# Timelike Compton Scattering - new theoretical results and experimental possibilities

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# Outline

# DVCS

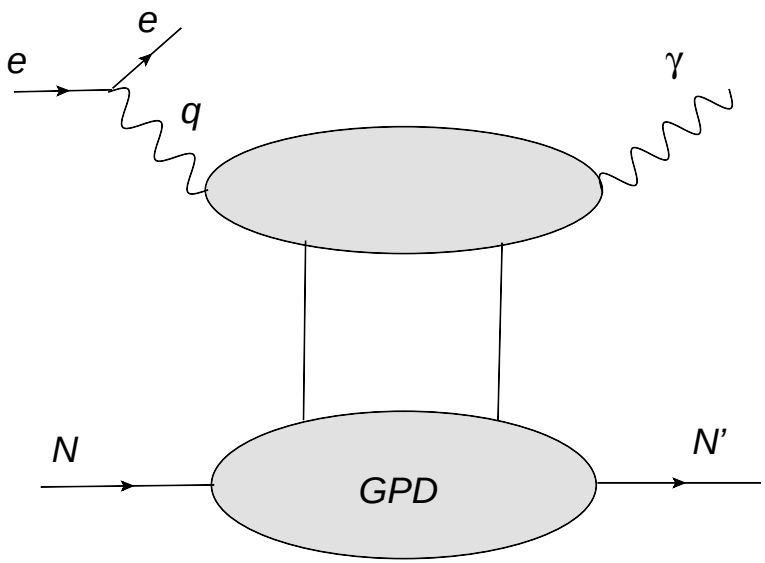



Figure: Deeply Virtual Compton Scattering : $lN \to l'N'\gamma$

# TCS

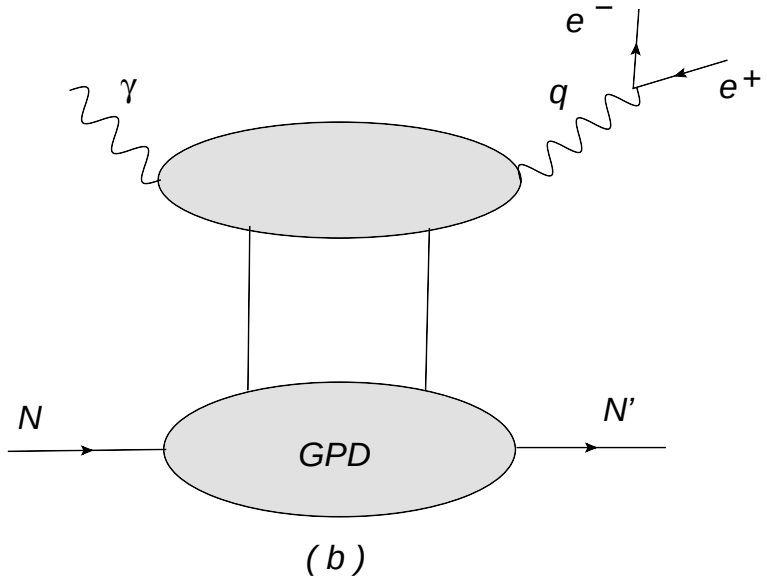



Figure: Timelike Compton Scattering: $\gamma N \to l^+ l^- N'$

# Why TCS?

- GDPs enter factorization theorems for hard exlusive reactions (DVCS, deeply virtual meson production, TCS etc.), in a similar manner as PDFs enter factorization theorem for DIS
- First moment of GPDs enters the Ji's sum rule for the angular momentum carried by partons in the nucleon,
- Deeply Virtual Compton Scattering (DVCS) is a golden channel for GPDs extraction,
- Why TCS: universality of the GPDs, another source for GPDs (special sensitivity on real part), spacelike-timelike crossing and understanding the structure of the NLO corrections,
- Experiments *at low energy*: CLAS 6 GeV $\rightarrow$ CLAS 12 GeV, *at high energy*: RHIC, LHC ?

# Coordinates

Berger, Diehl, Pire, 2002

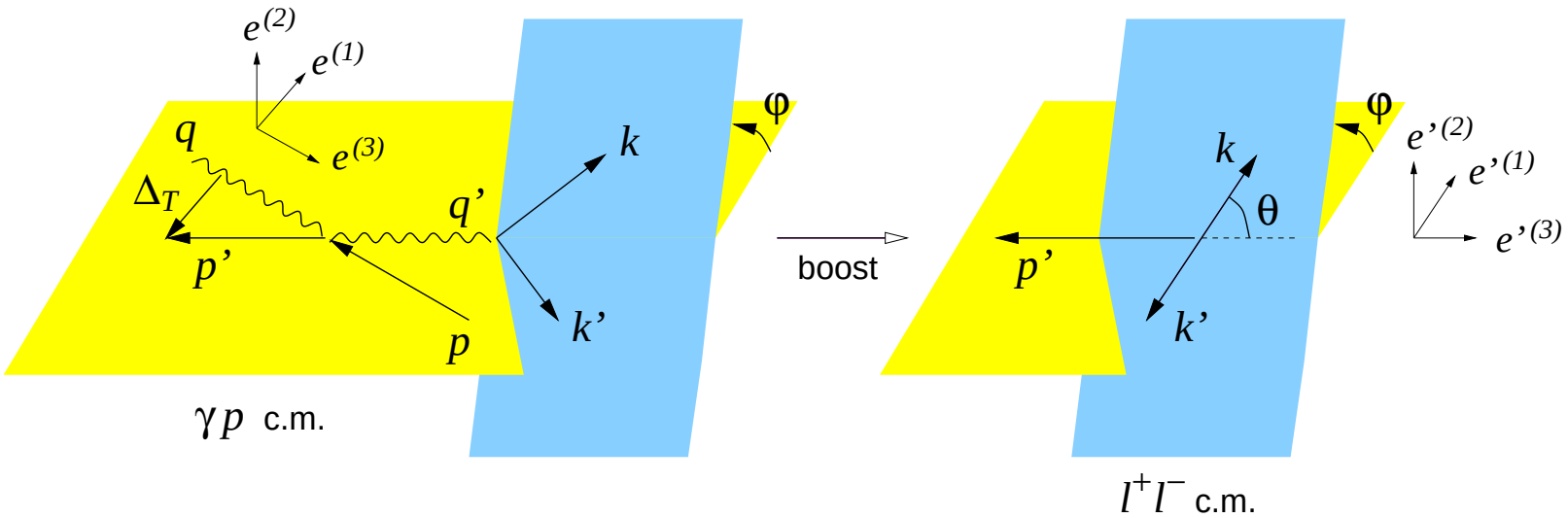



Figure: Kinematical variables and coordinate axes in the $\gamma p$ and $\ell^+\ell^-$ c.m. frames.

