Status and perspectives for GPD extraction

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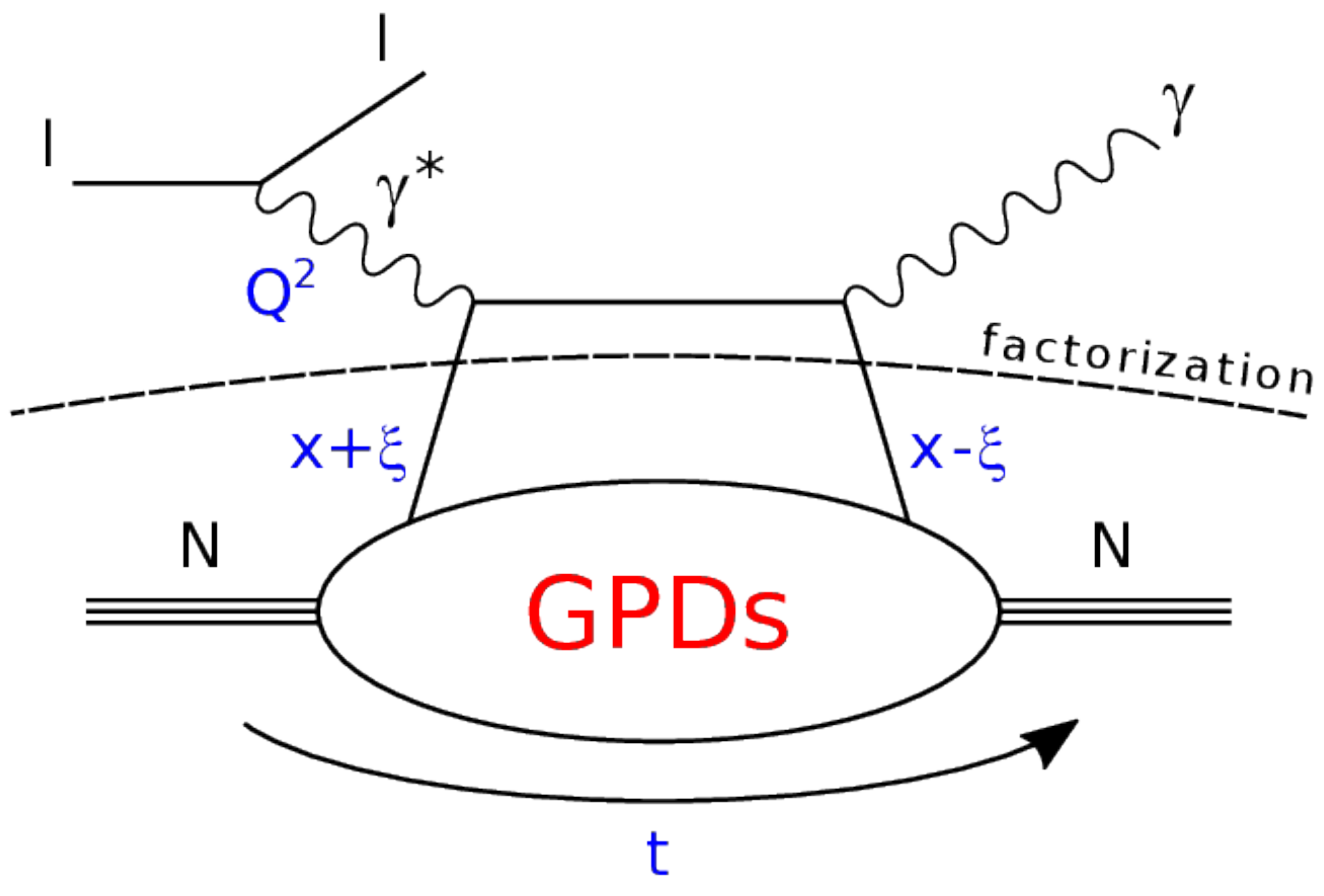
Paris, France, March 22nd, 2022

Outline

- General introduction
- GPD phenomenology
- New sources of GPD information
- Summary

Deeply Virtual Compton Scattering (DVCS)

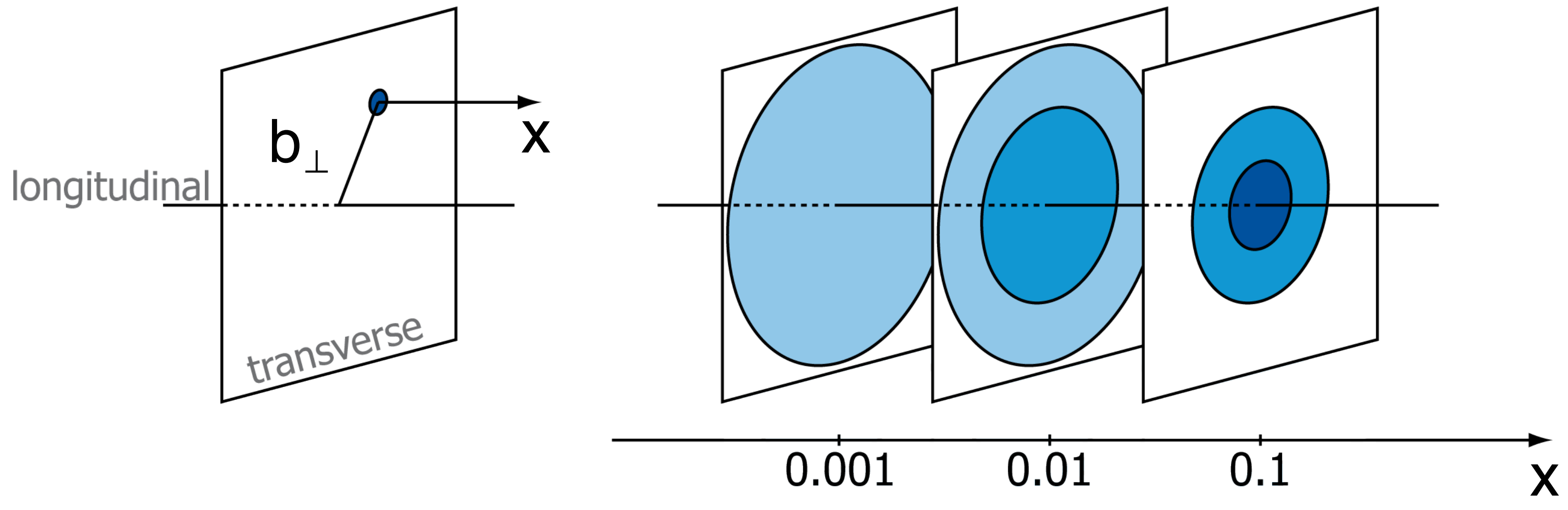


factorisation for |t|/Q² ≪ 1

Chiral-even GPDs:
(helicity of parton conserved)

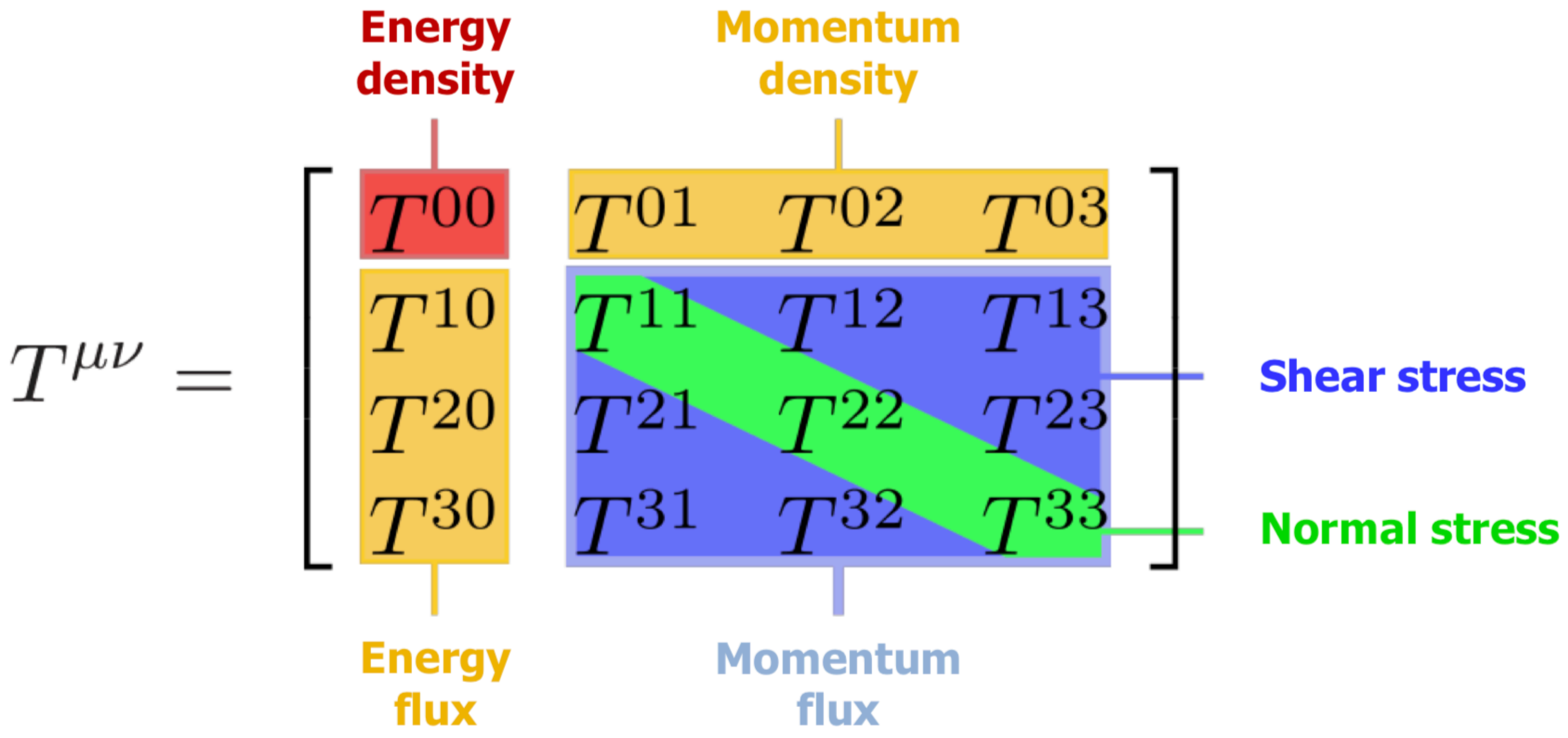
$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

Introduction



Nucleon tomography:

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



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

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

Reduction to PDF:

$$H(x, \xi = 0, t = 0) \equiv q(x)$$

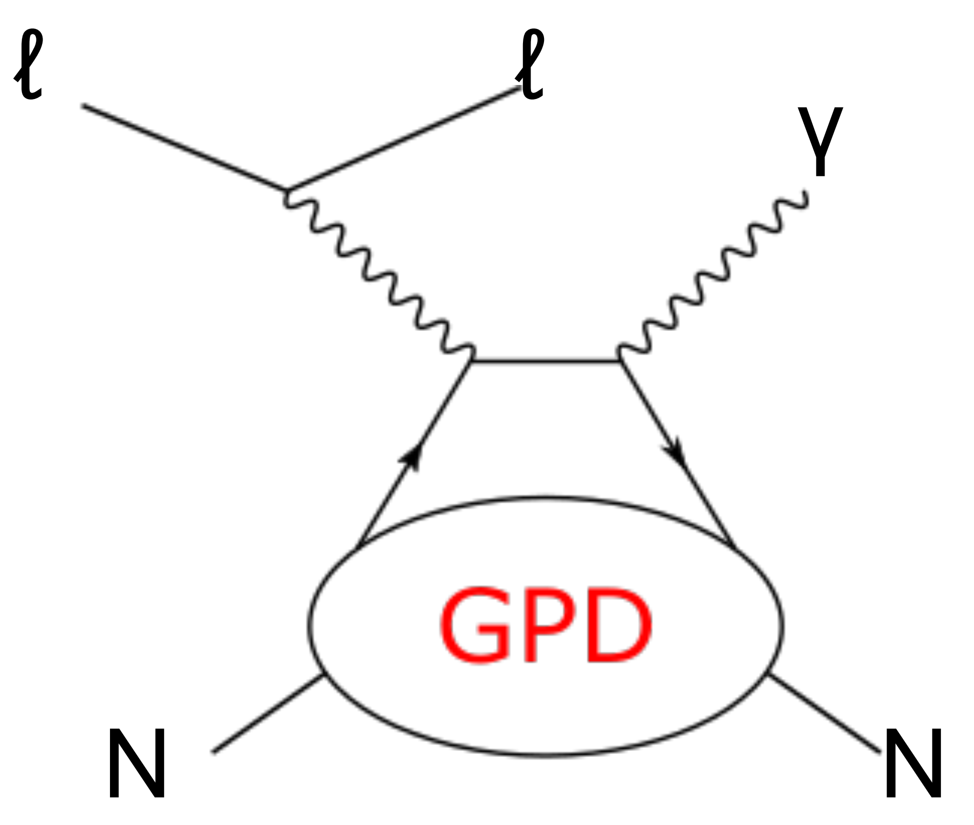
Polynomiality - non-trivial consequence of Lorentz invariance:

$$\mathcal{A}_n(\xi, t) = \int_{-1}^{1} \mathrm{d}x x^n H(x, \xi, t) = \sum_{\substack{j=0 \\ \text{even}}}^{n} \xi^j A_{n,j}(t) + \mathrm{mod}(n, 2)\xi^{n+1} A_{n,n+1}(t)$$

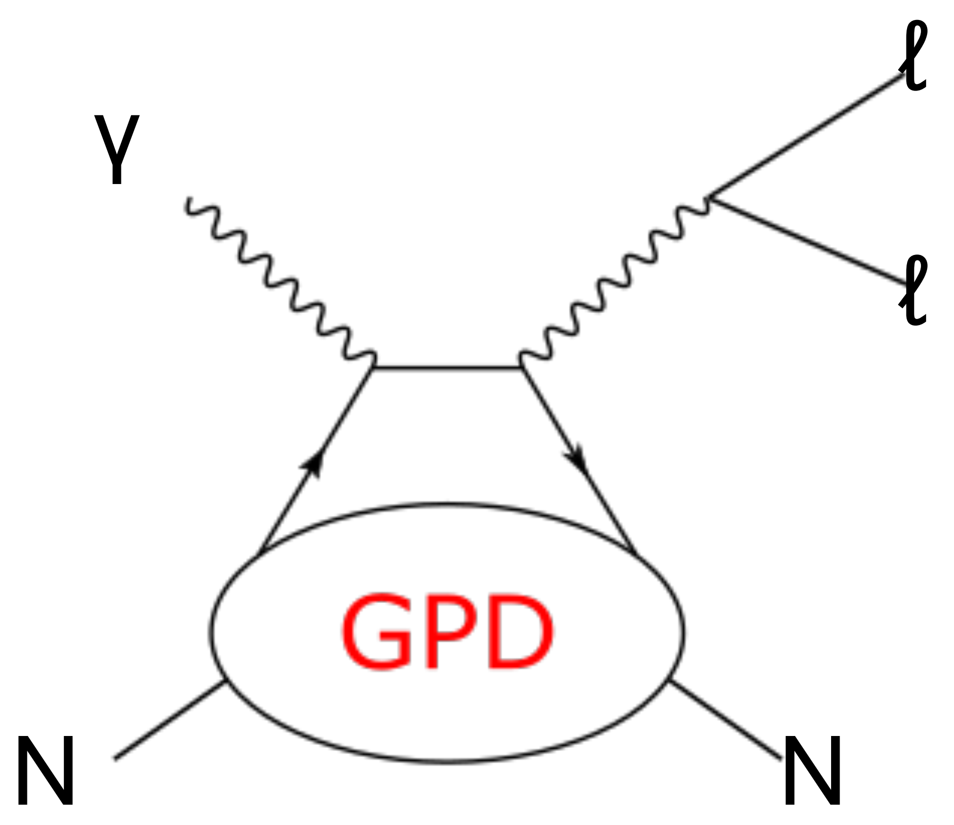
Positivity bounds - positivity of norm in Hilbert space, e.g.:

$$|H(x, \xi, t)| \leq \sqrt{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right) \frac{1}{1-\xi^2}}$$

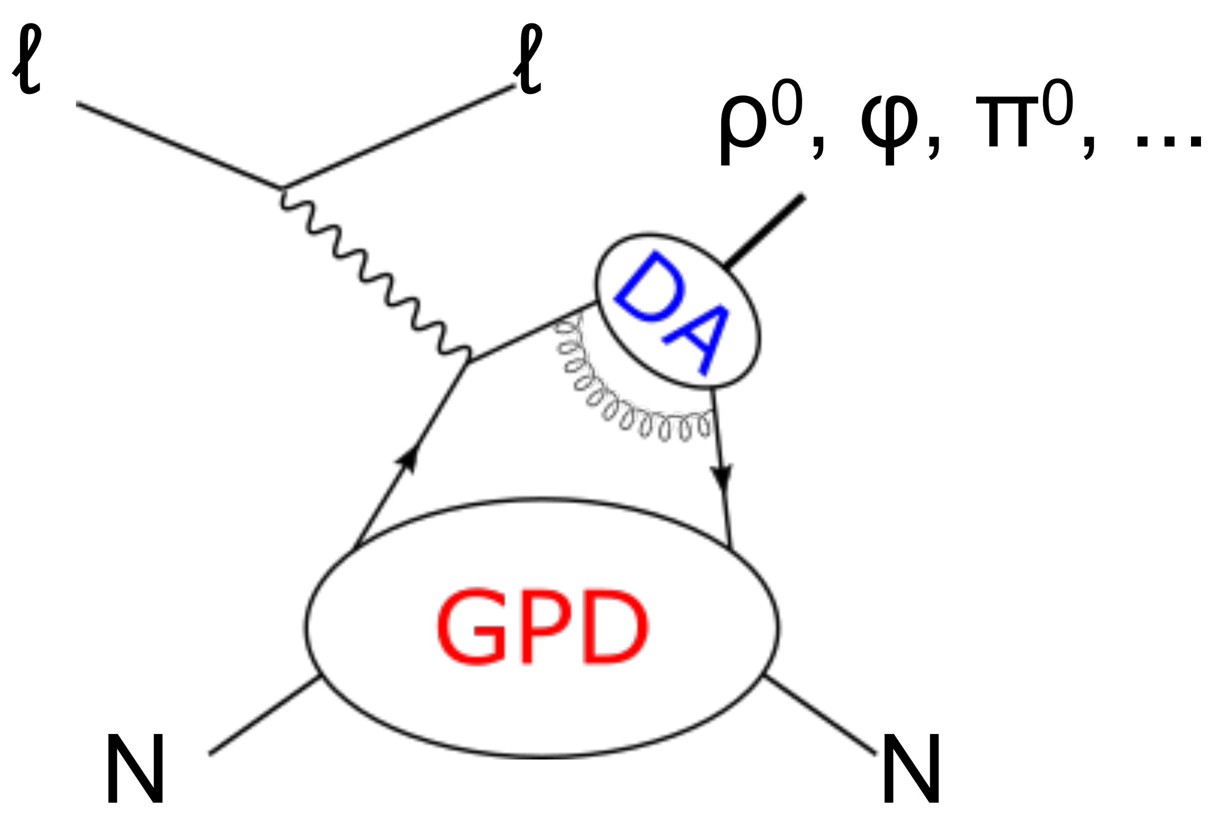
GPDs accessible in various production channels and observables
→ experimental filters



DVCS
Deeply Virtual Compton Scattering



TCS
Timelike Compton Scattering



HEMP
Hard Exclusive Meson Production

more production channels sensitive to GPDs exist!

