Exclusive production of di-leptons

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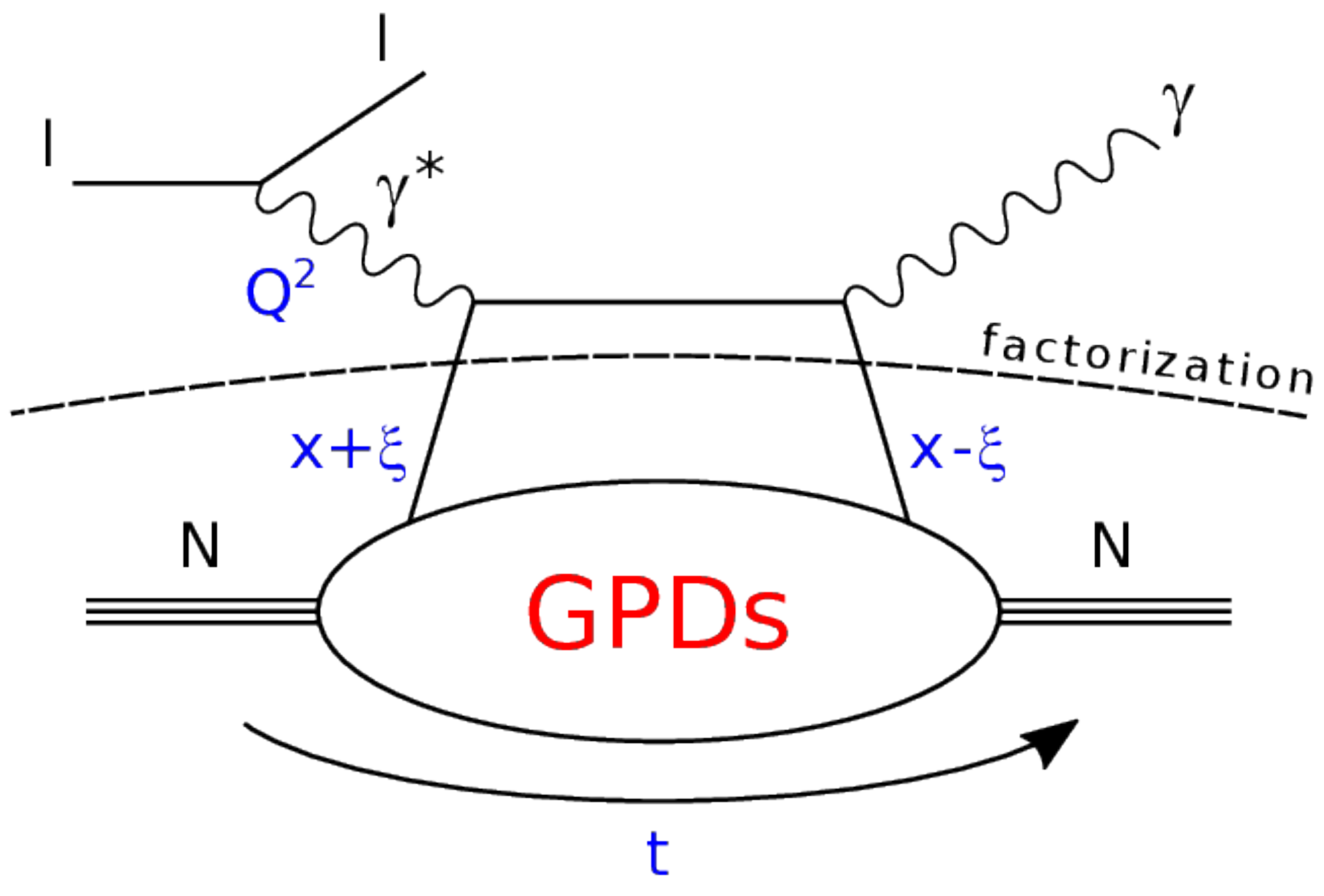
EIC UG 2nd IP meeting, Stony Brook, US, December 7th, 2022 (online participation)

Outline

- Introduction
- TCS, DDVCS and diphoton production
- Tools
- Summary

see Brandon's talk for proper definition of GPDs

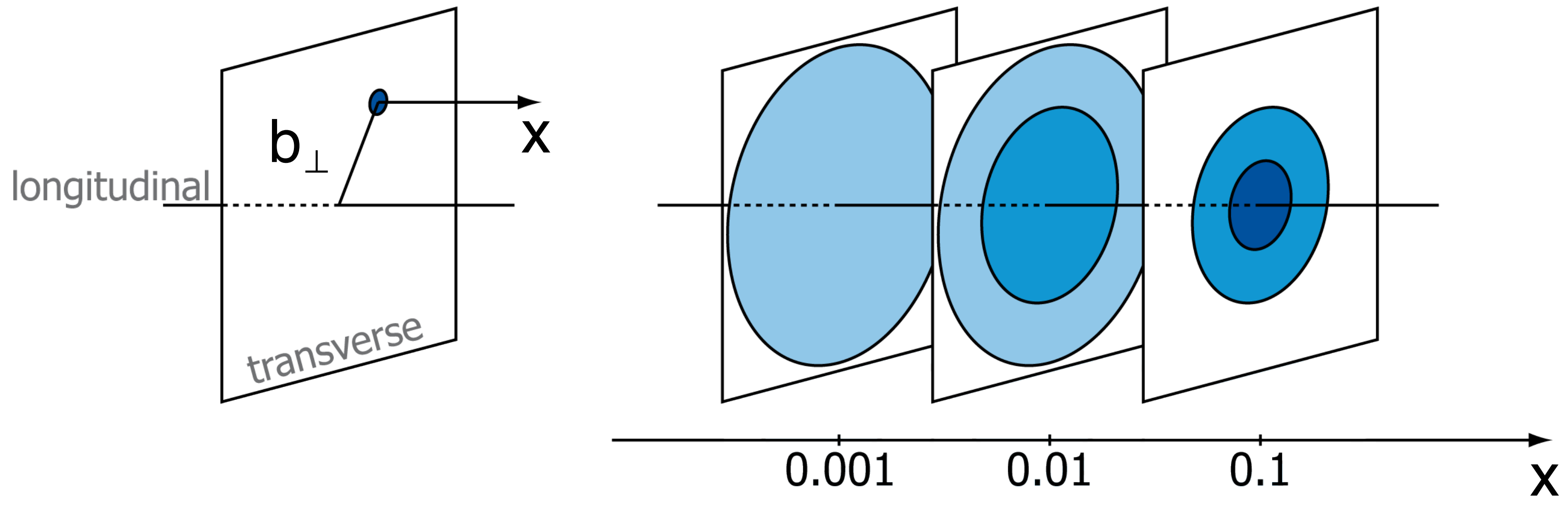
Deeply Virtual Compton Scattering (DVCS)



factorisation for $|t|/Q^2 \ll 1$

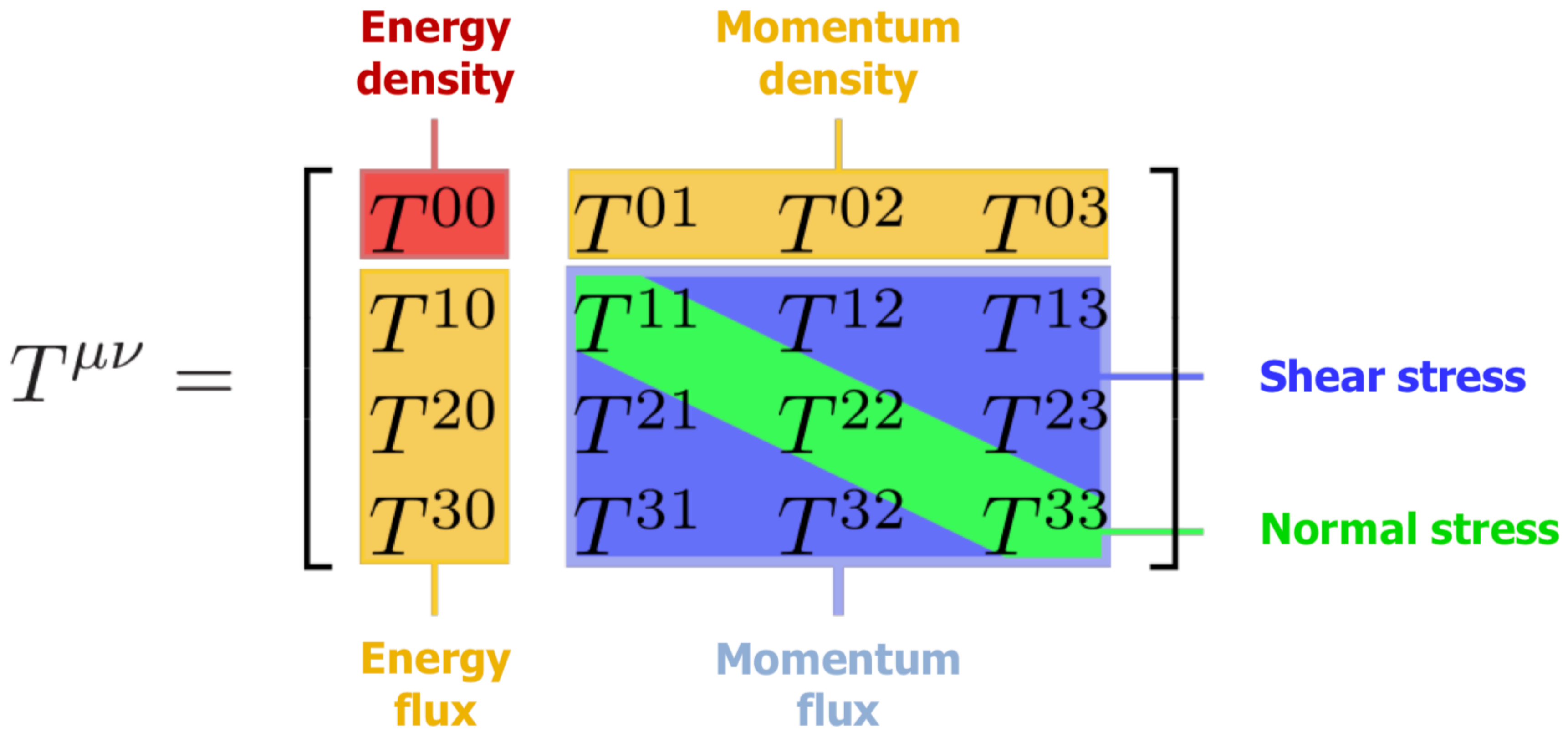
Chiral-even GPDs:
(helicity of parton conserved)

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	



Nucleon tomography:

