Timelike vs spacelike DVCS from JLab, COMPASS to colliders and to ultraperipheral collisions at AFTER@LHC

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Outline

DVCS

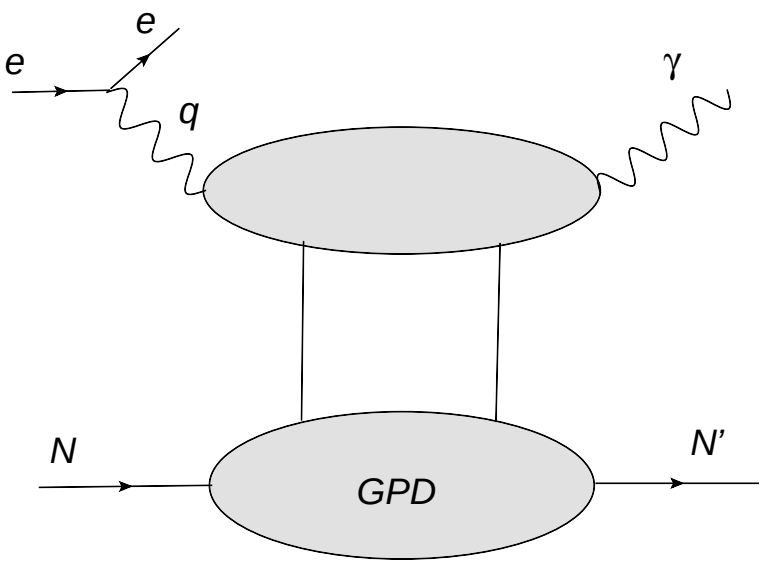


Figure: Deeply Virtual Compton Scattering : $lN \to l'N'\gamma$

Skewness ξ:

$$\xi = -\frac{(P' - P)n}{(P + P')n}$$

TCS

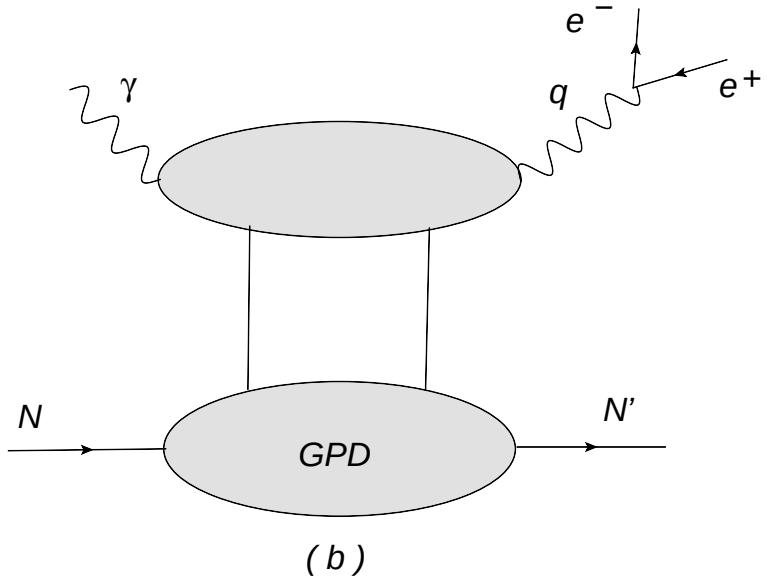


Figure: Timelike Compton Scattering: $\gamma N \to l^+ l^- N'$

Skewness η:

$$\eta = -\frac{(P' - P)n}{(P + P')n}$$

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, 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*: COMPASS, RHIC, LHC and AFTER@LHC ?

Coordinates

Berger, Diehl, Pire, 2002

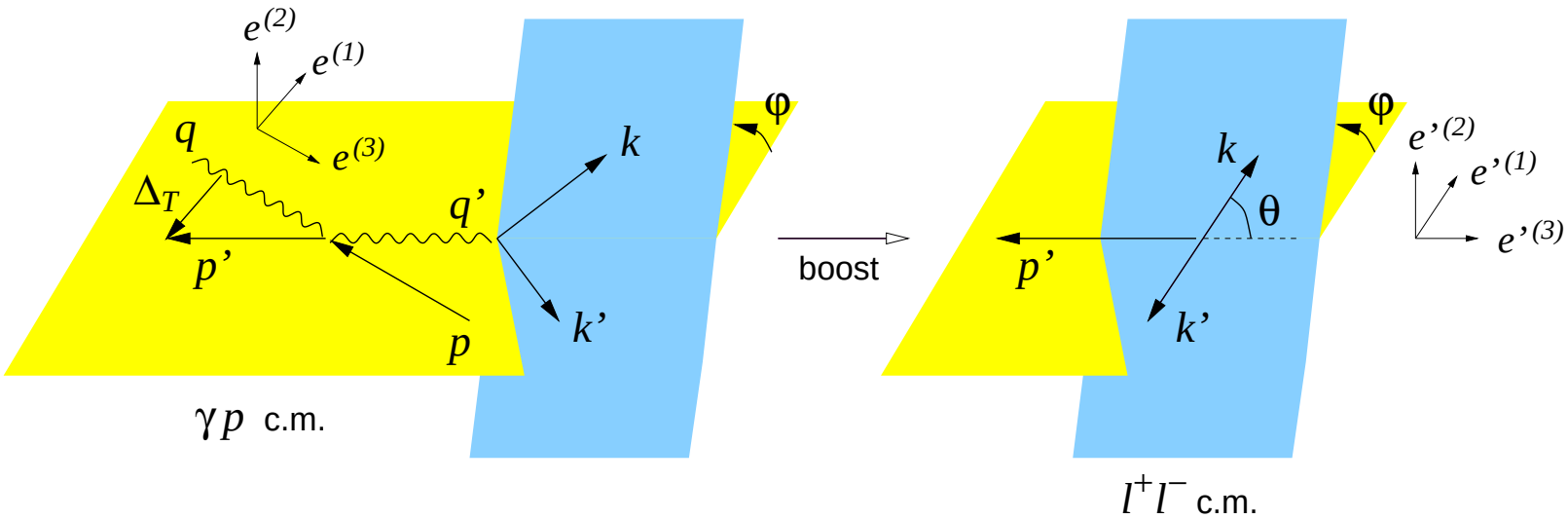


Figure: Kinematical variables and coordinate axes in the γp and $\ell^+\ell^-$ c.m. frames.

The Bethe-Heitler contribution

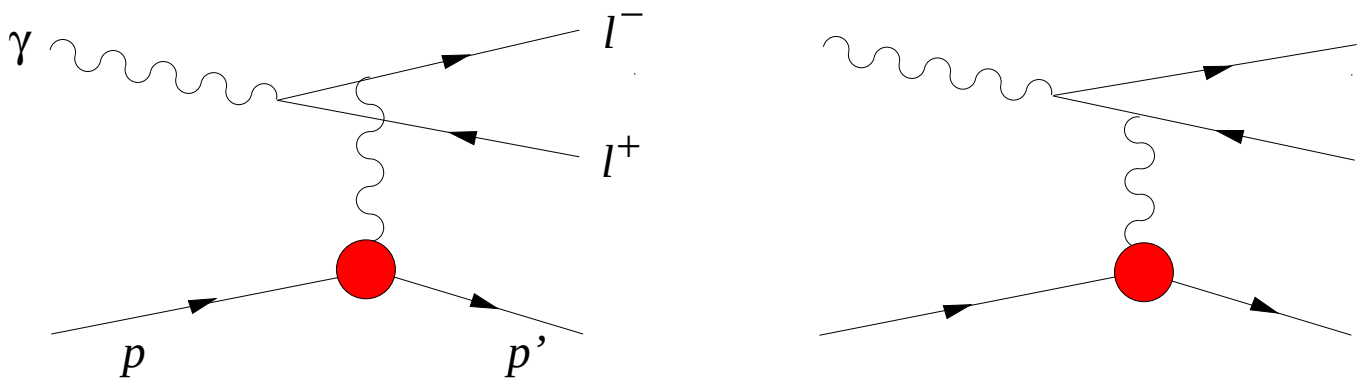


Figure: The Feynman diagrams for the Bethe-Heitler amplitude.

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

For small θ BH contribution becomes very large

The Compton contribution

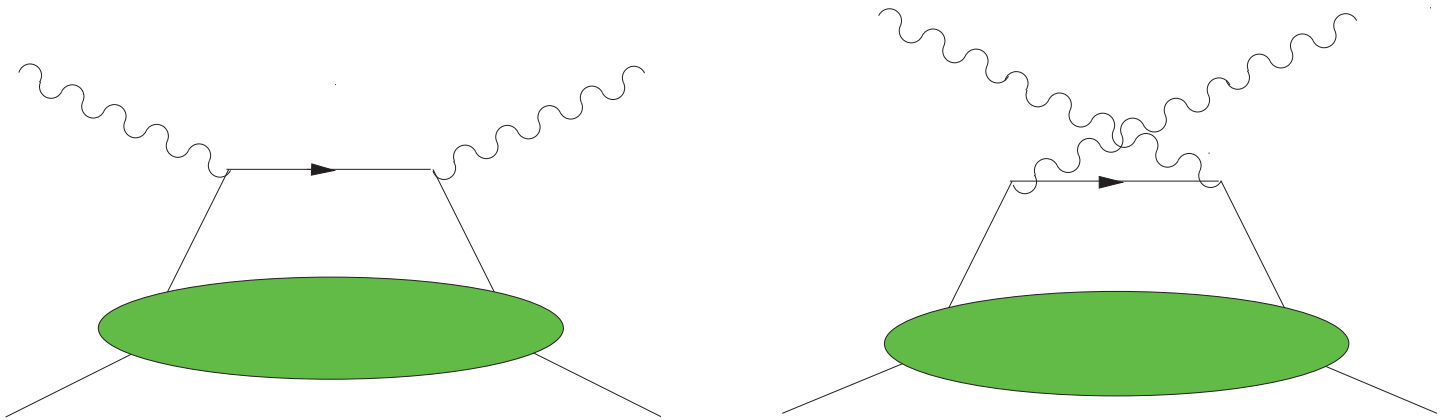


Figure: Handbag diagrams for the Compton process in the scaling limit.