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.,
Eur. Phys. J. C 82 (2022) 9, 819

- 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 (now: DVCS, TCS, DVπ^0P, diphoton; coming soon: DDVCS, J/ψ)

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

Deeply Virtual Compton scattering

H. Moutarde, PS, J. Wagner,
Eur. Phys. J. C 78 (2018) 11, 890

$$G^q(x,0,t) = \mathrm{pdf}^q_G(x)\ \exp(f^q_G(x)t) \qquad G = \{H, E, \widetilde{H}, \widetilde{E}\}$$
$$f^q_G(x) = A^q_G \log(1/x) + B^q_G(1-x)^2 + C^q_G(1-x)x$$

- reduction to PDFs and correspondence to EFFs
- modify "classical" log(1/x) term by $B_G^q(1-x)^2$ in low-x and by $C_G^q(1-x)x$ in high-x regions
- polynomials found in analysis of EFF data → good description of data
- allow to use the analytic regularisation prescription
- finite proton size at x → 1

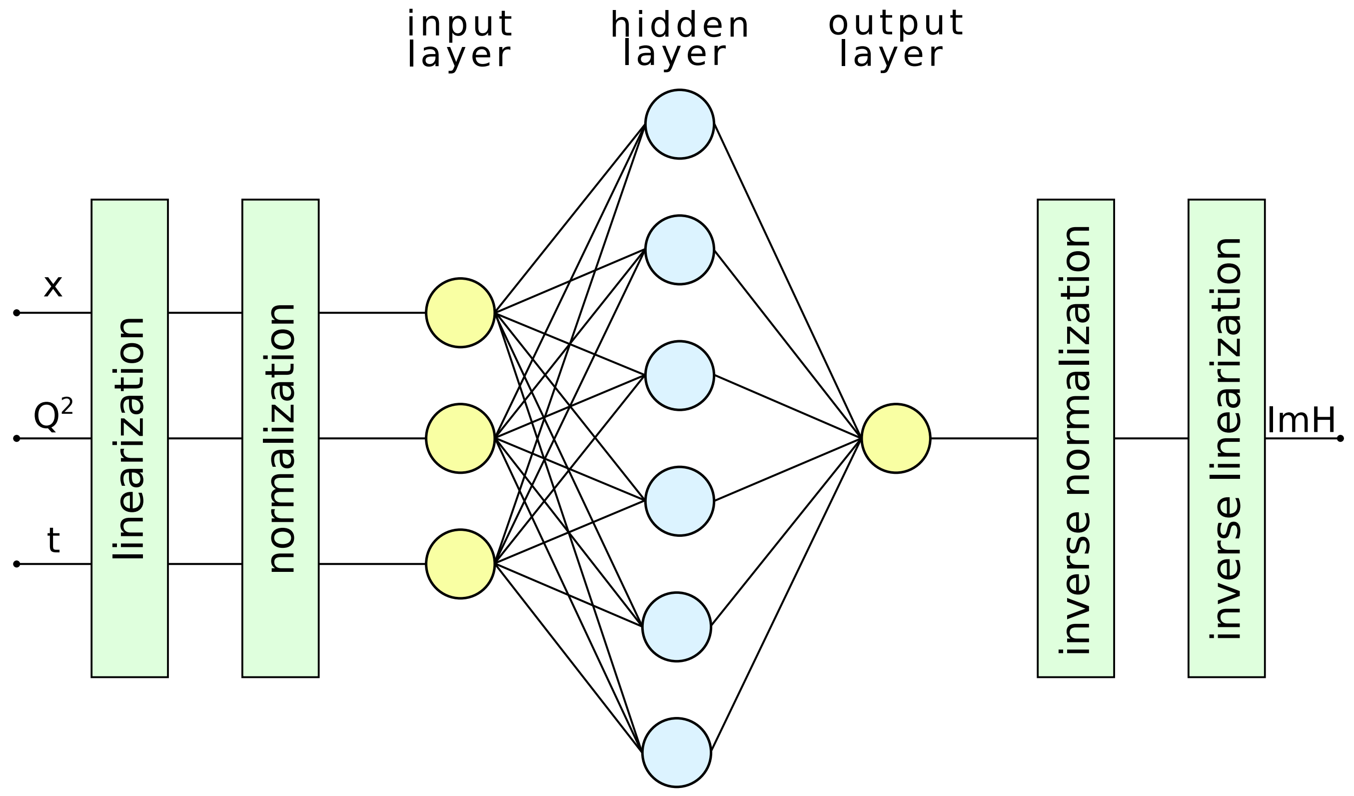
$$g^q_G(x,x,t) = \frac{a^q_G}{(1-x^2)^2}\left(1 + t(1-x)(b^q_G + c^q_G \log(1+x))\right)$$

- at x → 0 constant skewness effect
- at x → 1 reproduce power behaviour predicted for GPDs in Phys. Rev. D69, 051501 (2004)
- t-dependence similar to DD-models with (1-x) to avoid any t-dep. at x = 1

$$2\int_{(0)}^{1}\left(G^{q(+)}(x,x,t) - G^{q(+)}(x,0,t)\right)\frac{1}{x}dx$$

- subtraction constant as analytic continuation of Mellin moments to *j* = -1

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



- 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

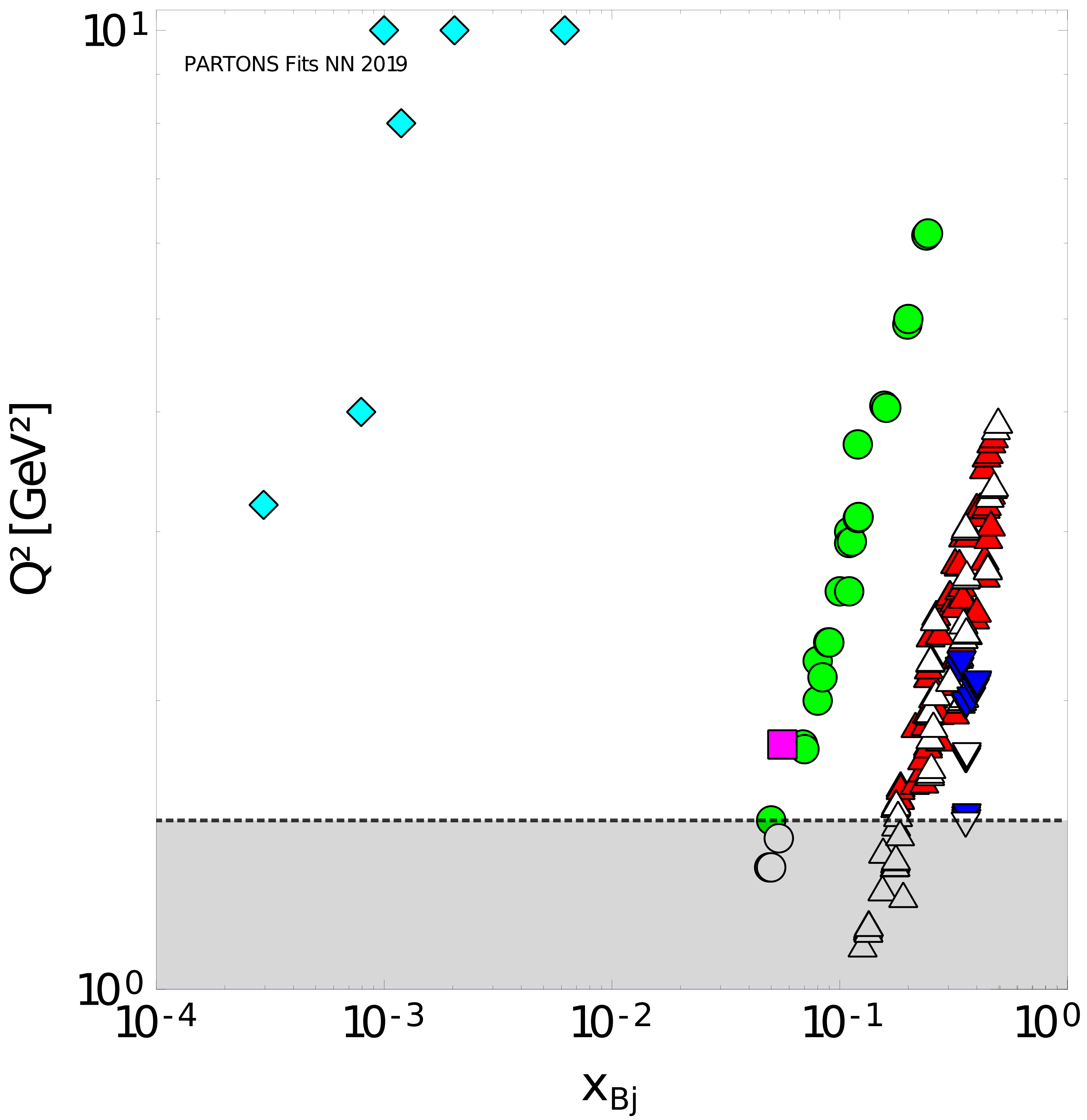
Deeply Virtual Compton scattering

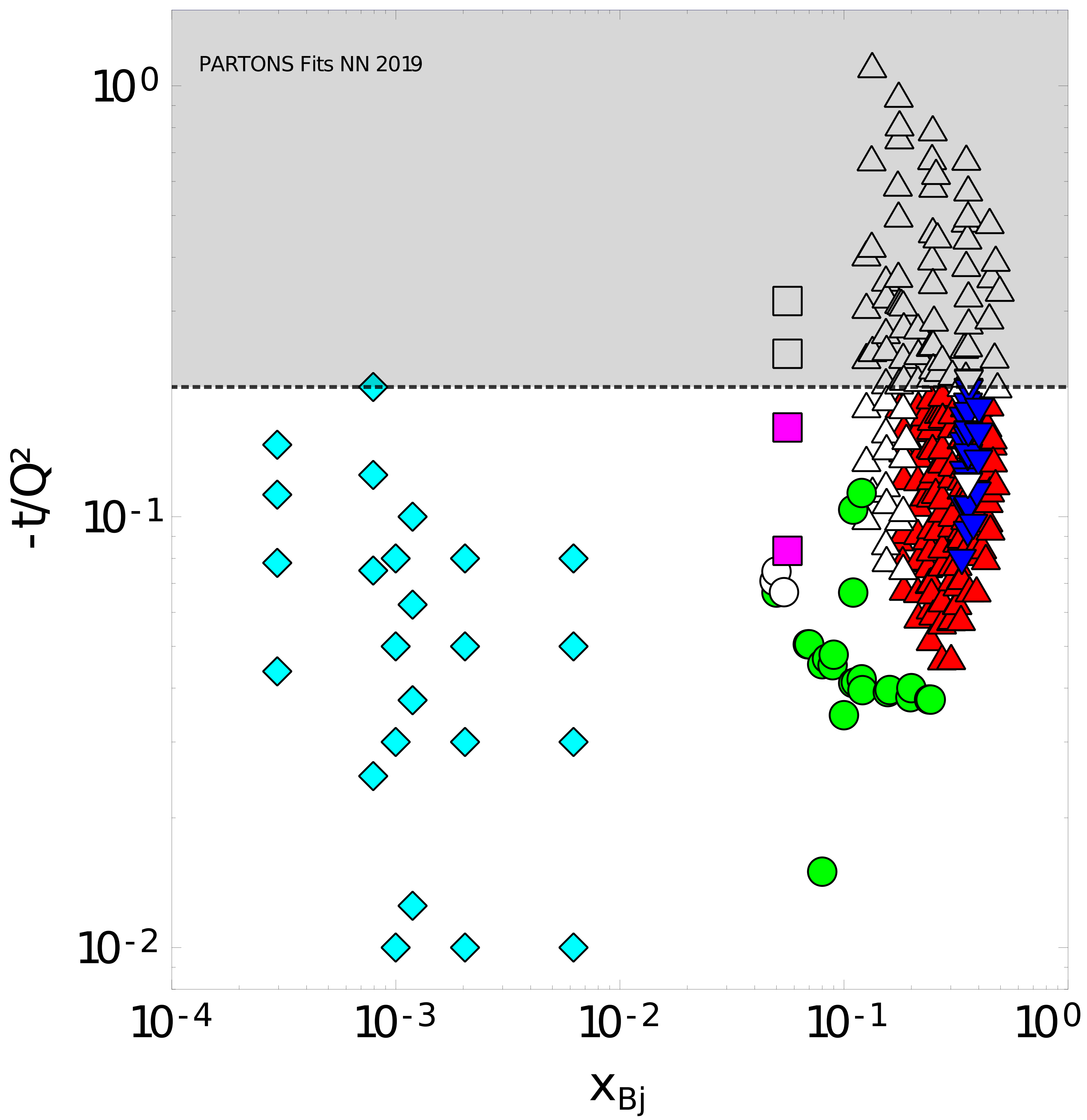
Kinematic cuts
used in our recent global
extractions of DVCS CFFs :