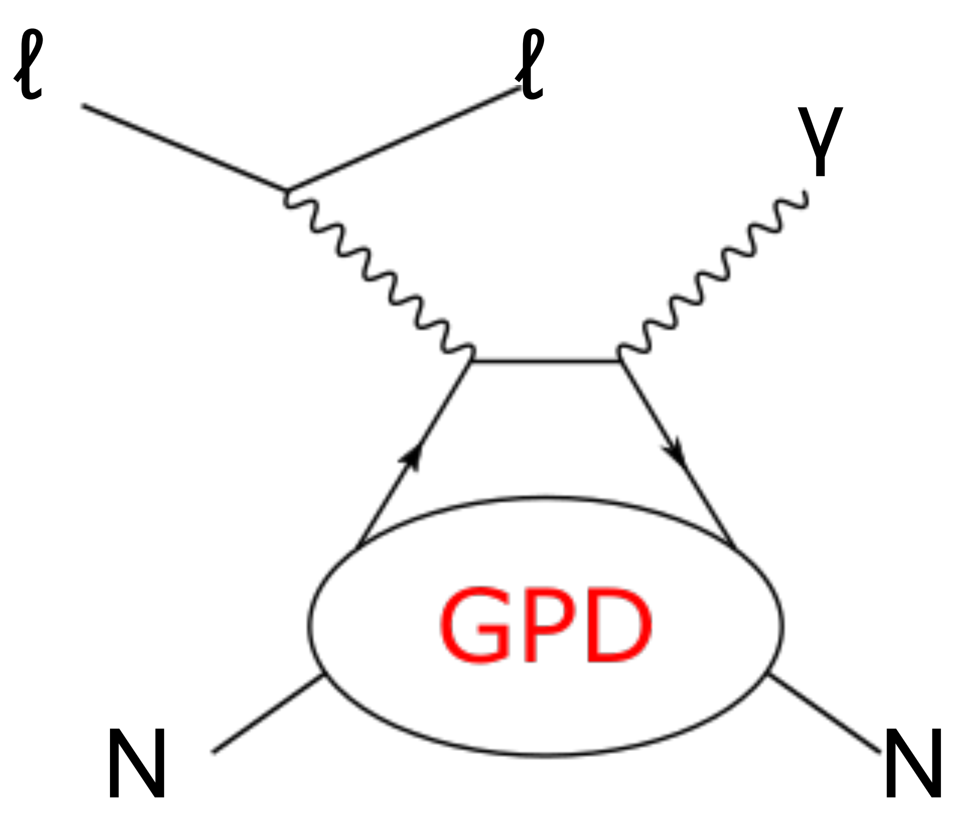
$$q(x, \mathbf{b}_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}}{4\pi^2} e^{-i\mathbf{b}_\perp \cdot \boldsymbol{\Delta}} H^q(x, 0, t = -\boldsymbol{\Delta}^2)$$



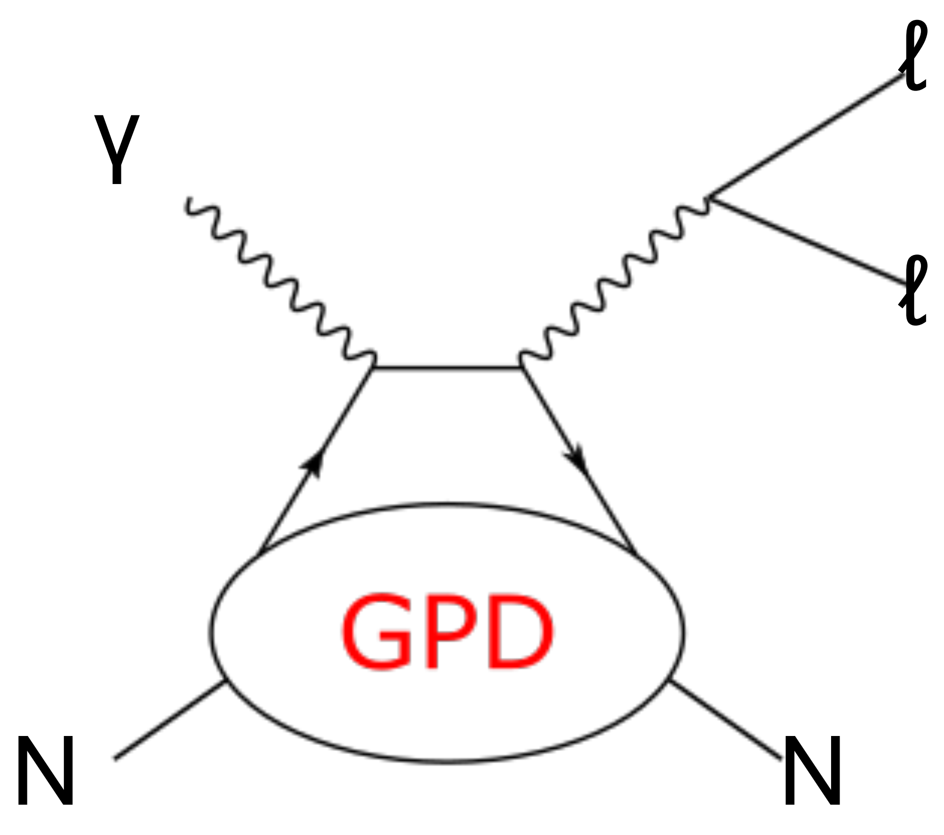
Energy momentum tensor in terms of form factors (OAM and mechanical forces):

$$\langle p', s' | \widehat{T}^{\mu\nu} | p, s \rangle = \bar{u}(p', s') \Bigg[\frac{P^\mu P^\nu}{M} A(t) + \frac{\Delta^\mu \Delta^\nu - \eta^{\mu\nu}\Delta^2}{M} C(t) + M\eta^{\mu\nu} \bar{C}(t) + \frac{P^\mu i\sigma^{\nu\lambda}\Delta_\lambda}{4M} [A(t) + B(t) + D(t)] + \frac{P^\nu i\sigma^{\mu\lambda}\Delta_\lambda}{4M} [A(t) + B(t) - D(t)] \Bigg] u(p, s)$$

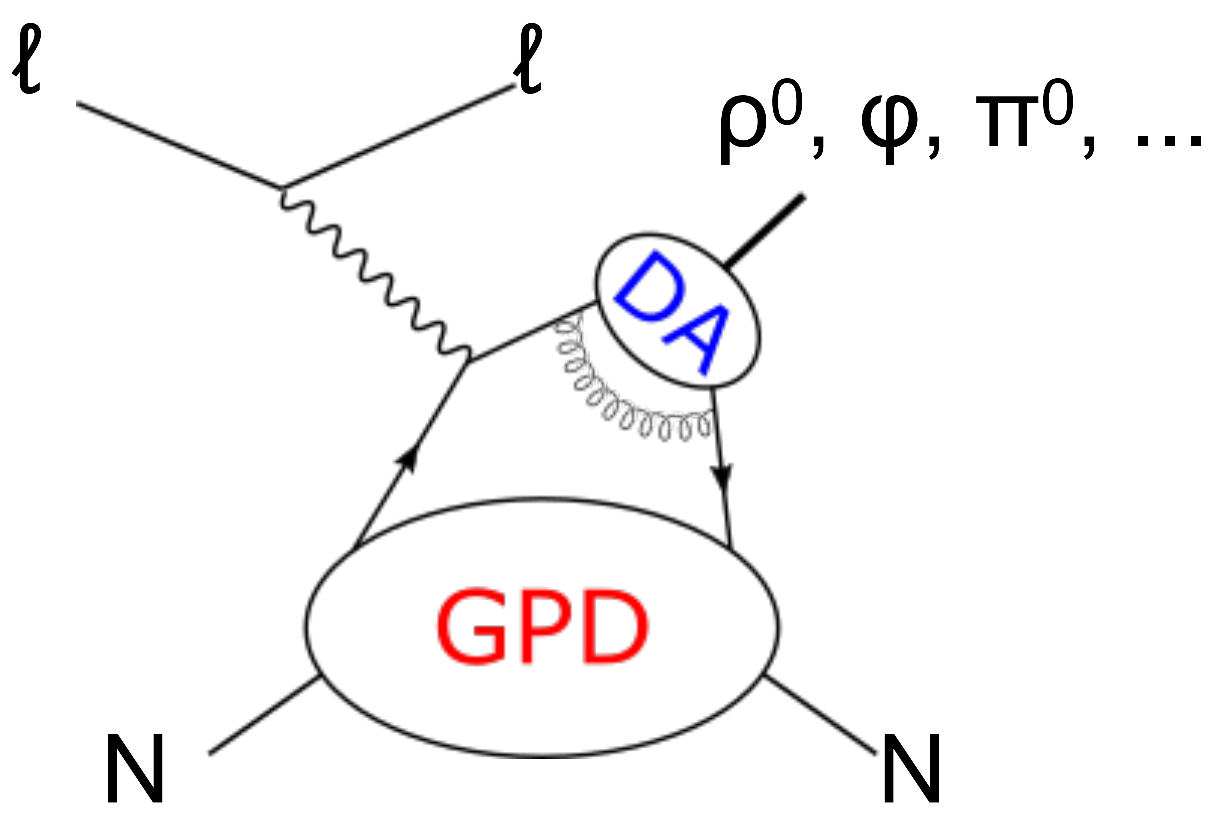
GPDs accessible in various production channels and observables
→ experimental filters



DVCS
Deeply Virtual Compton Scattering



TCS
Timelike Compton Scattering



HEMP
Hard Exclusive Meson Production

more production channels sensitive to GPDs exist!

for more details see:
Berger, Diehl, Pire
Eur. Phys. J. C23 675, 2002

Cross-section: $d\sigma \propto |\mathcal{T}_{\mathrm{BH}} + \mathcal{T}(M_{\lambda'\mu',\lambda\mu})|^2$

Helicity amplitudes: ${}^{X}M_{\lambda'\mu',\lambda\mu}$

(S)pace-like or (T)ime-like

Helicities (p'ɣ',pɣ), where ɣp→ɣ'p'

Compton Form Factors: $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$

DVCS:

$$
{}^{S}M_{++++} = \sqrt{1-\xi^2}\left[{}^{S}\mathcal{H} + {}^{S}\widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}({}^{S}\mathcal{E} + {}^{S}\widetilde{\mathcal{E}})\right]
$$
$$
{}^{S}M_{-+-+} = \sqrt{1-\xi^2}\left[{}^{S}\mathcal{H} - {}^{S}\widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}({}^{S}\mathcal{E} - {}^{S}\widetilde{\mathcal{E}})\right]
$$
$$
{}^{S}M_{++-+} = \frac{\sqrt{t_0-t}}{2M}\left[{}^{S}\mathcal{E} - \xi\,{}^{S}\widetilde{\mathcal{E}}\right]
$$
$$
{}^{S}M_{-+++} = -\frac{\sqrt{t_0-t}}{2M}\left[{}^{S}\mathcal{E} + \xi\,{}^{S}\widetilde{\mathcal{E}}\right]
$$

TCS:

$$
{}^{T}M_{+-+-} = \sqrt{1-\xi^2}\left[{}^{T}\mathcal{H} + {}^{T}\widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}({}^{T}\mathcal{E} + {}^{T}\widetilde{\mathcal{E}})\right]
$$
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{}^{T}M_{----} = \sqrt{1-\xi^2}\left[{}^{T}\mathcal{H} - {}^{T}\widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}({}^{T}\mathcal{E} - {}^{T}\widetilde{\mathcal{E}})\right]
$$
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$$

for more details see:
Mueller, Pire, Szymanowski, Wagner
Phys. Rev. D86, 031502 (2012)