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

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

Compton Form Factor

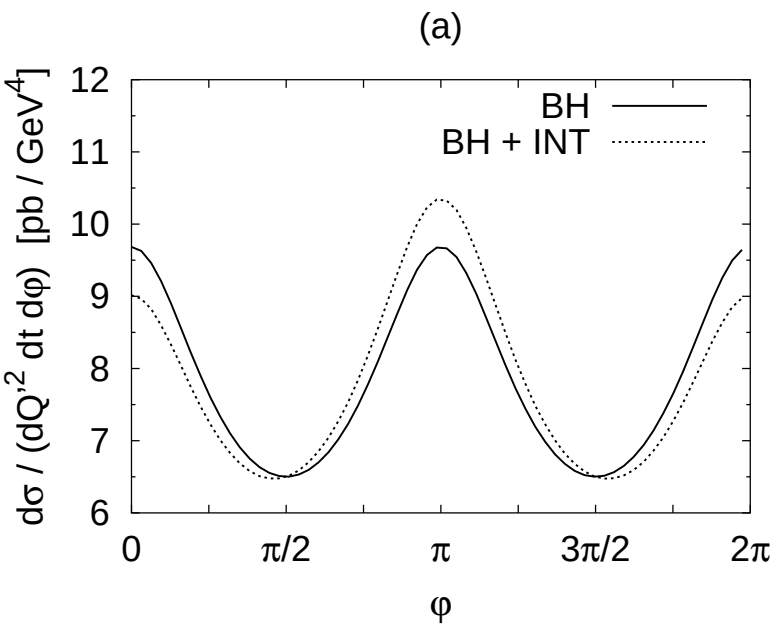
Interference

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

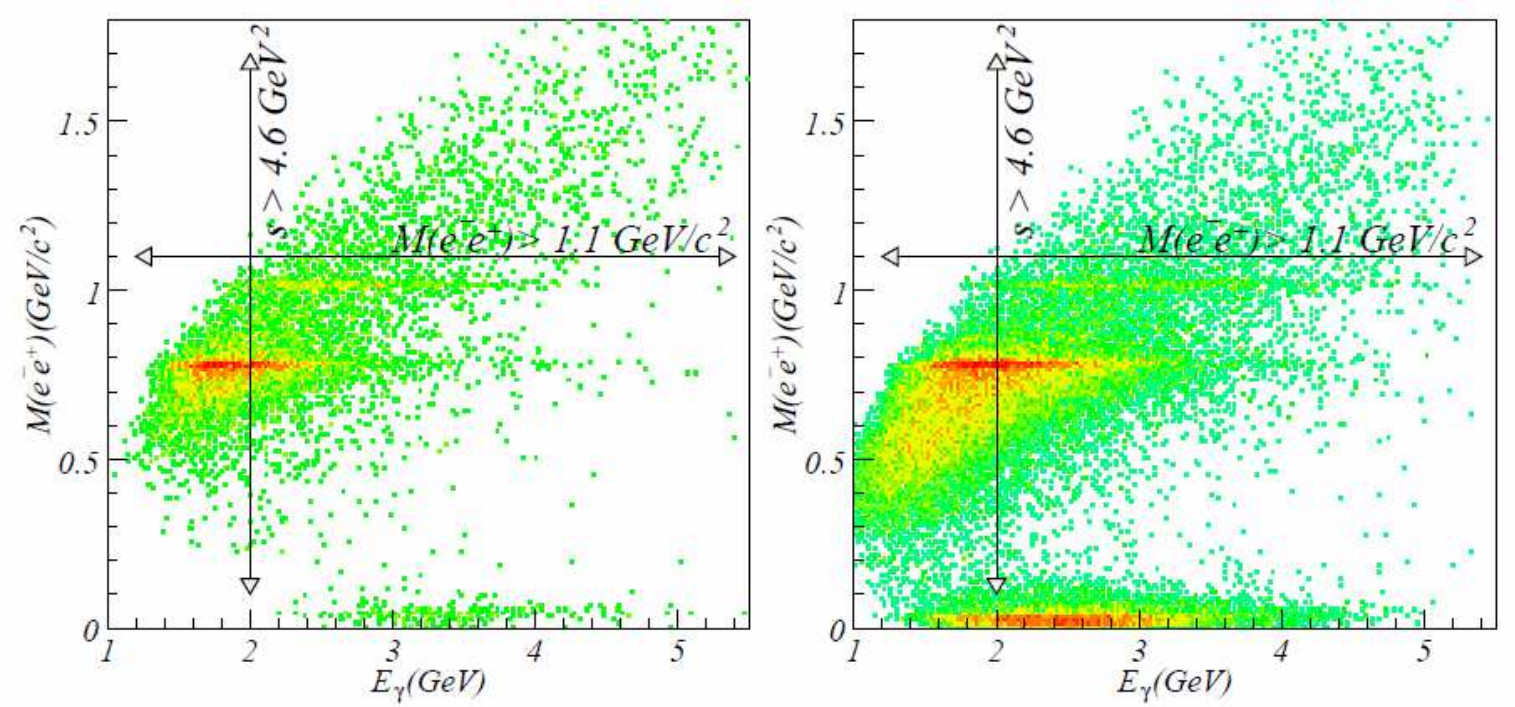


Figure: e^+e^- invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

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

Theory vs experiment

R.Paremuzyan and V.Guzey:

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

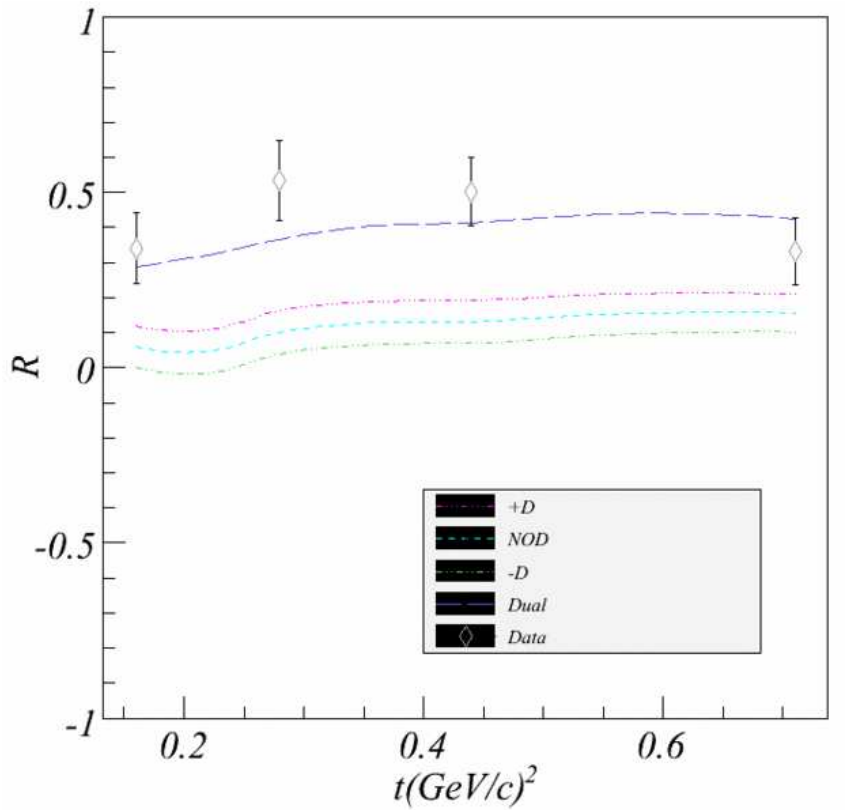


Figure: Theoretical prediction of the ratio R for various GPDs models. Data points after combining both e1-6 and e1f data sets.

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, L.Sz., Wagner, Phys.Rev.D83, 2011.

General Compton Scattering:

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

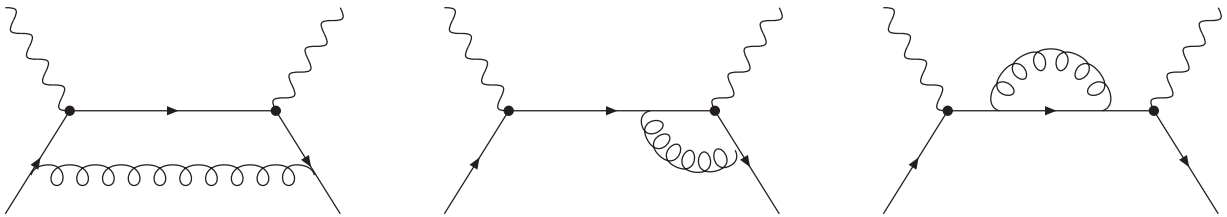
- DVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 = 0$
- TCS: $q_{in}^2 = 0\,, \quad q_{out}^2 > 0$
- DDVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 > 0$

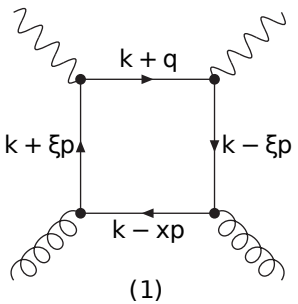
Amplitude:

$$\begin{aligned}\mathcal{A}^{\mu\nu} &= -g_T^{\mu\nu}\int_{-1}^{1}dx\left[\sum_q^{n_F} T^q(x)F^q(x)+T^g(x)F^g(x)\right]\\ &+ i\epsilon_T^{\mu\nu}\int_{-1}^{1}dx\left[\sum_q^{n_F}\widetilde{T}^q(x)\widetilde{F}^q(x)+\widetilde{T}^g(x)\widetilde{F}^g(x)\right],\end{aligned}$$

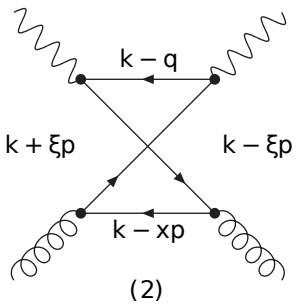
$$\begin{aligned}T^q(x) &= \left[C_0^q(x)+C_1^q(x)+\ln\left(\frac{Q^2}{\mu_F^2}\right)\cdot C_{coll}^q(x)\right]-(x\to -x),\\ T^g(x) &= \left[C_1^g(x)+\ln\left(\frac{Q^2}{\mu_F^2}\right)\cdot C_{coll}^g(x)\right]+(x\to -x),\\ \widetilde{T}^q(x) &= \left[\widetilde{C}_0^q(x)+\widetilde{C}_1^q(x)+\ln\left(\frac{Q^2}{\mu_F^2}\right)\cdot \widetilde{C}_{coll}^q(x)\right]+(x\to -x),\\ \widetilde{T}^g(x) &= \left[\widetilde{C}_1^g(x)+\ln\left(\frac{Q^2}{\mu_F^2}\right)\cdot \widetilde{C}_{coll}^g(x)\right]-(x\to -x).\end{aligned}$$

Diagrams

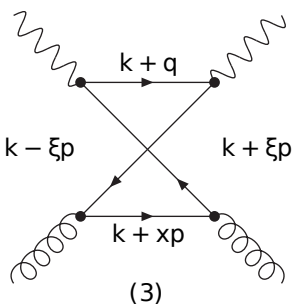




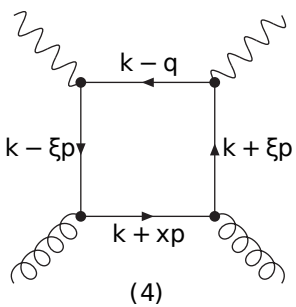
(1)



(2)



(3)



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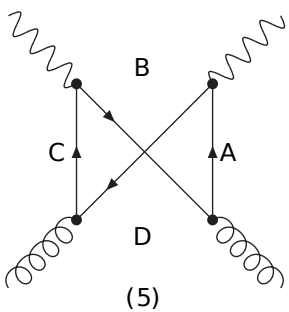

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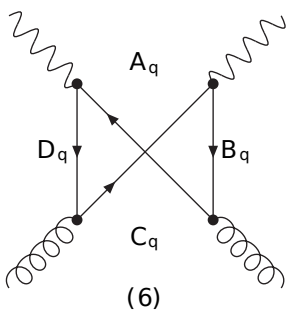


(6)