$$Q^2 > 1.5\ \mathrm{GeV}^2$$

$$-t/Q^2 < 0.2$$

▼ HALL A
▲ CLAS
● HERMES
■ COMPASS
◆ H1 and ZEUS





Deeply Virtual Compton scattering

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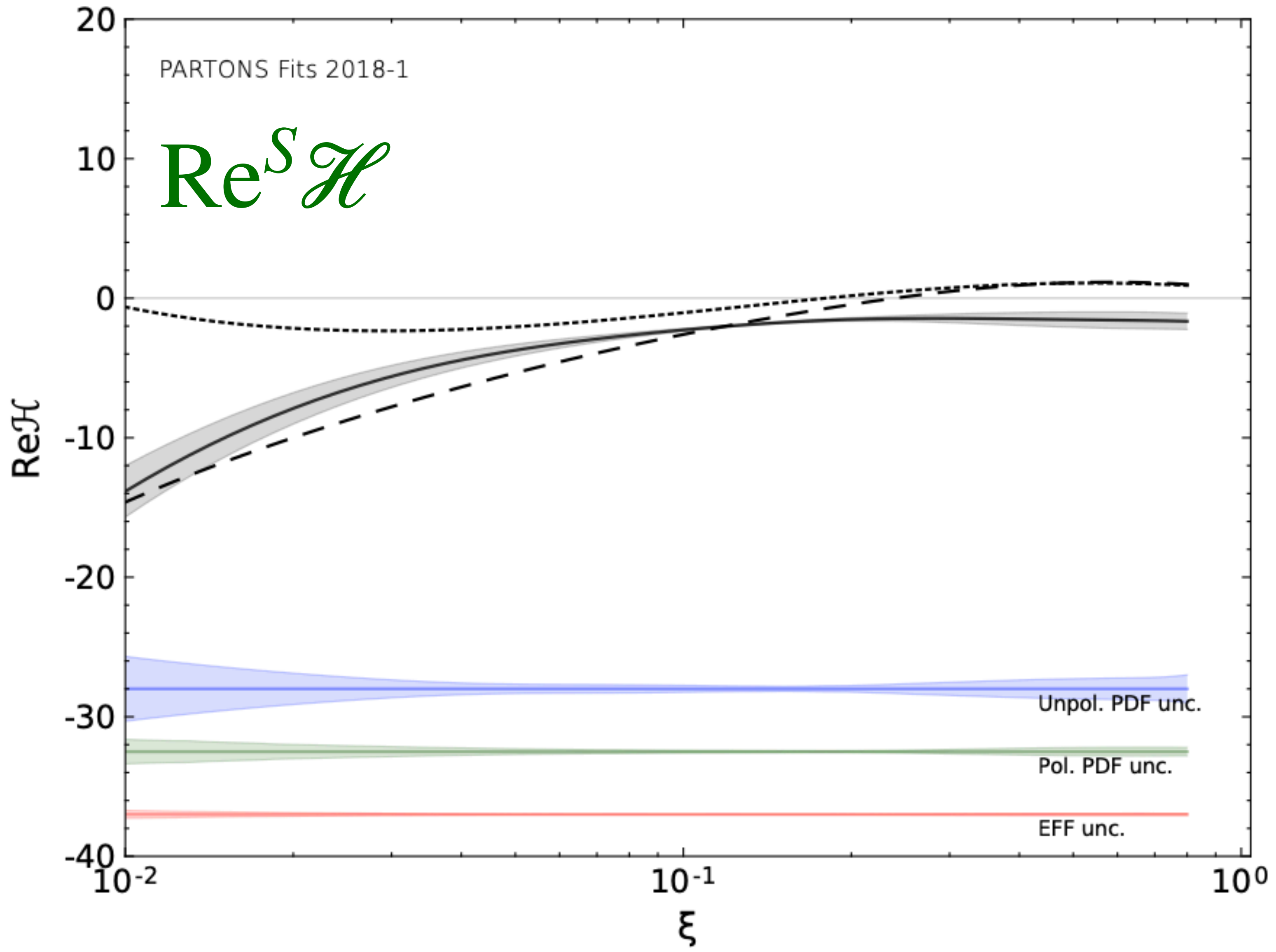
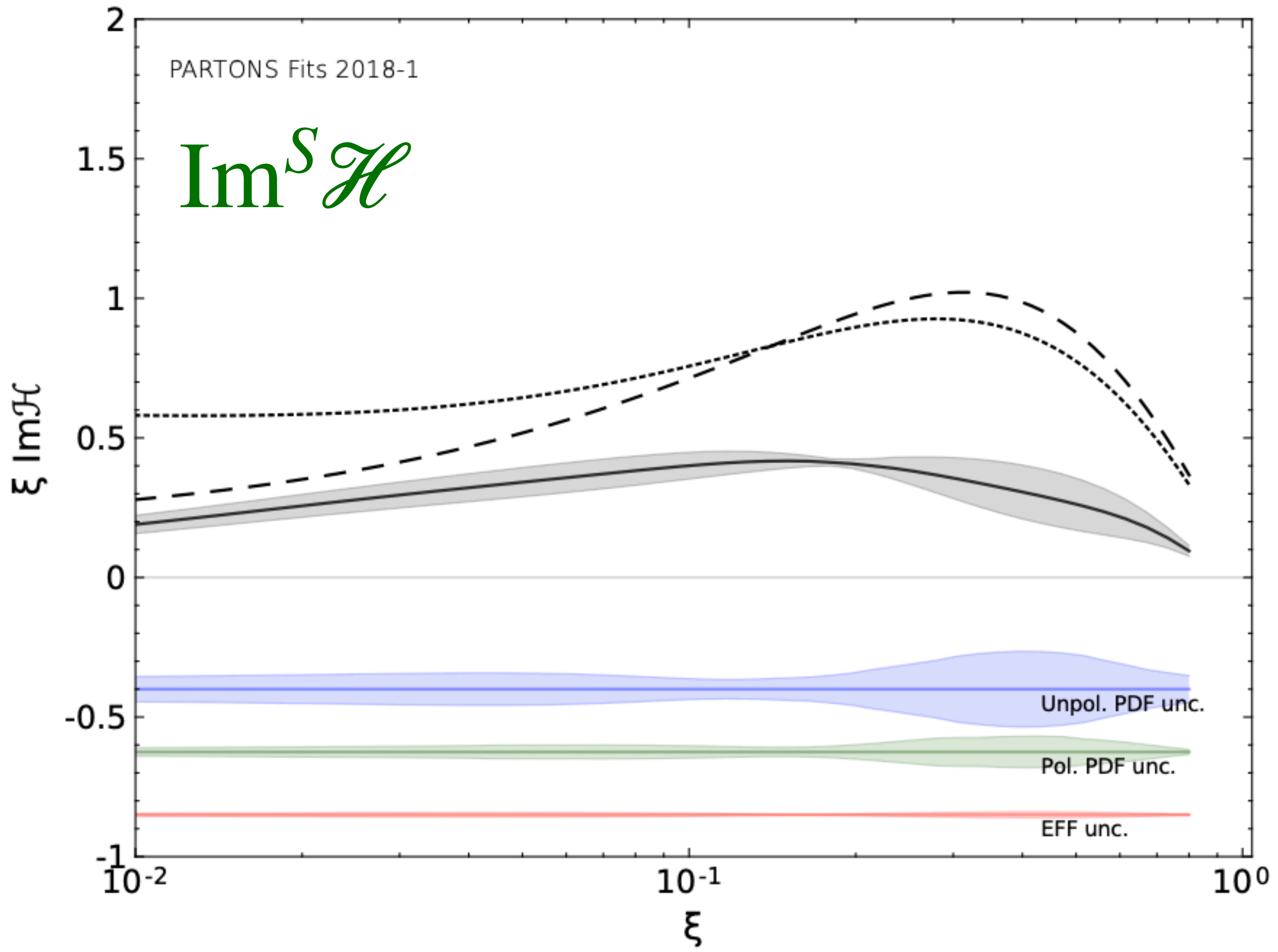
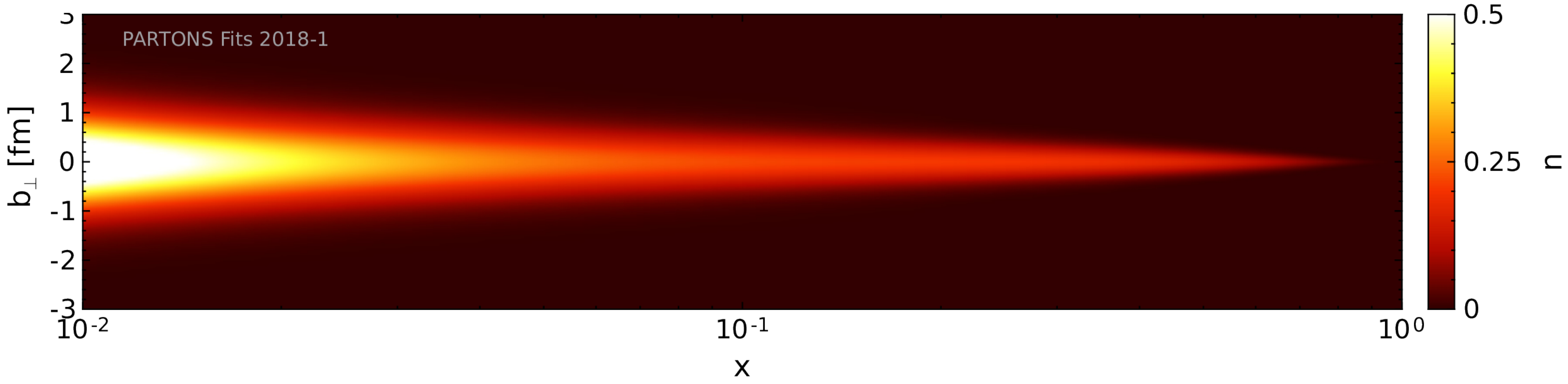
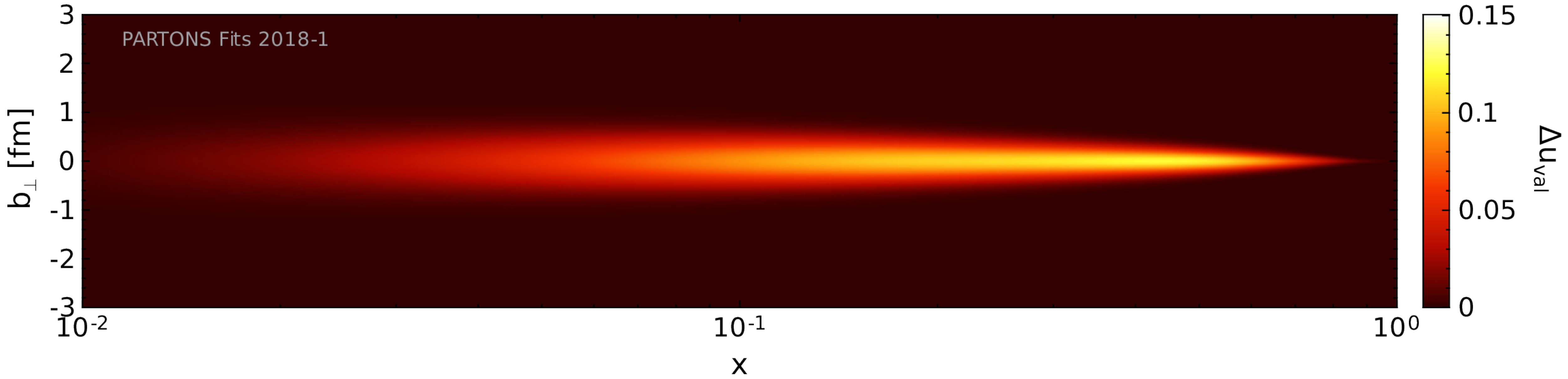




PARTONS fit

GK (LO) - - - VGG (LO)

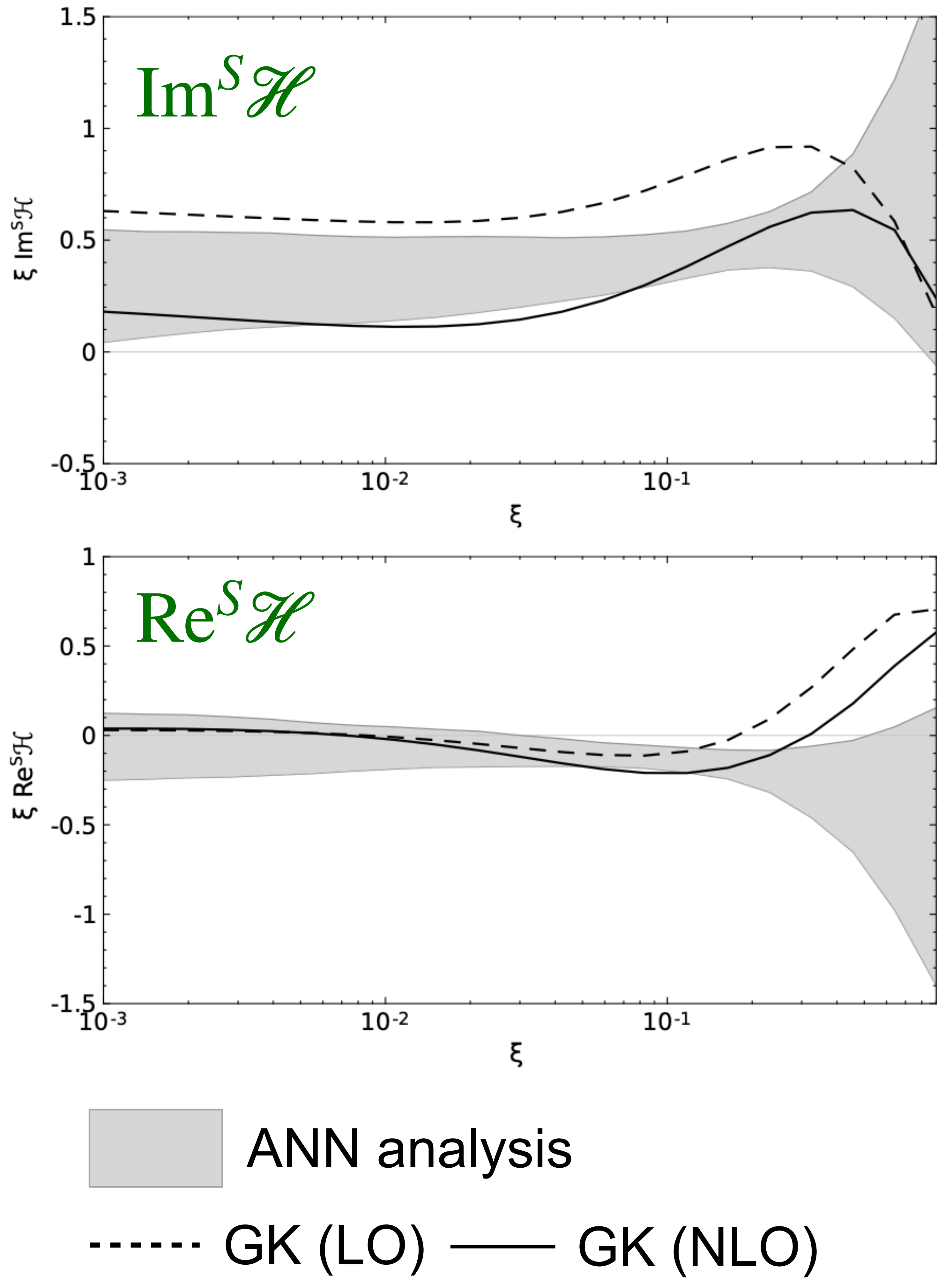




Main result: nucleon tomography

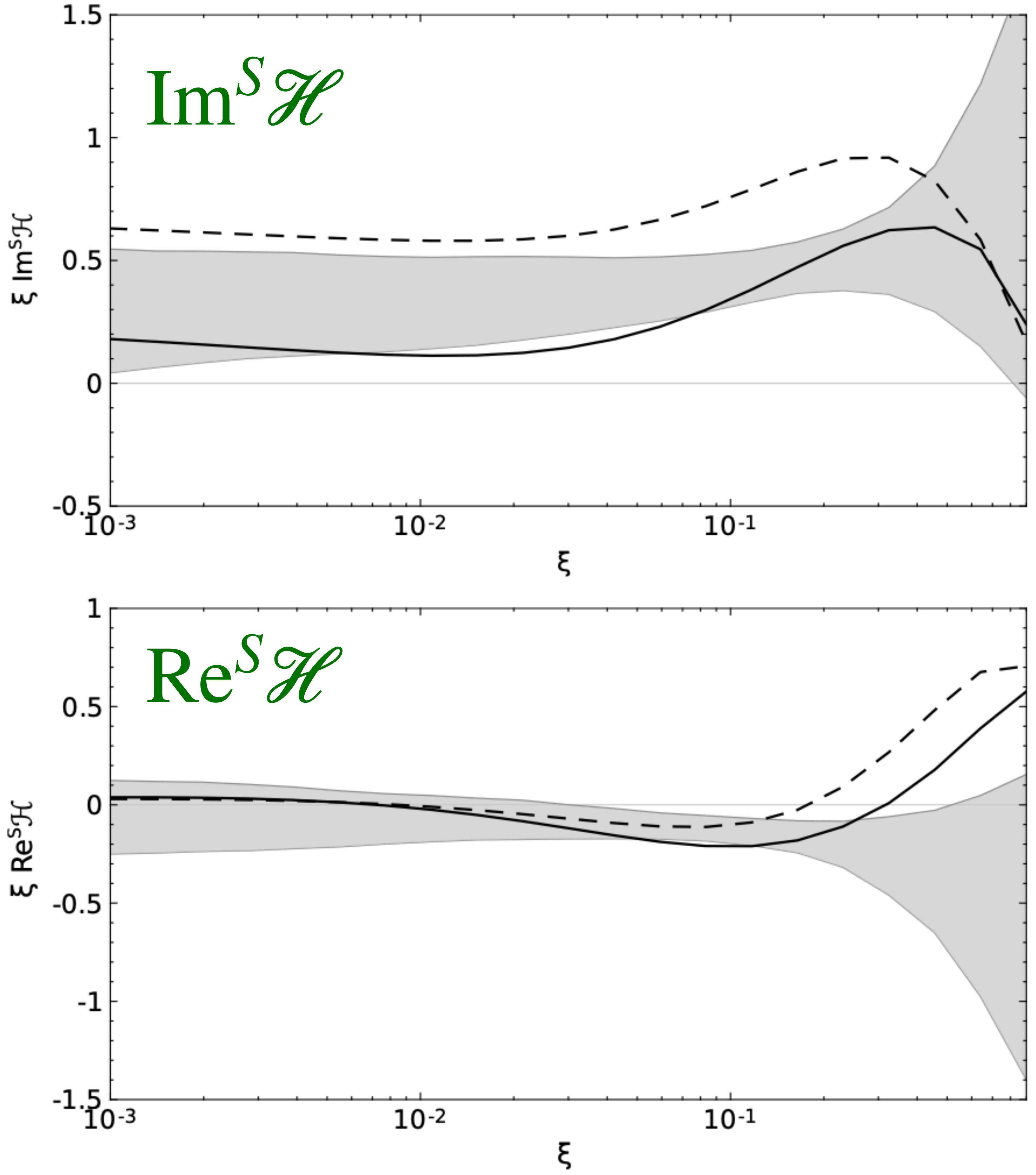
Deeply Virtual Compton scattering

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



Mechanical properties

H. Dutrieux et al., Eur. Phys. J. C 81 (2021), 300



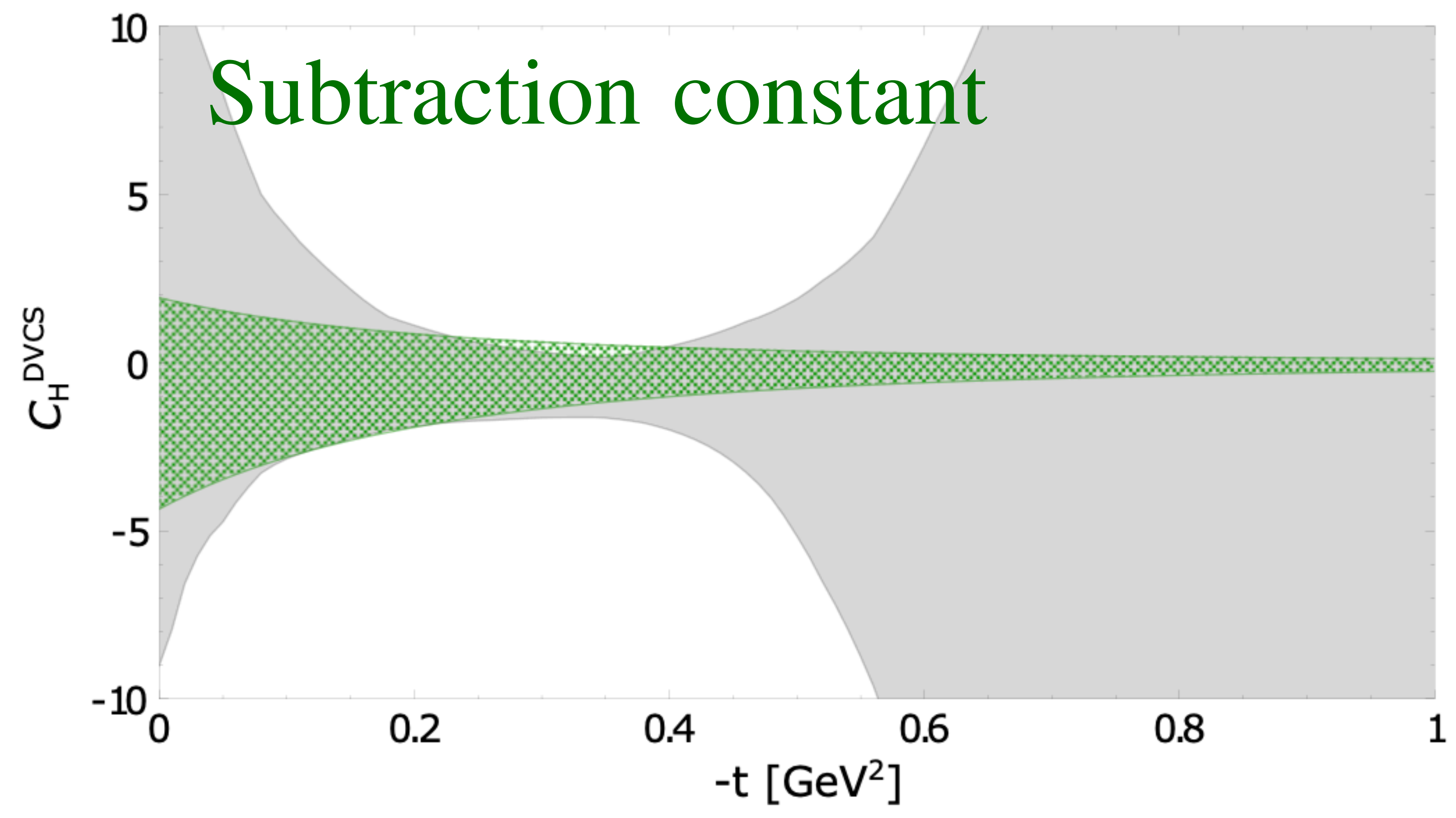
ANN analysis

------ GK (LO) —— GK (NLO)

Dispersion relation

$$\mathcal{C}_H(t, Q^2) = \mathrm{Re}\,\mathcal{H}(\xi, t, Q^2)$$

$$-\frac{1}{\pi}\int_0^1 \mathrm{d}\xi' \, \mathrm{Im}\,\mathcal{H}(\xi', t, Q^2)\left(\frac{1}{\xi - \xi'} - \frac{1}{\xi + \xi'}\right)$$