# The Bethe-Heitler contribution

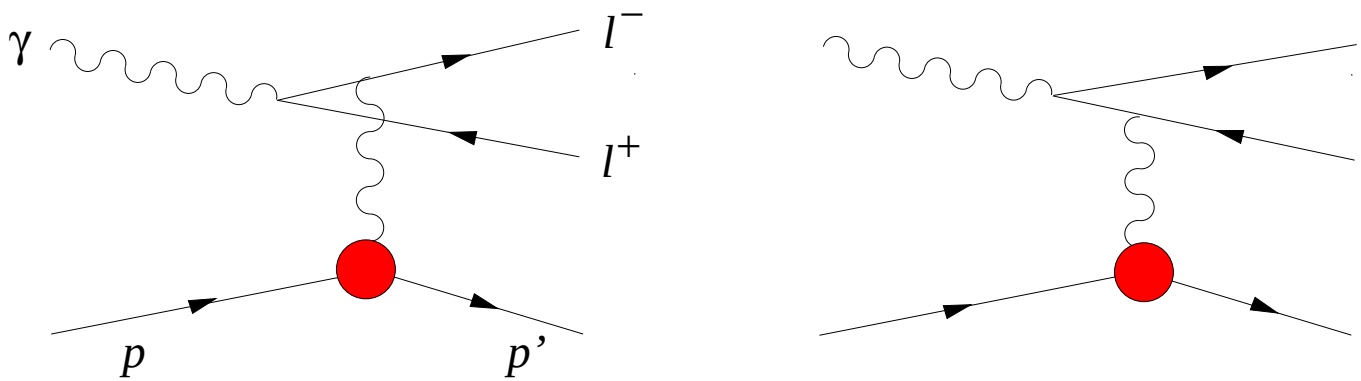



Figure: The Feynman diagrams for the Bethe-Heitler amplitude.

$$\frac{d\sigma_{BH}}{dQ'^2 dt d\cos\theta} \approx 2\alpha^3 \frac{1}{-tQ'^4} \frac{1+\cos^2\theta}{1-\cos^2\theta} \left( F_1(t)^2 - \frac{t}{4M_p^2} F_2(t)^2 \right),$$

For small $\theta$ BH contribution becomes very large

# The Compton contribution

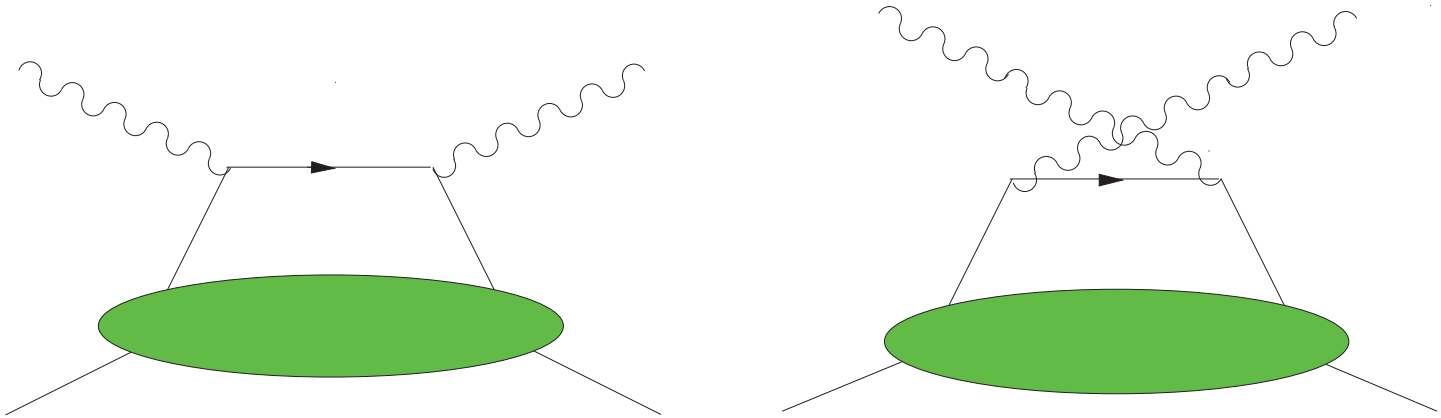


Figure: Handbag diagrams for the Compton process in the scaling limit.

$$\frac{d\sigma_{TCS}}{dQ'^2 d\Omega dt} \approx \frac{\alpha^3}{8\pi}\frac{1}{s^2}\frac{1}{Q'^2}\left(\frac{1+\cos^2\theta}{4}\right)2(1-\xi^2)\left|\mathcal{H}(\xi,t)\right|^2,$$

$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx T(x,\xi,Q') H^q(x,\xi,t),$$

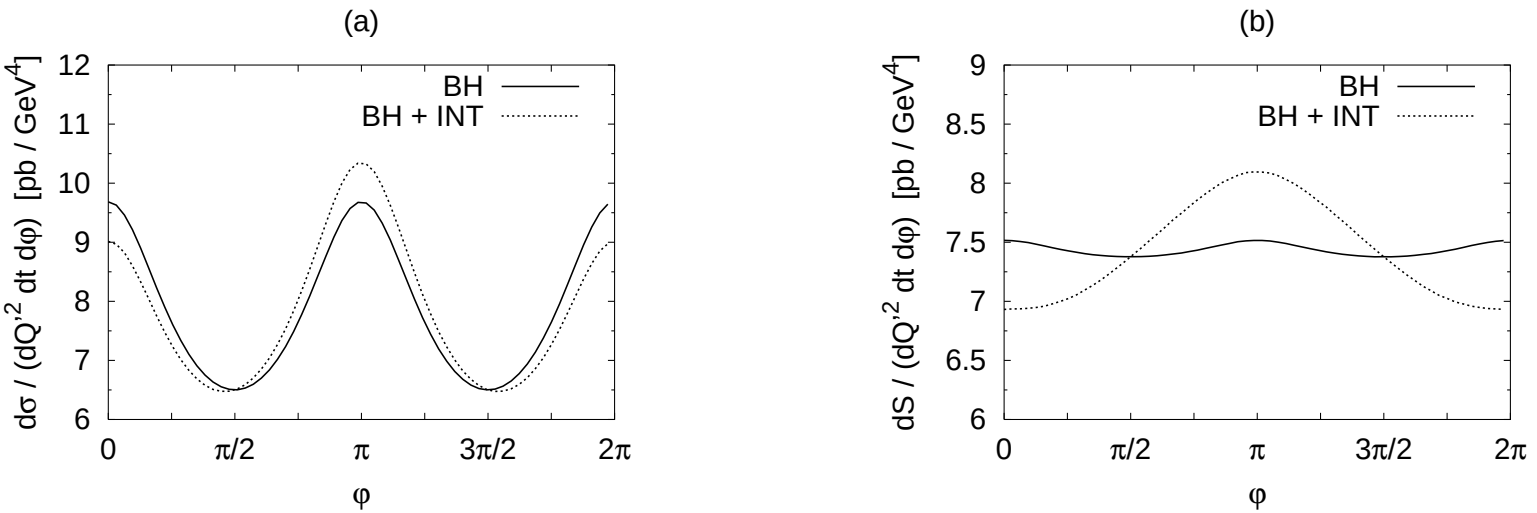
# Interference

The interference part of the cross-section for $\gamma p \to \ell^+ \ell^- p$ with unpolarized protons and photons is given at leading order by

$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d\cos\theta\, d\varphi} \sim \cos\varphi\ \mathrm{Re}\,\mathcal{H}(\xi, t)$$

Linear in GPD's, odd under exchange of the $l^+$ and $l^-$ momenta $\Rightarrow$ angular distribution of lepton pairs is a good tool to study interference term.