Results: TCS + DVCS + DDVCS

DVCS:
Quark coefficient functions:

$$
\begin{aligned}
C_0^q(x,\xi) &= -e_q^2 \frac{1}{x+\xi-i\varepsilon}\,, \\
C_1^q(x,\xi) &= \frac{e_q^2\alpha_S C_F}{4\pi}\frac{1}{x+\xi-i\varepsilon}\left[9-3\frac{x+\xi}{x-\xi}\log(\frac{x+\xi}{2\xi}-i\varepsilon)-\log^2(\frac{x+\xi}{2\xi}-i\varepsilon)\right], \\
C_{coll}^q(x,\xi) &= \frac{e_q^2\alpha_S C_F}{4\pi}\frac{1}{x+\xi-i\varepsilon}\left[-3-2\log(\frac{x+\xi}{2\xi}-i\varepsilon)\right], \\
\widetilde{C}_0^q(x,\xi) &= -e_q^2 \frac{1}{x+\xi-i\varepsilon}\,, \\
\widetilde{C}_1^q(x,\xi) &= \frac{e_q^2\alpha_S C_F}{4\pi}\frac{1}{x+\xi-i\varepsilon}\left[9-\frac{x+\xi}{x-\xi}\log(\frac{x+\xi}{2\xi}-i\varepsilon)-\log^2(\frac{x+\xi}{2\xi}-i\varepsilon)\right], \\
\widetilde{C}_{coll}^q(x,\xi) &= \frac{e_q^2\alpha_S C_F}{4\pi}\frac{1}{x+\xi-i\varepsilon}\left[-3-2\log(\frac{x+\xi}{2\xi}-i\varepsilon)\right],
\end{aligned}
$$

where $C_F = (N_c^2-1)/(2N_c)$

DVCS
Gluon coefficient functions:

$$
\begin{aligned}
C_1^g(x,\xi) &= \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{1}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} \times \\
&\left[2\frac{x+3\xi}{x-\xi} \log\left(\frac{x+\xi}{2\xi} - i\varepsilon\right) - \frac{x+\xi}{x-\xi} \log^2\left(\frac{x+\xi}{2\xi} - i\varepsilon\right) \right], \\
C_{coll}^g(x,\xi) &= \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{2}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} \left[-\frac{x+\xi}{x-\xi} \log\left(\frac{x+\xi}{2\xi} - i\varepsilon\right) \right], \\
\widetilde{C}_1^g(x,\xi) &= \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{1}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} \times \\
&\left[-2\frac{3x+\xi}{x-\xi} \log\left(\frac{x+\xi}{2\xi} - i\varepsilon\right) + \frac{x+\xi}{x-\xi} \log^2\left(\frac{x+\xi}{2\xi} - i\varepsilon\right) \right], \\
\widetilde{C}_{coll}^g(x,\xi) &= \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{2}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} \left[\frac{x+\xi}{x-\xi} \log\left(\frac{x+\xi}{2\xi} - i\varepsilon\right) \right],
\end{aligned}
$$

where $T_F = \frac{1}{2}$

Discussion

D. Mueller, B. Pire, L. Sz. and J. Wagner, Phys. Rev. D 86

The relation between the coefficient functions for NLO DVCS and NLO TCS:

$$
\begin{aligned}
{}^{TCS}T^{q} &= {}^{DVCS}T^{q\,*} - i\pi\, {}^{DVCS}C^{q\,*}_{coll} \\
{}^{TCS}T^{g} &= {}^{DVCS}T^{g\,*} - i\pi\, {}^{DVCS}C^{g\,*}_{coll}\,.
\end{aligned}
$$

Models for GPDs

Double distribution + D-term

Müller 94, Ji 97, Radyushkin 97, Polyakov, Weiss 99

$$F_i(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-x)\, f_i(\beta,\alpha,t) + D_i^F\left(\frac{x}{\xi},t\right)\Theta(\xi^2-x^2)\,,$$

$f_i(\beta,\alpha,t)$ - double distribution (DD)

$D_i^F\left(\frac{x}{\xi},t\right)$ - D-term

- the polynomiality (Lorentz inv.) of the Mellin moments satisfied authomatically

Models for GPDs

Double distribution + D-term

Müller 94, Ji 97, Radyushkin 97, Polyakov, Weiss 99

$$F_i(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-x)\, f_i(\beta,\alpha,t) + D_i^F\left(\frac{x}{\xi},t\right)\Theta(\xi^2-x^2)\,,$$

- the polynomiality (Lorentz inv.) of the Mellin moments satisfied authomatically

- models for DD $f_i(\beta,\alpha,t)$:

$$f_i(\beta,\alpha,t) = g_i(\beta,t)\quad h_i(\beta)\quad \frac{\Gamma(2n_i+2)}{2^{2n_i+1}\Gamma^2(n_i+1)}\,\frac{[(1-|\beta|)^2-\alpha^2]^{n_i}}{(1-|\beta|)^{2n_i+1}}\,,$$

the profile function $h_i(\beta)$ related to forward PDF e.g. $h^q_{\rm val}(\beta) = q_{\rm val}(\beta)\,\Theta(\beta)$

$g_i(\beta,t)$ controls $t-$dependence of GPDs

Models for GPDs

Our predictions are based on two models of GPDs:

- Goloskokov-Kroll (GK) model

CTEQ6m PDFs and Regge type t-dependence $g_i(\beta,t) = \mathrm{e}^{b_i t}\,|\beta|^{-\alpha_i' t}$

- model based on MSTW08 PDFs and on nucleon e-m. FFs

$$\begin{aligned} g_u(\beta,t) &= \frac{1}{2}F_1^u(t)\,, \\ g_d(\beta,t) &= F_1^d(t)\,, \\ g_s(\beta,t) &= g_g(\beta,t) = F_D(t)\,, \end{aligned}$$

where

$$\begin{aligned} F_1^u(t) &= 2F_1^p(t) + F_1^n(t)\,, \\ F_1^d(t) &= F_1^p(t) + 2F_1^n(t)\,, \\ F_D(t) &= (1 - t/M_V^2)^{-2}\,, \end{aligned}$$

TCS: Re vs. Im parts of TCS FF MSTW08

H. Moutarde, B. Pire, F. Sabatie, L.Sz. and J. Wagner, "On timelike and spacelike deeply virtual Compton scattering at next to leading order," arXiv:1301.3819

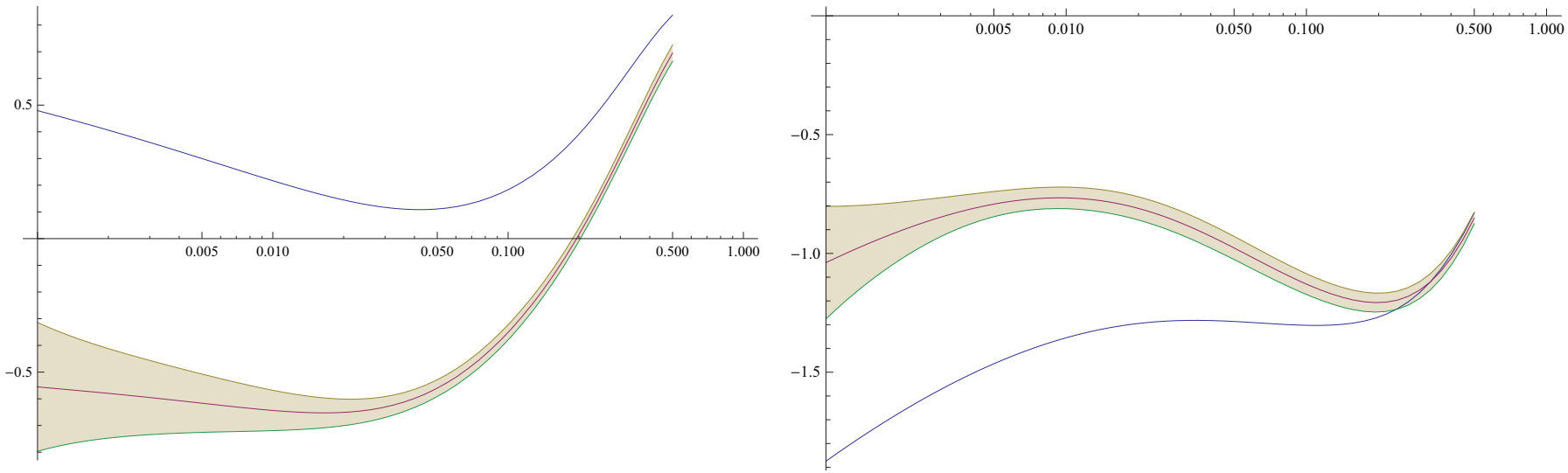


Figure: The real (left) and imaginary(right) parts of the TCS Compton Form Factor $\mathcal{H}$ multiplied by ξ, as a function of ξ in the double distribution model based on MSTW08 parametrization, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. The shaded bands show the effect of a one sigma uncertainty of the input MSTW08 fit to the parton distributions.

TCS: LO vs. NLO-quark vs. NLO-gluon MSTW08

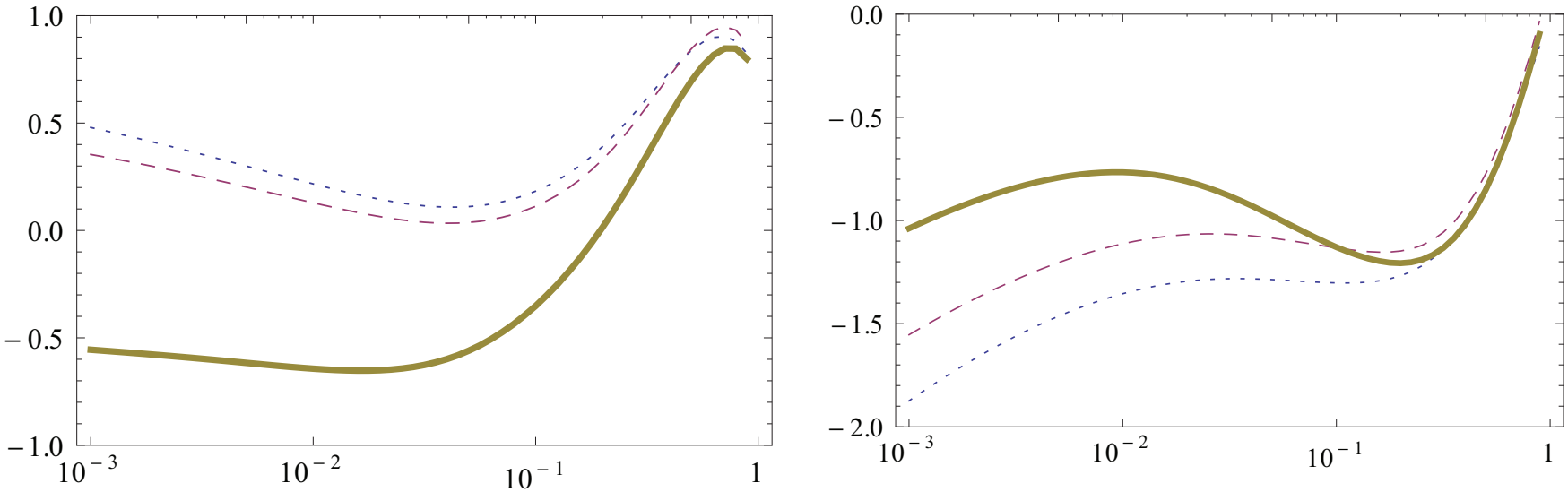


Figure: The real (left) and imaginary(right) parts of the TCS Compton Form Factor $\mathcal{H}$ multiplied by ξ, as a function of ξ in the double distribution model based on MSTW08 parametrization, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2.

