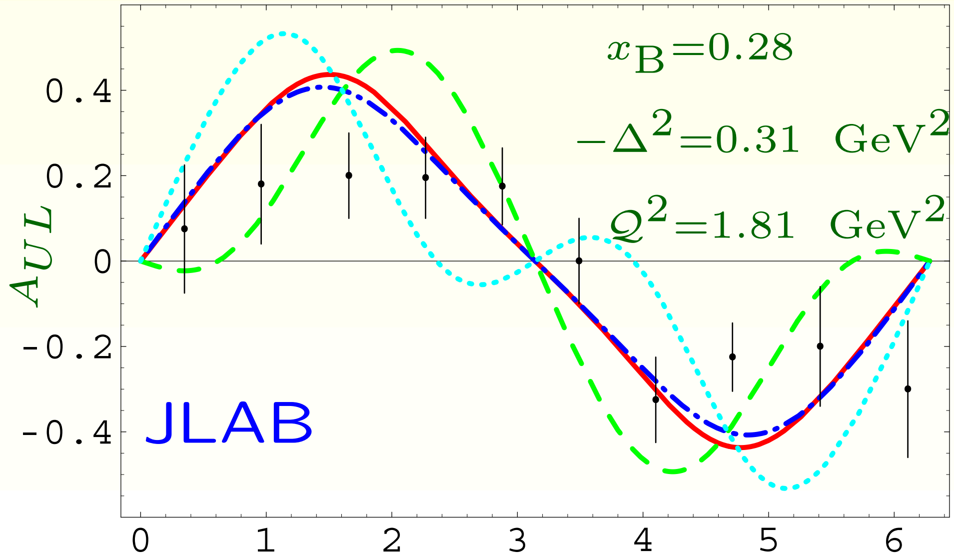
$$\frac{A_{\mathrm{C}}^{A(1)}}{A_{\mathrm{LU}}^{A}} \sim \frac{2-2y+y^2}{(2-y)y} \frac{R^{u_{\mathrm{val}}} q^{u_{\mathrm{val}}} + R^{d_{\mathrm{val}}} q^{d_{\mathrm{val}}}}{q^{u_{\mathrm{val}}} + q^{d_{\mathrm{val}}}} \sim -0.7\,.$$

Longitudinally single target spin asymmetry

$$A^{A}_{\mathrm{UL}}(\phi) = \frac{d\sigma^{\Lambda=+1} - d\sigma^{\Lambda=-1}}{d\sigma^{\Lambda=+1} + d\sigma^{\Lambda=-1} \ (+d\sigma^{\Lambda=0})} \quad \text{(for } \theta = 0) \, .$$

Proton target

$$A_{\mathrm{UL}}(\phi) \propto \left\{ F_1 \widetilde{\mathcal{H}} + \xi \, (F_1 + F_2) \, \mathcal{H} + \cdots \right\} \sin\phi$$



sign is *fixed* in popular models

2 contributions $\widetilde{\mathcal{H}}$ and $\mathcal{H}$

sensitive to the details of GPDs

Ratio of longitudinally polarized target to beam spin asymmetry is free from BH squared contributions and is sensitive to $\widetilde{H}, \widetilde{H}_1$:

- proton target

$$\frac{A_{\rm UL}(\phi)}{A_{\rm LU}(\phi)} \sim \frac{2-2y+y^2}{(2-y)y}\left[\frac{Q_u^2 \Delta q^{u_{\rm val}} + Q_d^2 \Delta q^{d_{\rm val}}}{Q_u^2 q^{u_{\rm val}} + Q_d^2 q^{d_{\rm val}}} + \frac{x_{\rm B}}{2}\frac{F_1+F_2}{F_1}\right],$$

- isoscalar spin-1/2 nuclei target

$$\frac{A^A_{\rm UL}(\phi)}{A^A_{\rm LU}(\phi)} \sim \frac{2-2y+y^2}{(2-y)y}\left[\frac{\Delta q^{u_{\rm val}} + \Delta q^{d_{\rm val}}}{q^{u_{\rm val}} + q^{d_{\rm val}}} + \frac{x_{\rm B}}{2A}\frac{F^A_1+F^A_2}{F^A_1}\right],$$

- deuteron

$$\frac{A^d_{\rm UL}(\phi)}{A^d_{\rm LU}(\phi)} \propto \left[\frac{\Delta q^{u_{\rm val}} + \Delta q^{d_{\rm val}}}{q^{u_{\rm val}} + q^{d_{\rm val}}} + \frac{x_{\rm B}}{4}\frac{G_2}{G_1-\tau G_3}\right] \Rightarrow \text{few\%} \ \ldots \sim 20\%$$

Transversely single target spin asymmetry

$$A_{\rm UT}(\phi,\varphi)=\frac{d\sigma^{\Lambda=+1}-d\sigma^{\Lambda=-1}}{d\sigma^{\Lambda=+1}+d\sigma^{\Lambda=-1}\ (+d\sigma^{\Lambda=0})}\qquad (\text{for } \theta=\pi/2)\,.$$

- Allows to *access* two further combinations of GPDs.