Berger, Diehl, Pire, 2002




B-H dominant for small energies;

# JLAB 6 GeV data

Rafayel Paremuzyan PhD thesis

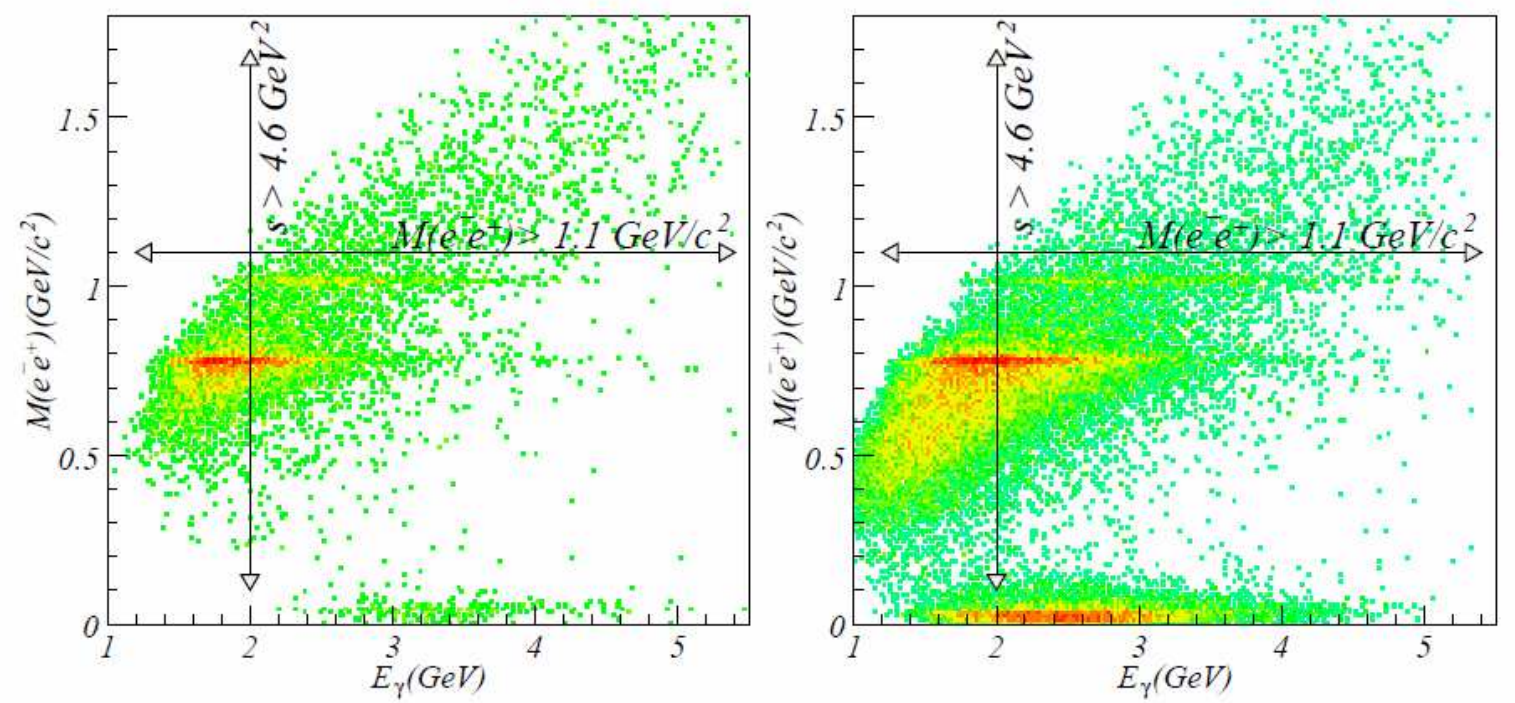



Figure: $e^+e^-$ invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

There is more data from g12 data set, soon to be analyzed. 12 $\mathrm{GeV}$ upgrade enables exploration of invariant masses up to $Q^2 = 9\,\mathrm{GeV}^2$ mass.

# Theory vs experiment

R.Paremuzyan and V.Guzey:

$$R = \frac{\int d\phi \ \cos\phi \ d\sigma}{\int \ d\phi \ d\sigma}$$

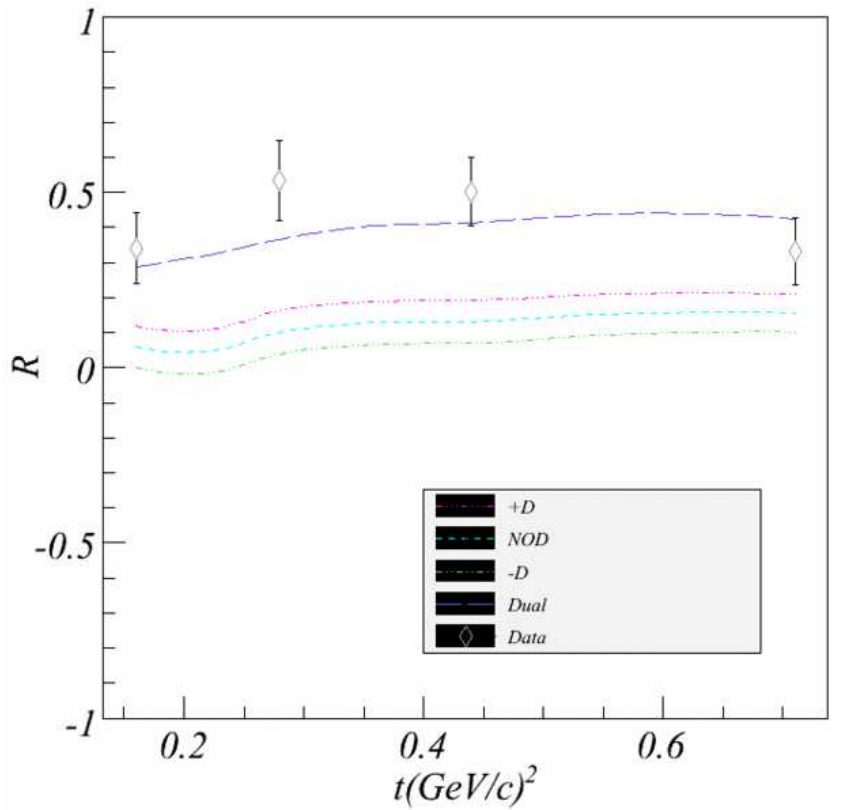



Figure: Thoeretical prediction of the ratio $R$ for various GPDs models. Data points after combining both e1-6 and e1f data sets.