LO : dotted line

LO + NLO-quark : dashed line

LO + NLO-quark + NLO-gluon: solid line

TCS: GK vs MSTW

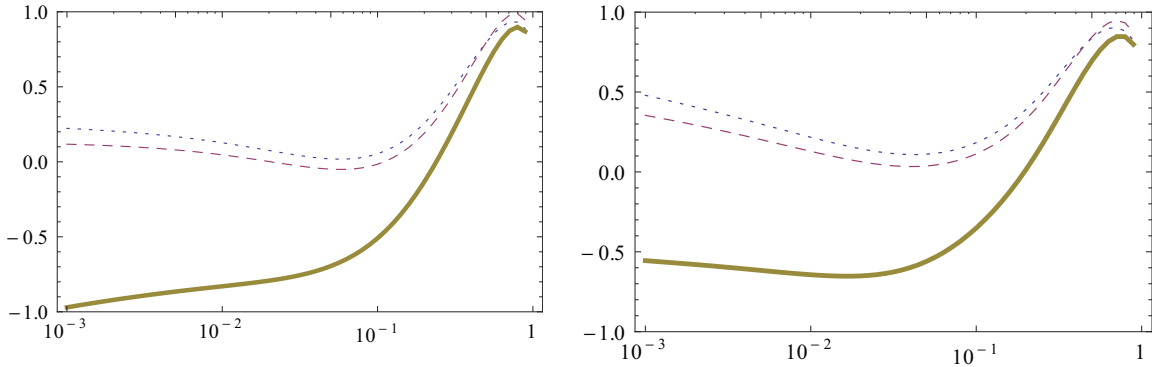


Figure: The real parts of the TCS Compton Form Factor $\mathcal{H}$ multiplied by ξ, as a function of ξ in the double distribution model, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. GK- left figure, MSTW- right figure

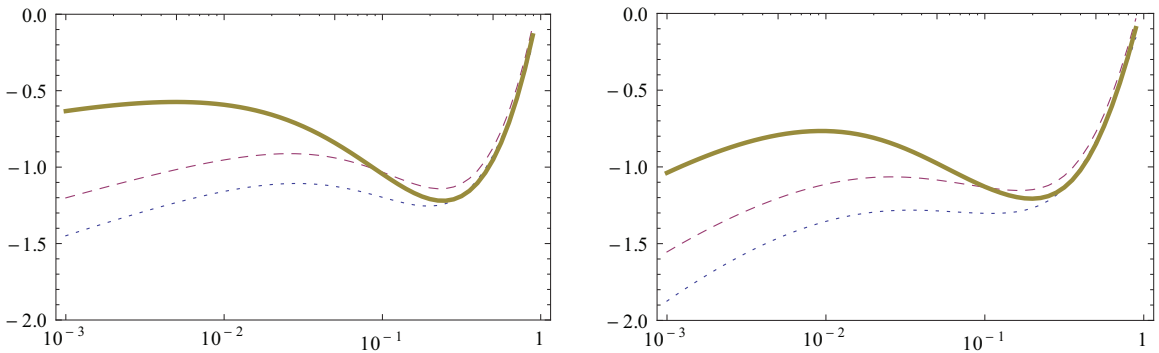


Figure: The imaginary parts of the TCS Compton Form Factor $\mathcal{H}$ multiplied by ξ, as a function of ξ in the double distribution model, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. GK- left figure, MSTW- right figure

LO: dotted line LO + NLO-quark: dashed line LO + NLO-quark +NLO-gluon: solid line

Observables

These CFFs are the GPD dependent quantities which enter the scattering amplitudes

For DVCS they are defined as

$$\mathcal{A}^{\mu\nu}(\xi,t) = -e^2 \frac{1}{(P+P')^+}\,\bar{u}(P')\left[g_T^{\mu\nu}\left(\mathcal{H}(\xi,t)\,\gamma^+ + \mathcal{E}(\xi,t)\,\frac{i\sigma^{+\rho}\Delta_\rho}{2M}\right) + i\epsilon_T^{\mu\nu}\left(\widetilde{\mathcal{H}}(\xi,t)\,\gamma^+\gamma_5 + \widetilde{\mathcal{E}}(\xi,t)\,\frac{\Delta^+\gamma_5}{2M}\right)\right] u(P)$$

Similar relation holds for TCS with ξ replaced by η.

DVCS: Observables for JLab — KG model

$d\sigma(l_+) + d\sigma(l_-)$ $d\sigma(l_-) - d\sigma(l_+)$ Asymmetry

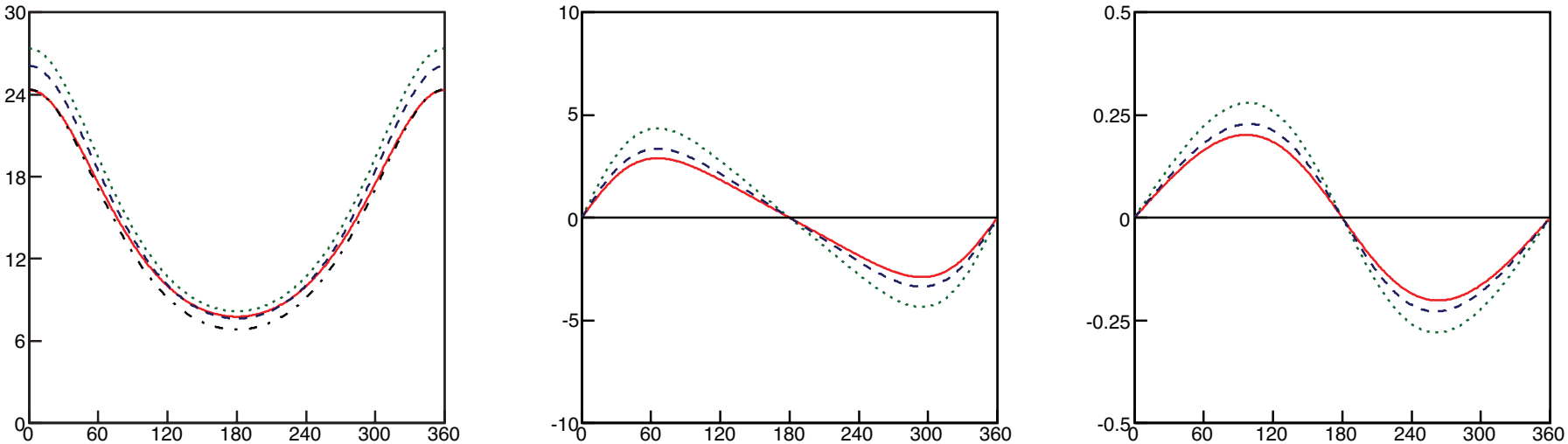


Figure: From left to right, the total DVCS cross section in pb/GeV^4, the difference of cross sections for opposite lepton helicities in pb/GeV^4, the corresponding asymmetry, all as a function of the usual ϕ angle (in Trento conventions) for E_e = 11 GeV; $\mu_F^2 = Q^2$ = 4 GeV^2 and t = - 0.2 GeV^2. The GPD $H(x;\xi;t)$ is parametrized by the GK model. The contributions from other GPDs are not included. The Bethe-Heitler contribution appears as the dash-dotted line in the cross section plots (left part)

LO: dotted line LO + NLO-quark: dashed line LO + NLO-quark +NLO-gluon: solid line

DVCS: Observables for COMPASS GK model

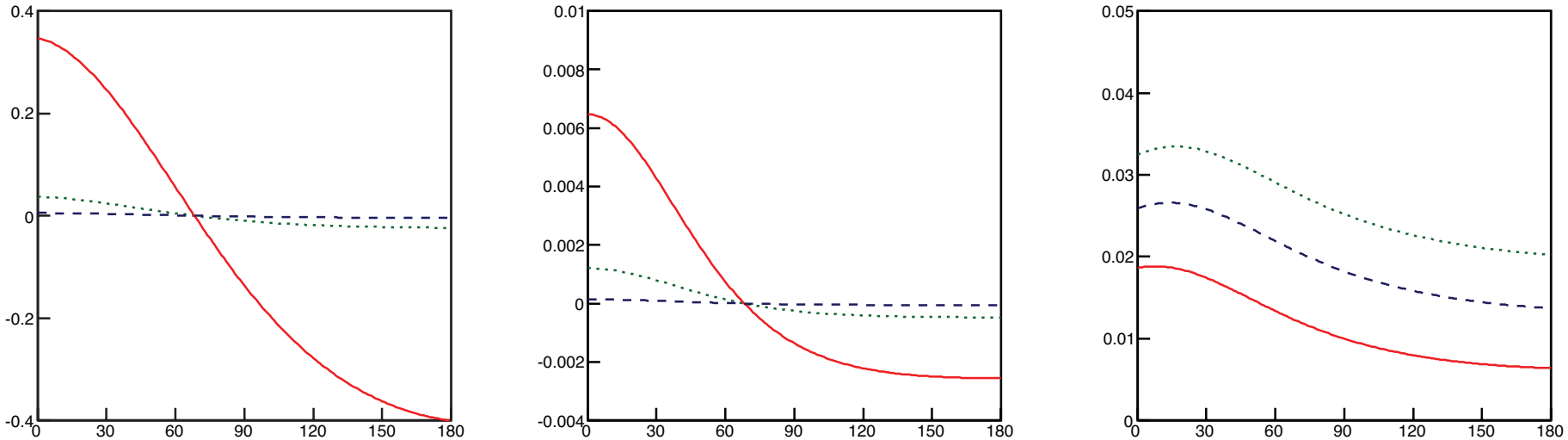


Figure: From left to right: mixed charge-spin asymmetry, mixed charge-spin difference and mixed charge-spin sum. The kinematical point is chosen as $\xi = 0.05$, $Q^2 = 4$ GeV^2, $-t = 0.2$ GeV^2. The GPD $H(x;\xi;t)$ is parametrized by the GK model. The contributions from other GPDs are not included.

$$\mathcal{A}_{CS,U}(\phi) \equiv \frac{\mathcal{D}_{CS,U}}{\mathcal{S}_{CS,U}}\,, \qquad \mathcal{D}_{CS,U}(\phi) \equiv d\sigma^{\overrightarrow{+}} - d\sigma^{\overleftarrow{-}}\,, \qquad \mathcal{S}_{CS,U}(\phi) \equiv d\sigma^{\overrightarrow{+}} + d\sigma^{\overleftarrow{-}}$$

LO: dotted line LO + NLO-quark: dashed line LO + NLO-quark +NLO-gluon: solid line

