Can one measure timelike Compton scattering at LHC?

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OUTLINE OF THE TALK.

1. Deeply virtual Compton scattering (DVCS) and Generalized Parton Distributions (GDPs)
   - Big theoretical and experimental effort in the DVCS ($\gamma^*p \rightarrow \gamma p$), an exclusive reaction where GPDs factorize from perturbative coefficient functions, when the virtuality of the incoming photon is high.
   - GDPs - encodes also transverse momentum dependence of partons.

2. Properties of Timelike Compton Scattering (TCS)
   - Exclusive process ($\gamma p \rightarrow \gamma^*p$), for large timelike virtuality shares many features of DVCS
   - Crossing from spacelike to timelike probe - important test of QCD corrections.

3. Timelike Compton Scattering at LHC.
   - Hadron Colliders as powerful sources of quasi real photons in UPC.
   - First study of the feasibility of extraction of the TCS signal.
DIS vs. DVCS

- Deep Inelastic Scattering:

\[ e + \gamma^* + p \rightarrow eX \]

- Deeply Virtual Scattering (DVCS):

\[ e + p \rightarrow e + p\gamma \]

\[ \gamma^* + p \rightarrow \gamma + p \]
DIS vs. DVCS

- DIS vs. DVCS

- factorization:
  
  \[
  \text{DIS} \quad : \quad \sigma = [\text{PDF}] \otimes [\text{partonic cross section}]
  \]
  
  \[
  \text{DVCS} \quad : \quad M = [\text{GPD}] \otimes [\text{partonic amplitude}].
  \]
Definition of GPDs

- Definition of PDFs:
  \[ q(x) = \frac{1}{2} \sum_{\text{spin}} \int \frac{d\lambda}{2\pi} e^{-i\lambda x} \langle p(P) | \bar{\psi}_q(z) \not\! n \psi_q(0) | p(P) \rangle \]
  where: \( z^\mu = \lambda n^\mu, \ n^2 = 0, \ n \cdot P = 1. \)

- Definition of GPDs:
  \[ \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle p(P') | \bar{\psi}_q(-z/2) \not\! n \psi_q(z/2) | p(P) \rangle = H^q(x, \xi, t) \bar{u}(P') \not\! n u(P) \]
  \[ + \ E^q(x, \xi, t) \bar{u}(P') \frac{i\sigma^\alpha \Delta^\alpha n_\beta u(P)}{2M} \]
  where: \( z^\mu = \lambda n^\mu, \ n^2 = 0, \ n \cdot \frac{P + P'}{2} = 1, \ \Delta^\mu = (P' - P)^\mu, \ t = \Delta^2. \)
GENERALIZED PARTON DISTRIBUTIONS

- GDPs enters factorization theorems for hard exclusive reactions (DVCS, deeply virtual meson production etc.), in a similar manner as PDFs enter factorization theorem for DIS.

- GPDs are functions of three kinematical variables: longitudinal momentum fraction $x$, longitudinal momentum transfer $\xi$ and overall momentum transfer $t$. 
GENERALIZED PARTON DISTRIBUTIONS (2)

• In the forward limit: $t, \xi \to 0$, GPDs reduce to PDFs.

$$H^q(x, \xi = 0, t = 0) = \begin{cases} 
q(x) & \text{for } x > 0 \\
-\bar{q}(-x) & \text{for } x < 0 
\end{cases}$$

• When integrated over $x$, GPDs reduce to elastic form factors.

$$F_1(t) = \sum_q e_q \int_{-1}^{+1} dx H^q(x, \xi, t)$$
$$F_2(t) = \sum_q e_q \int_{-1}^{+1} dx E^q(x, \xi, t)$$

$\xi$ dependence vanishes after integration over $x$ (also factorization scale dependence).
**Generalized Parton Distributions**

- First moment of GPDs, enter the Ji’s sum rule for the angular momentum carried by partons in the nucleon.

