On Deeply Virtual Compton Scattering at Next to Leading Order

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Motivation.
Study the nucleon structure to shed new light on non-perturbative QCD.

- Define **universal** objects describing 3D nucleon structure: Generalized Parton Distributions (GPD).
- Relate GPDs to measurements using **factorization**: Space- and timelike Compton Scattering (DVCS, TCS).
- Get **experimental knowledge** of nucleon structure.
Motivations.
3D imaging of nucleon’s partonic content but also...

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in the nucleon.
- Insights on:
  - **Spin** structure,
  - **Energy-momentum** structure.
- **Probabilistic interpretation** of Fourier transform of $GPD(x, \xi = 0, t)$ in **transverse plane**.

Obtain this 3d picture from exclusive measurements?

Timelike and spacelike Compton Scattering.
Scattering amplitudes and their partonic interpretation.

Compton Form Factors (CFF)
- Parametrize amplitudes.
Timelike and spacelike Compton Scattering. Scattering amplitudes and their partonic interpretation.

**Compton Form Factors (CFF)**
- Parametrize amplitudes.
- Evaluation at LO.

**DVCS**
\[ e^- \rightarrow e^- \gamma Q^2 \rightarrow p \]

**TCS**
\[ e^+ \rightarrow e^- \gamma Q^2 \rightarrow p \]

**Factorization**
\[ x + \xi \rightarrow x - \xi \]
Timelike and spacelike Compton Scattering.
Scattering amplitudes and their partonic interpretation.

**Compton Form Factors (CFF)**
- Parametrize amplitudes.
- Evaluation at LO.
- Evaluation at NLO.

**DVCS**
\[
\begin{align*}
\gamma & \quad Q^2 \\
\rightarrow & \quad \rightarrow \\
\gamma & \quad \gamma
\end{align*}
\]

**Compton Form Factors**
- Factorization $\mu_F$
- $x + \xi$
- $x - \xi$
- $p \quad p$
Timelike and spacelike Compton Scattering. Scattering amplitudes and their partonic interpretation.

Compton Form Factors (CFF)
- Parametrize amplitudes.
- Evaluation at LO.
- Evaluation at NLO.
- Other diagrams at NLO, including gluon GPDs.
Explicit expressions of Compton Form Factors. 
Quark and gluon contributions to the CFF $\mathcal{H}$ at LO and NLO (at fixed $t$).

- Convolution of singlet GPD $H^+_q(x) \equiv H_q(x) - H_q(-x)$:

$$
\mathcal{H}_q(\xi, Q^2) = \int_{-1}^{+1} dx \frac{H^+_q(x, \xi, \mu_F)}{T_q \left( x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F} \right)}
+ \int_{-1}^{+1} dx \frac{H_g(x, \xi, \mu_F)}{T_g \left( x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F} \right)}
$$

Explicit expressions of Compton Form Factors.
Quark and gluon contributions to the CFF $\mathcal{H}$ at LO and NLO (at fixed $t$).

- Convolution of singlet GPD $H_q^+(x) \equiv H_q(x) - H_q(-x)$:

$$\mathcal{H}_q(\xi, Q^2) \overset{\text{LO}}{=} \int_{-1}^{+1} dx \ H_q^+(x, \xi, \mu_F) \ C_0^q(x, \xi)$$

$$+ \int_{-1}^{+1} dx \ H_g(x, \xi, \mu_F) \ 0$$


- Integration yields imaginary parts to $\mathcal{H}$:

$$\text{Im} \mathcal{H}_q(\xi, Q^2) \overset{\text{LO}}{=} \pi H_q^+(\xi, \xi, \mu_F)$$
Explicit expressions of Compton Form Factors.
Quark and gluon contributions to the CFF $\mathcal{H}$ at LO and NLO (at fixed $t$).