ANN analysis

Parametric model

$$d_1^{uds}(t, \mu_F^2) = d_1^{uds}(\mu_F^2)\left(1 - \frac{t}{\Lambda^2}\right)^{-\alpha}$$

$$\alpha = 3$$

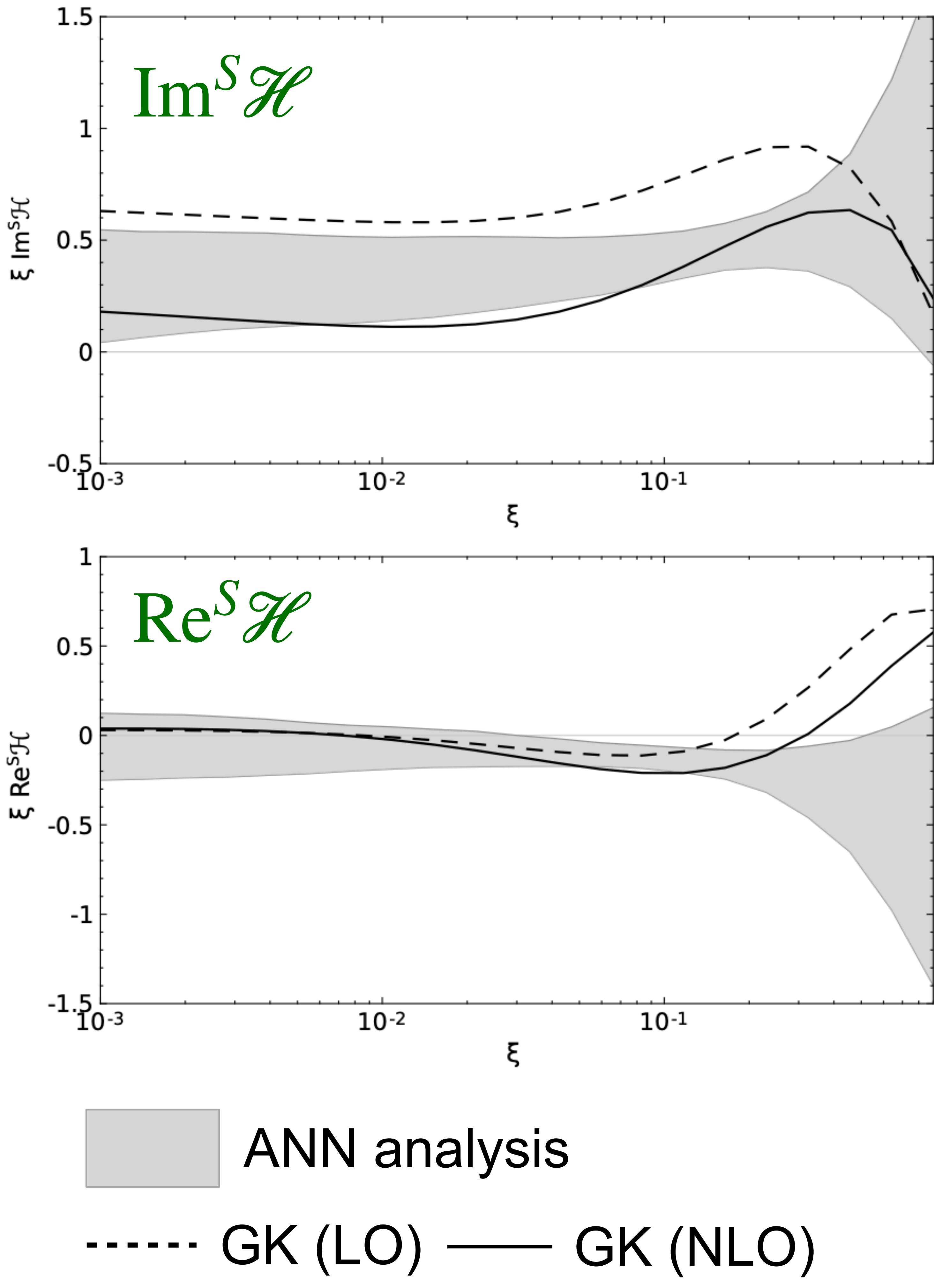
$$\Lambda = 0.8\ \mathrm{GeV}$$

Results:

Parameter	Value @$\mu_F^2 = 2$ GeV^2
$d_1^{uds}(\mu_F^2)$	-0.5 ± 1.2
$d_1^{c}(\mu_F^2)$	-0.0020 ± 0.0053
$d_1^{g}(\mu_F^2)$	-0.6 ± 1.6

Impact of positron beam

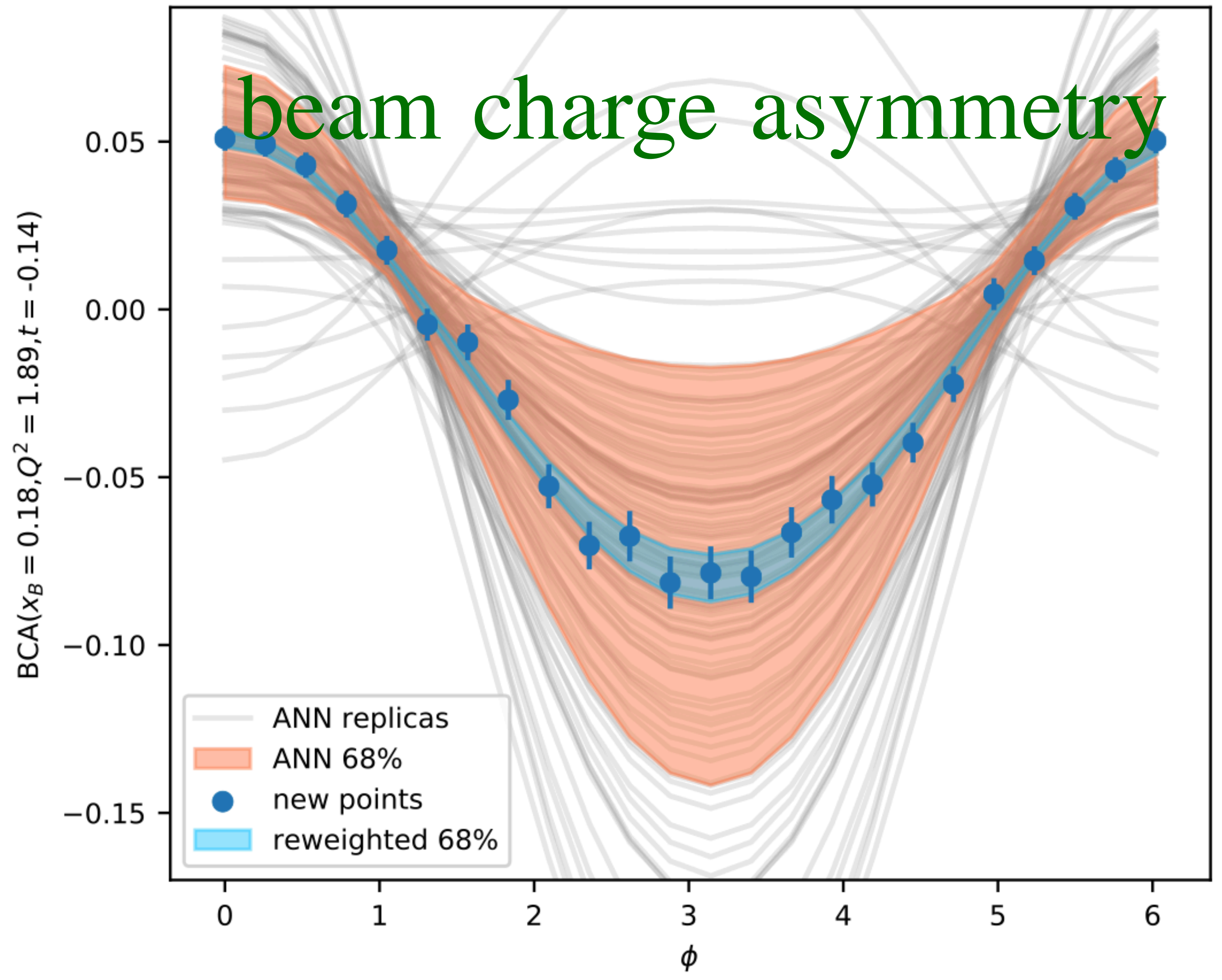
H. Dutrieux et al.,
Eur. Phys. J. A 57 (2021) 8, 250

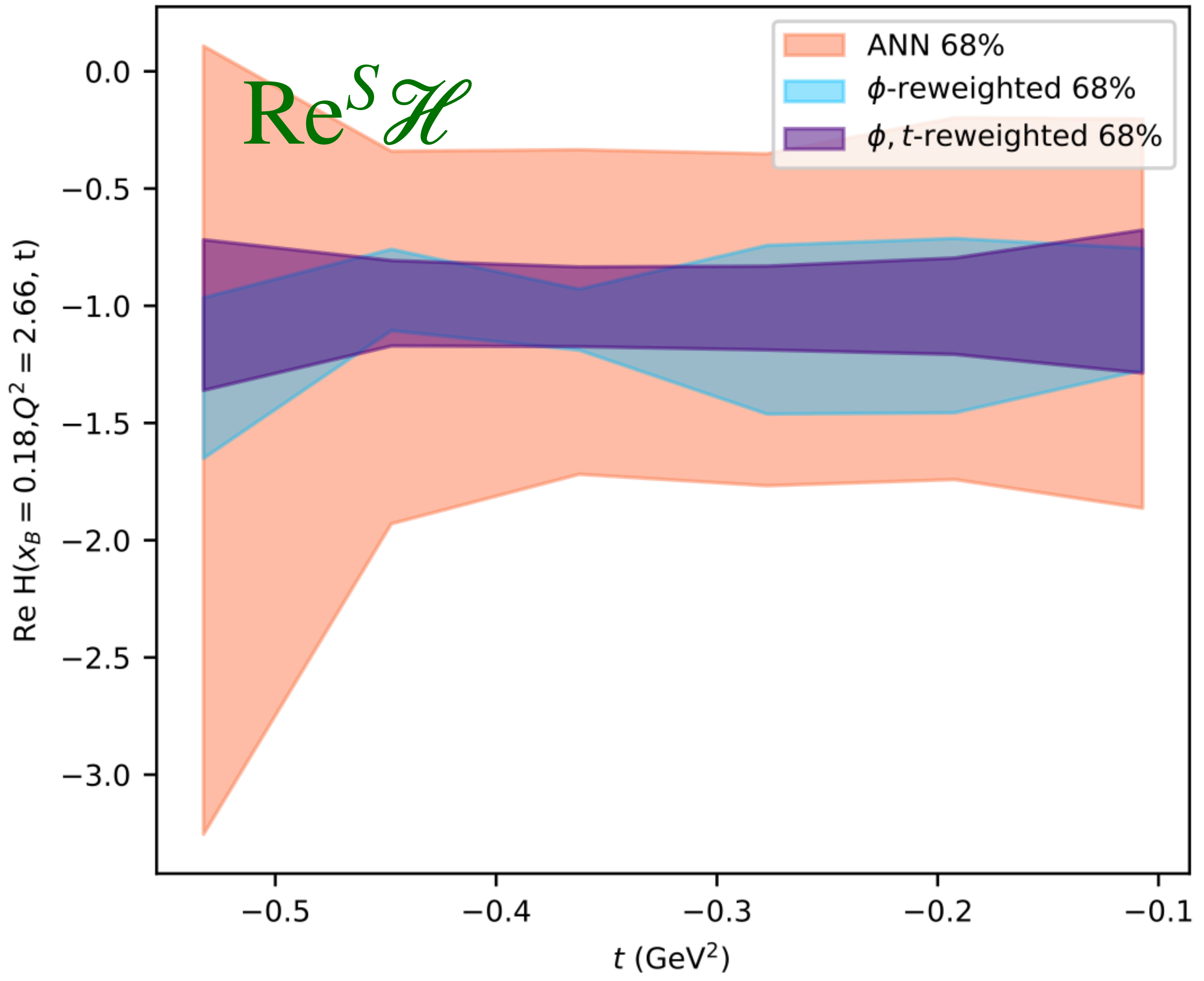


Re-weighting with positron pseudo-data

$$\omega_k = \frac{1}{Z}\chi_k^{n-1}\exp(-\chi_k^2/2)$$

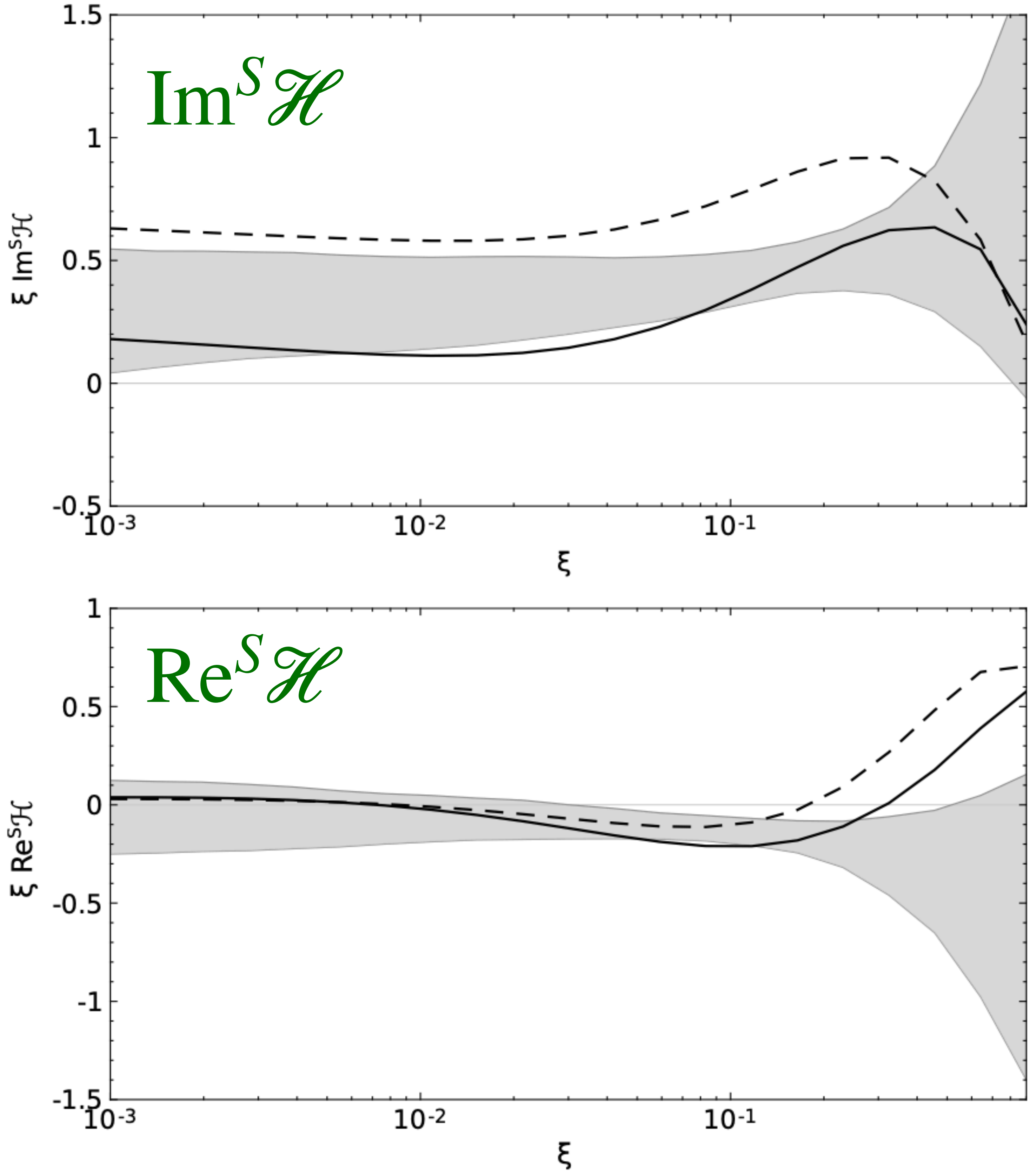
$$\chi_k^2 = (y - y_k)\Sigma^{-1}(y - y_k)^T$$





Timelike Compton scattering

O. Grocholski et al., Eur. Phys. J. C 80 (2020) 2, 171



ANN analysis

------ GK (LO) —— GK (NLO)

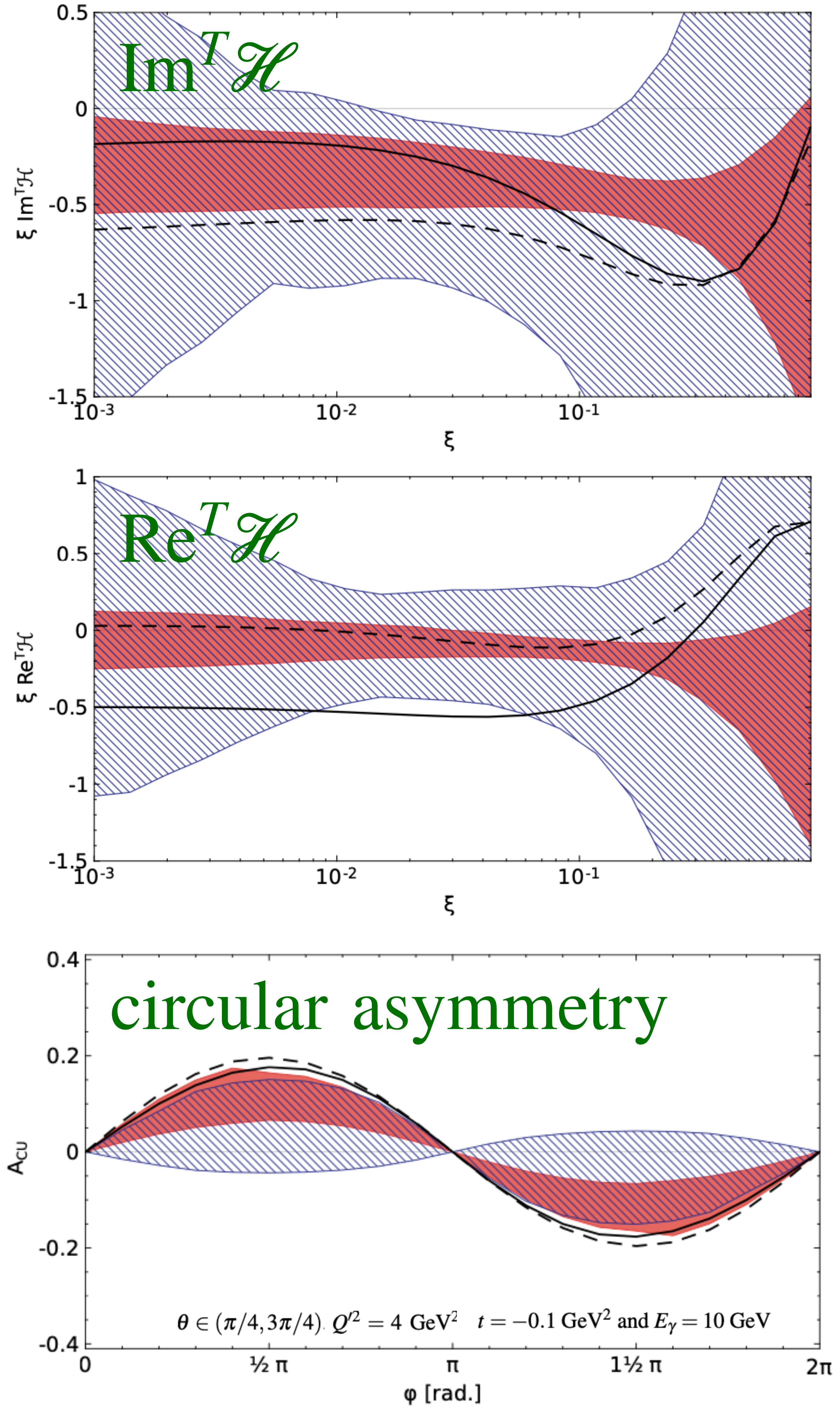
Relation between space-like and time-like amplitudes

$$^T\mathcal{H} \overset{\text{LO}}{=} {}^S\mathcal{H}^*$$

$$^T\widetilde{\mathcal{H}} \overset{\text{LO}}{=} -{}^S\widetilde{\mathcal{H}}^*$$

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

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



TCS from DVCS (LO)

TCS from DVCS (NLO)