- *Unfortunately*, it is kinematically suppressed:

$$\frac{A^A_{\rm UT}(\phi,\varphi)}{A^A_{\rm LU}(\phi)}\sim\frac{M_N}{A\sqrt{-\Delta^2}}\left\{\cos(\varphi)\mathcal{C}_+\!\left(x_{\rm B}^2\frac{F(\xi_N,\xi_N)}{H(\xi_N,\xi_N)},\frac{\Delta^2}{M_N^2}\frac{F(\xi_N,\xi_N)}{H(\xi_N,\xi_N)}\right)\right.$$
$$\left.+\sin(\varphi)\,\mathcal{C}_-\!\left(x_{\rm B}^2\frac{F(\xi_N,\xi_N)}{H(\xi_N,\xi_N)},\frac{\Delta^2}{M_N^2}\frac{F(\xi_N,\xi_N)}{H(\xi_N,\xi_N)}\right)\right\}.$$

- It *vanishes* for large A.

- Helicity non-conserved GPDs, e.g., E, enter on the same kinematical level as H.

Tensor polarization for spin-1 target

$$A^d_{\mathrm{zz}}(\phi) = \frac{2d\sigma^{\Lambda=0} - d\sigma^{\Lambda=+1} - d\sigma^{\Lambda=-1}}{d\sigma^{\Lambda=0} + d\sigma^{\Lambda=+1} + d\sigma^{\Lambda=-1}}$$

has a constant piece arising from the squared Bethe-Heitler term.

To get rid of it *Tensor polarization* might be combined with

- beam polarization

$$A^d_{\mathrm{Lzz}}(\phi) = \frac{2d\sigma^{\uparrow\Lambda=0} - d\sigma^{\uparrow\Lambda=+1} - d\sigma^{\uparrow\Lambda=-1} - \{\uparrow \to -\downarrow\}}{d\sigma^{\uparrow\Lambda=0} + d\sigma^{\uparrow\Lambda=+1} + d\sigma^{\uparrow\Lambda=-1} + \{\uparrow \to -\downarrow\}}$$

$$\frac{A^d_{\mathrm{Lzz}}}{A^d_{\mathrm{LU}}} = -\frac{2}{3}\frac{\Im\mathrm{m}\mathcal{H}_3 + \Im\mathrm{m}\mathcal{H}_5 + \frac{\tau G3}{G1}\Im\mathrm{m}\left(\mathcal{H}_1 - 2\mathcal{H}_3 - \frac{1}{3}\mathcal{H}_5\right)}{\Im\mathrm{m}\mathcal{H}_1 - \frac{2}{3}\Im\mathrm{m}\mathcal{H}_3 - \frac{2\tau G3}{3G1}\Im\mathrm{m}\left(\mathcal{H}_1 - 2\mathcal{H}_3 - \frac{1}{3}\mathcal{H}_5\right)}$$

- charge asymmetry

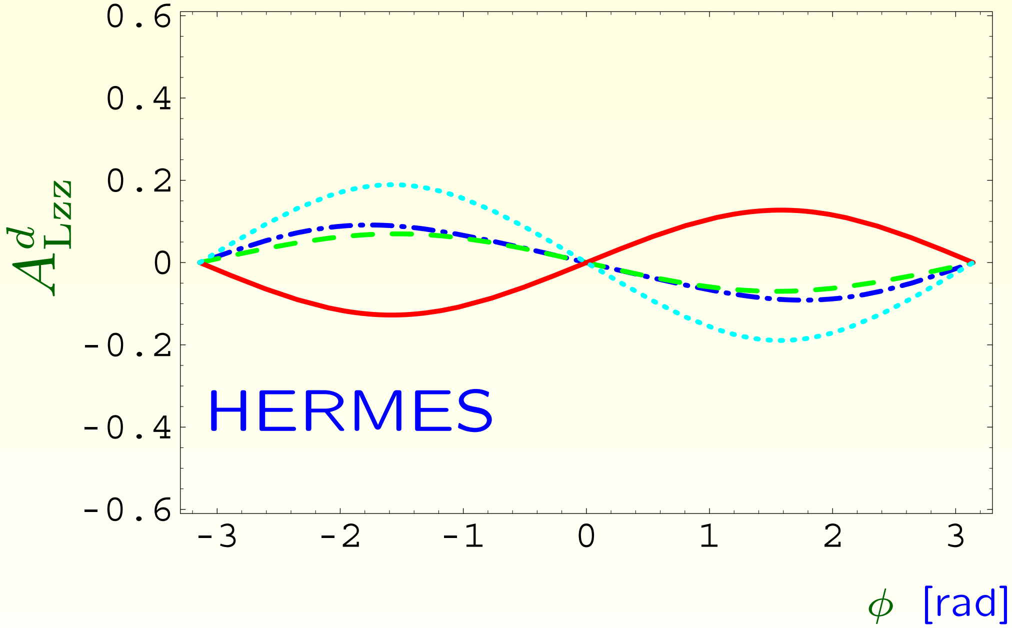
$$A^d_{\mathrm{Czz}}(\phi) = \frac{2d\sigma^{+\Lambda=0} - d\sigma^{+\Lambda=+1} - d\sigma^{+\Lambda=-1} - \{e^+ \to -e^-\}}{d\sigma^{+\Lambda=0} + d\sigma^{+\Lambda=+1} + d\sigma^{+\Lambda=-1} + \{e^+ \to -e^-\}}$$