TCS: Observables for JLab@12GeV GK model

Cross-section:

fixed $t = -0.2\text{GeV}^2$ fixed $\eta = 0.11$

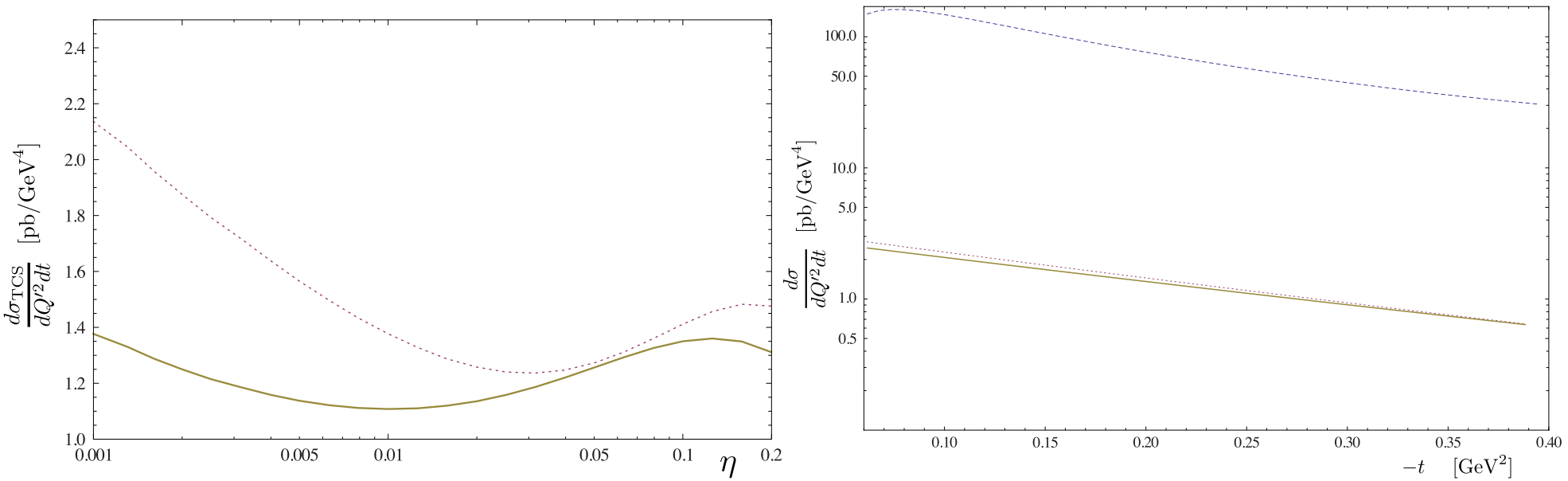


Figure: left : LO (dotted) and NLO (solid) the TCS contribution to the cross-section as a function of η for $Q^2 = \mu^2 = 4$ GeV^2, and $t = -0.2$ GeV^2 integrated over $\theta \in (\pi/4, 3\pi/4)$ and over $\phi \in (0, 2\pi)$. Right : LO (dotted) and NLO (solid) TCS and Bethe-Heitler (dashed) contributions to the cross-section as a function of t for $Q^2 = \mu^2 = 4$ GeV^2 integrated over $\theta \in (\pi/4, 3\pi/4)$ and over $\phi \in (0, 2\pi)$ for $E_\gamma = 10\,\text{GeV}$ $(\eta \approx 0.11)$.

large BH $\Rightarrow$ need for more differential observables

TCS: Observables for JLab@12GeV GK model

Azimuthal-dependent cross-section:

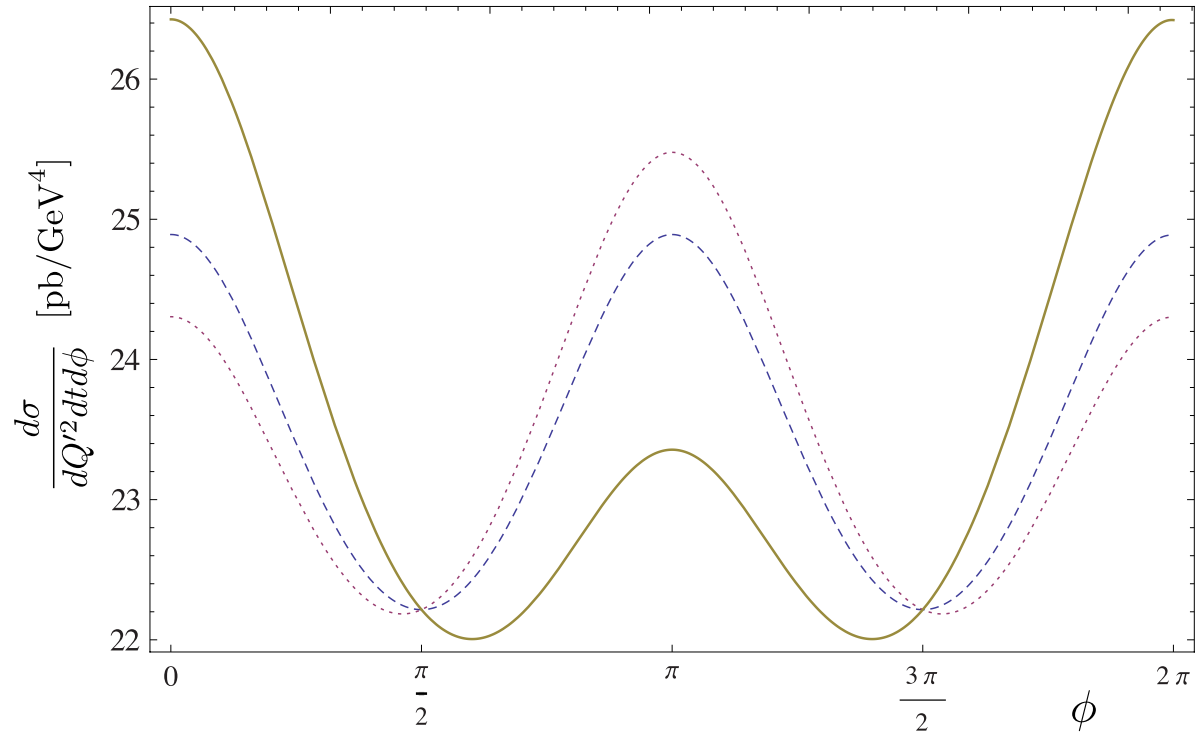


Figure: The ϕ dependence of the cross-section at $E_\gamma = 10$ GeV, $Q^2 = \mu^2 = 4$ GeV^2, and $t = -0.1$ GeV^2 integrated over $\theta \in (\pi/4, 3\pi/4)$: pure Bethe-Heitler contribution (dashed), Bethe-Heitler plus interference contribution at LO (dotted) and NLO (solid).

TCS: Observables for JLab@12GeV GK model

Observable linear in $Re\mathcal{H}$: $dS \sim d\sigma$

$$R(\eta) = \frac{2\int_0^{2\pi} d\phi \, cos\phi \, \frac{dS}{dQ^2 \, dt \, d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ^2 \, dt \, d\phi}}$$

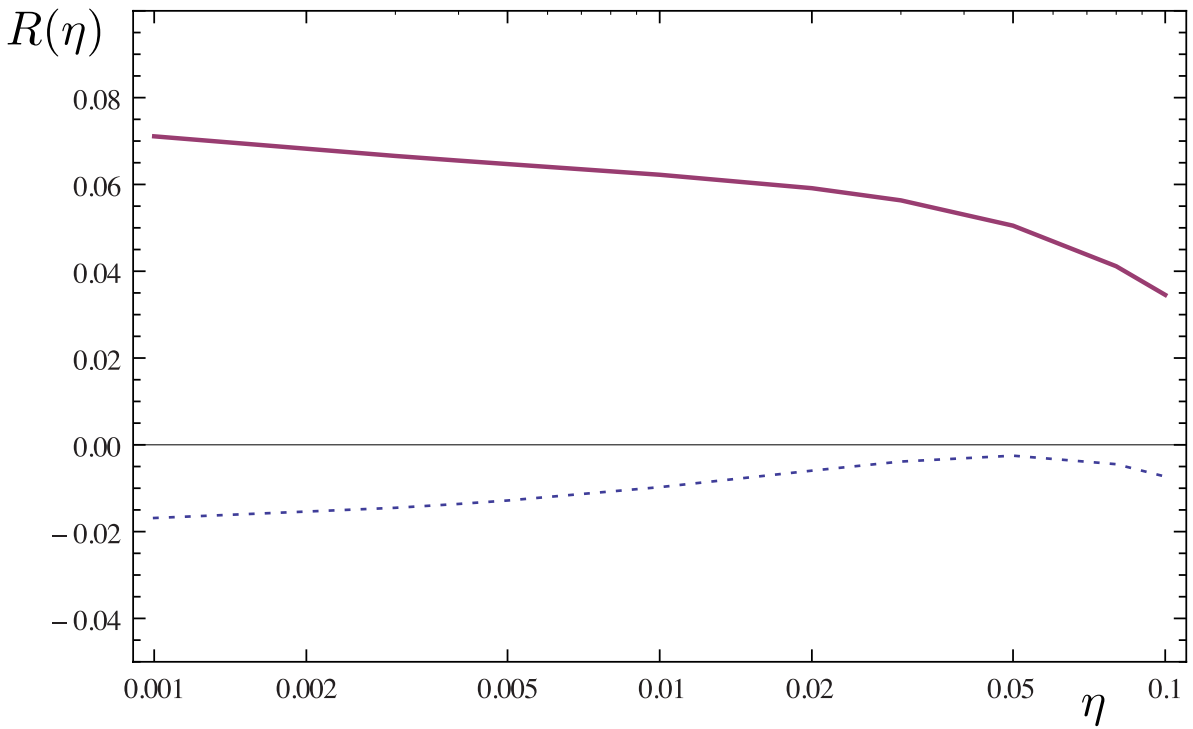


Figure: Ratio R as a function of η, for $Q^2 = \mu_F^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. The dotted line represents LO contribution and the solid line represents NLO result.

TCS: Observables for JLab@12GeV GK model

The measure of $Im\mathcal{H}$: the photon beam circular polarization asymmetry

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

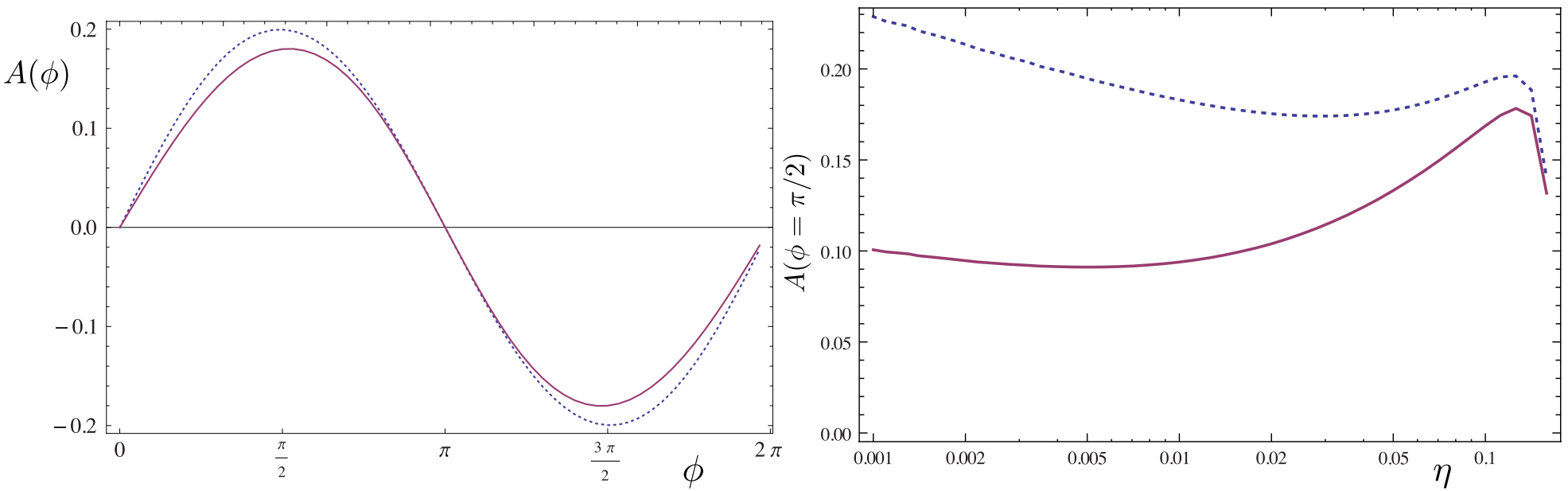
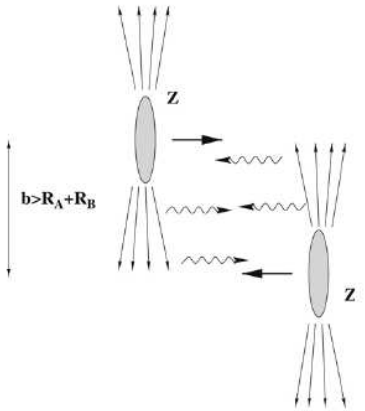


Figure: (left) Photon beam circular polarization asymmetry as a function of ϕ, for $t = -0.1$ GeV^2, $Q^2 = \mu^2 = 4$ GeV^2, integrated over $\theta \in (\pi/4, 3\pi/4)$ and for $E_\gamma = 10$ GeV^2 ($\eta \approx 0.11$). (right) The η dependence of the photon beam circular polarization asymmetry for $Q^2 = \mu^2 = 4$ GeV^2, and $t = -0.2$ GeV^2 integrated over $\theta \in (\pi/4, 3\pi/4)$. The LO result is shown as the dotted line, the full NLO result by the solid line.