Double DVCS

K. Deja, V. Martínez-Fernández,
B. Pire, PS, J. Wagner
preliminary

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

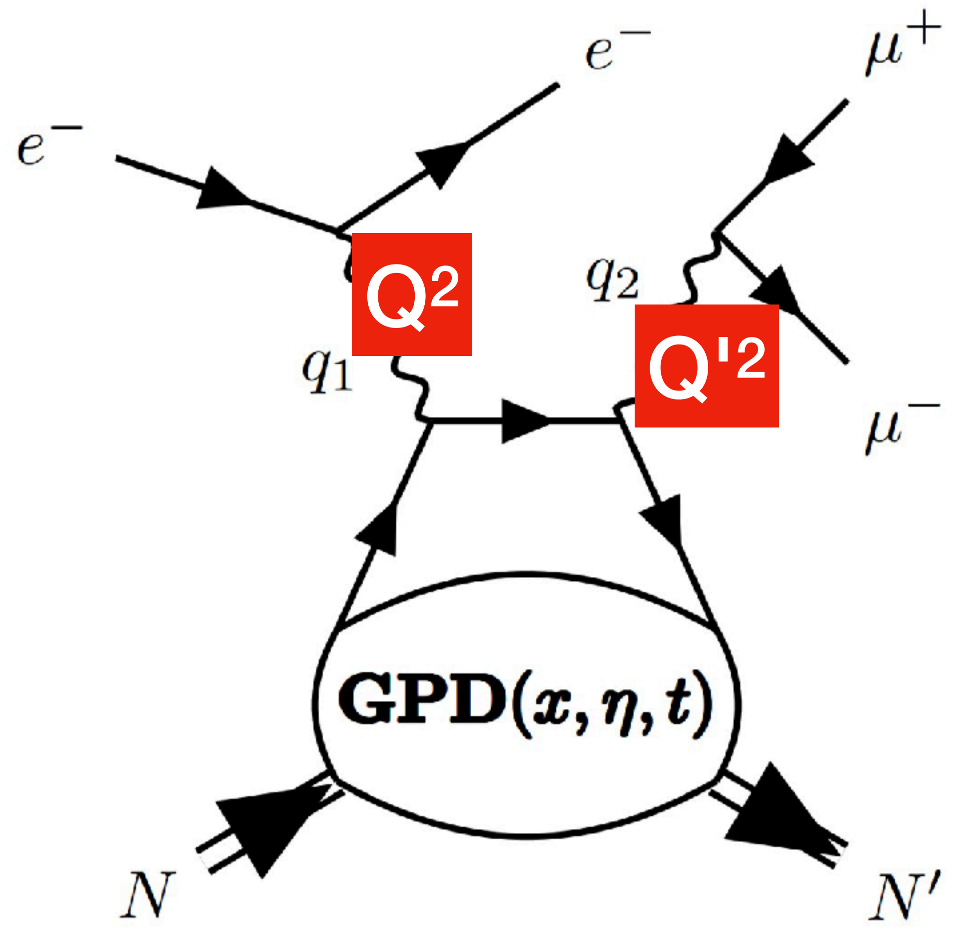
$$(\mathcal{H},\mathcal{E})(\rho,\xi,t) = \sum_{f=\{u,d,s\}} \int_{-1}^{1} dx\; C_f^{(-)}(x,\rho)(H_f,E_f)(x,\xi,t)$$

$$(\widetilde{\mathcal{H}},\widetilde{\mathcal{E}})(\rho,\xi,t) = \sum_{f=\{u,d,s\}} \int_{-1}^{1} dx\; C_f^{(+)}(x,\rho)(\widetilde{H}_f,\widetilde{E}_f)(x,\xi,t)$$

$$C_f^{(\pm)}(x,\rho) \stackrel{LO}{=} \left(\frac{e_f}{e}\right)^2 \left(\frac{1}{\rho - x - i0} \pm \frac{1}{\rho + x - i0}\right)$$

$$\xi = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2}$$

$$\rho = \xi\frac{Q^2 - Q'^2}{Q^2 + Q'^2}$$



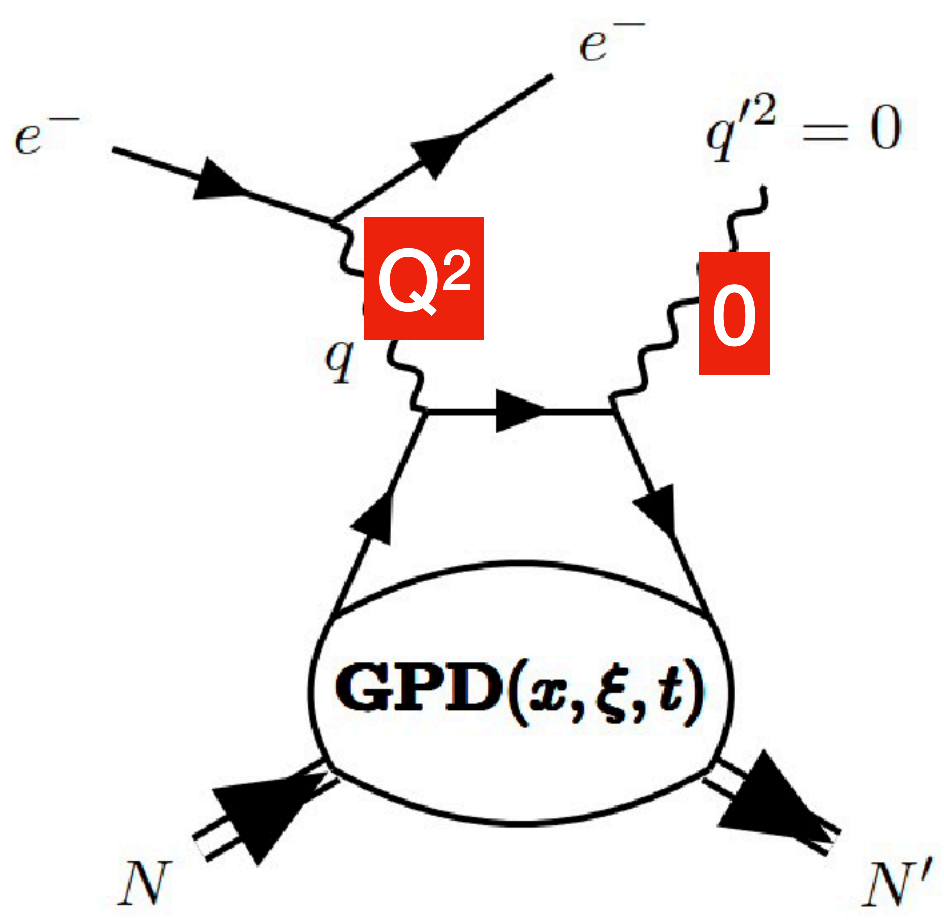
- We revisit DDVCS phenomenology in view of new experiments, including reevaluation of DDVCS and BH cross-sections with Kleiss-Stirling spinor techniques

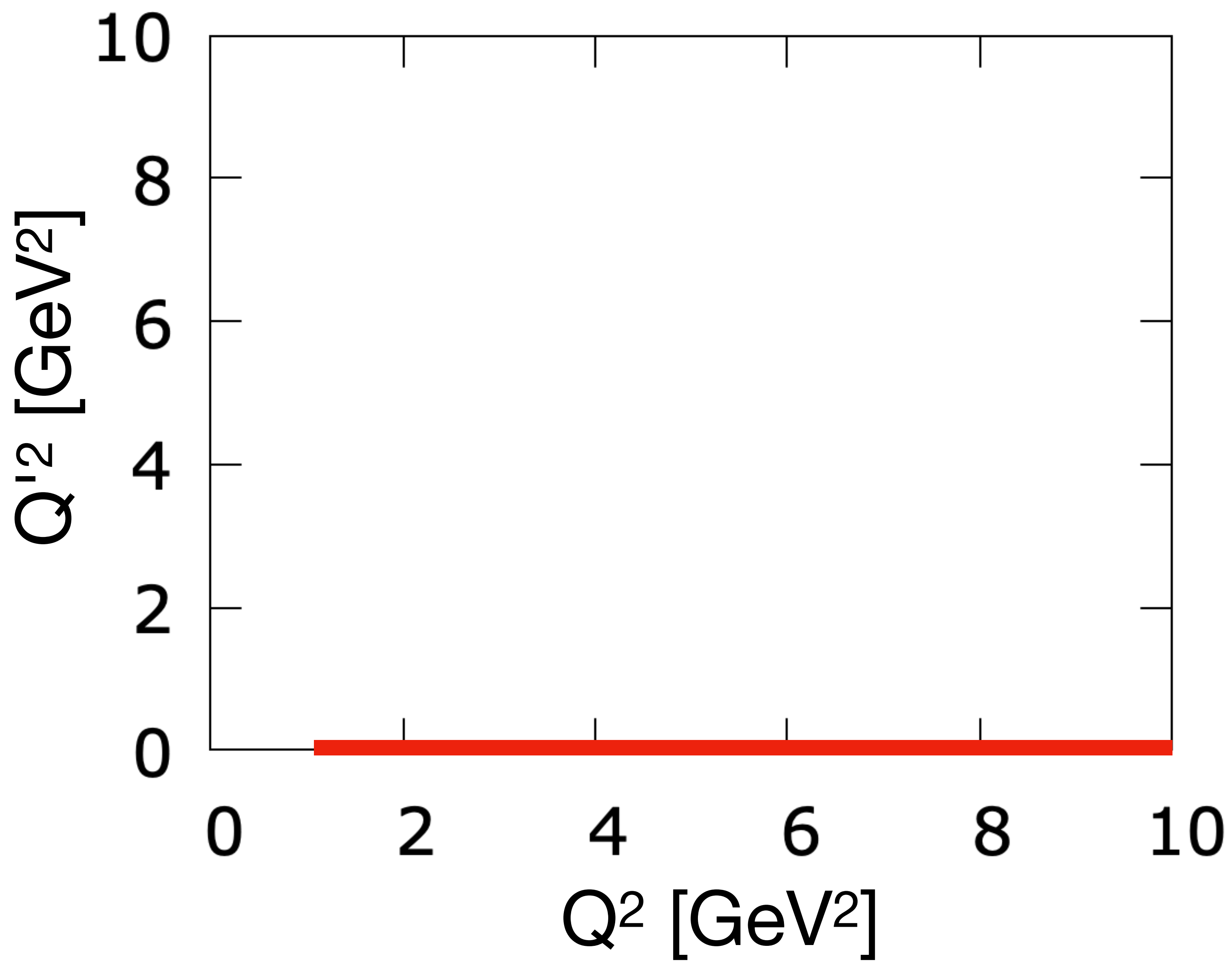
- Obtained results will be available in PARTONS and EpIC MC generator

- See talk by V. Martínez-Fernández at DIS'23 for final results and more details

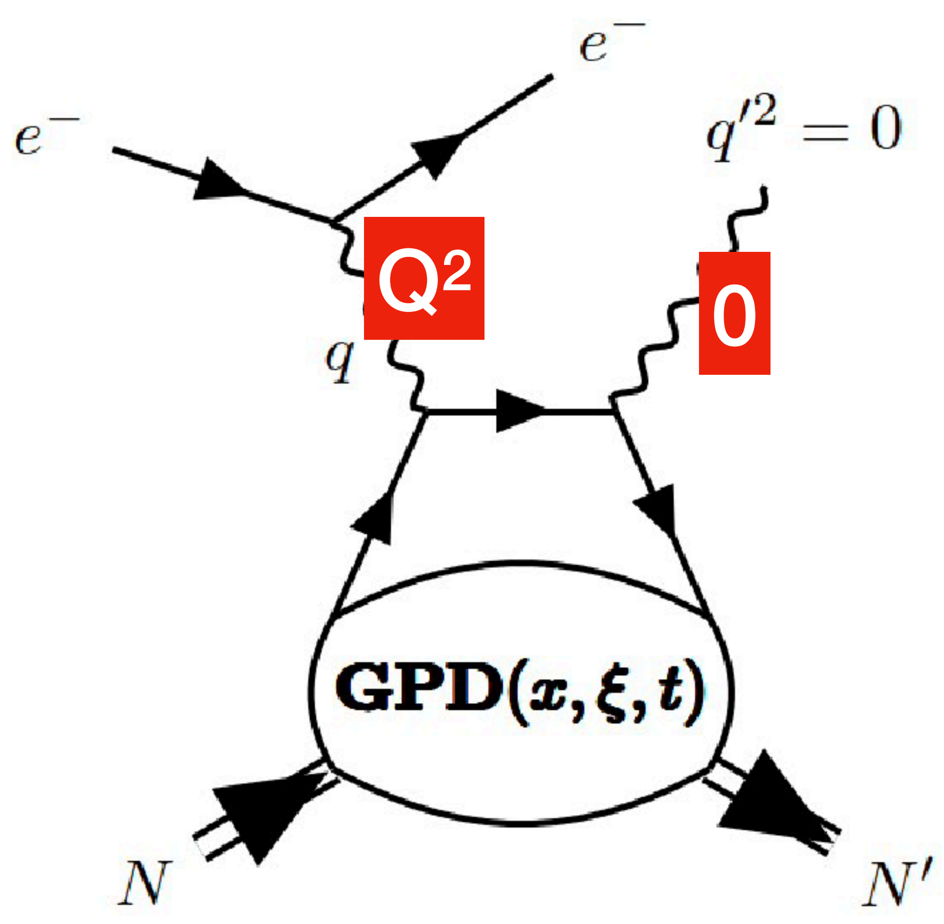
Double DVCS

DVCS



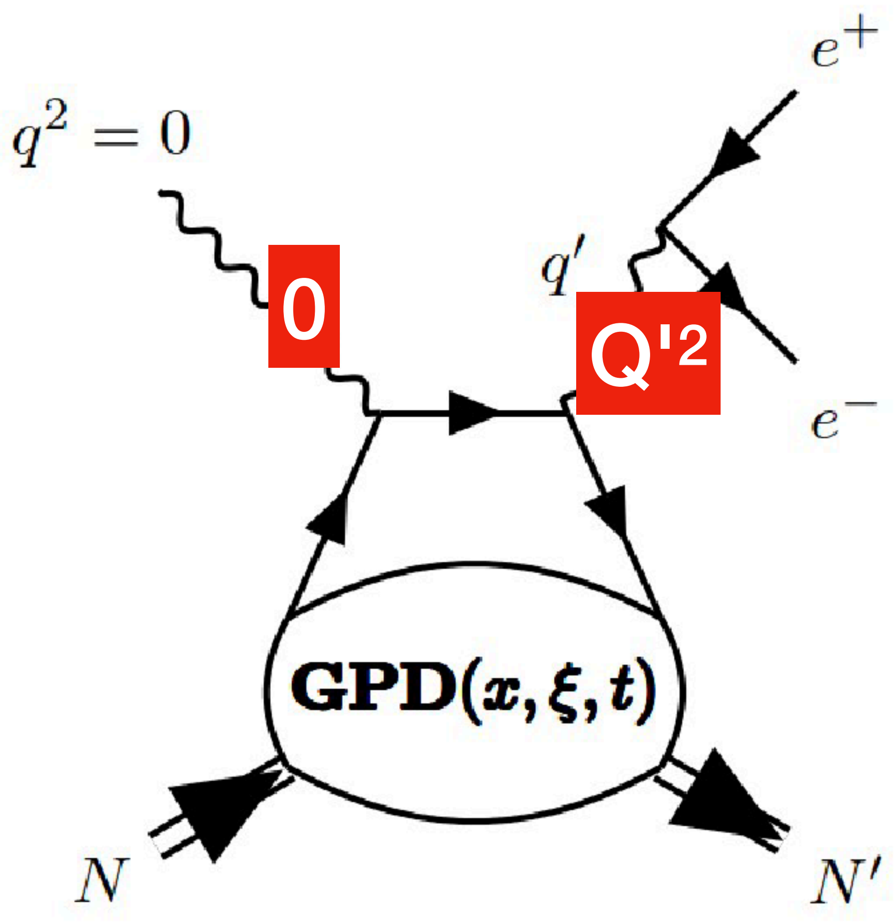


DVCS

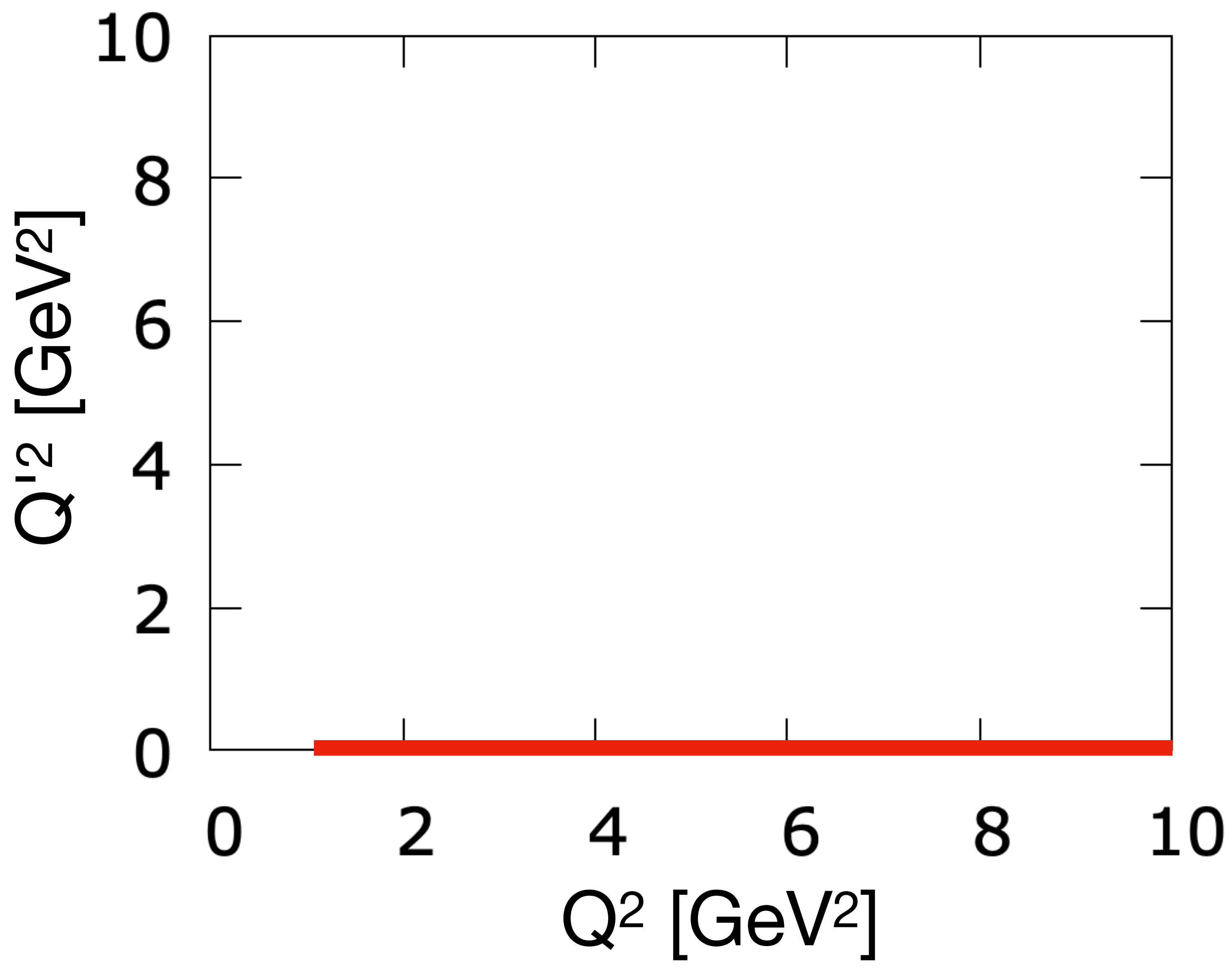


e^-
e^-
$q'^2 = 0$
Q²
0
q
$\mathbf{GPD}(x, \xi, t)$
N
N'