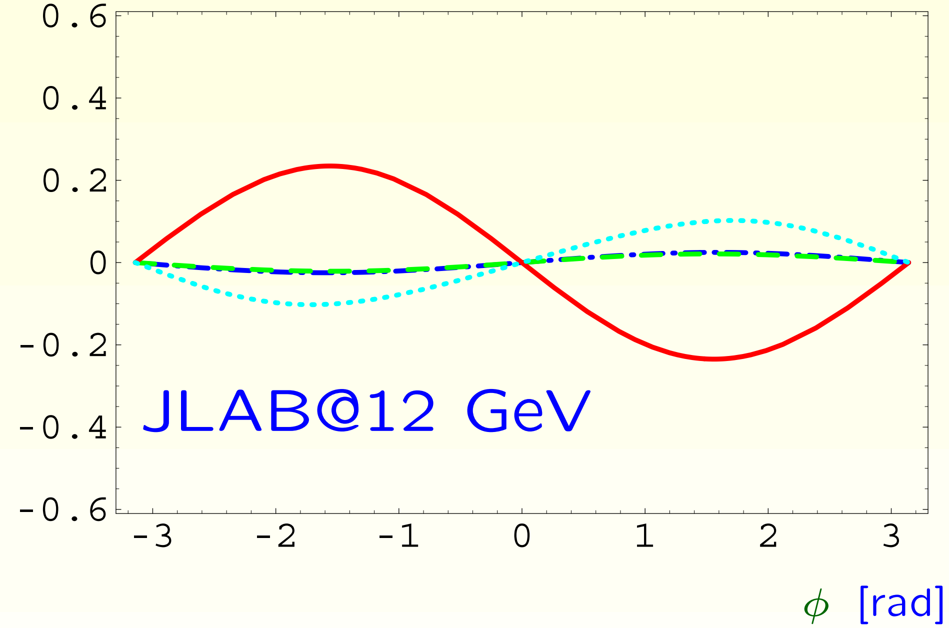
$$\frac{A^d_{\mathrm{Czz}}}{A^d_{\mathrm{C}}} = -\frac{2}{3}\frac{\Re\mathrm{e}\mathcal{H}_3 + \Re\mathrm{e}\mathcal{H}_5 + \frac{\tau G3}{G1}\Re\mathrm{e}\left(\mathcal{H}_1 - 2\mathcal{H}_3 - \frac{1}{3}\mathcal{H}_5\right)}{\Re\mathrm{e}\mathcal{H}_1 - \frac{2}{3}\Re\mathrm{e}\mathcal{H}_3 - \frac{2\tau G3}{3G1}\Re\mathrm{e}\left(\mathcal{H}_1 - 2\mathcal{H}_3 - \frac{1}{3}\mathcal{H}_5\right)}$$

Tensor polarization is promising to access *bound state* effects

Prediction for $\mathcal{H}_3 = \mathcal{H}_5 = 0$:

$$\frac{A^d_{\mathrm{Lzz}}}{A^d_{\mathrm{LU}}} = \frac{A^{d(1)}_{\mathrm{Czz}}}{A^{d(1)}_{\mathrm{C}}} \simeq -\frac{2}{3}\frac{\tau G_3(\Delta^2)}{G_1(\Delta^2) - \frac{2\tau}{3} G_3(\Delta^2)}\,.$$





NOTE: $\{A^d_{\mathrm{LU}}, A^d_{\mathrm{L}\pm}, A^d_{\mathrm{Lzz}}\}$; $\{A^d_{\mathrm{C}}, A^d_{\mathrm{C}\pm}, A^d_{\mathrm{Czz}}\}$ are *not independent*.

Summary

- DVCS off deuteron is *worked out* at *twist-two* level to *NLO*.
- Cross section, depending on nine twist–two GPDs, has a *complex* angular dependence.
- Only a limited set of the twist–two CFFs can be accessed.
- Even more non-perturbative functions appear at:
  qGq, and gluon transversity GPDs.
- *Take care* one the *appropriate definition* of observables!
- An *oversimplified* and *unrealistic* GPD ansatz with suppressed sea quarks *describes existing DVCS data* on proton at LO
- Based on this qualitative understanding we *estimated* beam spin, single target spin, and charge asymmetries.
- DVCS allows to study the *deuteron* from a *new perspective*:
  - fundamental degrees of freedom
  - nuclear degrees of freedom.