Compton Form Factors in terms of GPDs:

$$\mathscr{F}(\xi, t, \mathscr{Q}^2) = \int_{-1}^{1} dx \sum_{i=u,d,\ldots,g} T^i(x, \xi, \mathscr{Q}^2) F^i(x, \xi, t)$$

Coefficient functions:

DVCS:

$${}^{S}T^{i} \overset{\mathrm{LO}}{=} {}^{S}C_0^{i}$$

$${}^{S}T^{i} \overset{\mathrm{NLO}}{=} {}^{S}C_0^{i} + \frac{\alpha_s(\mu_R^2)}{2\pi}\left[{}^{S}C_1^{i} + {}^{S}C_{\mathrm{coll}}^{i} \ln\frac{\mathscr{Q}^2}{\mu_F^2}\right]$$

TCS:

$${}^{T}T^{i} \overset{\mathrm{LO}}{=} \pm {}^{S}T^{i*}$$

$${}^{T}T^{i} \overset{\mathrm{NLO}}{=} \pm {}^{S}T^{i*} \mp i\pi \frac{\alpha_s(\mu_R^2)}{2\pi} {}^{S}C_{\mathrm{coll}}^{i*}$$

Relation between DVCS and TCS CFFs:

$${}^{T}\mathscr{H} \overset{\mathrm{LO}}{=} {}^{S}\mathscr{H}^{*}$$

$${}^{T}\widetilde{\mathscr{H}} \overset{\mathrm{LO}}{=} -{}^{S}\widetilde{\mathscr{H}}^{*}$$

$${}^{T}\mathscr{H} \overset{\mathrm{NLO}}{=} {}^{S}\mathscr{H}^{*} - i\pi\, \mathscr{Q}^2 \frac{\partial}{\partial \mathscr{Q}^2} {}^{S}\mathscr{H}^{*}$$

$${}^{T}\widetilde{\mathscr{H}} \overset{\mathrm{NLO}}{=} -{}^{S}\widetilde{\mathscr{H}}^{*} + i\pi\, \mathscr{Q}^2 \frac{\partial}{\partial \mathscr{Q}^2} {}^{S}\widetilde{\mathscr{H}}^{*}.$$

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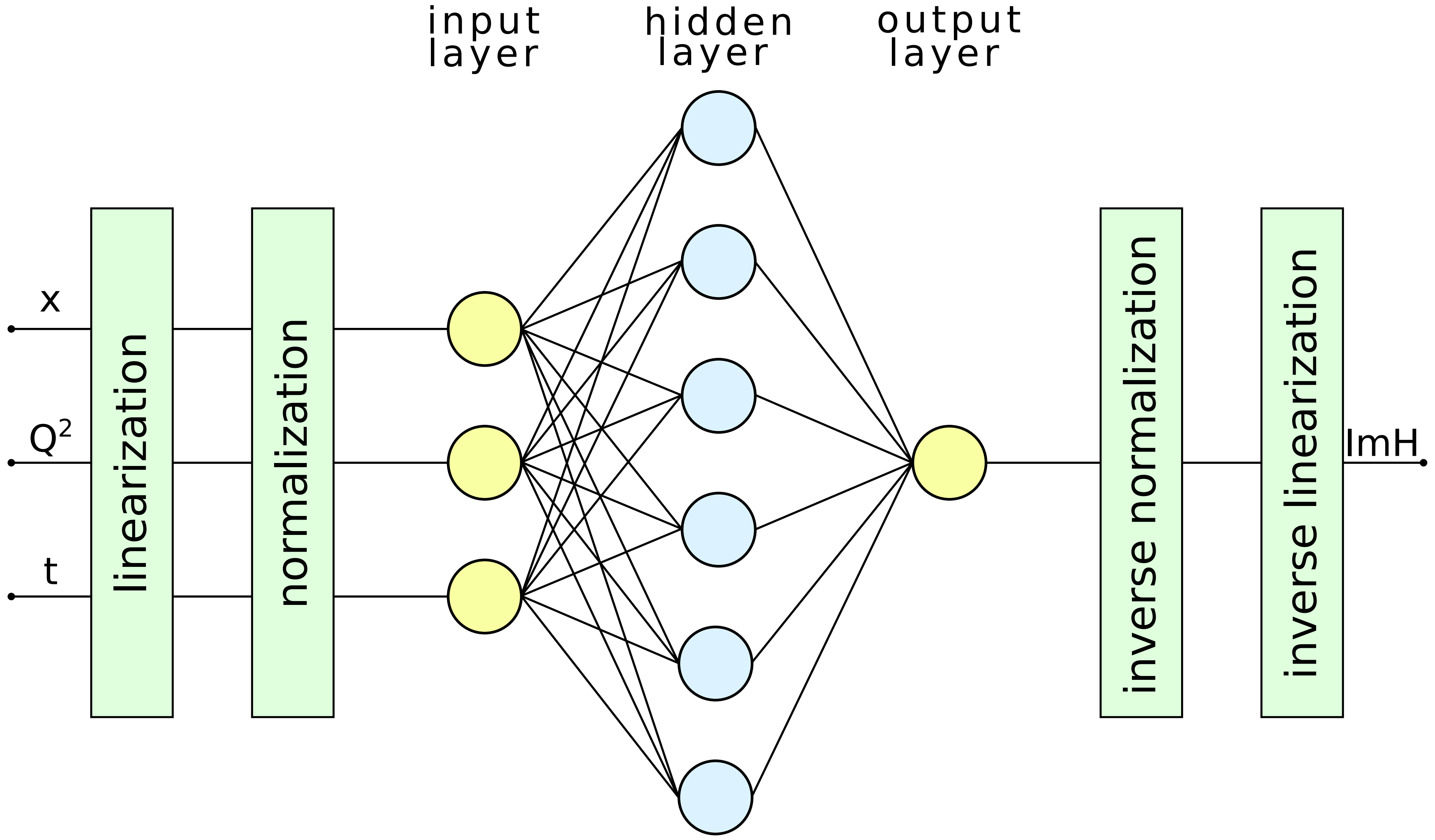
$${}^{T}\widetilde{\mathscr{H}} \stackrel{\mathrm{NLO}}{=} -{}^{S}\widetilde{\mathscr{H}}^{*} + i\pi\,\mathcal{Q}^2 \frac{\partial}{\partial \mathcal{Q}^2}\, {}^{S}\widetilde{\mathscr{H}}^{*}\,.$$

Combined study of DVCS and TCS:

- source of GPD information
- useful to prove universality of GPDs
- impact of NLO corrections
- constrain Q2-dep. of CFFs

Non-parametric Ansatz of CFFs

H. Moutarde, PS, J. Wagner,
Eur. Phys. J. C 79 (2019) 7, 614



Features of analysis:

- Independent artificial neural network for each CFF and Re/Im parts
- Functions of x_B, Q^2 and t
- Network size determined using benchmark sample
- No power-behaviour pre-factors
- Trained with genetic algorithm
- Regularisation method based on early stopping criterion
- Replica method for propagation of experimental uncertainties

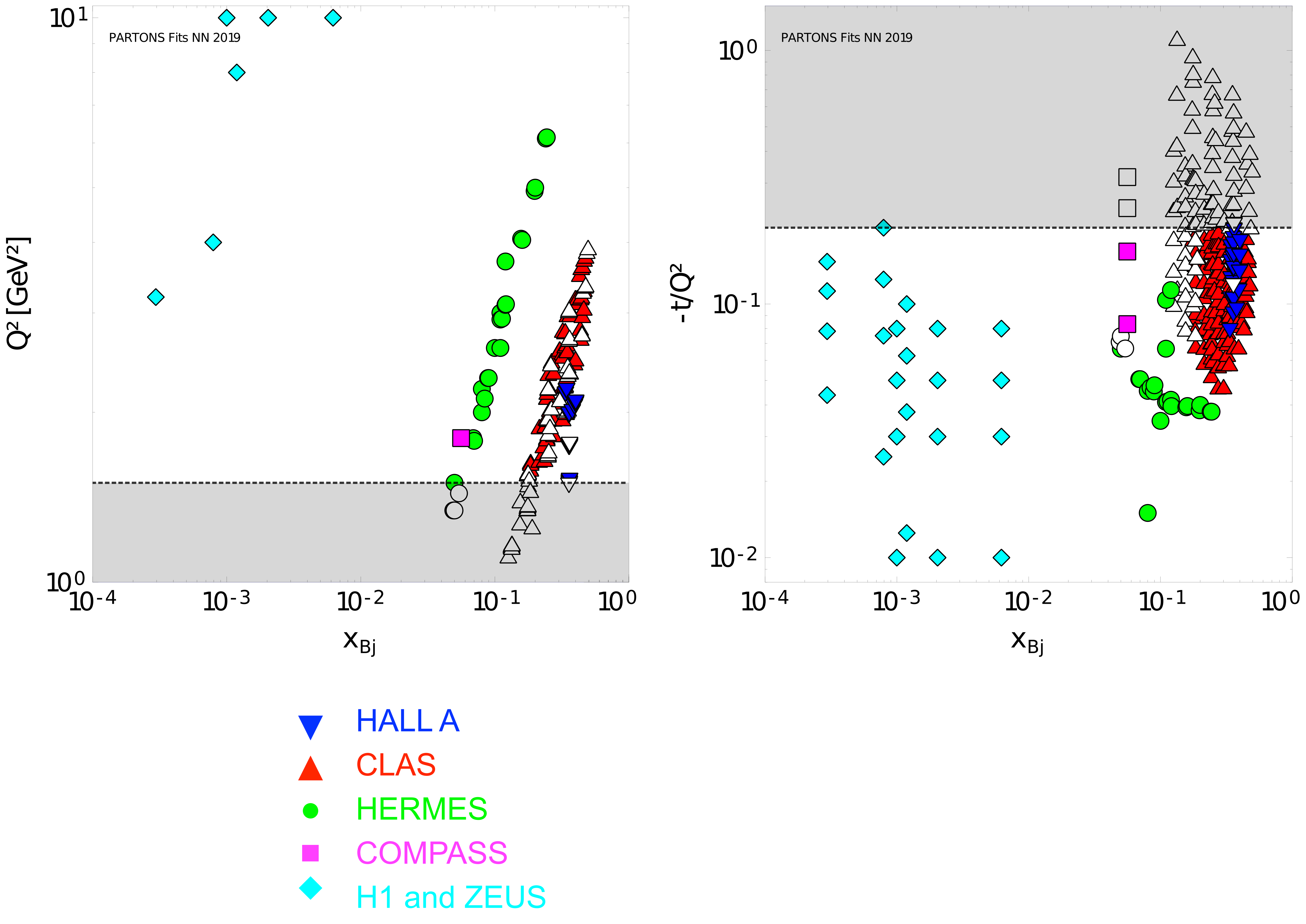
Non-parametric Ansatz of CFFs

H. Moutarde, PS, J. Wagner,
Eur. Phys. J. C78 (2018) 11, 890

H. Moutarde, PS, J. Wagner,
Eur. Phys. J. C 79 (2019) 7, 614

Extraction of DVCS CFFs from world proton data:

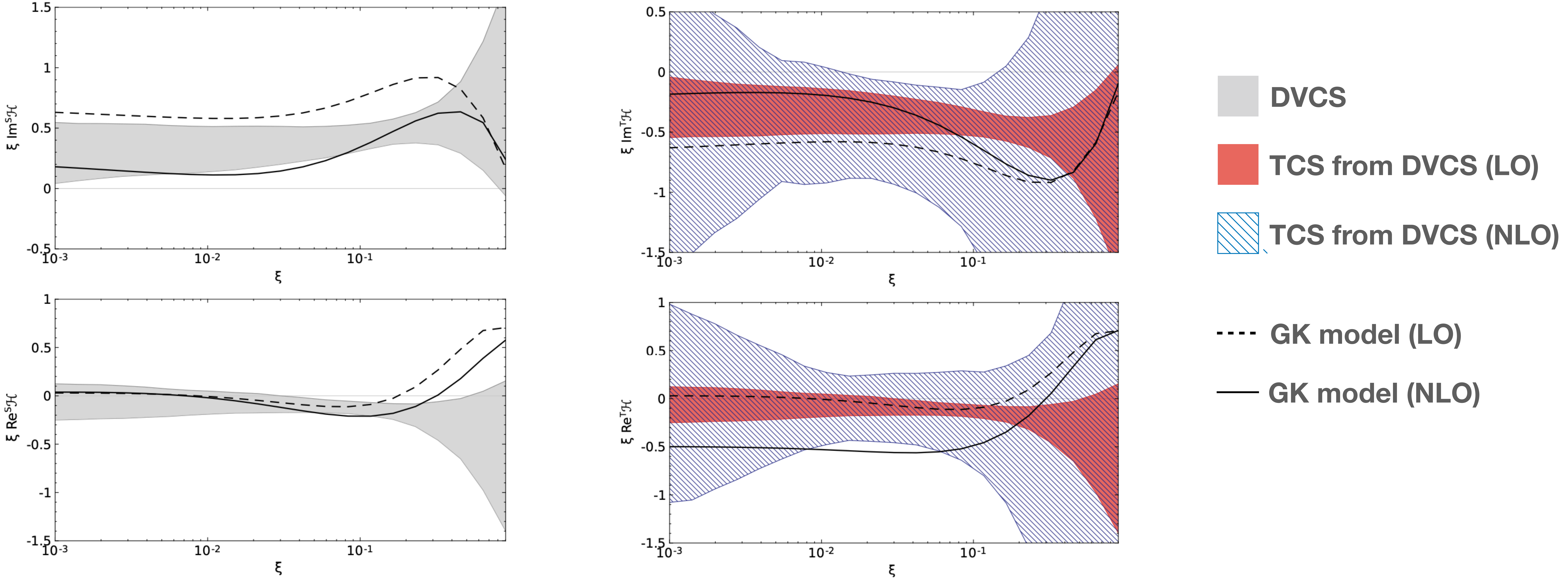
No.	Collab.	Year	Observable		Kinematic dependence	No. of points used / all
1	HERMES	2001	A^{+}_{LU}		ϕ	10 / 10
2		2006	$A^{\cos i\phi}_{C}$	$i = 1$	t	4 / 4
3		2008	$A^{\cos i\phi}_{C}$	$i = 0, 1$	x_{Bj}	18 / 24
			$A^{\sin(\phi-\phi_S)\cos i\phi}_{UT,\mathrm{DVCS}}$	$i = 0$		
			$A^{\sin(\phi-\phi_S)\cos i\phi}_{UT,\mathrm{I}}$	$i = 0, 1$		
			$A^{\cos(\phi-\phi_S)\sin i\phi}_{UT,\mathrm{I}}$	$i = 1$		
4		2009	$A^{\sin i\phi}_{LU,\mathrm{I}}$	$i = 1, 2$	x_{Bj}	35 / 42
			$A^{\sin i\phi}_{LU,\mathrm{DVCS}}$	$i = 1$		
			$A^{\cos i\phi}_{C}$	$i = 0, 1, 2, 3$		
5		2010	$A^{+,\sin i\phi}_{UL}$	$i = 1, 2, 3$	x_{Bj}	18 / 24
			$A^{+,\cos i\phi}_{LL}$	$i = 0, 1, 2$		
6		2011	$A^{\cos(\phi-\phi_S)\cos i\phi}_{LT,\mathrm{DVCS}}$	$i = 0, 1$	x_{Bj}	24 / 32
			$A^{\sin(\phi-\phi_S)\sin i\phi}_{LT,\mathrm{DVCS}}$	$i = 1$		
			$A^{\cos(\phi-\phi_S)\cos i\phi}_{LT,\mathrm{I}}$	$i = 0, 1, 2$		
			$A^{\sin(\phi-\phi_S)\sin i\phi}_{LT,\mathrm{I}}$	$i = 1, 2$		
7		2012	$A^{\sin i\phi}_{LU,\mathrm{I}}$	$i = 1, 2$	x_{Bj}	35 / 42
			$A^{\sin i\phi}_{LU,\mathrm{DVCS}}$	$i = 1$		
			$A^{\cos i\phi}_{C}$	$i = 0, 1, 2, 3$		
8	CLAS	2001	$A^{-,\sin i\phi}_{LU}$	$i = 1, 2$	—	0 / 2
9		2006	$A^{-,\sin i\phi}_{UL}$	$i = 1, 2$	—	2 / 2
10		2008	A^{-}_{LU}		ϕ	283 / 737
11		2009	A^{-}_{LU}		ϕ	22 / 33
12		2015	A^{-}_{LU}, A^{-}_{UL}, A^{-}_{LL}		ϕ	311 / 497
13		2015	$d^4\sigma^{-}_{UU}$		ϕ	1333 / 1933
14	Hall A	2015	$\Delta d^4\sigma^{-}_{LU}$		ϕ	228 / 228
15		2017	$\Delta d^4\sigma^{-}_{LU}$		ϕ	276 / 358
16	COMPASS	2018	$d^3\sigma^{\pm}_{UU}$		t	2 / 4
17	ZEUS	2009	$d^3\sigma^{+}_{UU}$		t	4 / 4
18	H1	2005	$d^3\sigma^{+}_{UU}$		t	7 / 8
19		2009	$d^3\sigma^{\pm}_{UU}$		t	12 / 12
					SUM:	2624 / 3996