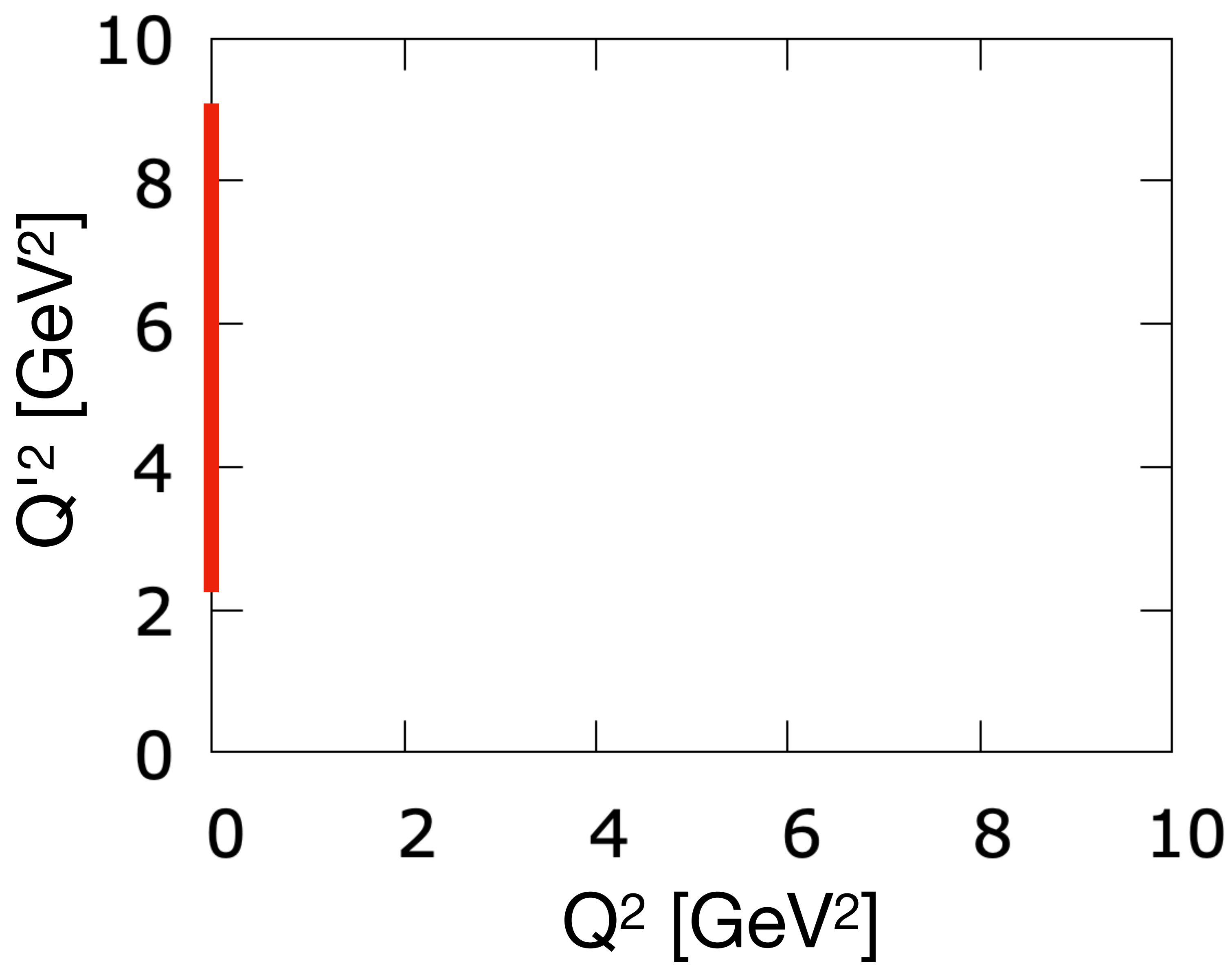
TCS



$q^2 = 0$
e^+
0
q'
Q'²
e^-
$\mathbf{GPD}(x, \xi, t)$
N
N'