- Convolution of singlet GPD $H_q^+(x) \equiv H_q(x) - H_q(-x)$:

$$\mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \int_{-1}^{+1} dx \, H_q^+(x, \xi, \mu_F) \left[ C_0^q + C_1^q + \frac{1}{2} \ln \frac{|Q^2|}{\mu_F^2} C_{\text{Coll}}^q \right]$$

$$+ \int_{-1}^{+1} dx \, H_g(x, \xi, \mu_F) \left( 0 + C_1^g + \frac{1}{2} \ln \frac{|Q^2|}{\mu_F^2} C_{\text{Coll}}^g \right)$$


- Integration yields **imaginary** parts to $\mathcal{H}$:

$$\text{Im}\mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \mathcal{I}(\xi) H_q^+(\xi, \xi, \mu_F)$$

$$+ \int_{-1}^{+1} dx \, \mathcal{T}_q(x) \left( H_q^+(x, \xi, \mu_F) - H_q^+(\xi, \xi, \mu_F) \right)$$

+ gluon contributions.
**Explicit expressions of Compton Form Factors.**

**Compton Scattering: LO vs NLO.**

**Imaginary part of Compton Form Factor $\mathcal{H}_q$ at NLO:**

\[
Im\mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} I(\xi)H_0^+(\xi, \xi, \mu_F) + \int_{-1}^{+1} dx \, T^q(x) \left( H_0^+(x, \xi, \mu_F) - H_0^+(\xi, \xi, \mu_F) \right) + \text{gluon contributions.}
\]

**Due to $O(\alpha_S(\mu_F))$ corrections:**
**Explicit expressions of Compton Form Factors.**

Compton Scattering: LO vs NLO.

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**Imaginary part of Compton Form Factor \( \mathcal{H}_q \) at NLO:**

\[
\text{Im} \mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \mathcal{I}(\xi) H^+_q(\xi, \xi, \mu_F) \\
+ \int_{-1}^{+1} dx \, T^q(x) \left( H^+_q(x, \xi, \mu_F) - H^+_q(\xi, \xi, \mu_F) \right) \\
+ \text{gluon contributions.}
\]

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**Due to \( \mathcal{O}(\alpha_S(\mu_F)) \) corrections:**

- \( \text{Im} \mathcal{H}_q \) is **no more equal** to \( \pi H^+_q(x = \xi, \xi) \) (LO):

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Explicit expressions of Compton Form Factors.
Compton Scattering: LO vs NLO.

**Imaginary part of Compton Form Factor \( \mathcal{H}_q \) at NLO:**

\[
\text{Im}\mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \mathcal{I}(\xi) H^+_q(\xi, \xi, \mu_F) \\
+ \int_{-1}^{+1} dx \mathcal{F}^q(x) \left( H^+_q(x, \xi, \mu_F) - H^+_q(\xi, \xi, \mu_F) \right) \\
+ \text{gluon contributions.}
\]

**Due to \( \mathcal{O}(\alpha_s(\mu_F)) \) corrections:**

- \( \text{Im}\mathcal{H}_q \) is **no more equal** to \( \pi H^+_q(x = \xi, \xi) \) (LO):
  - Multiplicative factor \( \mathcal{I} \) depends on \( \xi \).
Explicit expressions of Compton Form Factors.
Compton Scattering: LO vs NLO.

Imaginary part of Compton Form Factor $\mathcal{H}_q$ at NLO:

$$Im\mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \mathcal{I}(\xi) H^+_q(\xi, \xi, \mu_F)$$

$$+ \int_{-1}^{+1} dx \, T^q(x) \left( H^+_q(x, \xi, \mu_F) - H^+_q(\xi, \xi, \mu_F) \right)$$

$$+ \text{gluon contributions.}$$

Due to $O(\alpha_S(\mu_F))$ corrections:

- $Im\mathcal{H}_q$ is no more equal to $\pi H^+_q(x = \xi, \xi)$ (LO):
  - Multiplicative factor $\mathcal{I}$ depends on $\xi$.
  - Integral with off-diagonal terms.
Explicit expressions of Compton Form Factors. 
Compton Scattering: LO vs NLO.

Imaginary part of Compton Form Factor $\mathcal{H}_q$ at NLO:

$$Im\mathcal{H}_q(\xi, Q^2) \overset{NLO}{=} \mathcal{I}(\xi)H_q^+(\xi, \xi, \mu_F)$$

$$+ \int_{-1}^{+1} dx \, T^q(x) \left( H_q^+(x, \xi, \mu_F) - H_q^+(\xi, \xi, \mu_F) \right)$$

$$+ \text{gluon contributions.}$$

Due to $\mathcal{O}(\alpha_S(\mu_F))$ corrections:

- $Im\mathcal{H}_q$ is no more equal to $\pi H_q^+(x = \xi, \xi)$ (LO):
  - Multiplicative factor $\mathcal{I}$ depends on $\xi$.
  - Integral with off-diagonal terms.
  - $Im\mathcal{H}_q$ contains gluon contributions.
Explicit expressions of Compton Form Factors.
Compton Scattering: LO vs NLO.