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 γ'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

B. Pire, L.Sz, J. Wagner, Phys. Rev. D 2009

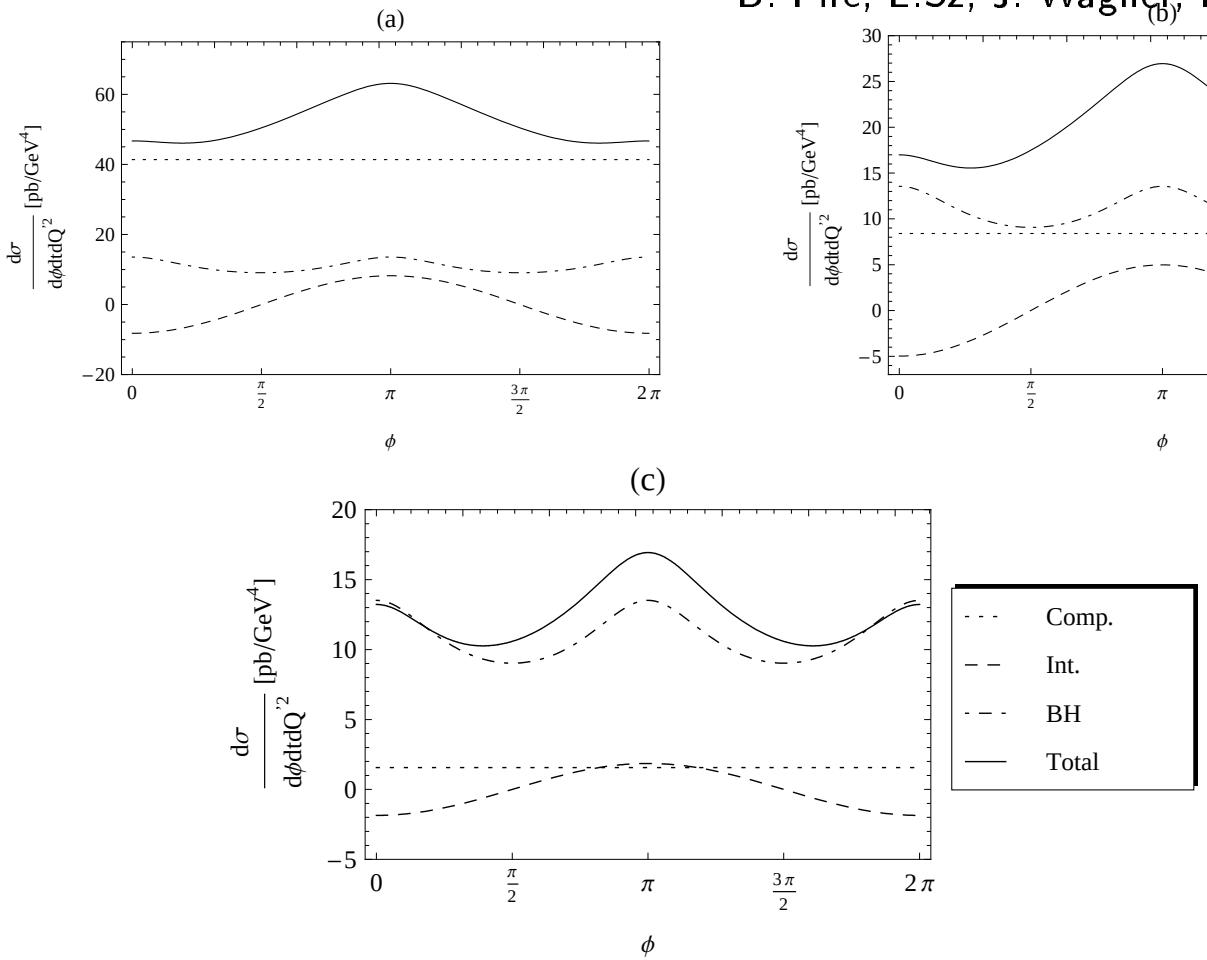


Figure: The differential cross sections (solid lines) for $t = -0.2\,\mathrm{GeV}^2$, $Q'^2 = 5\,\mathrm{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ, for $s = 10^7\,\mathrm{GeV}^2$ (a), $s = 10^5\,\mathrm{GeV}^2$(b), $s = 10^3\,\mathrm{GeV}^2$ (c) with $\mu_F^2 = 5\,\mathrm{GeV}^2$.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

Ultraperipheral collisions at RHIC

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

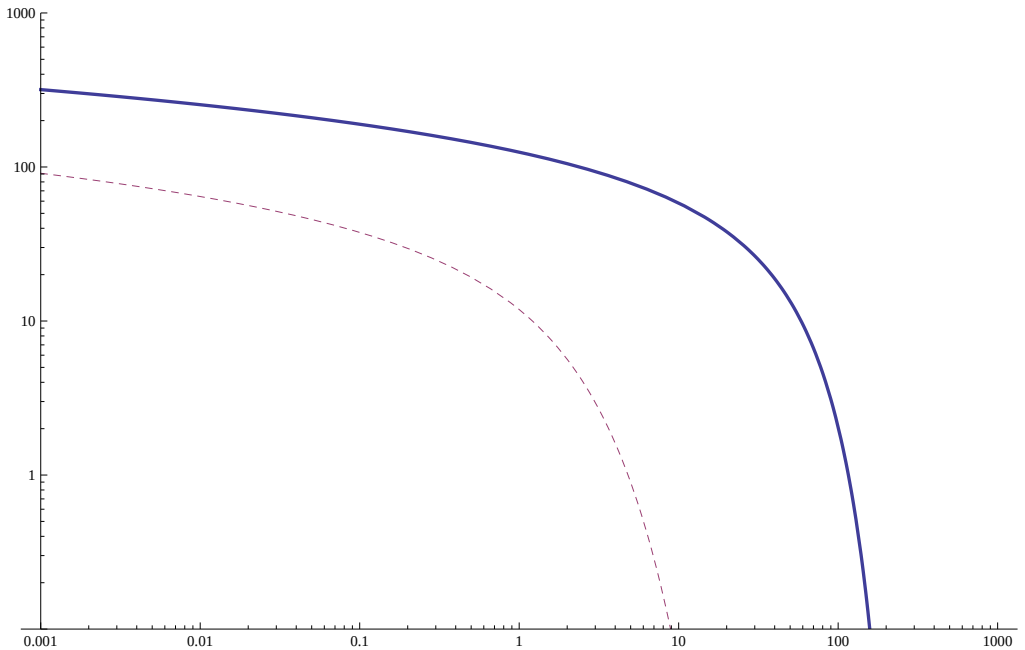


Figure: Effective luminosity of the photon flux from the Au-Au (dashed) and proton-proton (solid) collisions as a function of photon energy k(GeV).

RHIC

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

J. Wagner

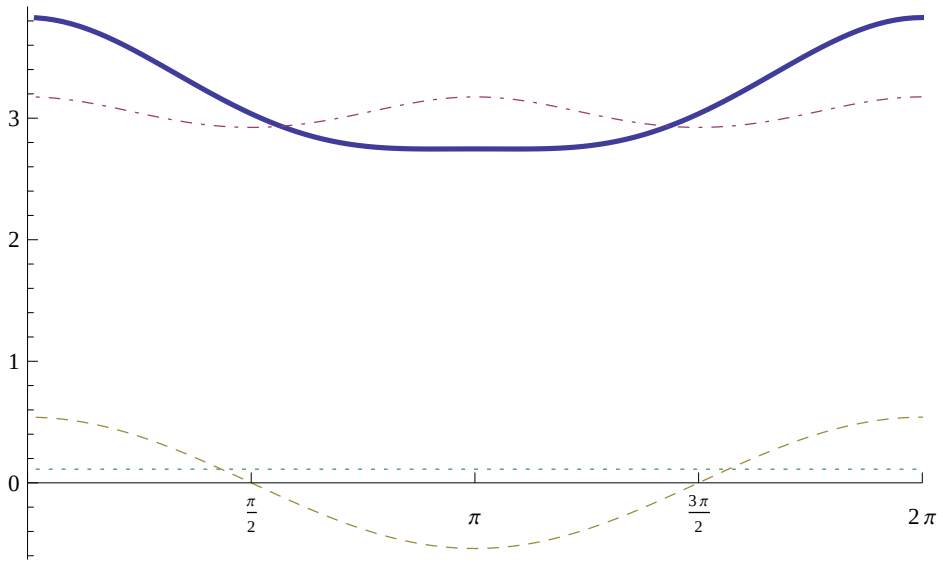


Figure: The differential cross sections (solid lines) for $t = -0.1\,\text{GeV}^2$, $Q'^2 = 5\,\text{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ. We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.

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 $\phi \in (0, 2\pi)$)

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

AFTER@LHC

Ultraperipheral scattering with A Fixed-Target ExpeRiment at the LHC

AFTER@LHC

Ultraperipheral scattering with A Fixed-Target ExpeRiment at the LHC

Motivation for AFTER@LHC:

"A Fixed-Target ExpeRiment at the LHC (AFTER@LHC) : luminosities, target polarisation and a selection of physics studies," PoS QNP (2012) 049 [arXiv:1207.3507 [hep-ex]]

"Ultra-relativistic heavy-ion physics with AFTER@LHC," arXiv:1211.1294 [nucl-ex]

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[b] INFN Sez. Torino, Via P. Giuria 1, I-10125, Torino, Italy
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[d] IPNO, Universit´e Paris-Sud, CNRS/IN2P3, F-91406, Orsay, France
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[h] Department of Physics and Astronomy, University of Aarhus, Denmark

AFTER@LHC Kinematics

J. Ph. Lansberg, L.Sz. and J. Wagner

Case A : proton beam on lead (Pb) target, $\sqrt{s} = 115\,\mathrm{GeV}$, $\epsilon = 1$

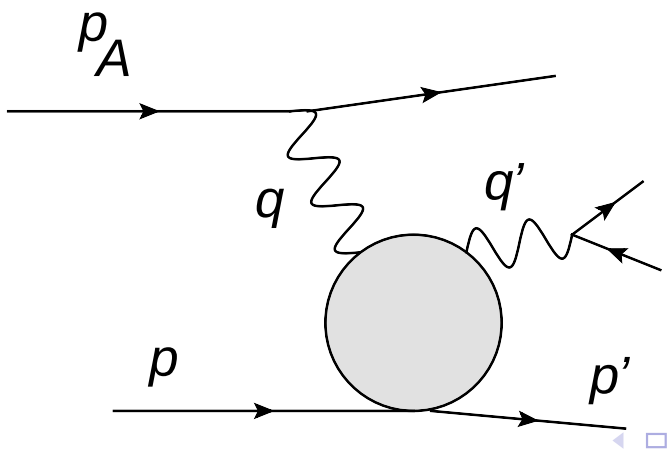
Case B : lead (Pb) beam on proton target, $\sqrt{s} = 72\,\mathrm{GeV}$, $\epsilon = -1$

$$p = \frac{\sqrt{s}}{2}(1, 0, 0, \epsilon\alpha) \qquad p_A = \frac{\sqrt{s}}{2}(1, 0, 0, -\epsilon\alpha)$$

$$q = x_\gamma \frac{\sqrt{s}}{2}(1, 0, 0, -\epsilon)$$

$$q' = (q'_0, q'_\perp, q'_z) \qquad p' = (p'_0, p'_\perp, p'_z)$$

where $\alpha = \sqrt{1 - \frac{4*M^2}{s}}$



AFTER@LHC Kinematics

Flux of γ's: Baltz et al, Phys. Rep. 458

$$\frac{dn}{dx_\gamma} = \frac{2Z^2\alpha_{EM}}{\pi x_\gamma}\left[\omega^{pA}K_0(\omega^{pA})K_1(\omega^{pA}) - \frac{{\omega^{pA}}^2}{2}\left(K_1^2(\omega^{pA}) - K_0^2(\omega^{pA})\right)\right]$$

where: $\omega^{pA} = x_\gamma M_p(r_p + R_A)$.