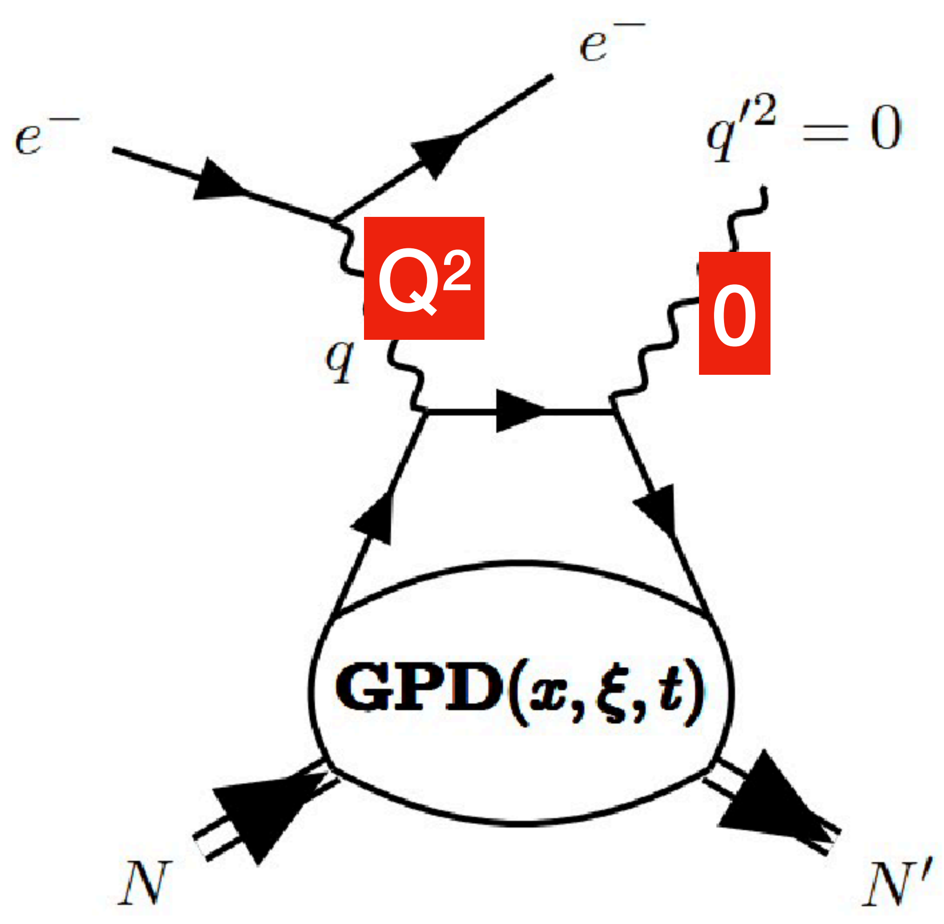
Q'² [GeV²]
Q² [GeV²]
0
2
4
6
8
10



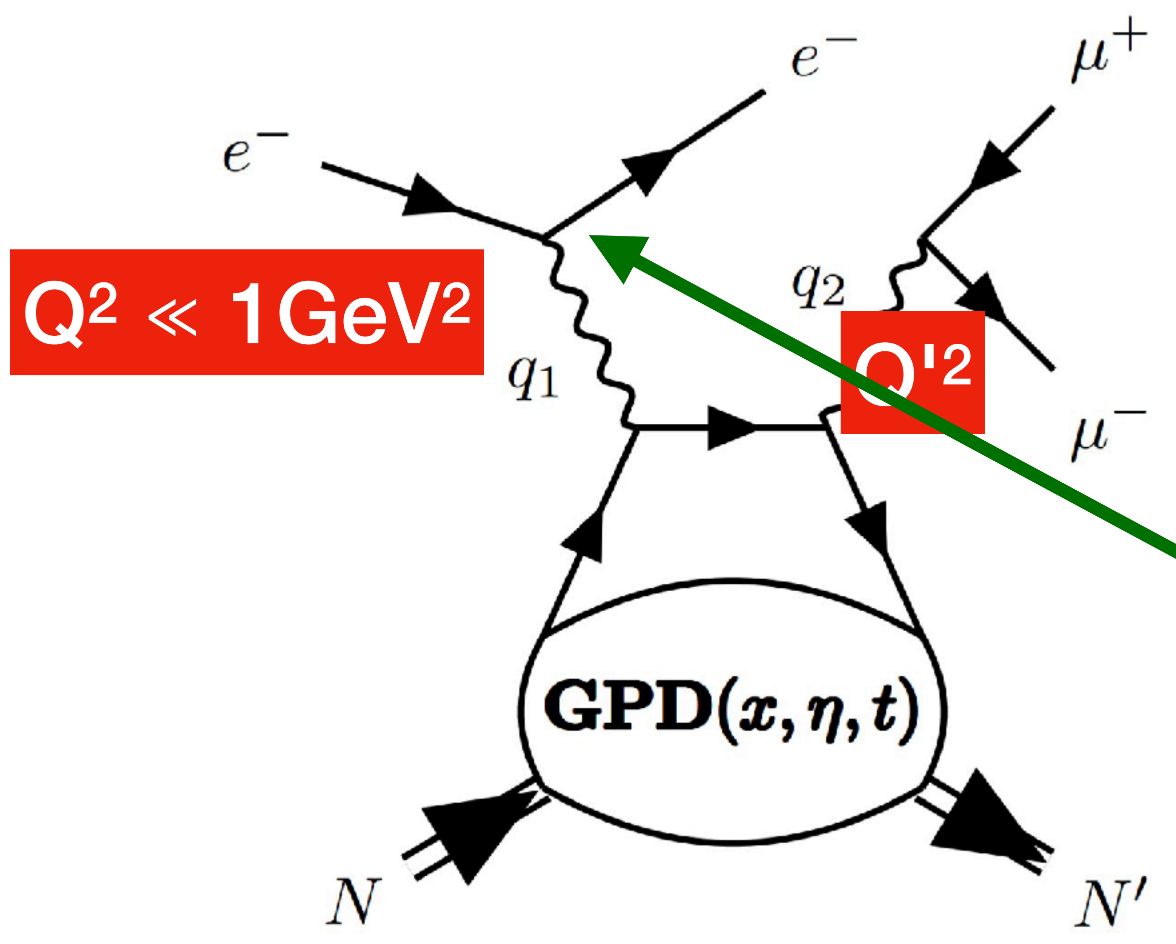
Q'² [GeV²]
Q² [GeV²]
0
2
4
6
8
10

Double DVCS

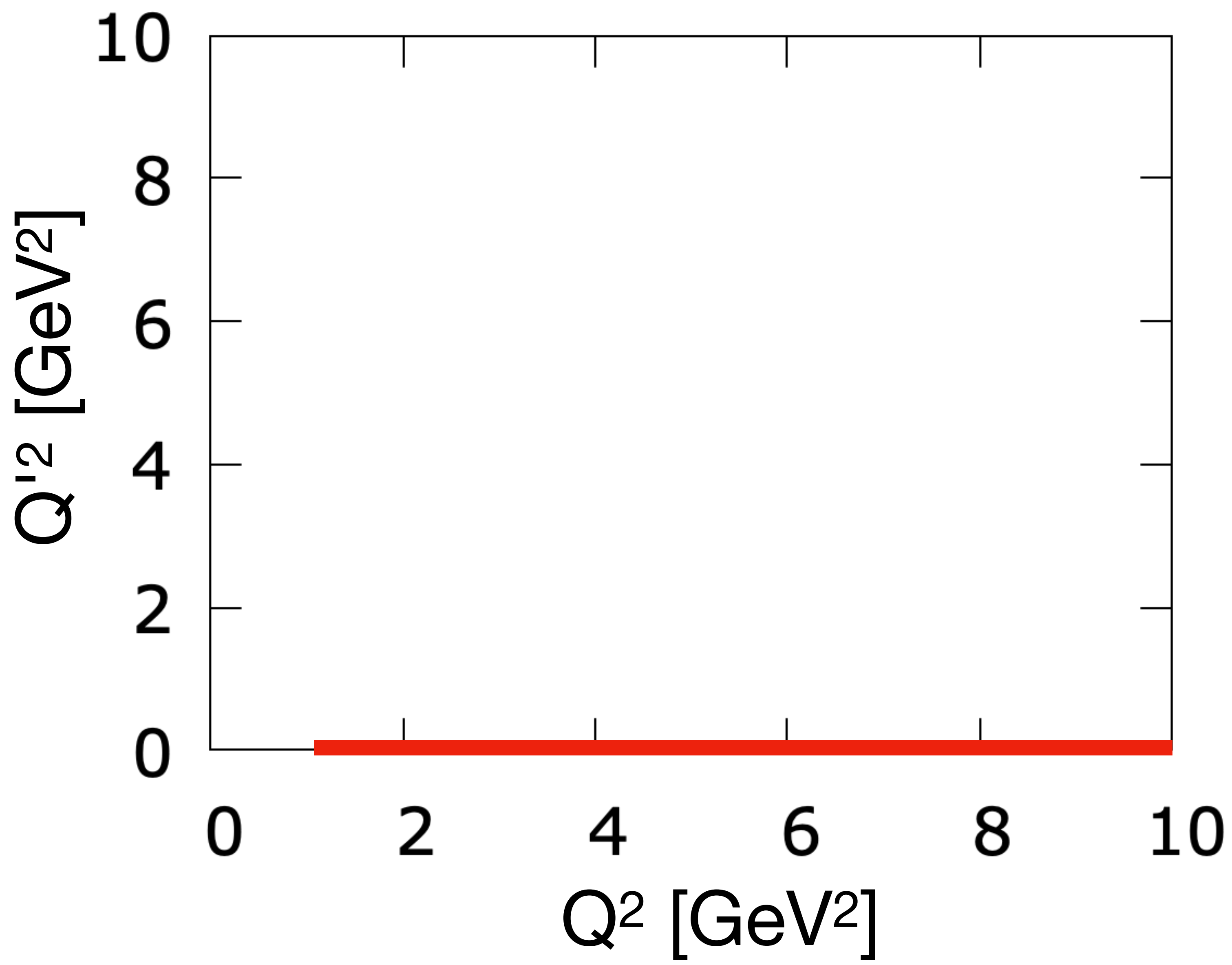
DVCS

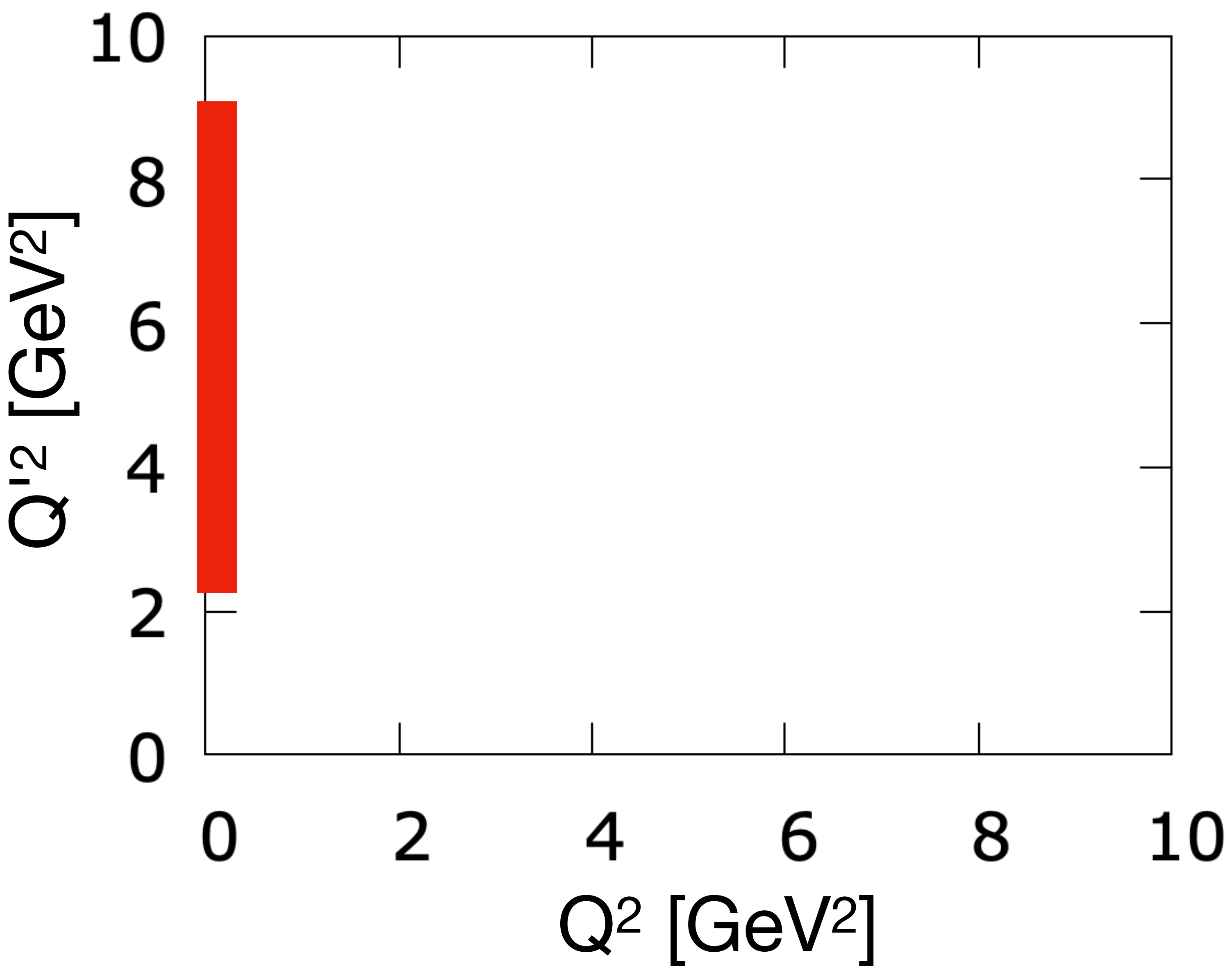


TCS in ep experiments



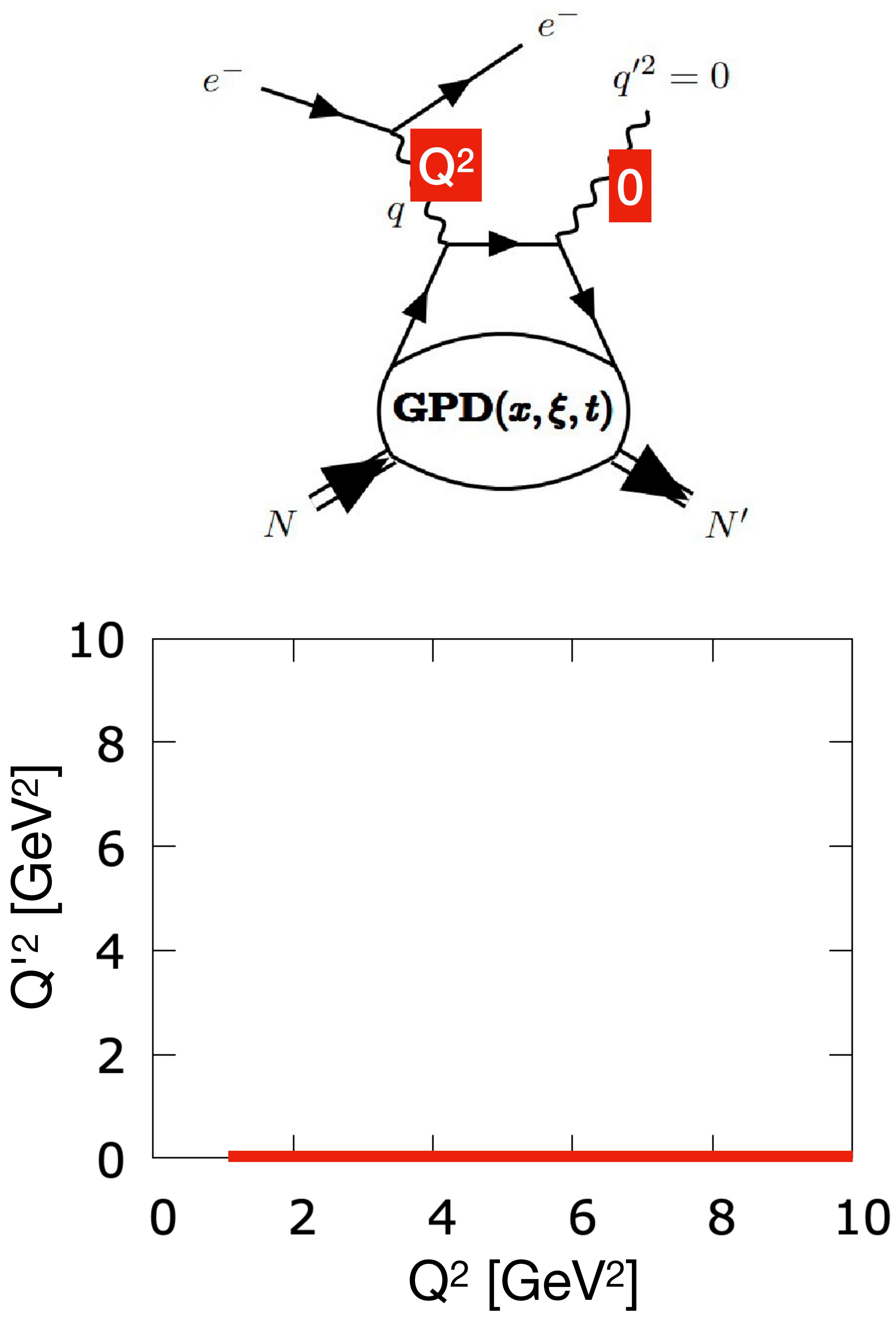
α_{EM} already here (in Γ)!



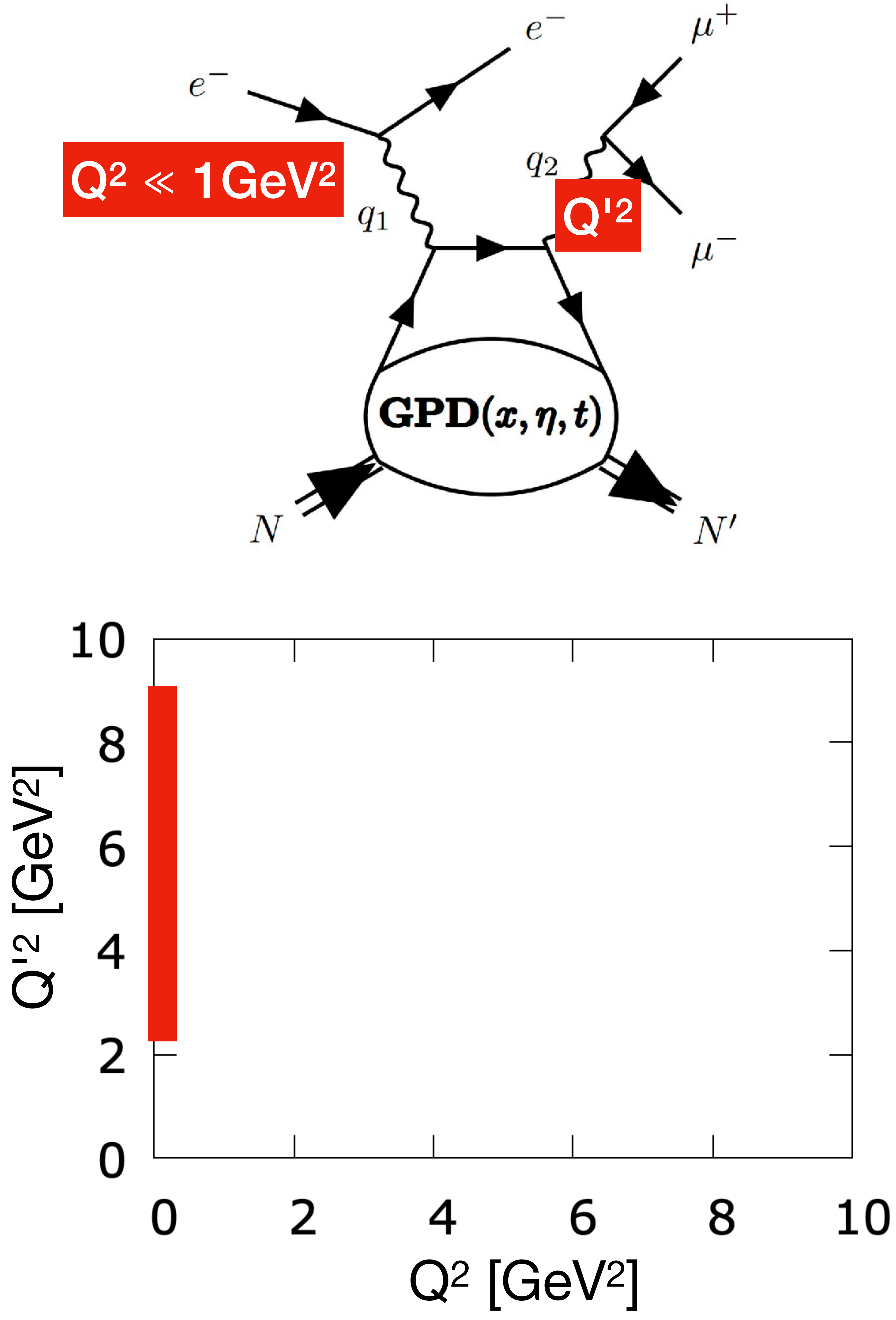


Double DVCS

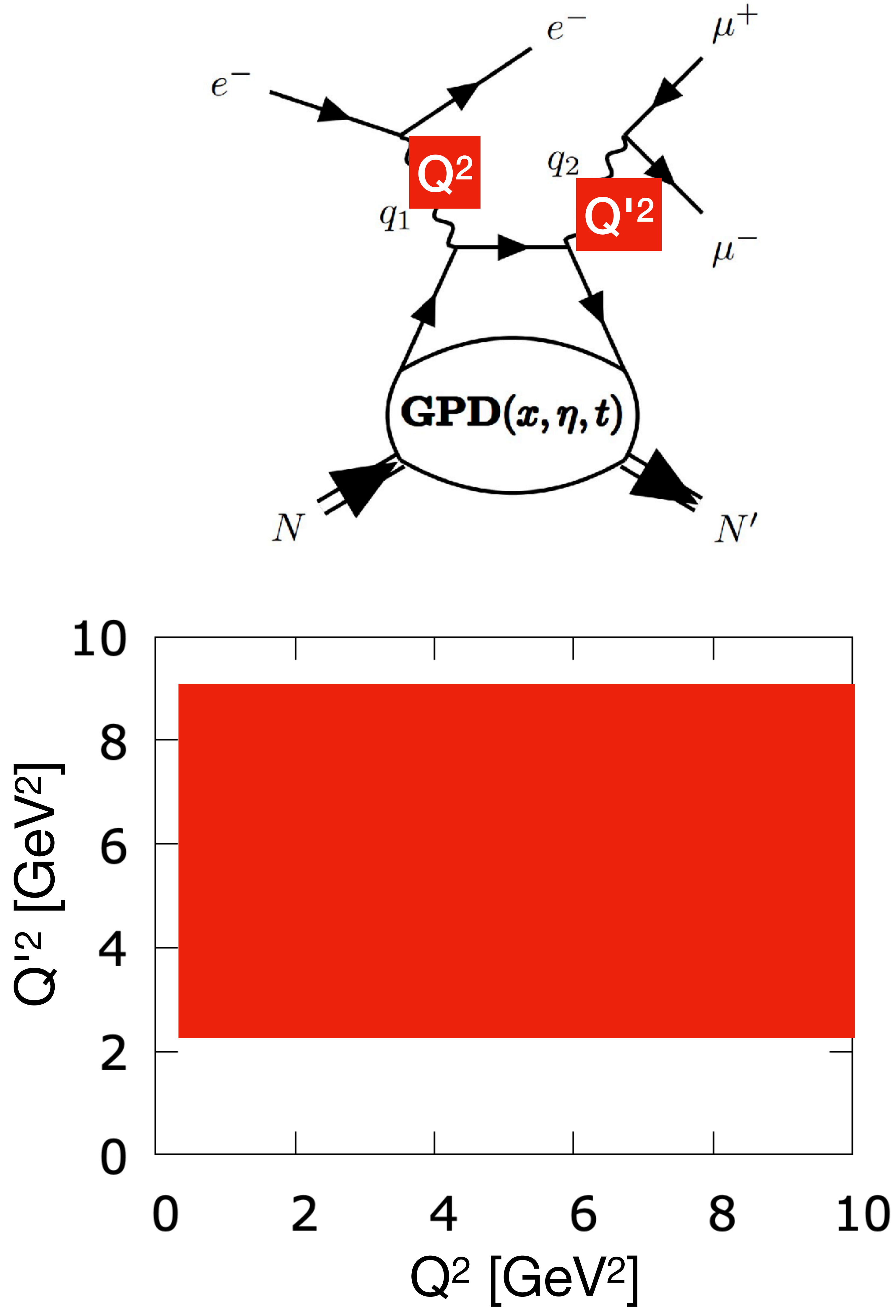
DVCS



TCS in ep experiments



DDVCS



Double DVCS

K. Deja, V. Martínez-Fernández,
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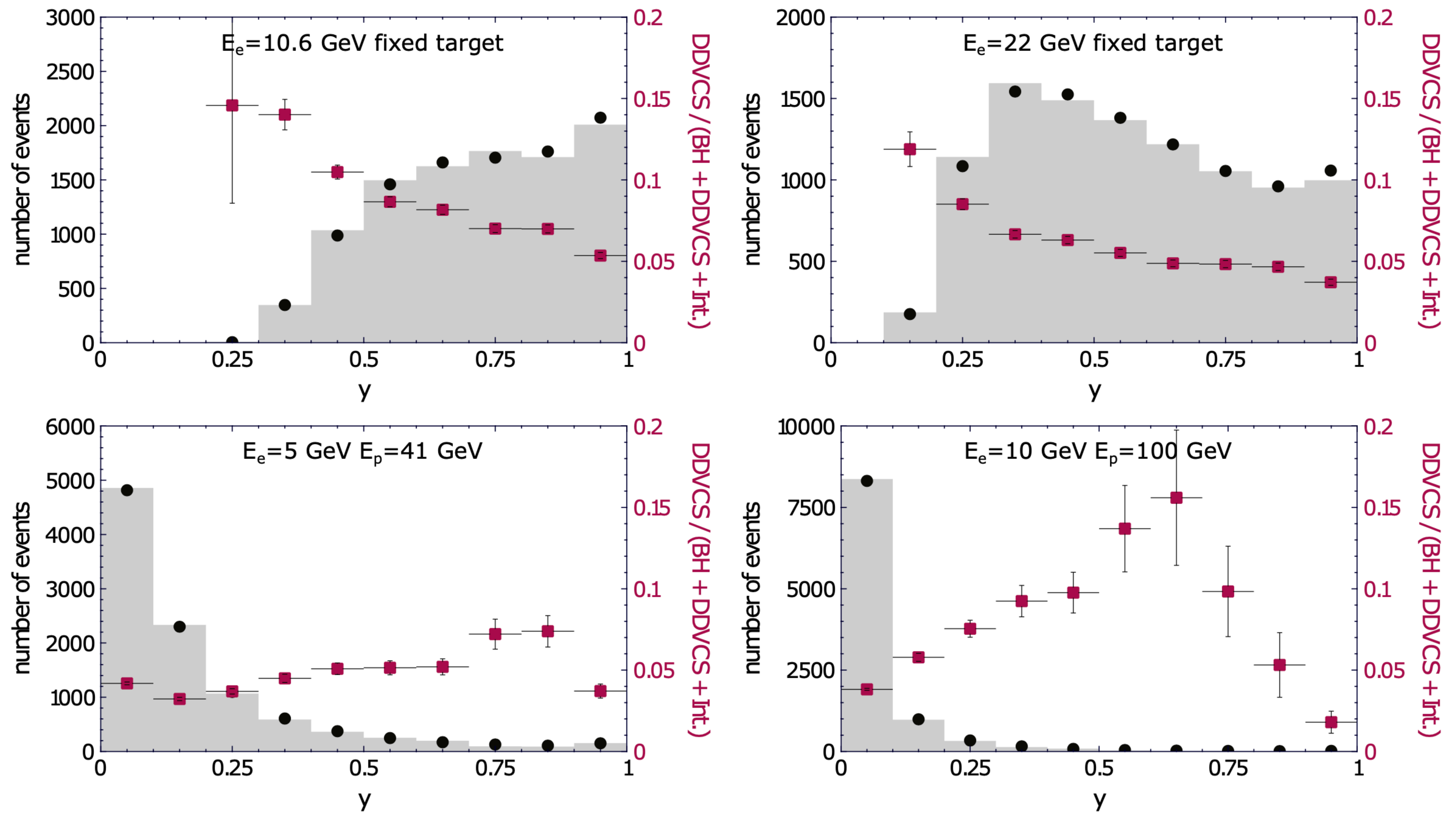
preliminary



EpIC MC
● integrated cross-section
■ pure DDVCS contribution

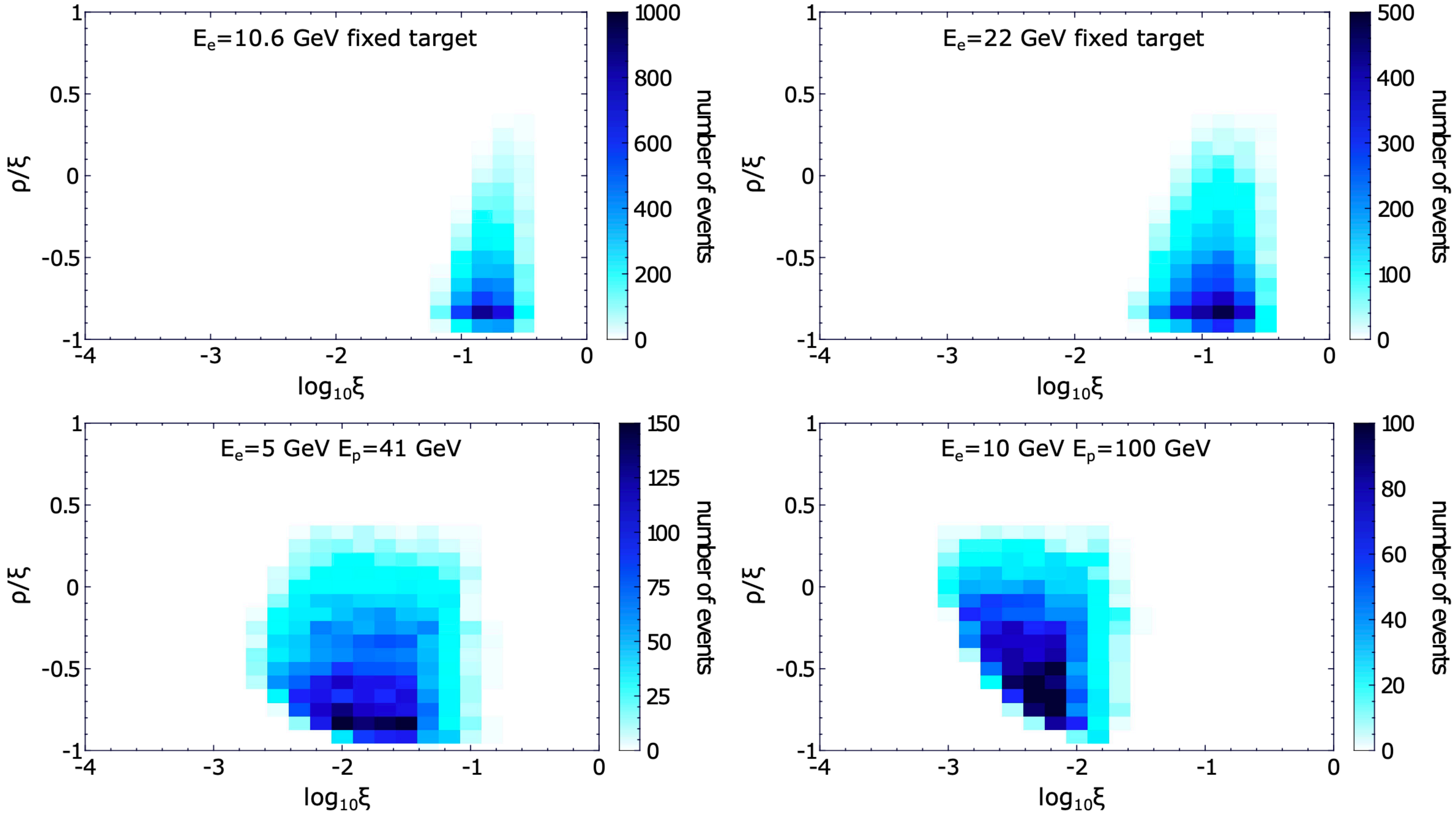
Kinematic cuts:

- 0.15 GeV² < Q² < 5 GeV²
- 2.25 GeV² < Q'² < 9 GeV²
- 0.1 GeV² < t < 0.8 GeV² (JLab)
- 0.05 GeV² < t < 1 GeV² (EIC)
- 0.1 < φ, φ$_l$ < 2π − 0.1
- π/4 < θ$_l$ < 3π/4
- 0.1 < y < 1 (JLab)
- 0.05 < y < 1 (EIC)