Imaginary part of Compton Form Factor $\mathcal{H}_q$ at NLO:

\[ \text{Im} \mathcal{H}_q(\xi, Q^2) \overset{\text{NLO}}{=} \mathcal{I}(\xi)H_q^+(\xi, \xi, \mu_F) \]
\[ + \int_{-1}^{+1} dx \, \mathcal{T}^q(x) \left( H_q^+(x, \xi, \mu_F) - H_q^+(\xi, \xi, \mu_F) \right) \]
\[ + \text{gluon contributions}. \]

Due to $O(\alpha_S(\mu_F))$ corrections:

- $\text{Im} \mathcal{H}_q$ is no more equal to $\pi H_q^+(x = \xi, \xi)$ (LO):
  - Multiplicative factor $\mathcal{I}$ depends on $\xi$.
  - Integral with off-diagonal terms.
  - $\text{Im} \mathcal{H}_q$ contains gluon contributions.

- No more direct link to $H_q$ even in valence region where $H_q(-\xi, \xi)$ is expected to be small.
Explicit expressions of Compton Form Factors. Compton Scattering: LO vs NLO.

Imaginary part of Compton Form Factor $H_q$ at NLO:

$$\text{Im} H_q(\xi, Q^2) \stackrel{\text{NLO}}{=} I(\xi) H_q^+(\xi, \xi, \mu_F)$$

$$+ \int_{-1}^{+1} dx T^q(x) \left( H_q^+(x, \xi, \mu_F) - H_q^+(\xi, \xi, \mu_F) \right)$$

$$+ \text{gluon contributions.}$$

Due to $O(\alpha_S(\mu_F))$ corrections:

- $\text{Im} H_q$ is no more equal to $\pi H_q^+(x = \xi, \xi)$ (LO):
  - Multiplicative factor $I$ depends on $\xi$.
  - Integral with off-diagonal terms.
  - $\text{Im} H_q$ contains gluon contributions.

- No more direct link to $H_q$ even in valence region where $H_q(-\xi, \xi)$ is expected to be small.

Question: What is the size of these $O(\alpha_S(\mu_F))$ corrections?
Double Distribution models of the GPD $H$.
Kroll - Goloskokov model.

- **Factorized Ansatz.** For $i = g, \text{sea or val}$:

\[ H_i(x, \xi, t) = \int_{|\alpha| + |\beta| \leq 1} d\beta d\alpha \delta(\beta + \xi \alpha - x)f_i(\beta, \alpha, t) \]

\[ f_i(\beta, \alpha, t) = e^{b_i t} \frac{1}{|\beta|^{\alpha^t}} h_i(\beta) \pi n_i(\beta, \alpha) \]

\[ \pi n_i(\beta, \alpha) = \frac{\Gamma(2n_i + 2)}{2^{2n_i + 1} \Gamma^2(n_i + 1)} \frac{(1 - |\beta|)^2 - \alpha^2}{(1 - |\beta|)^{2n_i + 1}} \]

- **Expressions for $h_i$ and $n_i$:**

\[ h_g(\beta) = |\beta| g(|\beta|) \quad n_g = 2 \]
\[ h_{\text{sea}}^q(\beta) = q_{\text{sea}}(|\beta|) \text{sign}(\beta) \quad n_{\text{sea}} = 2 \]
\[ h_{\text{val}}^q(\beta) = q_{\text{val}}(\beta) \Theta(\beta) \quad n_{\text{val}} = 1 \]


- **Comparison to existing DVCS measurements** at LO.

Double Distribution models of the GPD $H$.
MSTW08 based model with classical Radyushkin’s factorized Ansatz.

- Use MSTW08 Parton Distribution Functions.
- Assume factorized $t$-dependence:
  \[ H(x, \xi, t) = \int_{|\alpha|+|\beta|\leq 1} d\beta d\alpha \delta(\beta + \xi\alpha - x)\pi(\beta, \alpha)f(\beta, t) \]
- $u$ and $d$ quarks:
  \[ f_u(\beta, \alpha, t) = \frac{1}{2} F_1^u(t)u(\beta)\pi(\beta, \alpha) \]
  \[ f_d(\beta, \alpha, t) = F_1^d(t)d(\beta)\pi(\beta, \alpha) \]
  with $F_1^u$ and $F_1^d$ the $u$ and $d$ quark contributions to the proton form factor $F_1$.
- $s$ quark and gluons: dipole Ansatz.
- Add D-term from Chiral Quark Soliton Model.
Spacelike CFF $\mathcal{H}$: large NLO contribution.
 Mostly due to gluons, maximum in HERMES / COMPASS kinematic region.