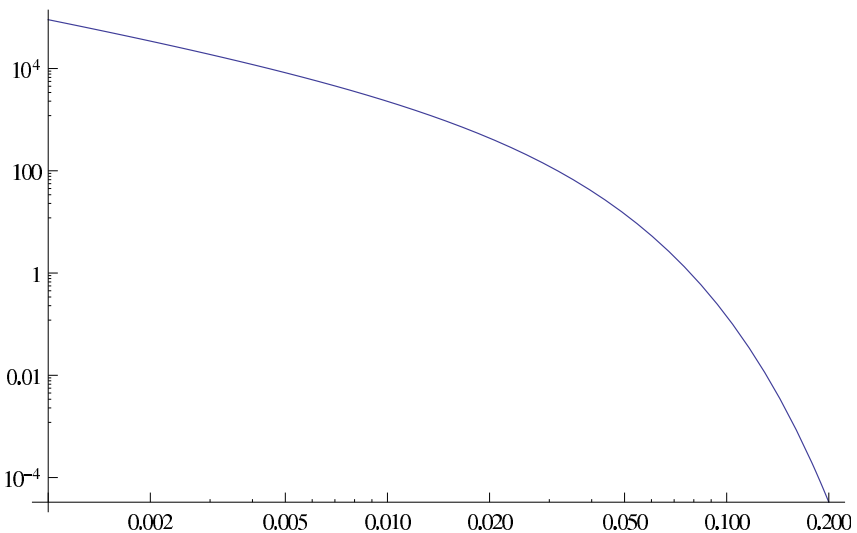


Figure: $\frac{dn}{dx_\gamma}$

AFTER@LHC Kinematics

Rapidity of the outgoing photon::

$$y = \frac{1}{2}\log\frac{q_0' + q_z'}{q_0' - q_z'} = \epsilon\frac{1}{2}\log\left[\frac{(Q^2 - t)(\alpha + 1)}{Q^2(\alpha - 1) - t(\alpha - 1 - 2x) + sx_\gamma^2(\alpha + 1)}\right]$$

Inverting we get:

$$\frac{dx_\gamma}{dy} = \frac{(-2\epsilon)(Q^2 - t)(\alpha + 1)e^{-2\epsilon y}}{\sqrt{4t^2 - 4s(Q^2 - t)(\alpha + 1)\left((\alpha - 1) - (\alpha + 1)e^{-2\epsilon y}\right)}}$$

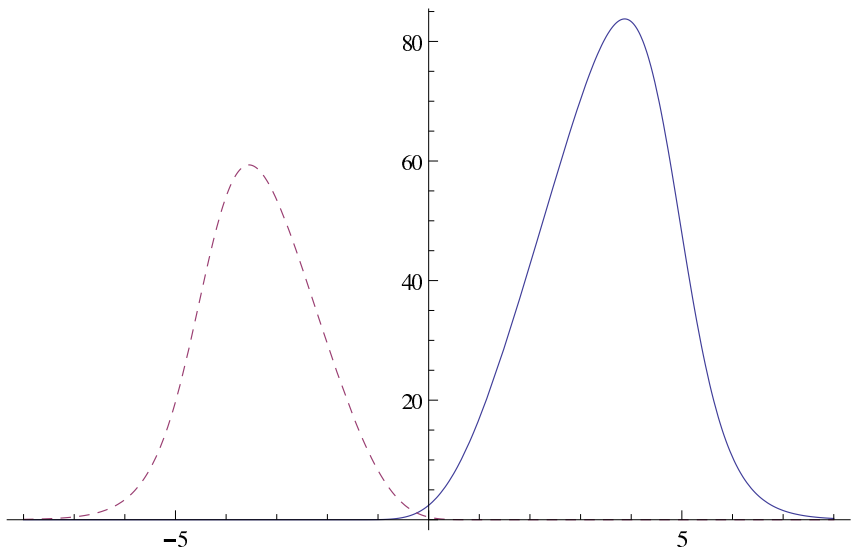


Figure: $\left|\frac{dn}{dy}\right|$,Case A(solid) and case B(dashed).

We consider Bethe-Heitler, TCS, and Interference term.

They are functions of $s_{p\gamma}$, t, Q, ϕ, θ.

We integrate over $\theta \in (\pi/4, 3\pi/4)$, in the region where the TCS/BH is the best seen.

Case A (p beam on Pb target):

LO CF NLO CF

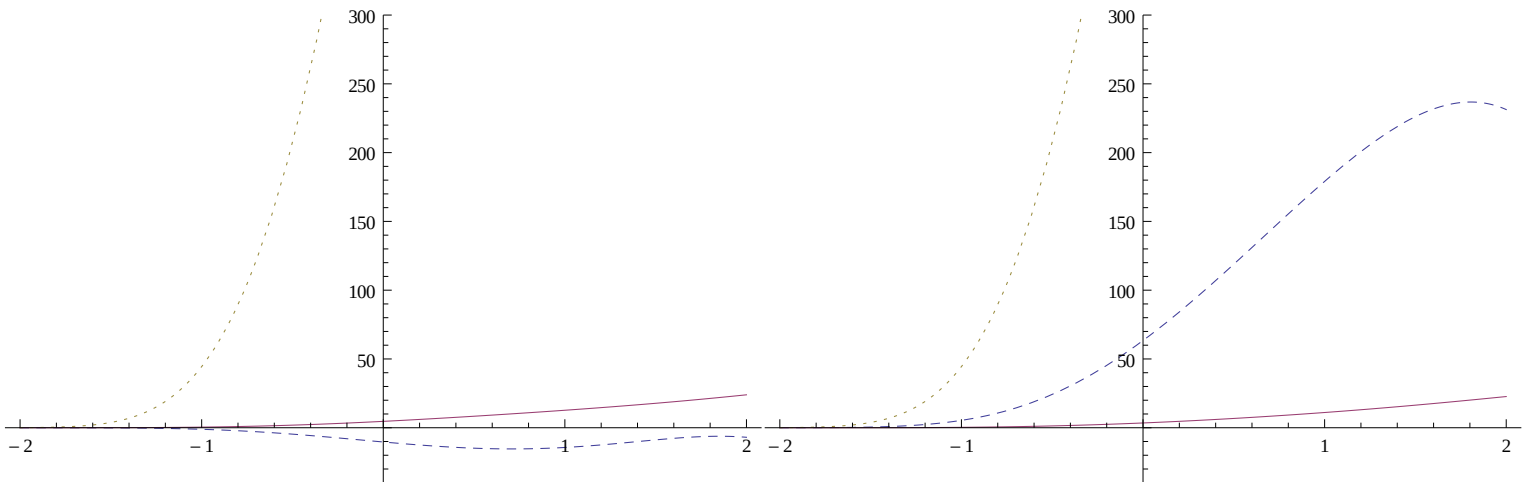


Figure: $\frac{d\sigma}{dQ^2 dt dy d\phi}$ in $pb/\,\mathrm{GeV}^4$ for BH(dotted), TCS(solid), Interference(dashed) as a function of y (in CMS) for $Q^2 = 4\,\mathrm{GeV}^2$, $t = -0.1\,\mathrm{GeV}^2$, $\phi = 0$.

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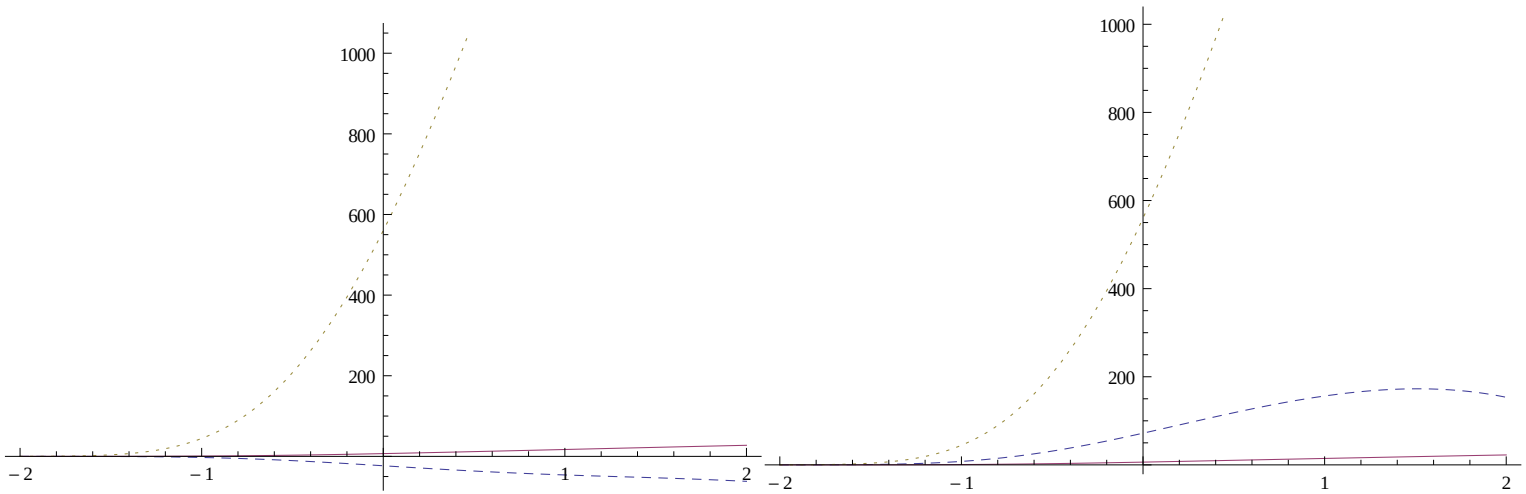