Grocholski, Moutarde, Pire, PS, Wagner
Eur. Phys. J. C 80 (2020) 2, 171

TCS amplitudes and observables from DVCS amplitudes

DVCS: **TCS:**

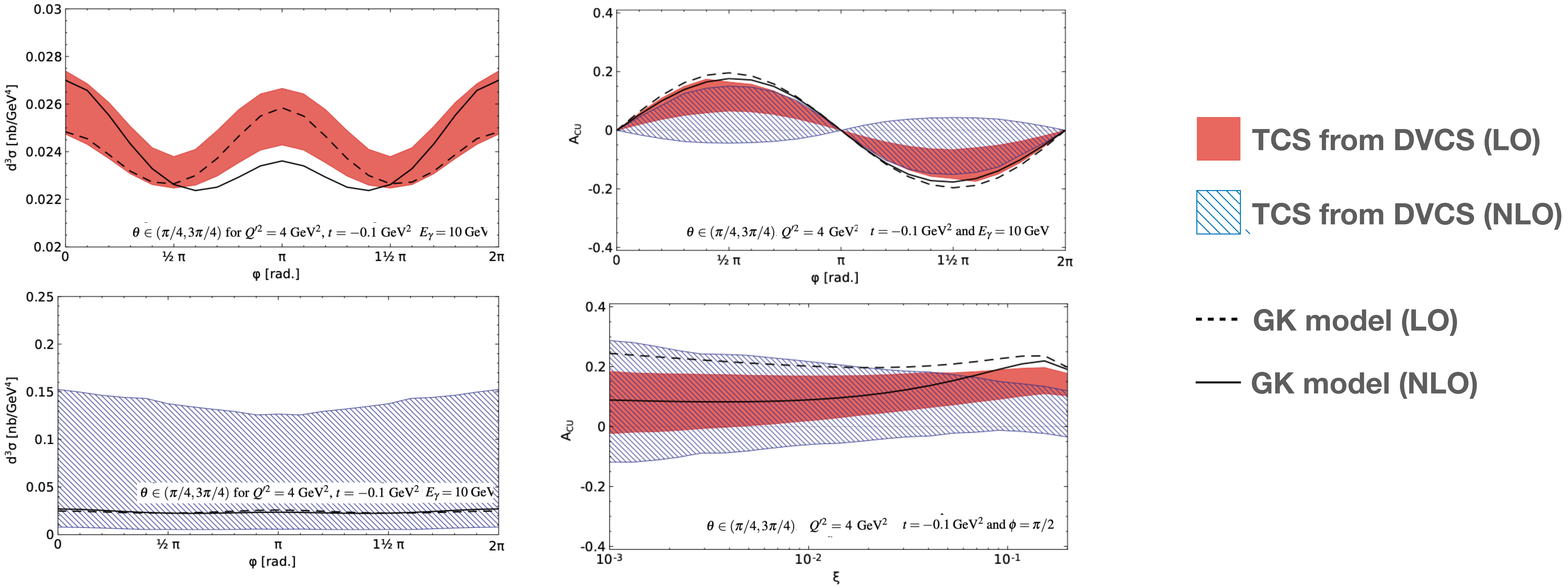


@ $Q^2 = 2$ GeV^2, $t = -0.3$ GeV^2

Grocholski, Moutarde, Pire, PS, Wagner
Eur. Phys. J. C 80 (2020) 2, 171

TCS amplitudes and observables from DVCS amplitudes

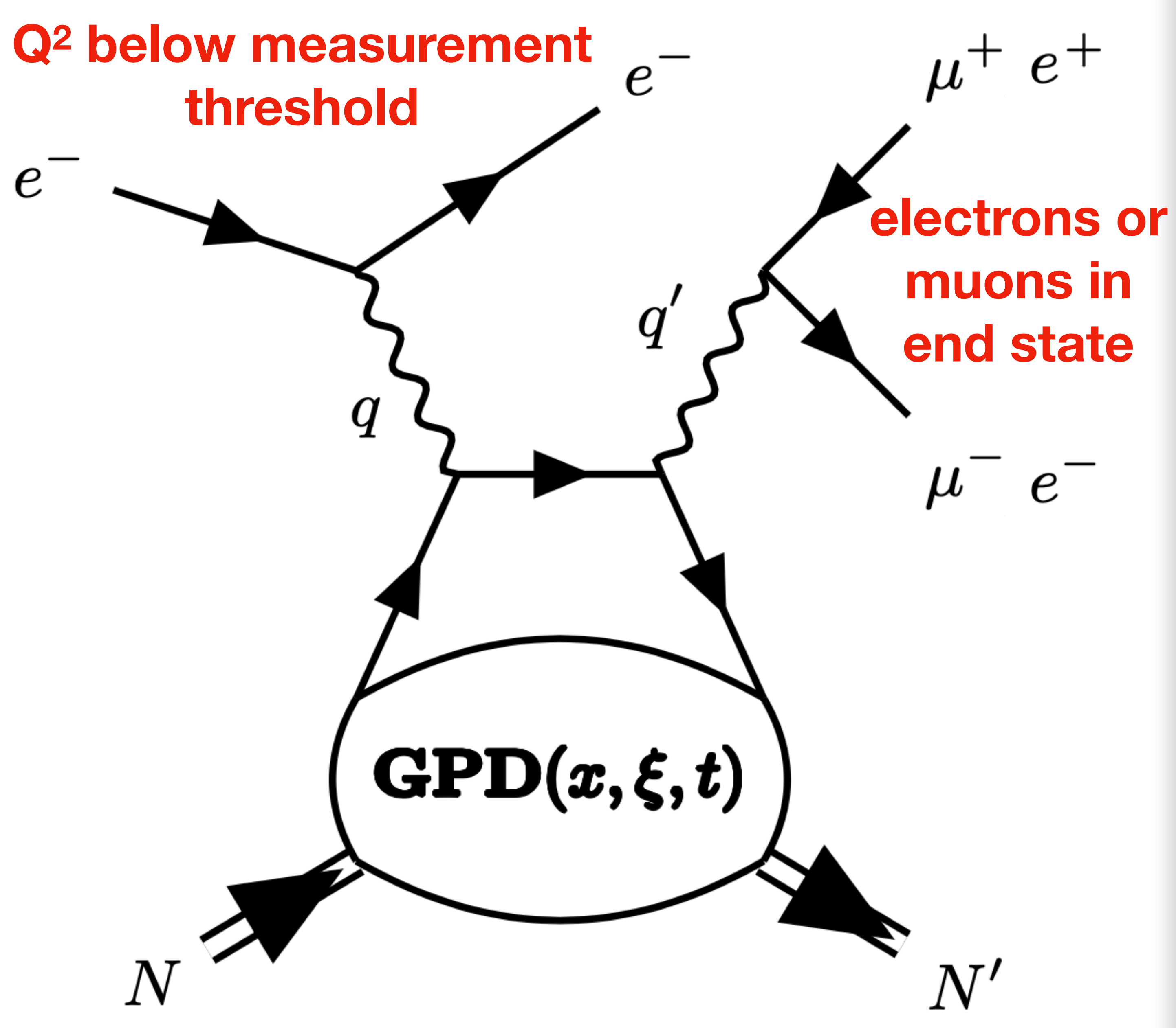
cross-section: **circular beam asymmetry:**



TCS at EIC

see Daria Sokhan's talk
at 3DPartons workshop

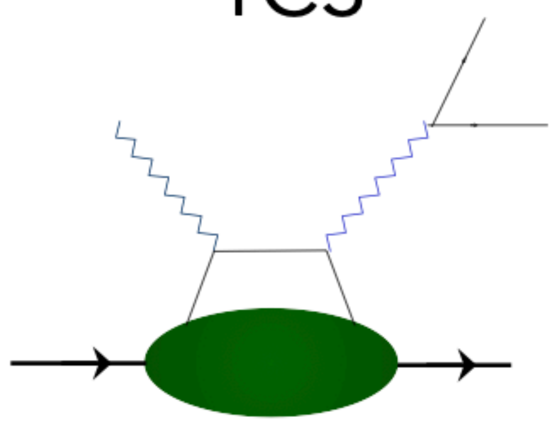
Practical realisation of TCS measurement



TCS (+ BH + Int) e⁺e⁻: observables

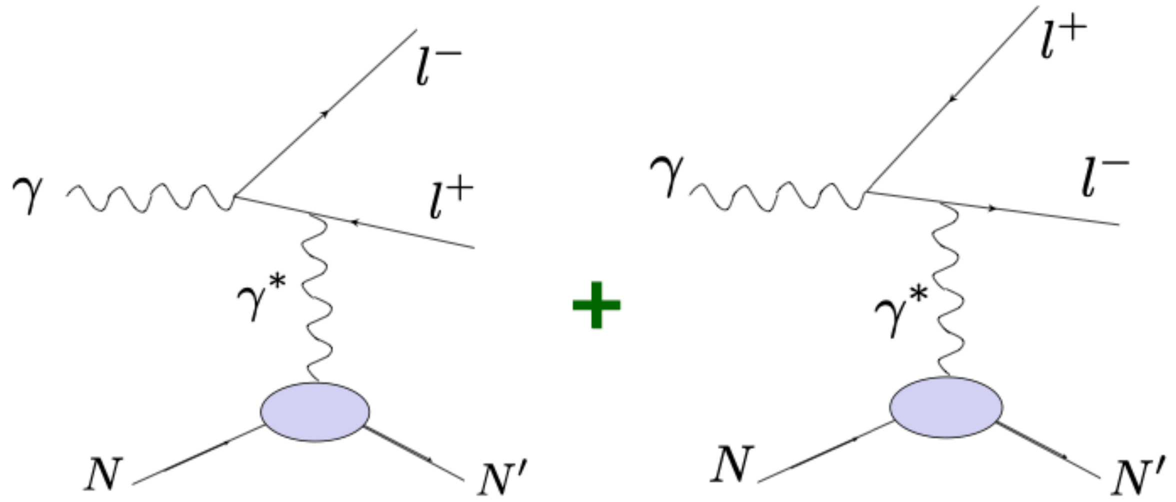
* Pure TCS cross-section is dominated by a factor of ~100 by Bethe-Heitler (BH): extract TCS signal from the BH-TCS interference.

TCS

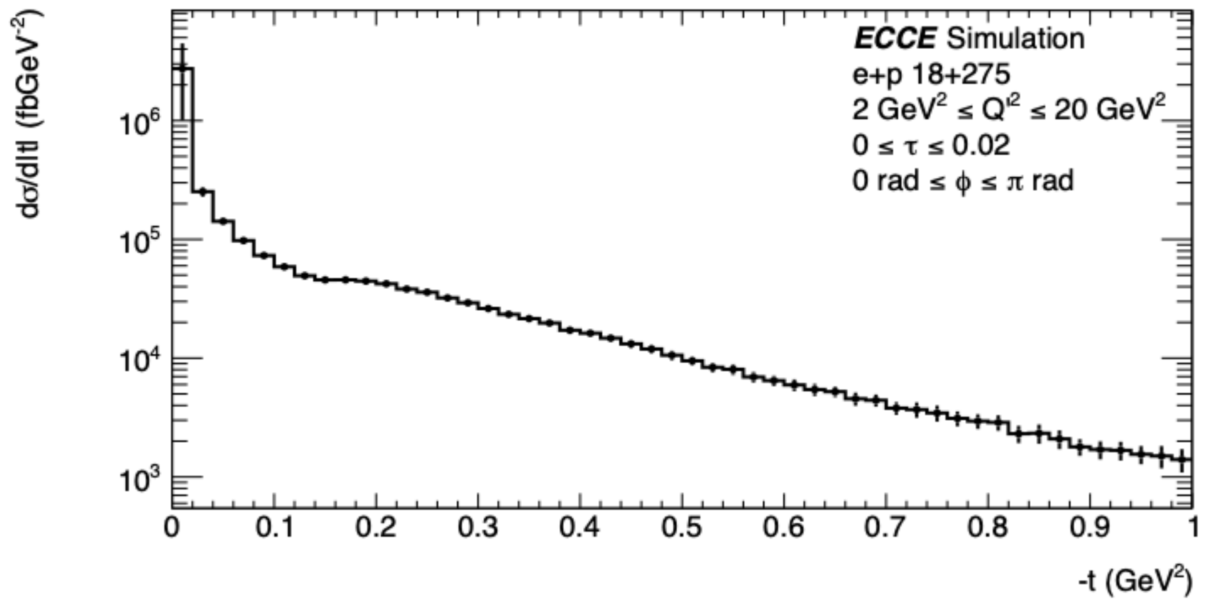


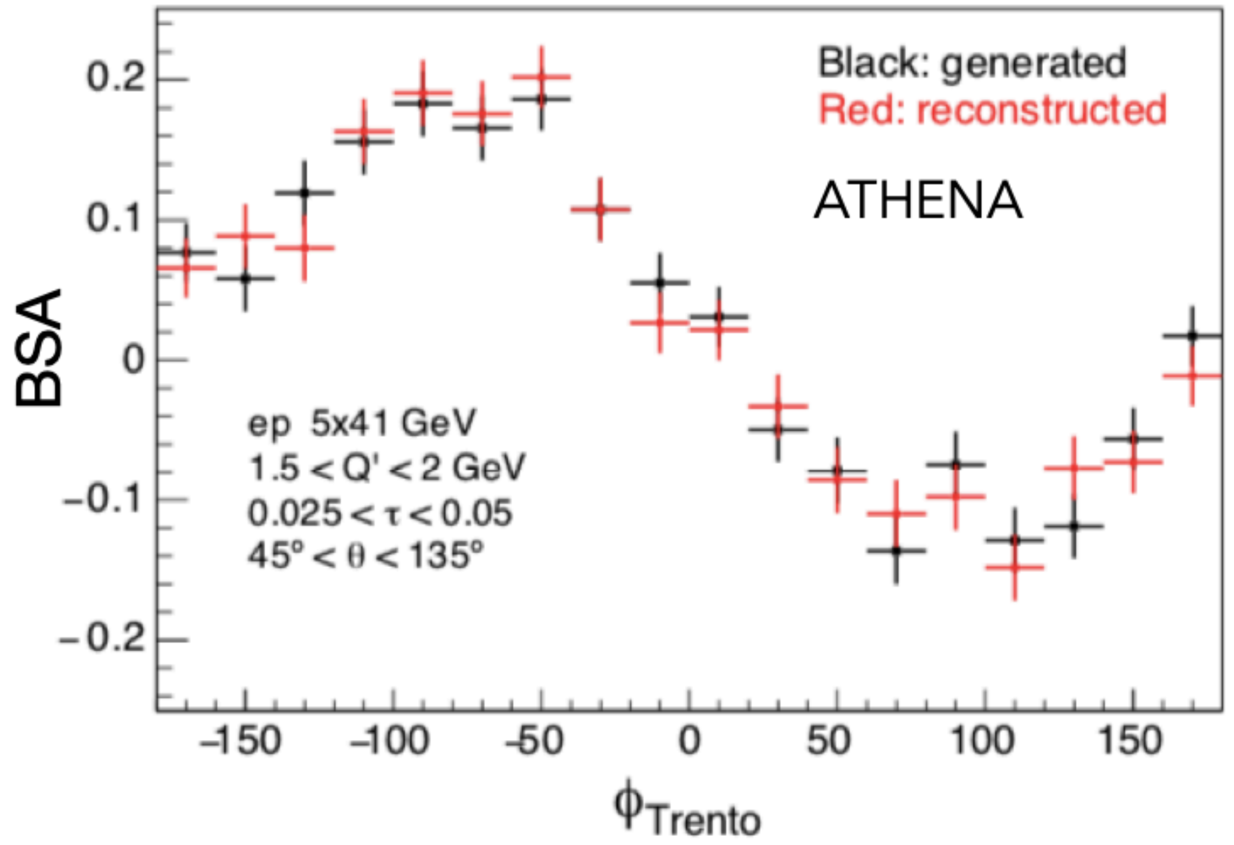
\+

Bethe-Heitler (BH)



$$\sigma(\gamma p \to p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$





* Sensitivity to Interference term in single-spin asymmetries: beam-spin (BSA), target-spin.