# Motivation for NLO

Why do we need NLO corrections to TCS:

- gluons enter at NLO,
- DIS versus Drell-Yan: big K-factors $\log \frac{-Q^2}{\mu_F^2} \to \log \frac{Q^2}{\mu_F^2} \pm i\pi,$
- reliability of the results, factorization scale dependence,

Belitsky, Mueller, Niedermeier, Schafer, Phys.Lett.B474 ,2000.
Pire, Szymanowski, Wagner, Phys.Rev.D83, 2011.

General Compton Scattering:

$$\gamma^*(q_{in})N \to \gamma^*(q_{out})N'$$

- DVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 = 0$
- TCS: $q_{in}^2 = 0\,, \quad q_{out}^2 > 0$
- DDVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 > 0$

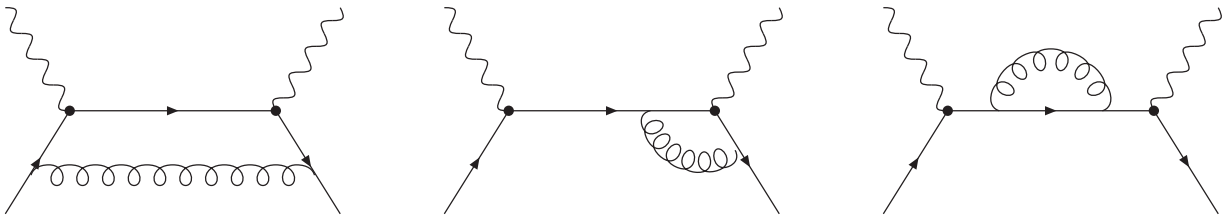
# Amplitude:

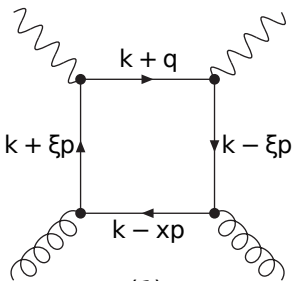
$$\mathcal{A}^{\mu\nu} = g_T^{\mu\nu} \int_{-1}^{1} dx \left[ \sum_q^{n_F} T^q(x) F^q(x) + T^g(x) F^g(x) \right]$$

where renormalized coefficient functions are given by:

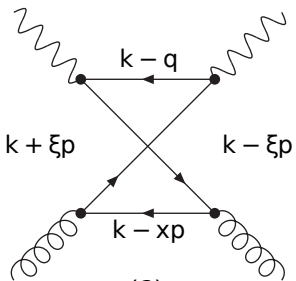
$$\begin{aligned} T^q &= C_0^q + C_1^q + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^q \,, \\ T^g &= C_1^g + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^g \end{aligned}$$

# Diagrams

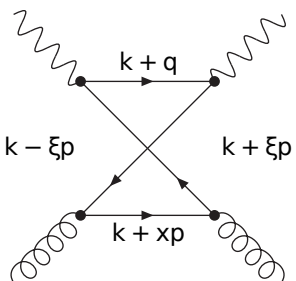




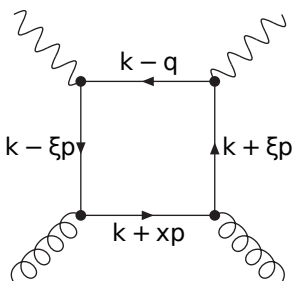

(1)



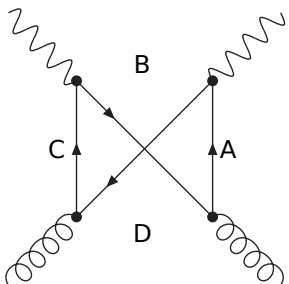

(2)



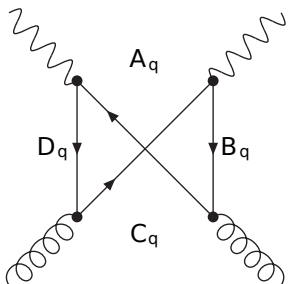

(3)




(4)




(5)




(6)

# Results: TCS + DVCS + DDVCS

TCS:
Quark coefficient functions:

$$C_0^q = e_q^2 \left( \frac{1}{x-\xi-i\varepsilon} + \frac{1}{x+\xi+i\varepsilon} \right),$$

$$C_1^q = \frac{e_q^2 \alpha_S C_F}{4\pi}$$

$$\left\{ \frac{1}{x-\xi-i\varepsilon} \left[ -9 + 3\log(-1+\frac{x}{\xi}-i\varepsilon) - 6\frac{\xi}{x+\xi}\log(-1+\frac{x}{\xi}-i\varepsilon) + 6\frac{\xi}{x+\xi}\log(-2-i\varepsilon) \right.\right.$$
$$\left. + \log^2(-1+\frac{x}{\xi}-i\varepsilon) - \log^2(-2-i\varepsilon) \right]$$
$$+ \frac{1}{x+\xi+i\varepsilon} \left[ -9 + 3\log(-1-\frac{x}{\xi}-i\varepsilon) + 6\frac{\xi}{x-\xi}\log(-1-\frac{x}{\xi}-i\varepsilon) - 6\frac{\xi}{x-\xi}\log(-2-i\varepsilon) \right.$$
$$\left.\left. + \log^2(-1-\frac{x}{\xi}-i\varepsilon) - \log^2(-2-i\varepsilon) \right] \right\},$$

$$C_{coll}^q = \frac{e_q^2 \alpha_S C_F}{4\pi} \left\{ \frac{1}{x-\xi-i\varepsilon} \left[ 3 + 2\log(-1+\frac{x}{\xi}-i\varepsilon) - 2\log(-2-i\varepsilon) \right] \right.$$
$$\left. + \frac{1}{x+\xi+i\varepsilon} \left[ 3 + 2\log(-1-\frac{x}{\xi}-i\varepsilon) - 2\log(-2-i\varepsilon) \right] \right\}$$