- Fourier transform of GPD’s to impact parameter space can be interpreted as „tomographic” 3D pictures of nucleon, describing charge distribution in the transverse plane, for a given value of $x$. 
DVCS and Bethe-Heitler contribution.

\[ \sigma \sim |A_{DVCS} + A_{BH}|^2 = |A_{DVCS}|^2 + |A_{BH}|^2 + A_{DVCS} A_{BH}^* + A_{DVCS}^* A_{BH} \]

Different beam charges allow to filter the interference term (linear in lepton charge), and extract information about GPDs.
**Exclusive photoproduction of dileptons, $\gamma N \rightarrow \ell^+\ell^- N$**

Figure 1: Real photon-proton scattering into a lepton pair and a proton.
Bethe-Heitler process

Figure 2: The Feynman diagrams for the Bethe-Heitler amplitude.

\[ \frac{d\sigma_{BH}}{dQ'^2 d\Omega dt} \rightarrow \frac{\alpha^3}{4\pi} \frac{1}{-tL} (1 + \cos^2 \theta) \left( F_1^2 - \frac{t}{4M_p^2} F_2^2 \right) \]

For small $\theta$ BH contribution becomes extremely large.
Timelike Compton Scattering

Figure 3: Handbag diagrams for the Compton process in the scaling limit. The plus-momentum fractions $x$, $\xi$, $\eta$ refer to the average proton momentum $\frac{1}{2}(p + p')$.

$$T^{\alpha\beta} = -\frac{1}{(p + p')^+} \bar{u}(p') \left[ g_T^{\alpha\beta} \left( \mathcal{H} \gamma^+ + \mathcal{E} \frac{i\sigma^\rho \Delta_\rho}{2M} \right) + i\varepsilon_T^{\alpha\beta} \left( \tilde{\mathcal{H}} \gamma^+ \gamma_5 + \tilde{\mathcal{E}} \frac{\Delta^+ \gamma_5}{2M} \right) \right] u(p)$$
Factorization

\[ H(\xi, \eta, t) = \sum_q e_q^2 \int_{-1}^{1} dx \left( \frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) H^q(x, \eta, t) \]

\[ E(\xi, \eta, t) = \sum_q e_q^2 \int_{-1}^{1} dx \left( \frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) E^q(x, \eta, t) \]

\[ \tilde{H}(\xi, \eta, t) = \sum_q e_q^2 \int_{-1}^{1} dx \left( \frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon} \right) \tilde{H}^q(x, \eta, t) \]

\[ \tilde{E}(\xi, \eta, t) = \sum_q e_q^2 \int_{-1}^{1} dx \left( \frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon} \right) \tilde{H}^q(x, \eta, t) \]

\[ \frac{d\sigma_{TCS}}{dQ'^2 d\Omega dt} \approx \frac{\alpha^3}{8\pi s^2 Q'^2} \left( \frac{1 + \cos^2 \theta}{4} \right)^2 (1 - \eta^2) \left( |H|^2 + |\tilde{H}|^2 \right) \]
Modelizing GPDs

In this first study of the feasibility of the extraction of the TCS signal, we simplify our calculations by using a factorization ansatz for the $t$ dependence of GPD's:

$$H^u(x, \eta, t) = h^u(x, \eta) \frac{1}{2} F_1^u(t)$$

$$H^d(x, \eta, t) = h^d(x, \eta) F_1^d(t)$$

$$H^s(x, \eta, t) = h^s(x, \eta) F_D(t)$$

and a double distribution ansatz for $h^q$:

$$h^q(x, \eta) = \int_0^1 dx' \int_{-1+x'}^{1-x'} dy' \left[ \delta(x - x' - \eta y') q(x') - \delta(x + x' - \eta y') \bar{q}(x') \right] \pi(x', y')$$

$$\pi(x', y') = \frac{3}{4} \frac{(1 - x')^2 - y'^2}{(1 - x')^3}$$
Factorization scale dependence.

Figure 4: The NLO($\overline{MS}$) GRVGJR 2008 parametrization of $u(x) + \bar{u}(x)$ for different factorization scales $\mu_F^2 = 4$ (dotted), 5 (dashed), 6 (dash-dotted), 10 (solid) GeV$^2$. 
Figure 5: Im $\mathcal{H}^u$ (up) and Re $\mathcal{H}^u$ (down) divided by $\frac{1}{2} F^u$ for various factorization scales $\mu_F^2 = 4$ (dotted), 5 (dashed), 6 (solid) GeV$^2$ and various ranges of $\xi : [1 \cdot 10^{-1}, 2 \cdot 10^{-1}], [1 \cdot 10^{-3}, 2 \cdot 10^{-3}], [1 \cdot 10^{-5}, 2 \cdot 10^{-5}]$. 
INTERFERENCE

\[
\frac{d\sigma_{\text{INT}}}{dQ'^2 \, dt \, d\cos \theta \, d\varphi} = - \frac{\alpha_{\text{em}}^3}{4\pi s^2} \frac{1}{-t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \cos \varphi \frac{1 + \cos^2 \theta}{\sin \theta} \Re M
\]

with

\[
M = \frac{2\sqrt{t_0 - t}}{M} \frac{1 - \eta}{1 + \eta} \left[ F_1 \mathcal{H} - \frac{t}{4M^2} F_2 \mathcal{E} \right]
\]