$\text{Re}\mathcal{H}$ at LO and NLO ($t = -0.1 \text{ GeV}^2$, $Q^2 = \mu_F^2 = 4. \text{ GeV}^2$)


dotted: LO  dashed: NLO quark corrections  solid: full NLO

Left: KG model  Right: MSTW08-based model
Spacelike CFF $\mathcal{H}$: large NLO contribution. Mostly due to gluons, maximum in HERMES / COMPASS kinematic region.

$\text{Im}\mathcal{H}$ at LO and NLO ($t = -0.1 \text{ GeV}^2$, $Q^2 = \mu_F^2 = 4. \text{ GeV}^2$)


dotted: LO  dashed: NLO quark corrections  solid: full NLO

Left: KG model  Right: MSTW08-based model

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Compton Scattering at NLO

Introduction

Theoretical framework

Compton scattering

Explicit Expressions

Evaluation of Compton Form Factors

GPD Models

Compton scattering

Impact on future experiments

CLAS12

COMPASS

Conclusion

Timelike CFF $H$: large NLO contribution. Mostly due to gluons, maximum in HERMES / COMPASS kinematic region.

$ReH$ at LO and NLO ($t = -0.1 \text{ GeV}^2$, $Q^2 = \mu_F^2 = 4. \text{ GeV}^2$)


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Timelike CFF $\mathcal{H}$: large NLO contribution.
Mostly due to gluons, maximum in HERMES / COMPASS kinematic region.

\[ \text{Im}\mathcal{H} \text{ at LO and NLO } (t = -0.1 \text{ GeV}^2, Q^2 = \mu_F^2 = 4. \text{ GeV}^2) \]

\[ \eta \]

\[ \eta \]

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dotted: LO  dashed: NLO quark corrections  solid: full NLO
Left: KG model  Right: MSTW08-based model
Projections: CLAS12 kinematics, DVCS channel.
Sizeable NLO corrections and gluon contributions.

\( E_e = 11 \text{ GeV}, \ x_B = 0.36, \ Q^2 = \mu_F^2 = 4. \text{ GeV}^2, \ t = -0.2 \text{ GeV}^2 \)


dotted: LO  dashed: NLO quark corrections  solid: full NLO

Upper line: KG model  Lower line: MSTW08-based model
Projections: CLAS12 kinematics, TCS channel.
Sizeable NLO corrections and gluon contributions.

\[ E_\gamma = 10 \text{ GeV} \ (\eta \simeq 0.11), \ Q^2 = \mu_F^2 = 4 \text{ GeV}^2, \ t = -0.1 \text{ GeV}^2 \]

- KG model
- Cross section integrated over \( \theta \in \left( \frac{\pi}{4}, \frac{3\pi}{4} \right) \)
Projections: COMPASS kinematics, DVCS channel.
Sizeable NLO corrections and gluon contributions.

\[ E_\mu = 160 \text{ GeV}, x_B = 0.1, Q^2 = \mu_F^2 = 4 \text{ GeV}^2, t = -0.2 \text{ GeV}^2 \]

\[ A_{CS,u}(\phi) \]
\[ D_{CS,u}(\phi) \text{ [nb/GeV}^4] \]
\[ S_{CS,u}(\phi) \text{ [nb/GeV}^4] \]


dotted: LO  dashed: NLO quark corrections  solid: full NLO

Upper line: KG model  Lower line: MSTW08-based model

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Conclusion.

Constraining gluon GPDs even from data in the valence region?

- **Large NLO ”corrections”** to DVCS and TCS amplitudes.
- Need resummed expressions!
  - Altinoluk et al., JHEP 1210 (049) 2012
- **Enhanced effect** in the TCS case.
- Sensitivity to **gluon GPDs** even in the **valence region**.
- Direct impact on extraction of CFFs from experimental data and their interpretation.
- Need global GPD fits to **separate quarks and gluon contributions** and allow an **accurate** interpretation of extracted data.
- DVCS experiments may provide constraints on gluon GPDs in the near future!