Gluon coefficient functions:

$$C^g_{coll} = \frac{\left(\sum_q e_q^2\right)\alpha_S T_F}{4\pi}\frac{2}{(x+\xi+i\varepsilon)(x-\xi-i\varepsilon)}\cdot$$

$$\left[\frac{x-\xi}{x+\xi}\log\left(-1+\frac{x}{\xi}-i\varepsilon\right)+\frac{x+\xi}{x-\xi}\log\left(-1-\frac{x}{\xi}-i\varepsilon\right)-2\frac{x^2+\xi^2}{x^2-\xi^2}\log(-2-i\varepsilon)\right],$$

$$C^g_1 = \frac{\left(\sum_q e_q^2\right)\alpha_S T_F}{4\pi}\frac{1}{(x+\xi+i\varepsilon)(x-\xi-i\varepsilon)}\cdot$$

$$\begin{aligned}\Big[&-2\frac{x-3\xi}{x+\xi}\log\left(-1+\frac{x}{\xi}-i\varepsilon\right)+\frac{x-\xi}{x+\xi}\log^2\left(-1+\frac{x}{\xi}-i\varepsilon\right)\\&-2\frac{x+3\xi}{x-\xi}\log\left(-1-\frac{x}{\xi}-i\varepsilon\right)+\frac{x+\xi}{x-\xi}\log^2\left(-1-\frac{x}{\xi}-i\varepsilon\right)\\&+4\frac{x^2+3\xi^2}{x^2-\xi^2}\log(-2-i\varepsilon)-2\frac{x^2+\xi^2}{x^2-\xi^2}\log^2(-2-i\varepsilon)\Big]\end{aligned}$$

# Discussion

The result may be summarized as follows:

$$\xi_D = \xi - i\epsilon \qquad \xi_T = \xi + i\epsilon$$

$$\begin{aligned}
{}^T C_0^q &= C_0^q(x,\xi_T) = C_0^q(x,\xi_D^*) = {}^D C_0^{q\,*} \\
{}^T C_{coll}^q &= C_{coll}^q(x,\xi_T) = C_{coll}^q(x,\xi_D^*) = {}^D C_{coll}^{q\,*} \\
{}^T C_1^q &= C_1^q(x,\xi_T) - i\pi C_{coll}^q(x,\xi_T) = {}^D C_1^{q\,*} - i\pi {}^D C_{coll}^{q\,*},
\end{aligned}$$

for the quark contributions and

$$\begin{aligned}
{}^T C_{coll}^g &= C_{coll}^g(x,\xi_T) = C_{coll}^g(x,\xi_D^*) = {}^D C_{coll}^{g\,*} \\
{}^T C_1^g &= C_1^g(x,\xi_T) - i\pi C_{coll}^g(x,\xi_T) = {}^D C_1^{g\,*} - i\pi {}^D C_{coll}^{g\,*}
\end{aligned}$$

for the gluonic contribution. The above relations lead to the following relations between the complete coefficient functions:

$${}^T T^q = {}^D T^{q\,*} - i\pi {}^D C_{coll}^{q\,*} \qquad {}^T T^g = {}^D T^{g\,*} - i\pi {}^D C_{coll}^{g\,*}\,.$$

# DVCS Compton Form Factors at NLO

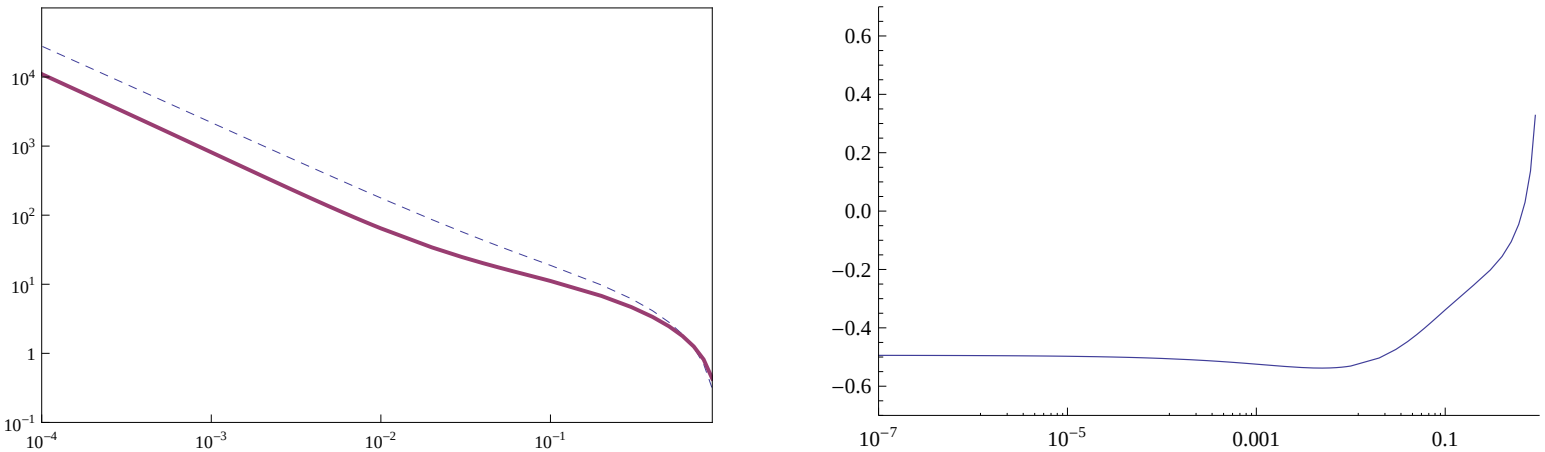



Figure: (left) Imaginary part of the DVCS Compton Form Factor $\mathcal{H}$, in the LO (dashed) and NLO (solid). (right) Ratio of the NLO corection to the Born term for imaginary part of the Compton Form Factor $\mathcal{H}$. Calculated for Kroll-Goloskokov model with $t = -0.1\ \mathrm{GeV}^2, Q^2 = 5\ \mathrm{GeV}^2$.