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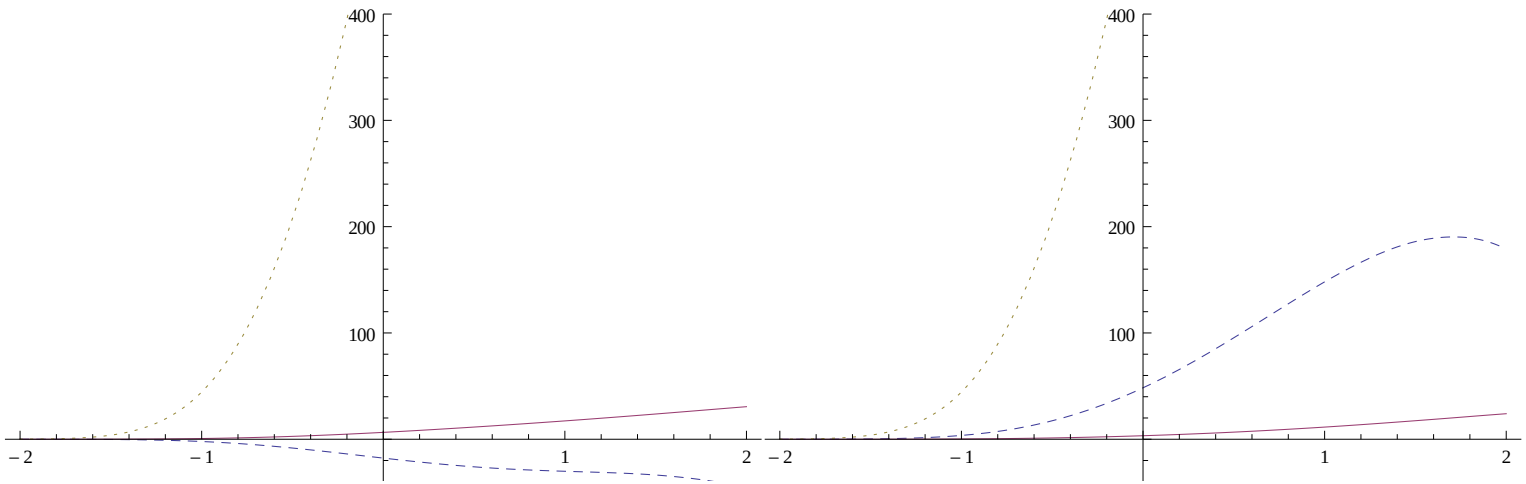

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Case B (Pb beam on p target):

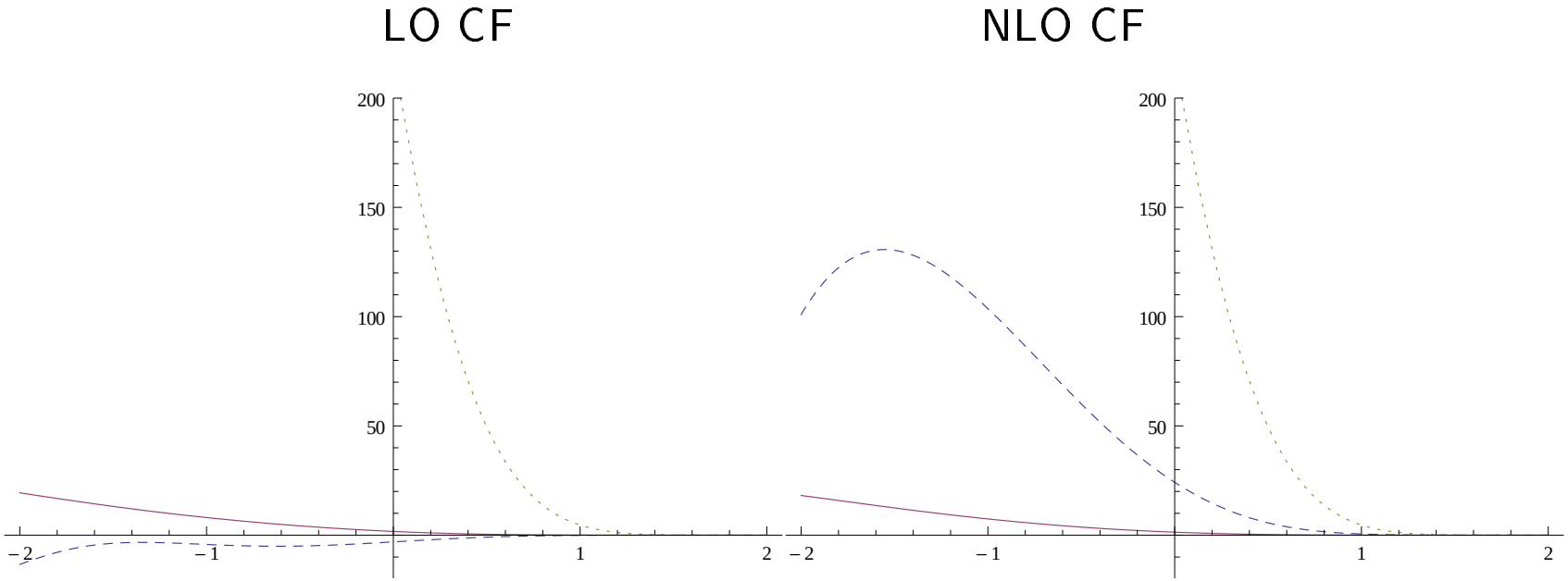

Figure: $\frac{d\sigma}{dQ^2 dt dy d\phi}$ in $pb/\,\mathrm{GeV}^4$ for BH(dotted), TCS(solid), Interference(dashed) as a function of y (in CMS) for $Q^2 = 4\,\mathrm{GeV}^2$, $t = -0.1\,\mathrm{GeV}^2$, $\phi = 0$.

Case B (Pb beam on p target):

LO CF NLO CF

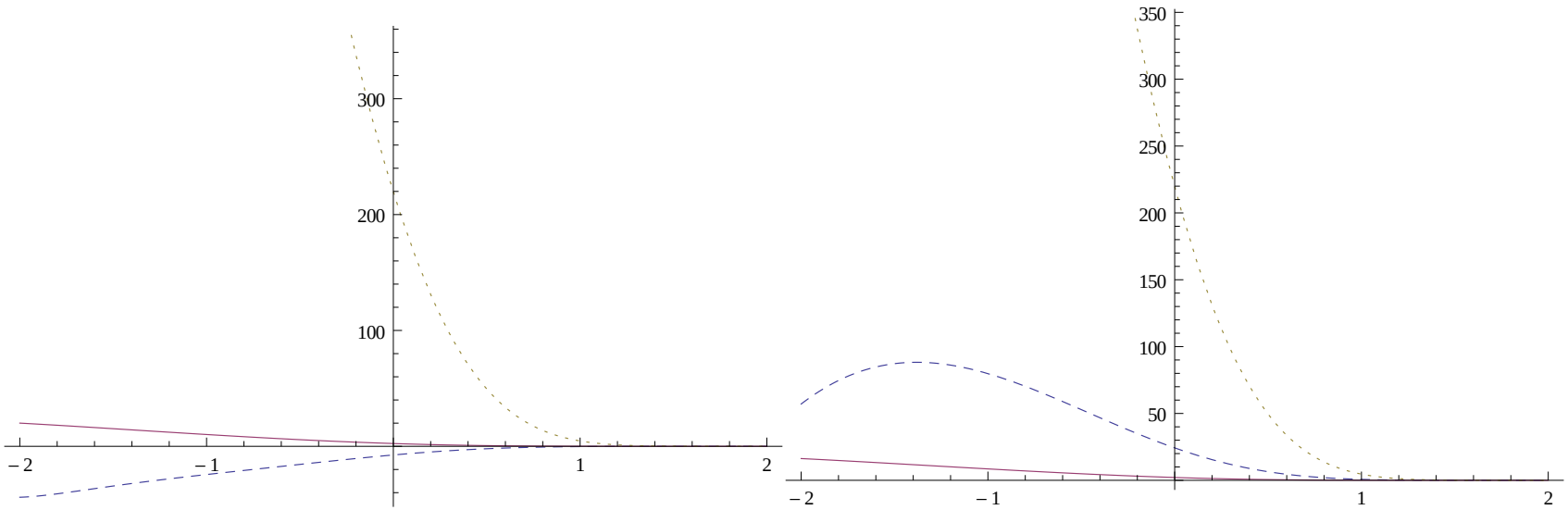

Figure: Case 2 (Pb beam on p target): $\frac{d\sigma}{dQ^2 dt dy d\phi}$ in $pb/\,\mathrm{GeV}^4$ for BH(dotted), TCS(solid), Interference(dashed) as a function of y (in CMS) for $Q^2 = 4\,\mathrm{GeV}^2$, $t = -0.1\,\mathrm{GeV}^2$, $\phi = 0$.

Case B (Pb beam on p target):

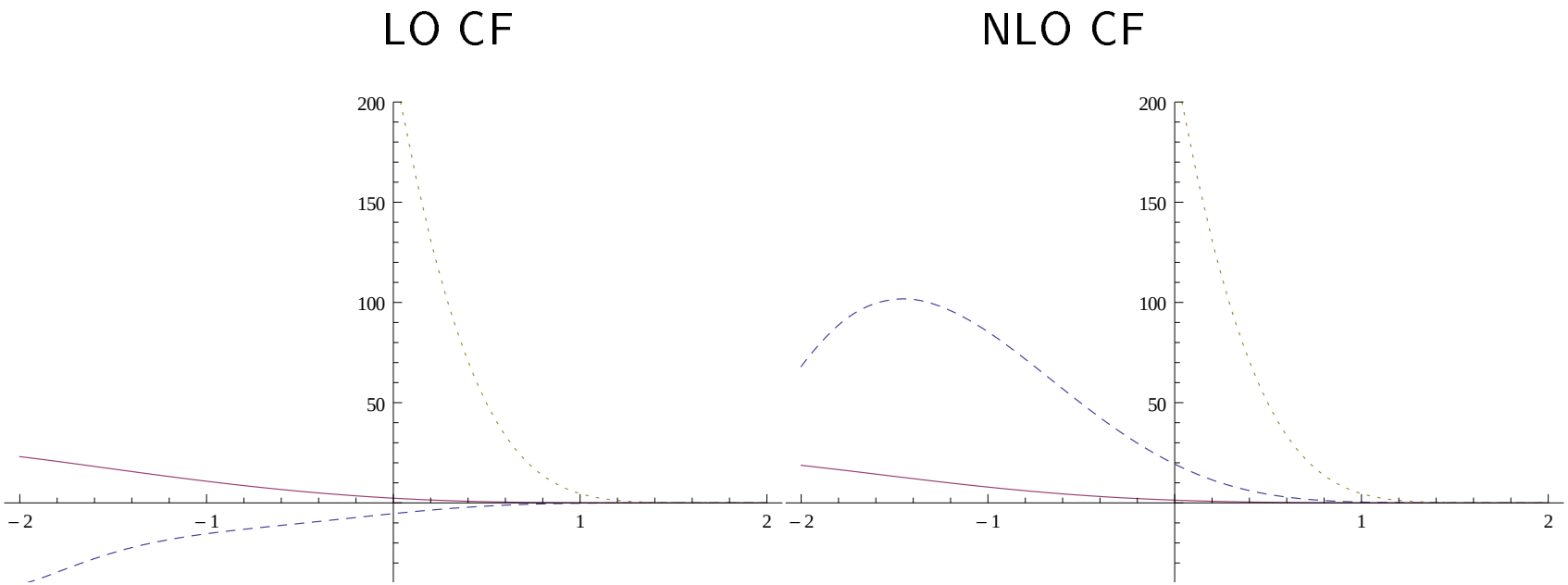

Figure: Case 2 (Pb beam on p target): $\frac{d\sigma}{dQ^2 dt dy d\phi}$ in $pb/\,\mathrm{GeV}^4$ for BH(dotted), TCS(solid), Interference(dashed) as a function of y (in CMS) for $Q^2 = 4\,\mathrm{GeV}^2$, $t = -0.1\,\mathrm{GeV}^2$, $\phi = 0$.

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 is needed - factorization scheme? resummation ?
- Compton scattering in ultraperipheral collisions at hadron colliders opens a new way to measure generalized parton distributions
- TCS is an experimentally challenging study at JLab, COMPASS, RHIC and LHC, in many cases due to limitations of original detectors

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- so we look forward for these studies at **AFTER@LHC**