* Studied with the EpIC generator using the PARTONS framework.

Plots: Kayleigh Gates (Glasgow), D.S.

20

Ambiguities in GPD extraction

V. Bertone et al.,
Phys. Rev. D 103 (2021) 11, 114019

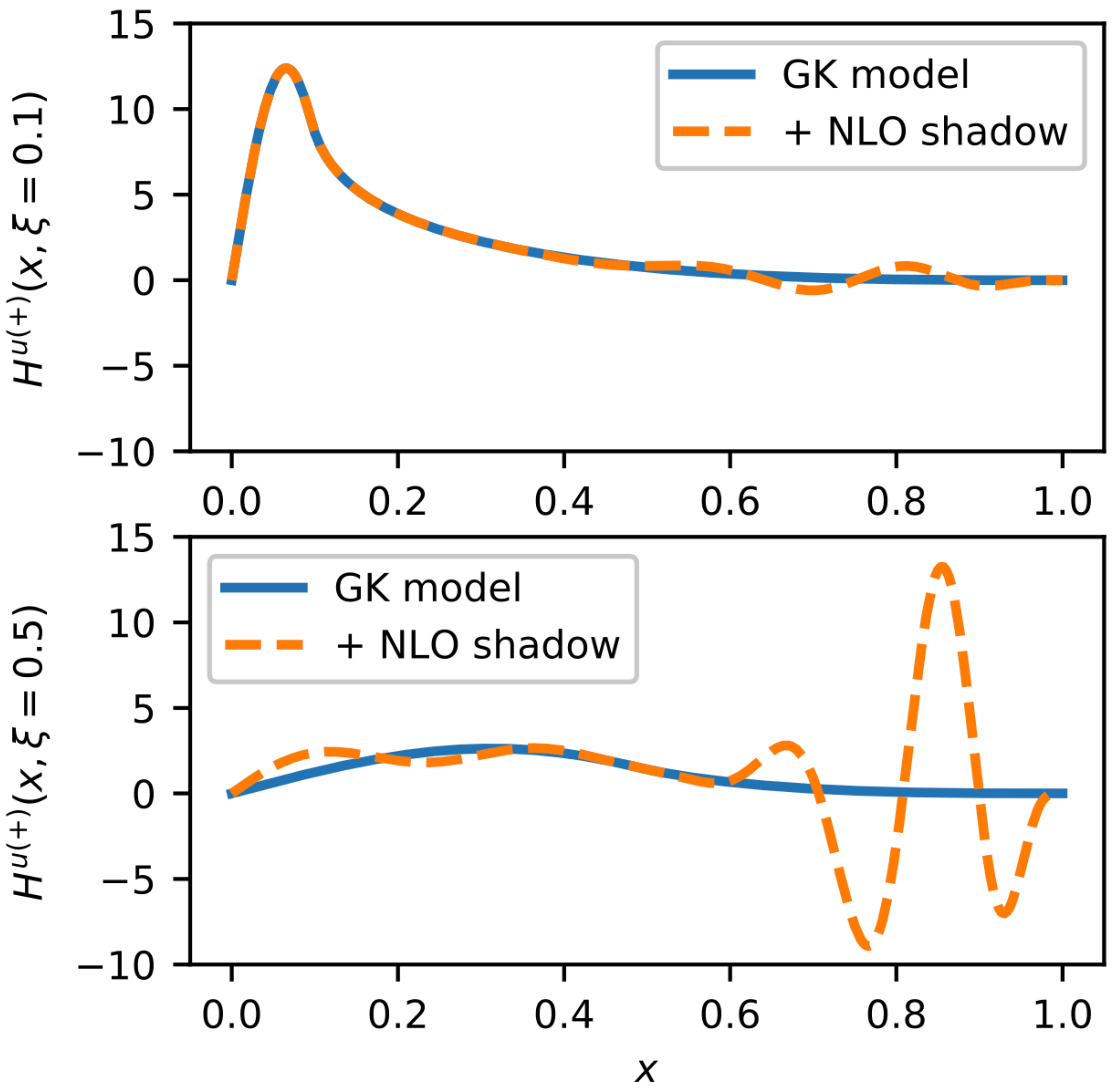
Shadow term is closely related to the so-called shadow GPDs

Shadow GPDs have considerable size and:

- at the initial scale do not contribute to both PDFs and CFFs
- at some other scale they contribute negligibly

making the deconvolution of CFFs ill-posed

We found such GPDs for both LO and NLO



Double DVCS

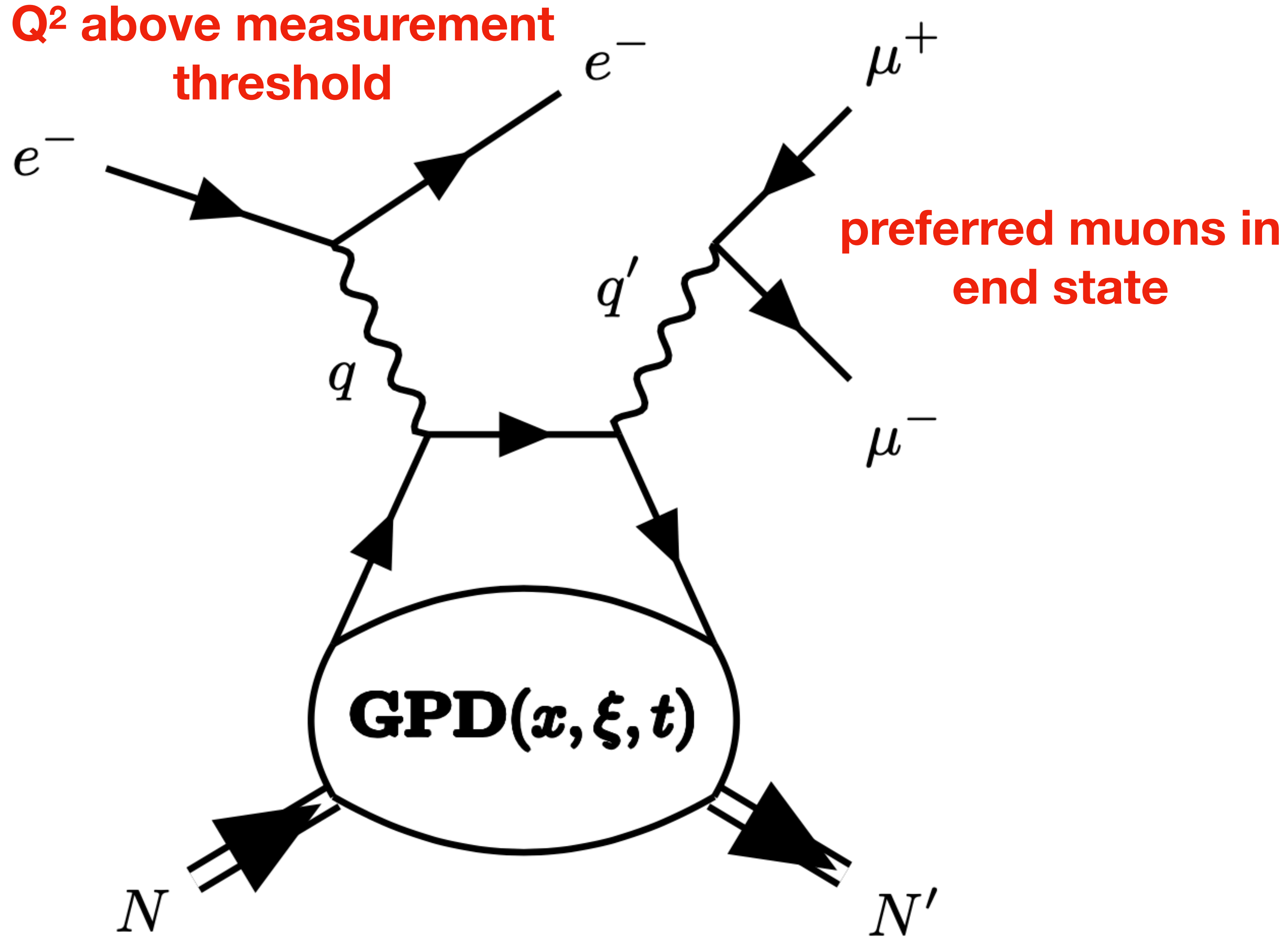
PRELIMINARY !!!

- The process allows to probe GPDs outside x=ξ line, but is much more challenging experimentally