see previous H.Moutarde talk

# TCS Compton Form Factors at NLO

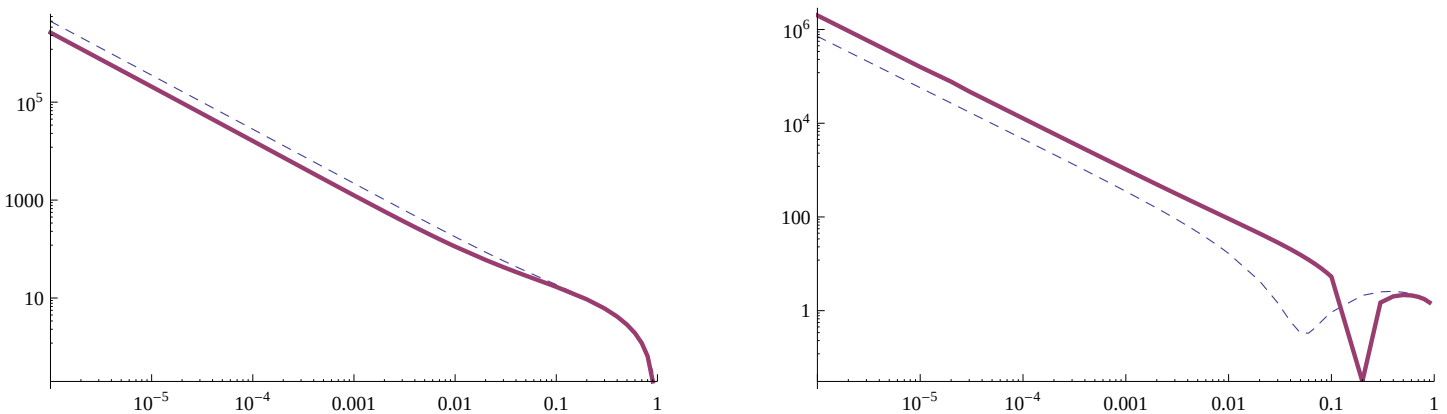



Figure: (left) Absolute value of the imaginary part of the TCS Compton Form Factor $\mathcal{H}$, in the LO (dashed) and NLO (solid). (right) Absolute value of the real part of the TCS Compton Form Factor $\mathcal{H}$, in the LO (dashed) and NLO (solid). Calculated for Kroll-Goloskokov model with $t = -0.1\ \mathrm{GeV}^2, Q^2 = 5\ \mathrm{GeV}^2$.

# TCS Compton Form Factors at NLO

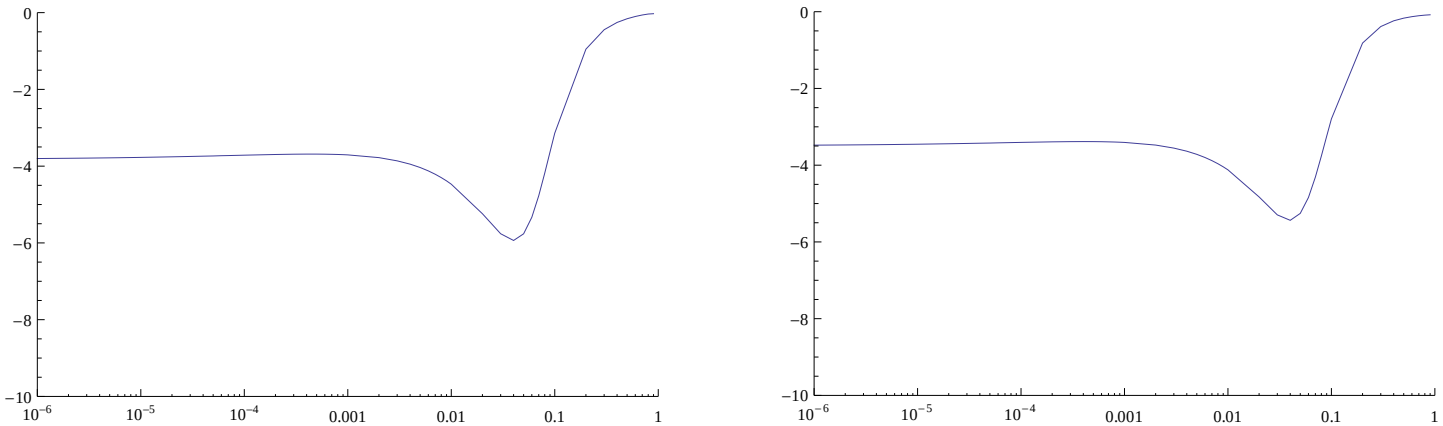



Figure: (left)Ratio of the NLO correction to the Born term for the **real** part of CFF $\mathcal{H}$. (right)Gluon contribution to that ratio.

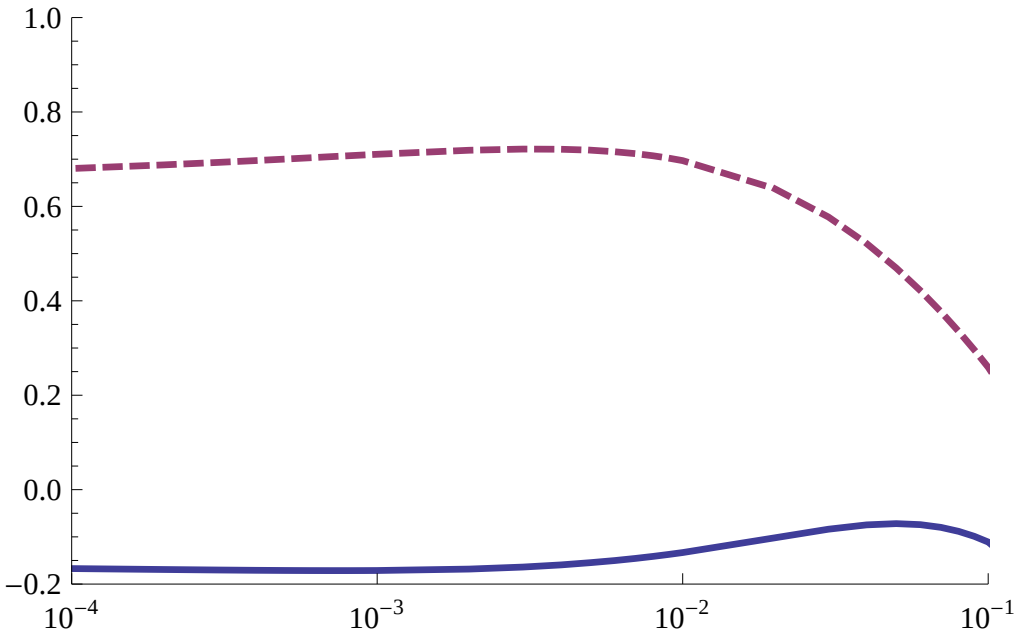
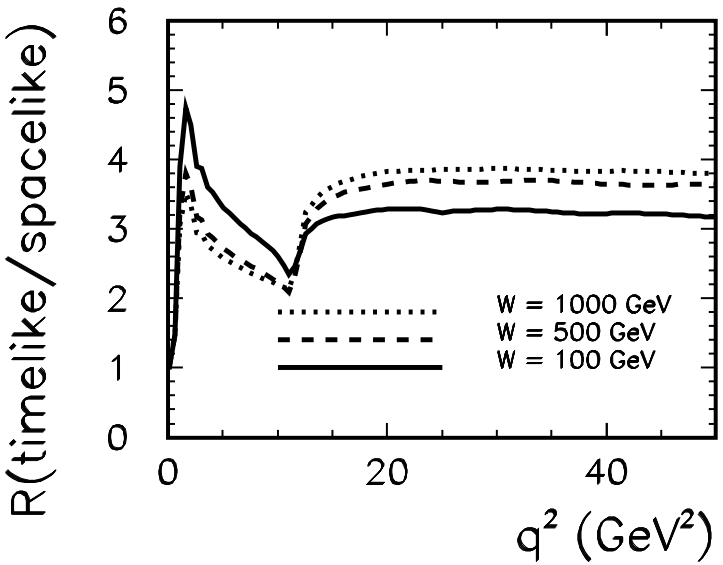
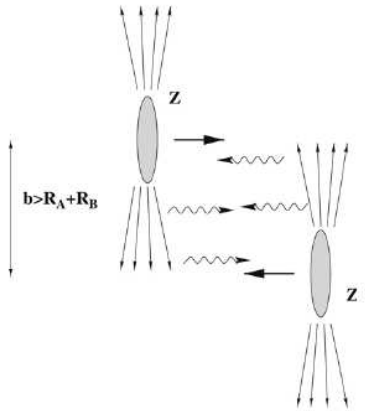



Figure: Ratio of the real to imaginary part of the TCS Compton Form Factor $\mathcal{H}$ in the LO (solid) and NLO (dashed).