Since the amplitudes for the Compton and Bethe-Heitler processes transform with opposite signs under reversal of the lepton charge, the interference term between TCS and BH is odd under exchange of the \( \ell^+ \) and \( \ell^- \) momenta. It is thus possible to project out the interference term through a clever use of the angular distribution of the lepton pair.
**CROSS SECTIONS**

Figure 6: (a) The BH cross section integrated over $\theta \in [\pi/4, 3\pi/4]$, $\varphi \in [0, 2\pi]$, $Q'^2 \in [4.5, 5.5] \text{ GeV}^2$, $|t| \in [0.05, 0.25] \text{ GeV}^2$, as a function of $\gamma p$ c.m. energy squared $s$. (b) $\sigma_{TCS}$ as a function of $\gamma p$ c.m. energy squared $s$, for GRVGJR2008 NLO parametrizations, for different factorization scales $\mu^2_F = 4$ (dotted), 5 (dashed), 6 (solid) GeV$^2$. 
Angular distributions

\[ \frac{d\sigma}{d\phi/dQ^2} \text{ [pb/GeV]} \]

(a) \[ \phi \]

(b) \[ \phi \]

(c) \[ \phi \]

\[ \frac{d\sigma}{d\phi/dQ^2} \text{ [pb/GeV]} \]

- Comp.
- Int.
- BH
- Total

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**Hadron colliders as photon colliders.**

Ultraperipherical collisions:
**Effective Photon Approximation**

The cross section for photoproduction in hadron collisions is given by:

\[
\sigma_{pp} = 2 \int \frac{dn(k)}{dk} \sigma_{\gamma p}(k) dk
\]

where \(\sigma_{\gamma p}(k)\) is the cross section for the \(\gamma p \rightarrow pl^+l^-\) process and \(k\) is the photon energy. \(\frac{dn(k)}{dk}\) is an equivalent photon flux (the number of photons with energy \(k\)), and is given by:

\[
\frac{dn(k)}{dk} = \frac{\alpha}{2\pi k} \left[ 1 + \left(1 - \frac{2k}{\sqrt{s_{pp}}}\right)^2 \right] \left( \ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3} \right)
\]

where: \(A = 1 + \frac{0.71\text{GeV}^2}{Q_{min}^2}\), \(Q_{min}^2 \approx \frac{4M_p^2k^2}{s_{pp}}\) is the minimal squared fourmomentum transfer for the reaction, and \(s_{pp}\) is the proton-proton energy squared \((\sqrt{s_{pp}} = 14\text{ TeV})\). The relationship between \(\gamma p\) energy squared \(s\) and \(k\) is given by:

\[
s \approx 2\sqrt{s_{pp}k}
\]
Full cross sections

The pure Bethe - Heitler contribution to $\sigma_{pp}$, integrated over $\theta = [\pi/4, 3\pi/4]$, $\phi = [0, 2\pi]$, $t = [-0.05 \text{ GeV}^2, -0.25 \text{ GeV}^2]$, $Q'^2 = [4.5 \text{ GeV}^2, 5.5 \text{ GeV}^2]$, and photon energies $k = [20, 900] \text{ GeV}$ gives:

$$\sigma_{pp}^{BH} = 2.9 \text{ pb} .$$

The Compton contribution (calculated with NLO GRVGJR2008 PDFs, and $\mu_F^2 = 5 \text{ GeV}^2$) gives:

$$\sigma_{pp}^{TCS} = 1.9 \text{ pb} .$$

- The range of photon energies - expected capabilities to tag photon energies at the LHC.
- $10^5$ events/year at the LHC with its nominal luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$).
Summary

• Compton scattering in ultraperipheral collisions at hadron colliders opens a new way to measure generalized parton distributions.

• Sizeable rates even for the lower luminosity which can be achieved in the first months of run.

• Our work has to be supplemented by studies of higher order contributions which will involve the gluon GPDs; they will hopefully lead to a weaker factorization scale dependence of the amplitudes.