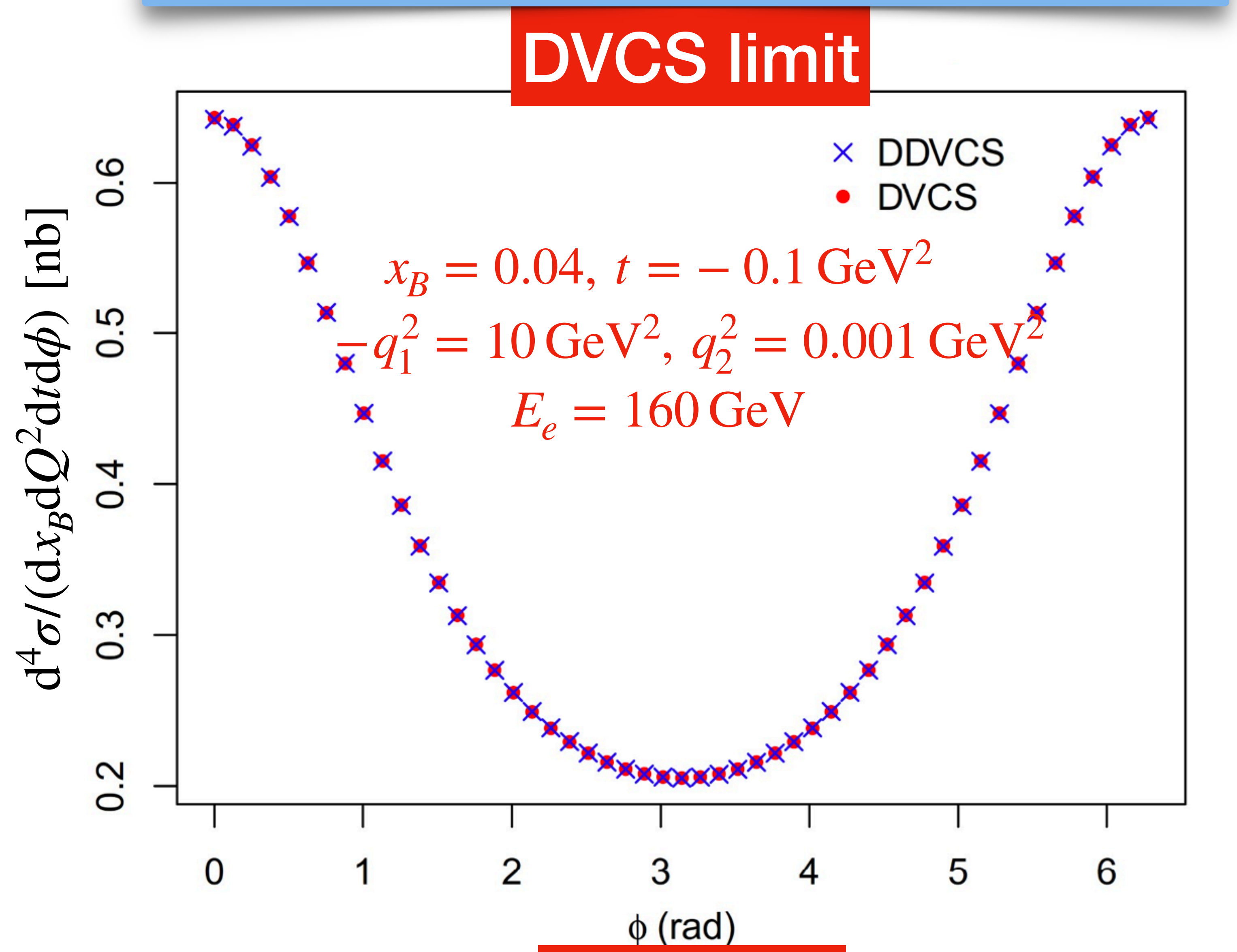
$$\mathcal{A}_{\mathrm{DDVCS}} \overset{LO}{\sim} \int_{-1}^{1} dx \, \frac{1}{x-\xi+i0} \mathrm{GPD}(x,\eta,t)$$

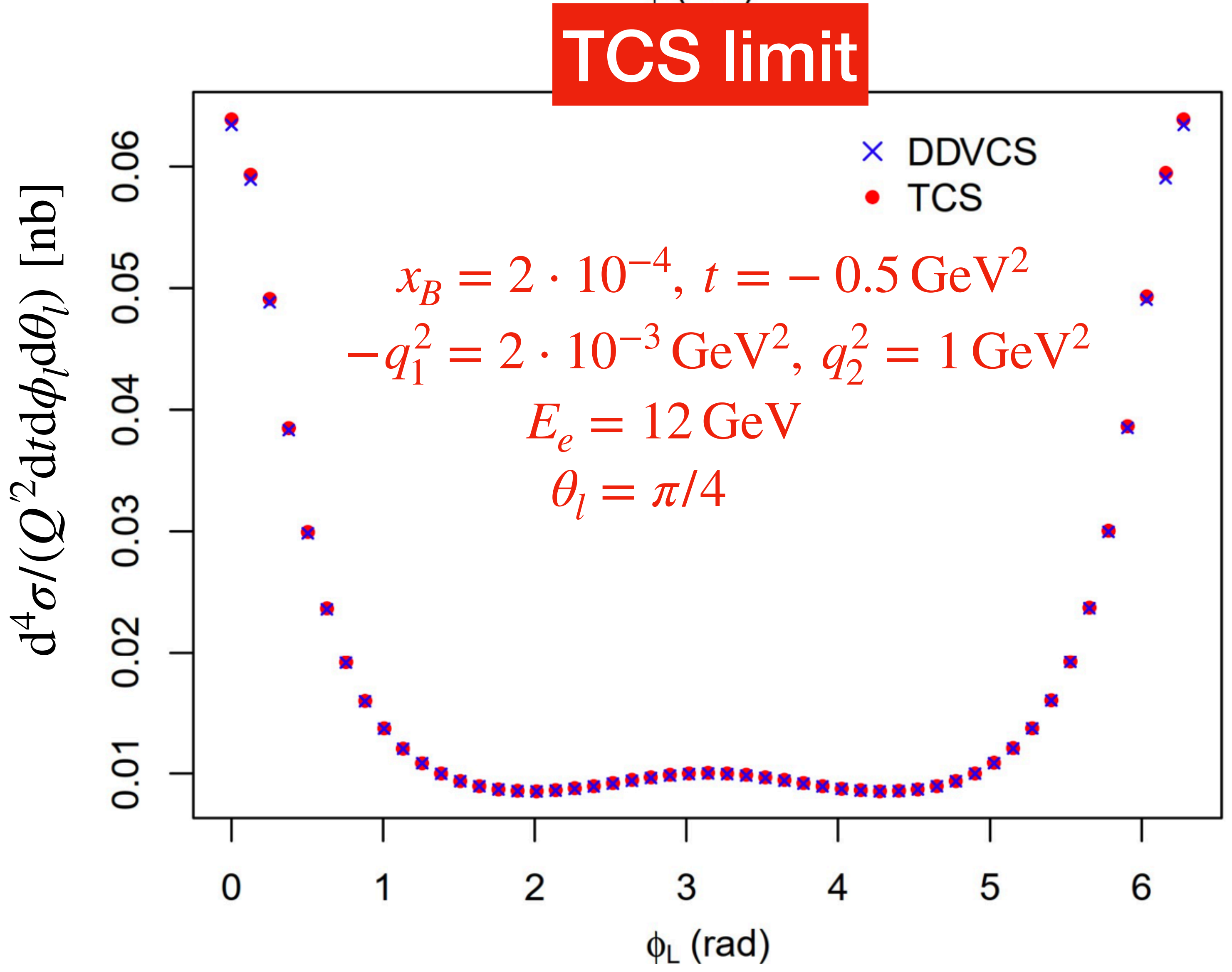
- We are revisiting DDVCS for phenomenological studies, i.e. we reevaluate DDVCS and related BH amplitudes using Kleiss-Stirling technique

- We plane to release obtained formulae in PARTONS and EpIC MC generator



Practical realisation of DDVCS measurement

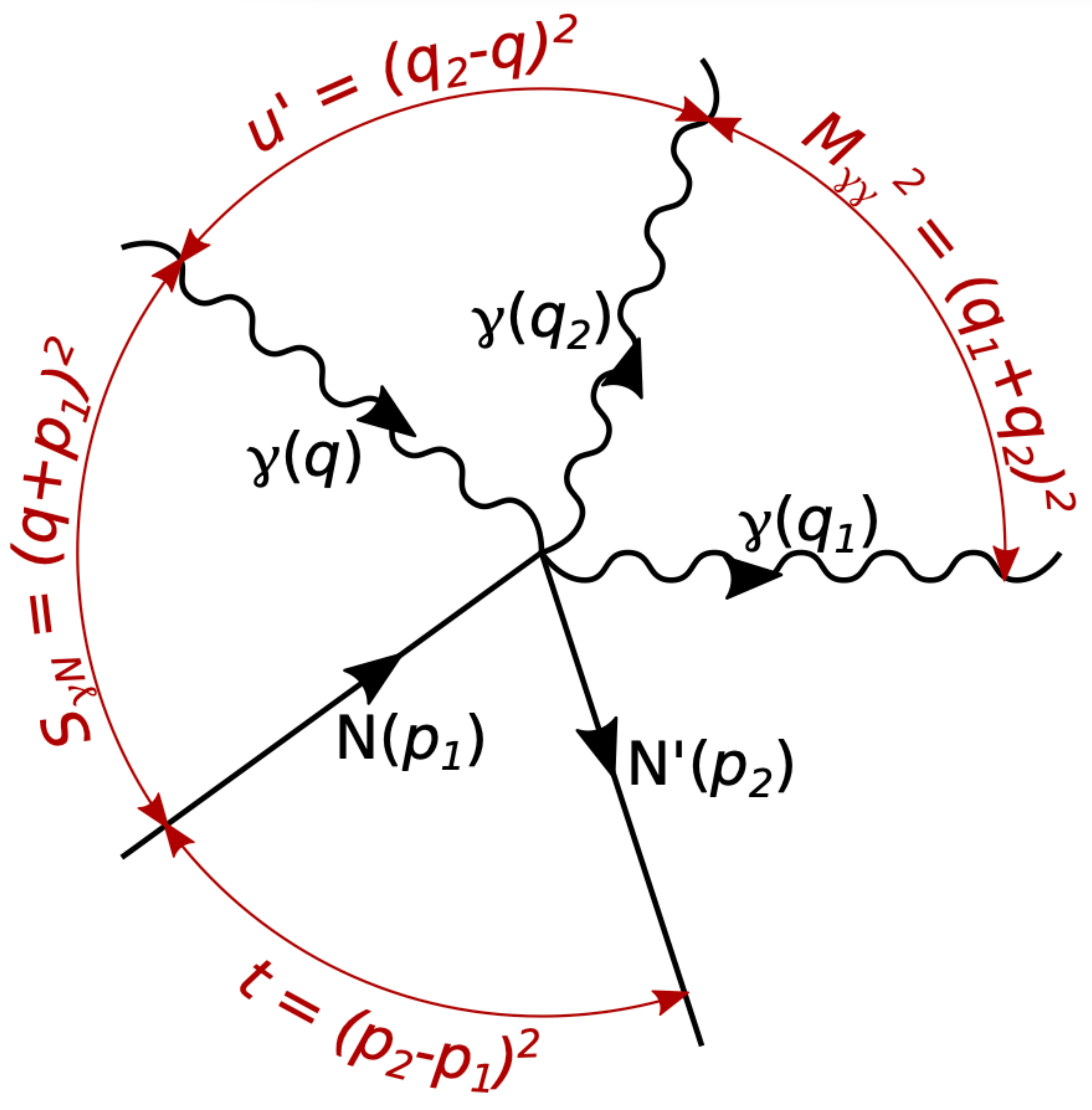




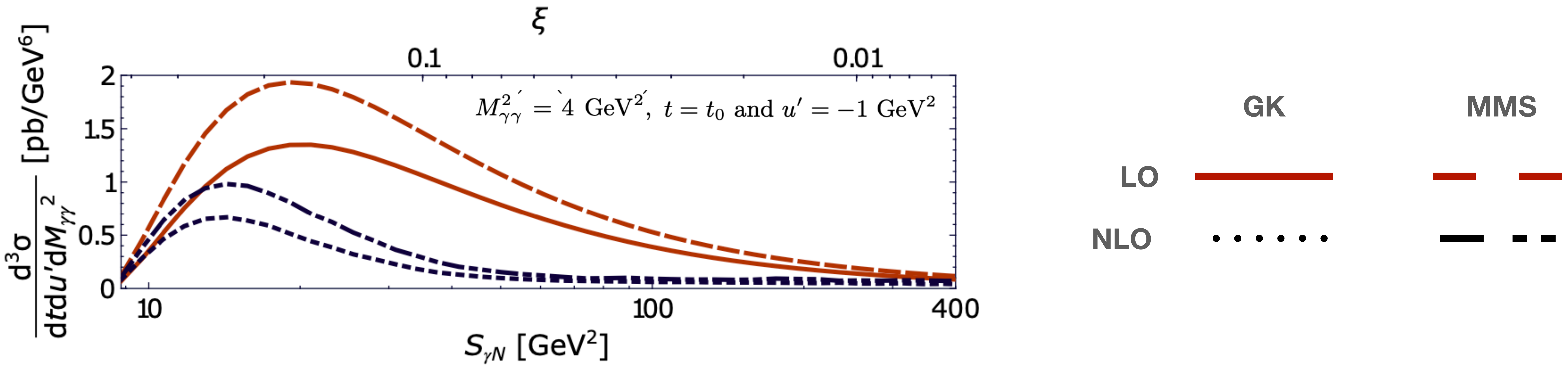
Exclusive diphoton photoproduction

O. Grocholski et al.,
Phys. Rev. D 105 (2022) 9, 094025
Phys. Rev. D 104 (2021) 11, 114006

- Process probes C-odd GPDs
- No contribution of D-term
- No non-perturbative ingredients other than GPDs
- Both LO and NLO description available
- Gluons do not contribute also at NLO