Interesting result in $k_T$ factorization:
W. Schafer, G. Slipek, A. Szczurek, Phys.Lett.B688:185-191,2010.



# Ultraperipheral collisions




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

$\sigma_{\gamma p}(k)$ is the cross section for the $\gamma p \to p l^+ l^-$ process and $k$ is the $\gamma$'s energy, and $\frac{dn(k)}{dk}$ is an equivalent photon flux.

For $\theta = [\pi/4, 3\pi/4]$, $\phi = [0, 2\pi]$, $t = [-0.05\,\mathrm{GeV}^2, -0.25\,\mathrm{GeV}^2]$, $Q'^2 = [4.5\,\mathrm{GeV}^2, 5.5\,\mathrm{GeV}^2]$, and photon energies $k = [20, 900]\,\mathrm{GeV}$ we get:

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

The Compton contribution gives:

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

# The interference cross section

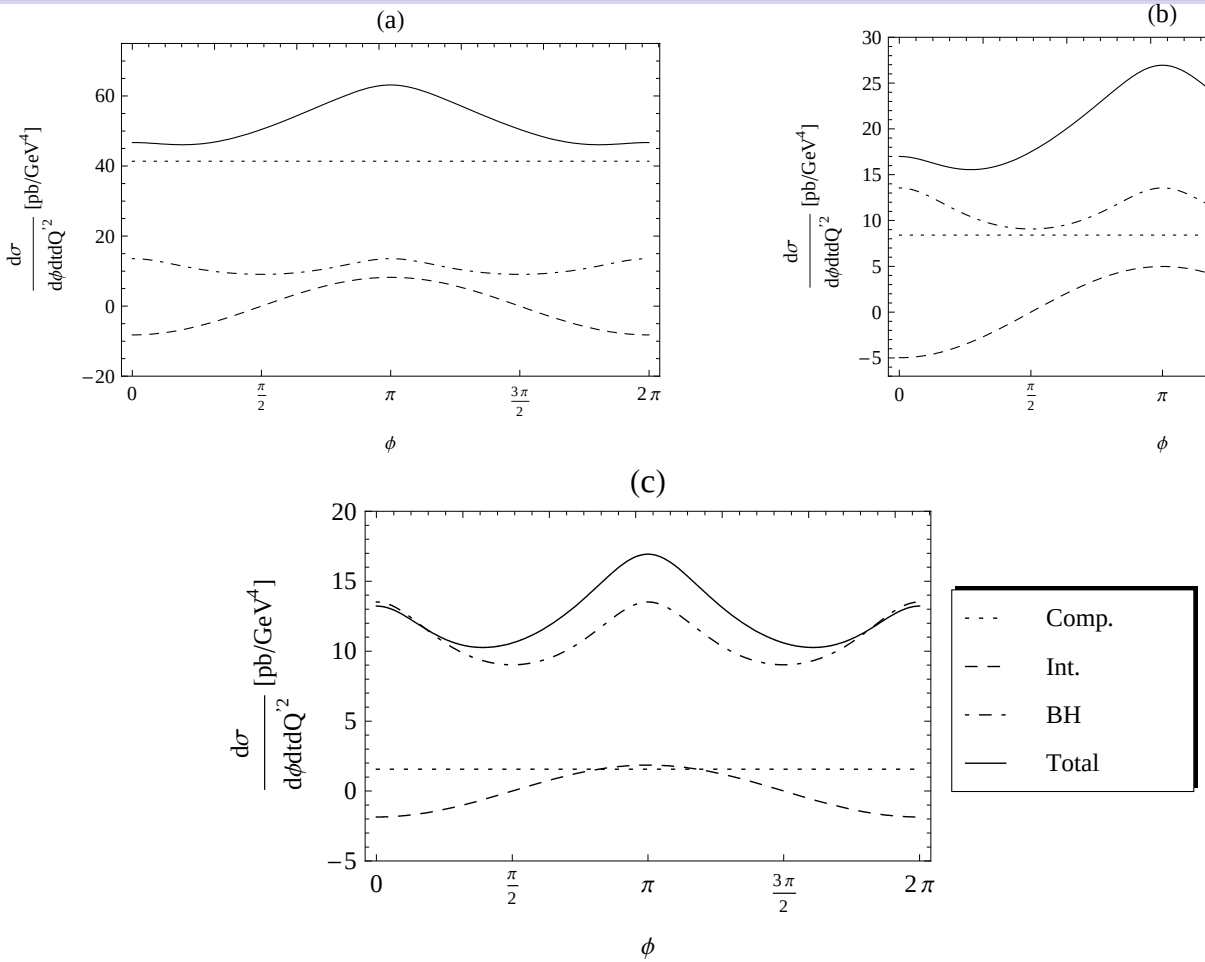



Figure: The differential cross sections (solid lines) for $t = -0.2\,\mathrm{GeV}^2$, $Q'^2 = 5\,\mathrm{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of $\varphi$, for $s = 10^7\,\mathrm{GeV}^2$ (a), $s = 10^5\,\mathrm{GeV}^2$(b), $s = 10^3\,\mathrm{GeV}^2$ (c) with $\mu_F^2 = 5\,\mathrm{GeV}^2$. We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.

# Ultraperipheral collisions at RHIC

$$L \cdot k \frac{dn}{dk}(\mathrm{mb}^{-1}\mathrm{sec}^{-1})$$

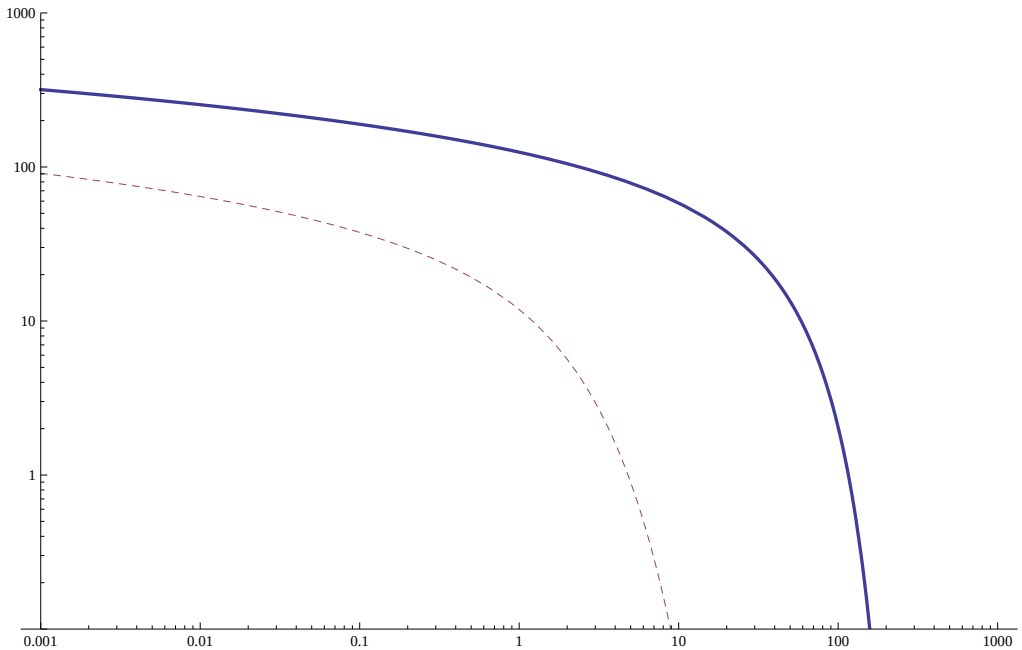



Figure: Effective luminosity of the photon flux from the Au-Au (dashed) and proton-proton (solid) collisions as a function of photon energy k(GeV).

# RHIC

$\frac{d\sigma^{AuAu}}{dQ^2 dt d\phi}(\mu\text{b GeV}^{-4})$

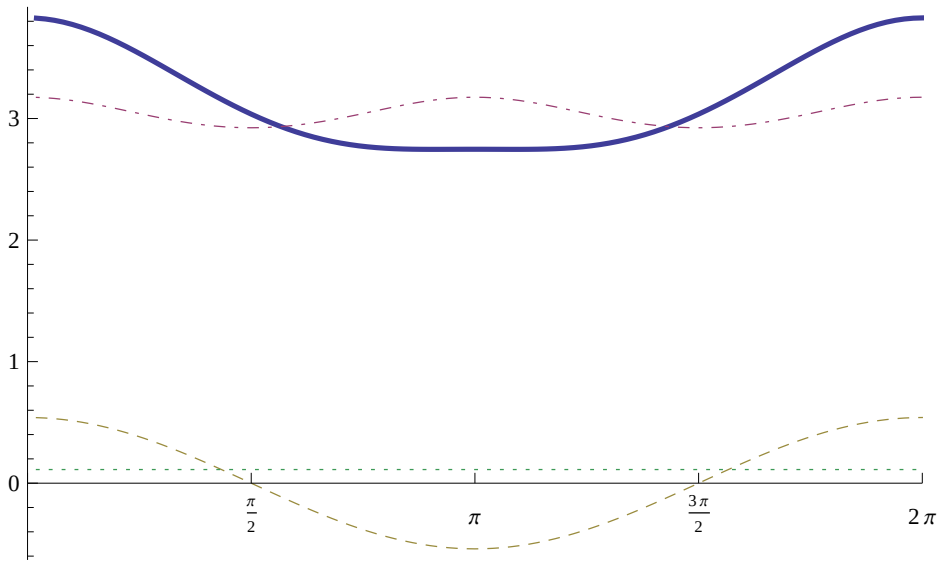



Figure: The differential cross sections (solid lines) for $t = -0.1\,\text{GeV}^2$, $Q'^2 = 5\,\text{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of $\varphi$. We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.

Total BH cross section (for $Q \in (2, 2.9)\,\text{GeV}$, $t \in (-0.2, -0.05)\,\text{GeV}^2$, $\theta = [\pi/4, 3\pi/4]$ and $\phi \in (0, 2\pi)$)

$$\sigma_{BH} = 41\mu\text{b} \qquad \text{Rate} = 0.04\text{Hz}$$

# RHIC

$\frac{d\sigma^{pp}}{dQ^2 dt d\phi}(\text{pb GeV}^{-4})$

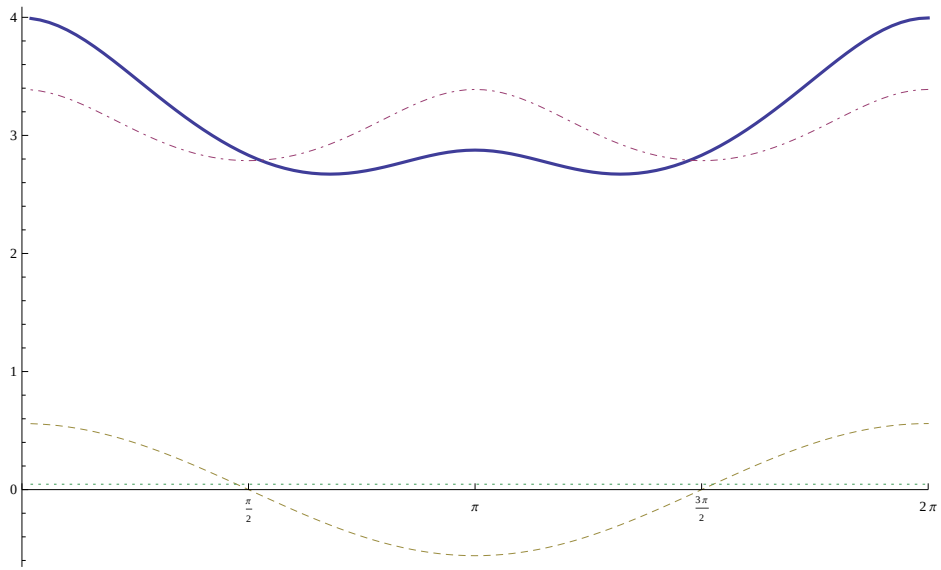



Figure: The differential cross sections (solid lines) for $t = -0.1\,\text{GeV}^2$, $Q'^2 = 5\,\text{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of $\varphi$. We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.

Total BH cross section (for $Q \in (2, 2.9)\,\text{GeV}$, $t \in (-0.2, -0.05)\,\text{GeV}^2$, $\theta = [\pi/4, 3\pi/4]$ and $\phi \in (0, 2\pi)$)

$$\sigma_{BH} = 9\text{pb} \qquad \text{Rate} = 5/\text{day}$$

# Summary

- TCS already measured in JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV.
- Big NLO corrections from gluon sector,
- Better understanding of large terms ($\pi^2$, ??) is needed - factorization scheme? resummation ?
- Compton scattering in ultraperipheral collisions at hadron colliders opens a new way to measure generalized parton distributions - experimentally challenging.