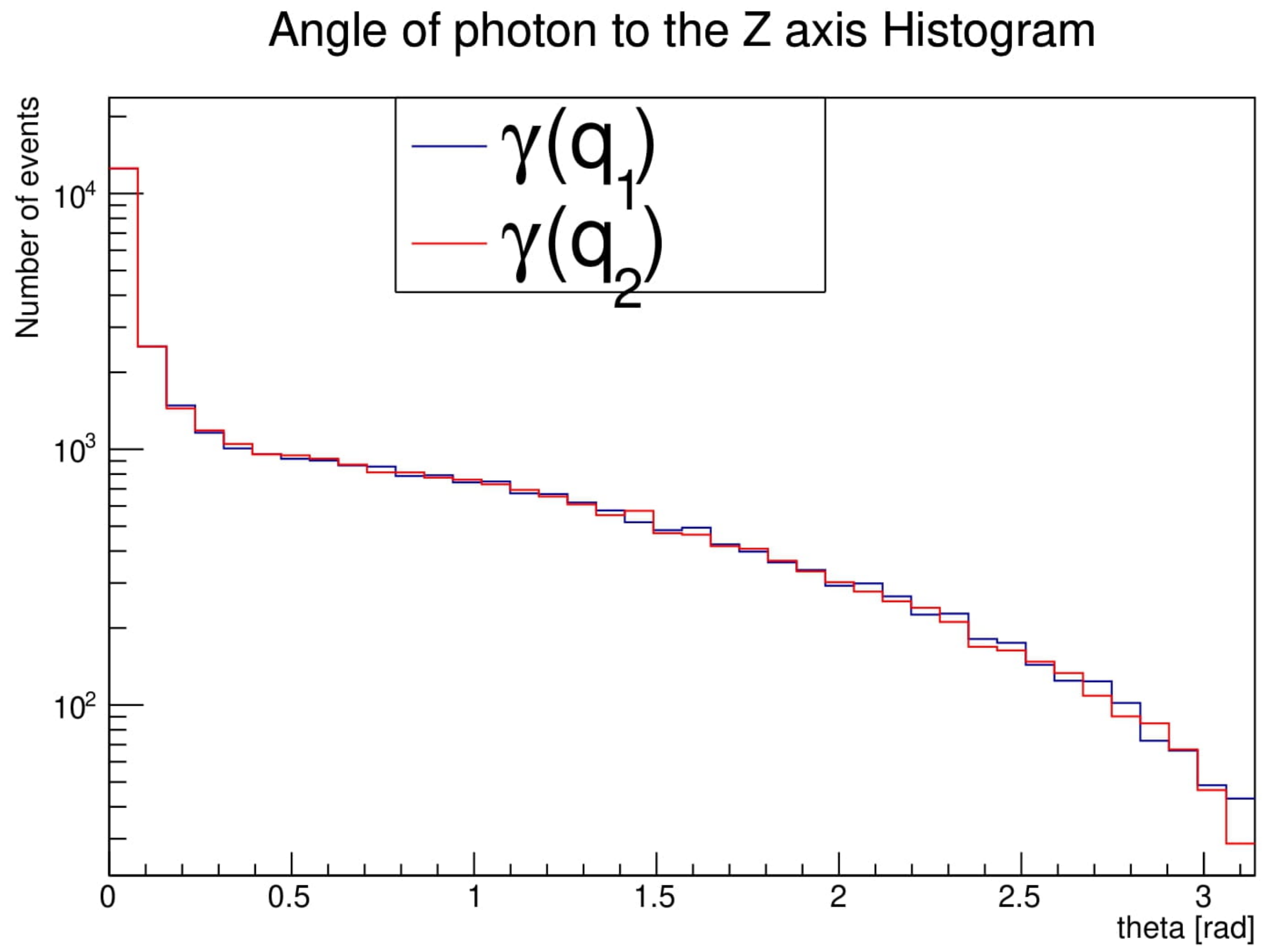


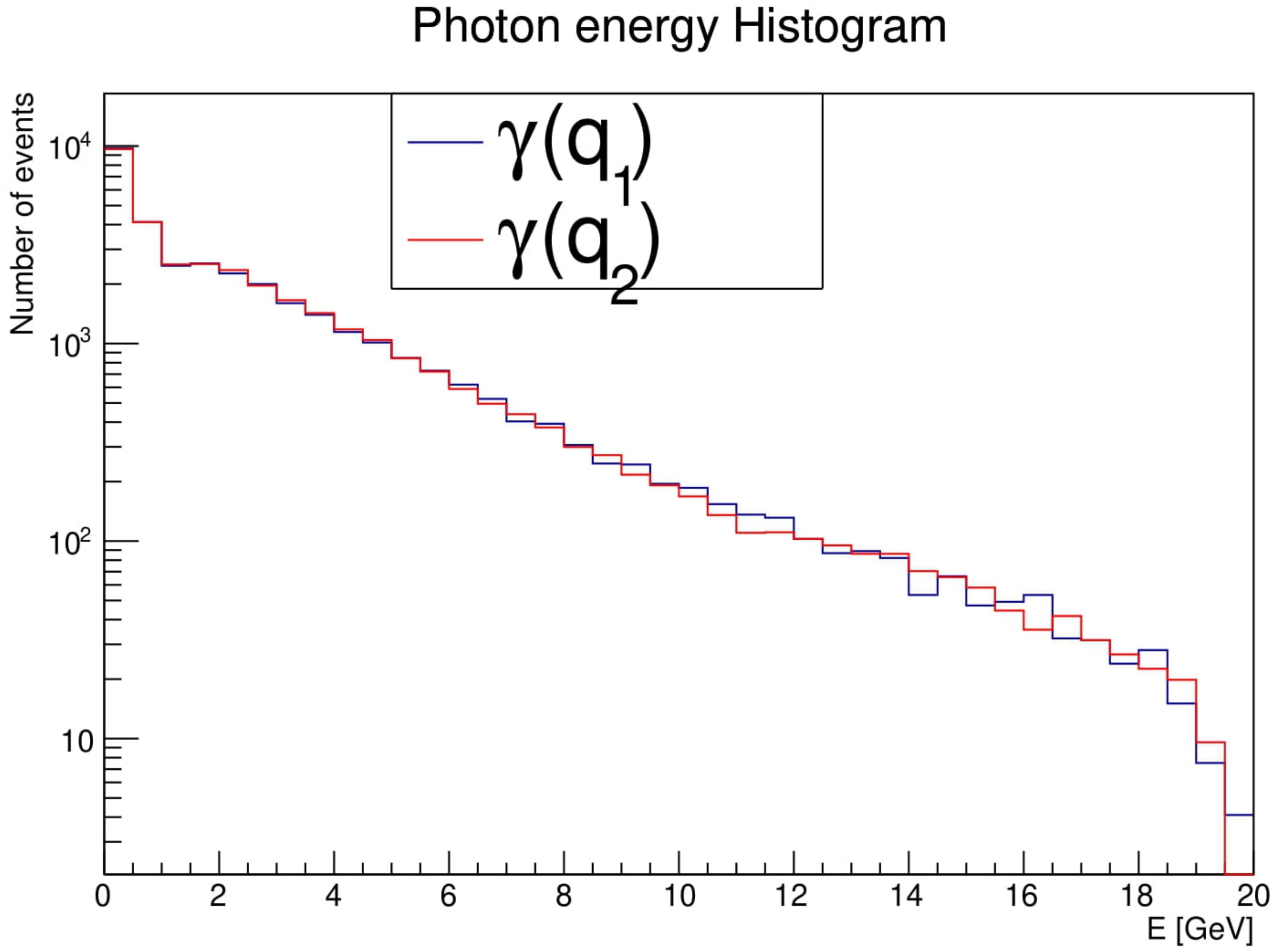
Cross-section



Exclusive diphoton photoproduction

B. Skura (Warsaw U. of Technology), PS
preliminary results





- The process implemented in EpIC MC generator

- Condition used in generation of events

$E = 20$ GeV

$0 < -t < 1$ GeV^2
$0 < -u < 6$ GeV^2
1 GeV$^2 < M_{\gamma\gamma}^2 < 5$ GeV^2
$0 < \phi < 2\pi$

$0 < y < 1$
$0 < Q^2 < 0.01$ GeV^2

- Event counts are scaled to 10 fb^{-1}

PARTONS project

B. Berthou et al., Eur. Phys. J. C 78 (2018) 6, 478

- PARTONS - open-source framework to study GPDs
  → *http://partons.cea.fr*
- Come with number of available physics developments implemented
- Written in C++, also available via virtual machines (VirtualBox) and containers (Docker)
- Addition of new developments as easy as possible
- Developed to support effort of GPD community,
  can be used by both theorists and experimentalists
- v3 version of PARTONS is now available!

EpIC MC generator

E. C. Aschenauer et al.,
2205.01762 [hep-ph]

- Novel MC generator called EpIC released
  → *https://pawelsznajder.github.io/epic*

- EpIC is based on PARTONS

- EpIC is characterised by:
  - flexible architecture that utilises a modular programming paradigm
  - a variety of modelling options, including radiative corrections
  - multichannel capability (initial version includes DVCS, TCS and DVMP)

- This is the new tool to be use in the precision era commenced by the new generation of experiments

Summary

Takeaway messages:

- TCS:
  - useful to prove universality of GPDs
  - impact of NLO corrections
  - constrain Q2-dependance of CFFs
- DDVCS
  - crucial to study GPD away of x=xi line
- other exclusive processes, like diphoton production, important to constrain GPDs

- Tools to study these processes available (or will be available in near future)

- Measurement of all these processes is very challenging, in particular we need:
  - high luminosity
  - muon ID
  - wide Q2 coverage

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case for 2nd detector