Experiment	Beam energies [GeV]	Range of $\|t\|$ [GeV^2]	$\sigma\|_{0<y<1}$ [pb]	$\mathcal{L}^{10k}\|_{0<y<1}$ [fb^{-1}]	$y_{\min}$	$\sigma\|_{y_{\min}<y<1}/\sigma\|_{0<y<1}$
JLab12	$E_e = 10.6,\ E_p = M$	$(0.1, 0.8)$	0.14	70	0.1	1
JLab2+	$E_e = 22,\ E_p = M$	$(0.1, 0.8)$	0.46	22	0.1	1
EIC	$E_e = 5,\ E_p = 41$	$(0.05, 1)$	3.9	2.6	0.05	0.73
EIC	$E_e = 10,\ E_p = 100$	$(0.05, 1)$	4.7	2.1	0.05	0.32

Double DVCS

K. Deja, V. Martínez-Fernández, B. Pire, PS, J. Wagner
preliminary



Kinematic cuts:

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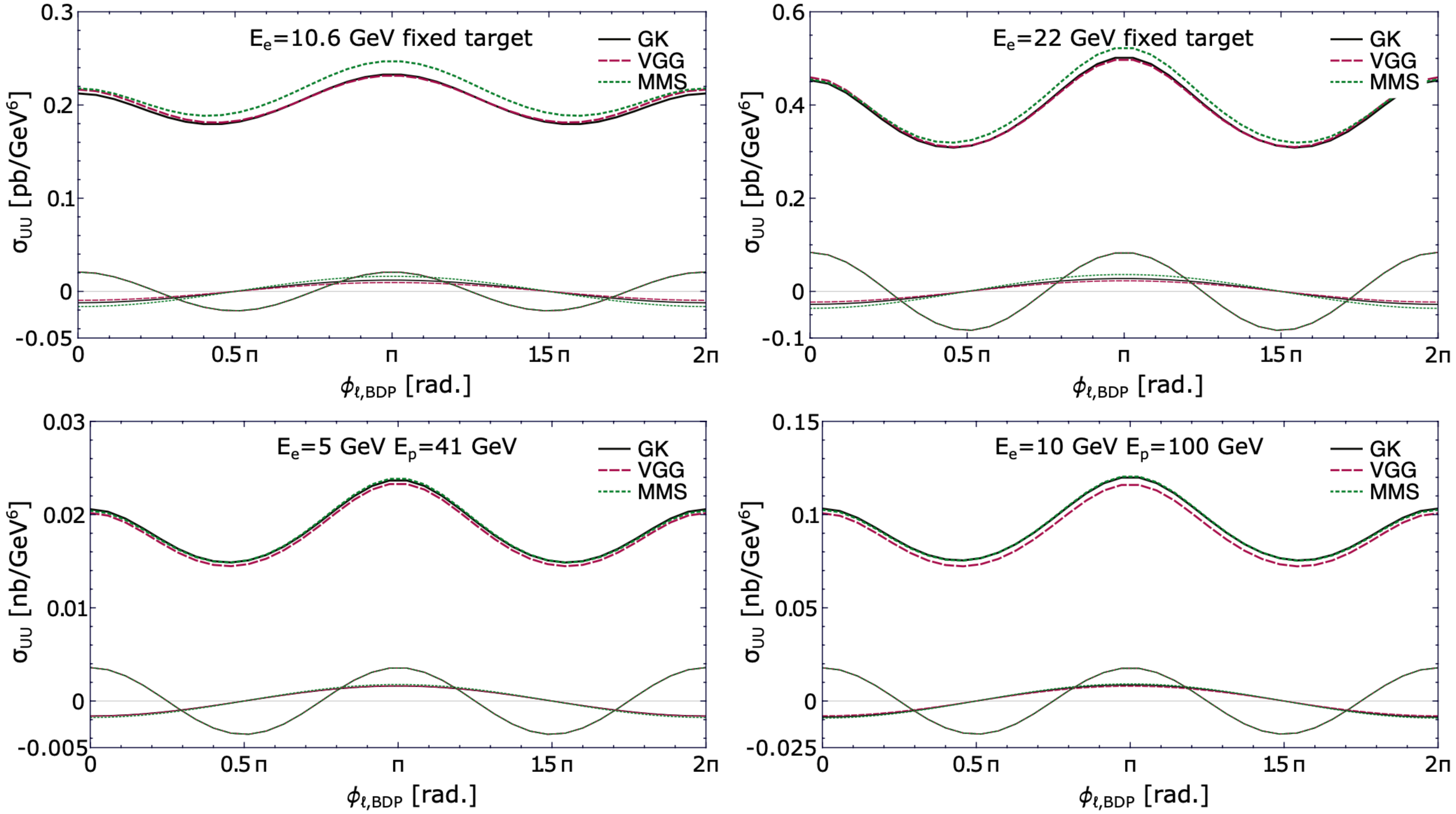
- 0.1 GeV^2 < t < 0.8 GeV^2 (JLab)
- 0.05 GeV^2 < t < 1 GeV^2 (EIC)
- 0.1 < φ, φ_l < $2\pi - 0.1$
- $\pi/4 < \theta_l < 3\pi/4$
- 0.1 < y < 1 (JLab)
- 0.05 < y < 1 (EIC)

Double DVCS

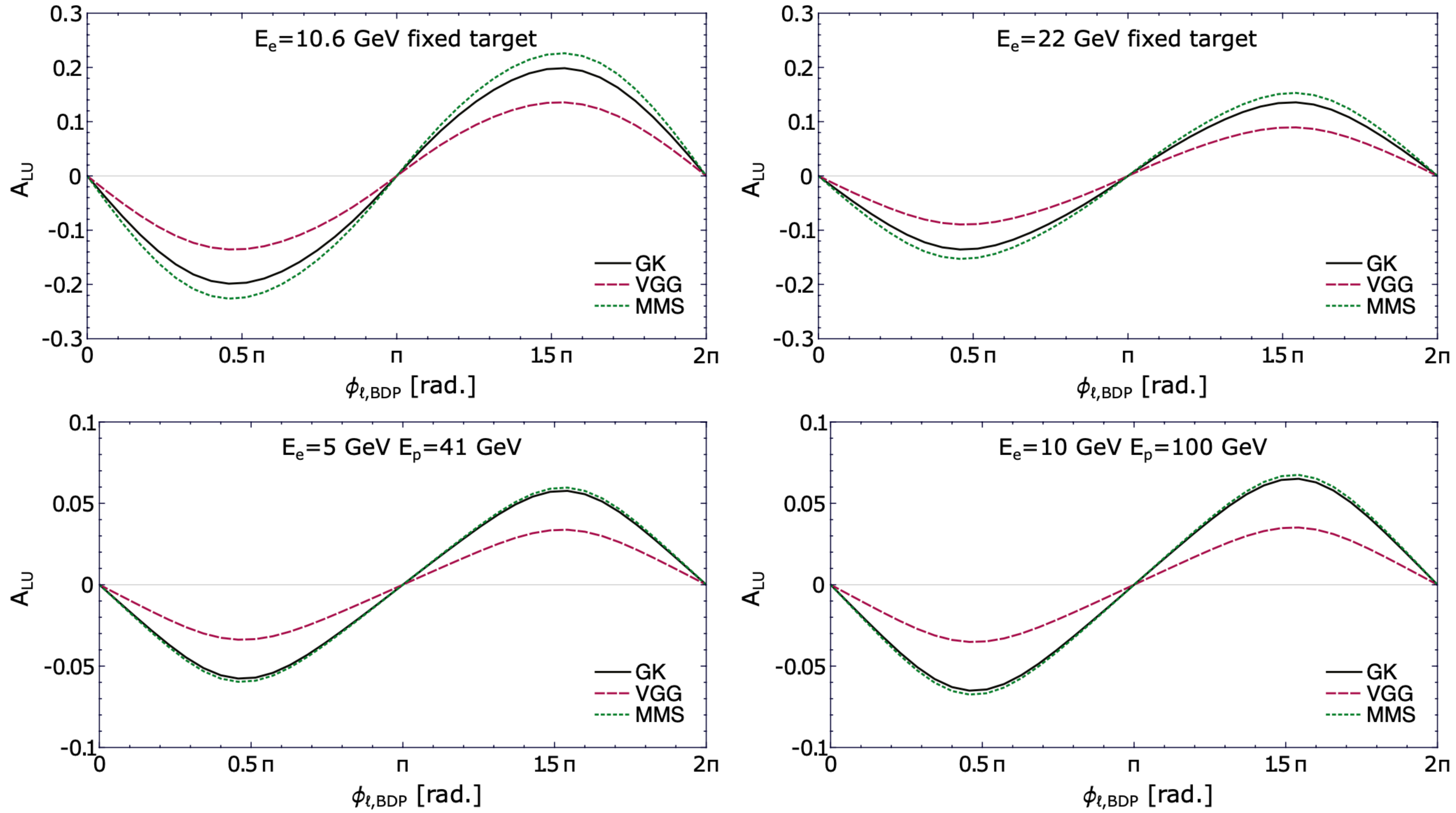
K. Deja, V. Martínez-Fernández,
B. Pire, PS, J. Wagner

preliminary

Unpolarised cross-section integrated over $0 < \phi < 2\pi$ and $\pi/4 < \theta l < 3\pi/4$



corresponding ALU asymmetry



GK

VGG

MMS

Experiment	Beam energies [GeV]	y	$\|t\|$ [GeV^2]	Q^2 [GeV^2]	Q'^2 [GeV^2]
JLab12	$E_e = 10.6,\ E_p = M$	0.5	0.2	0.6	2.5
JLab2+	$E_e = 22,\ E_p = M$	0.3	0.2	0.6	2.5
EIC	$E_e = 5,\ E_p = 41$	0.15	0.1	0.6	2.5
EIC	$E_e = 10,\ E_p = 100$	0.15	0.1	0.6	2.5

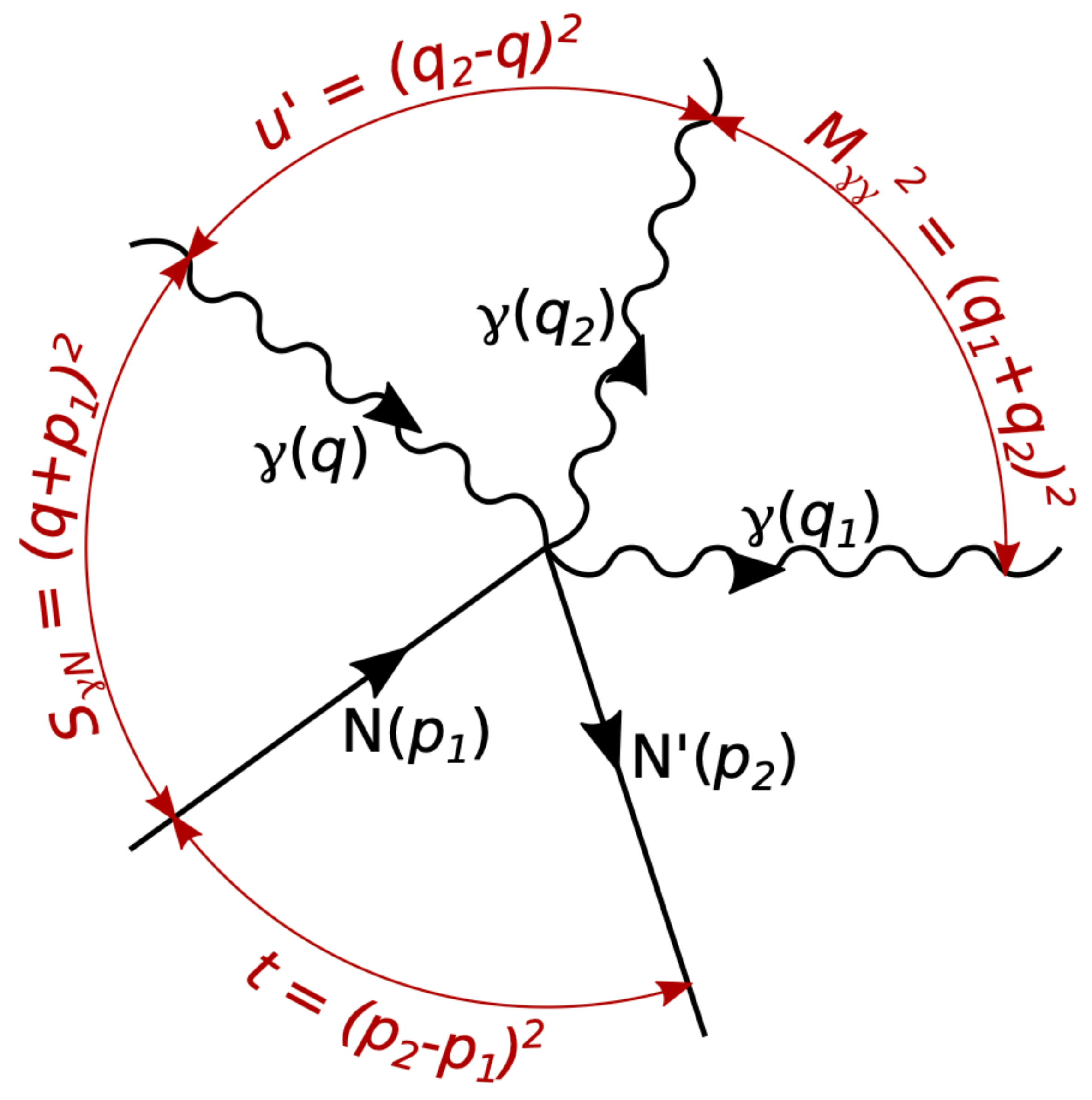
Exclusive diphoton photoproduction

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

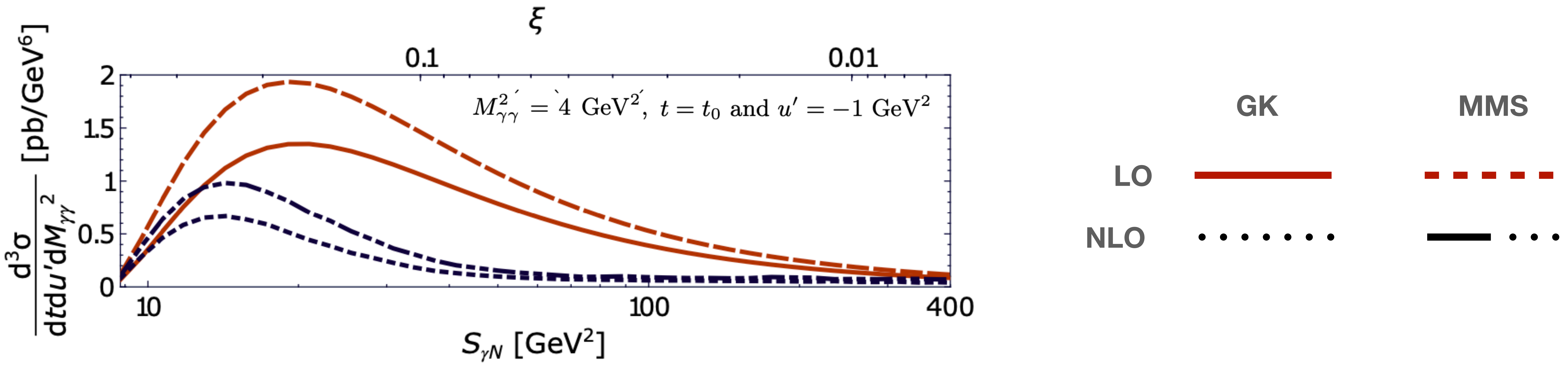
- Process probes C-odd GPDs
- No contribution of D-term
- No non-perturbative ingredients other than GPDs
- Gluons do not contribute also at NLO

- Both LO and NLO description available

- Description already available in PARTONS (not released yet), soon will be available in EpIC

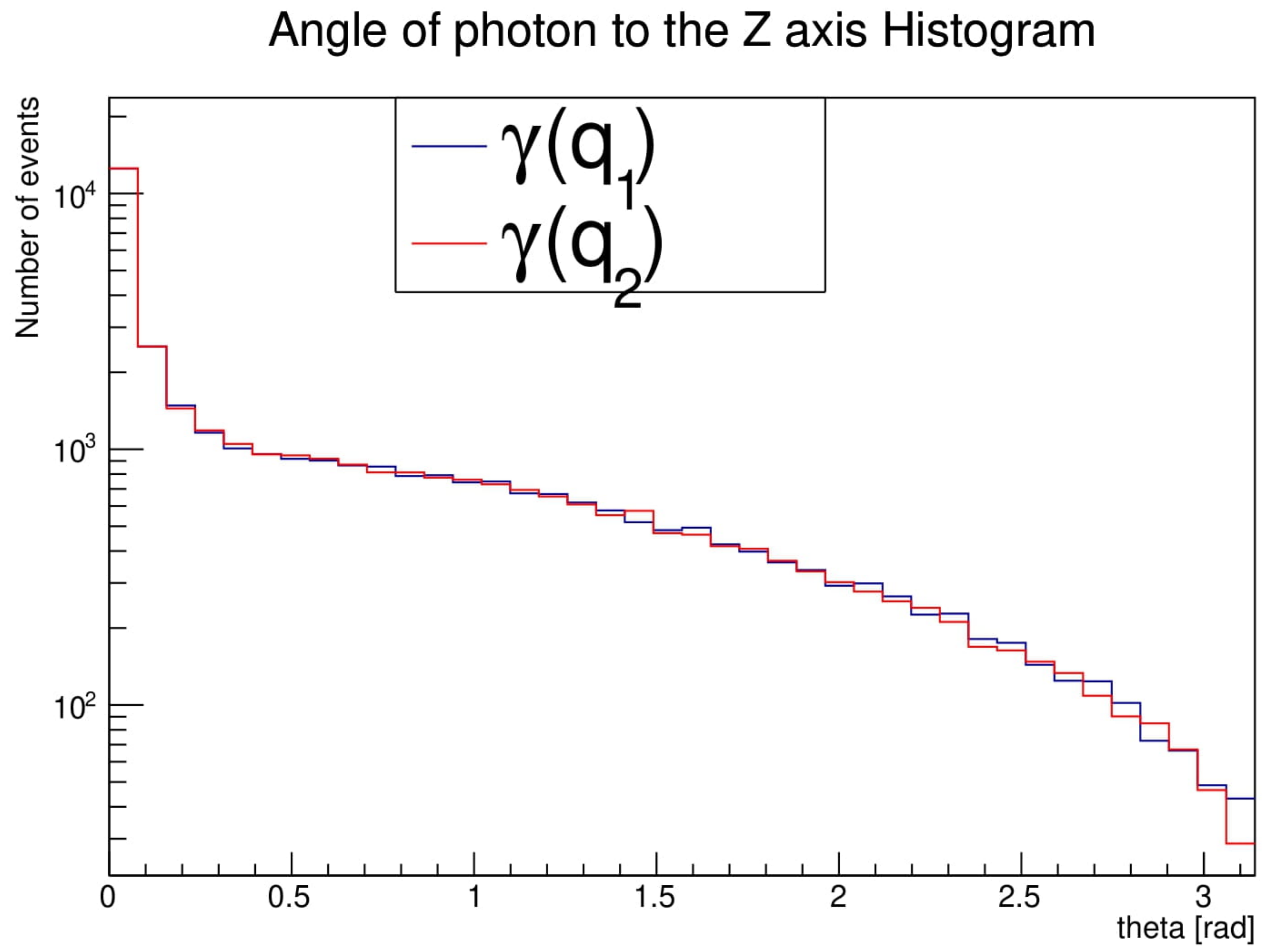


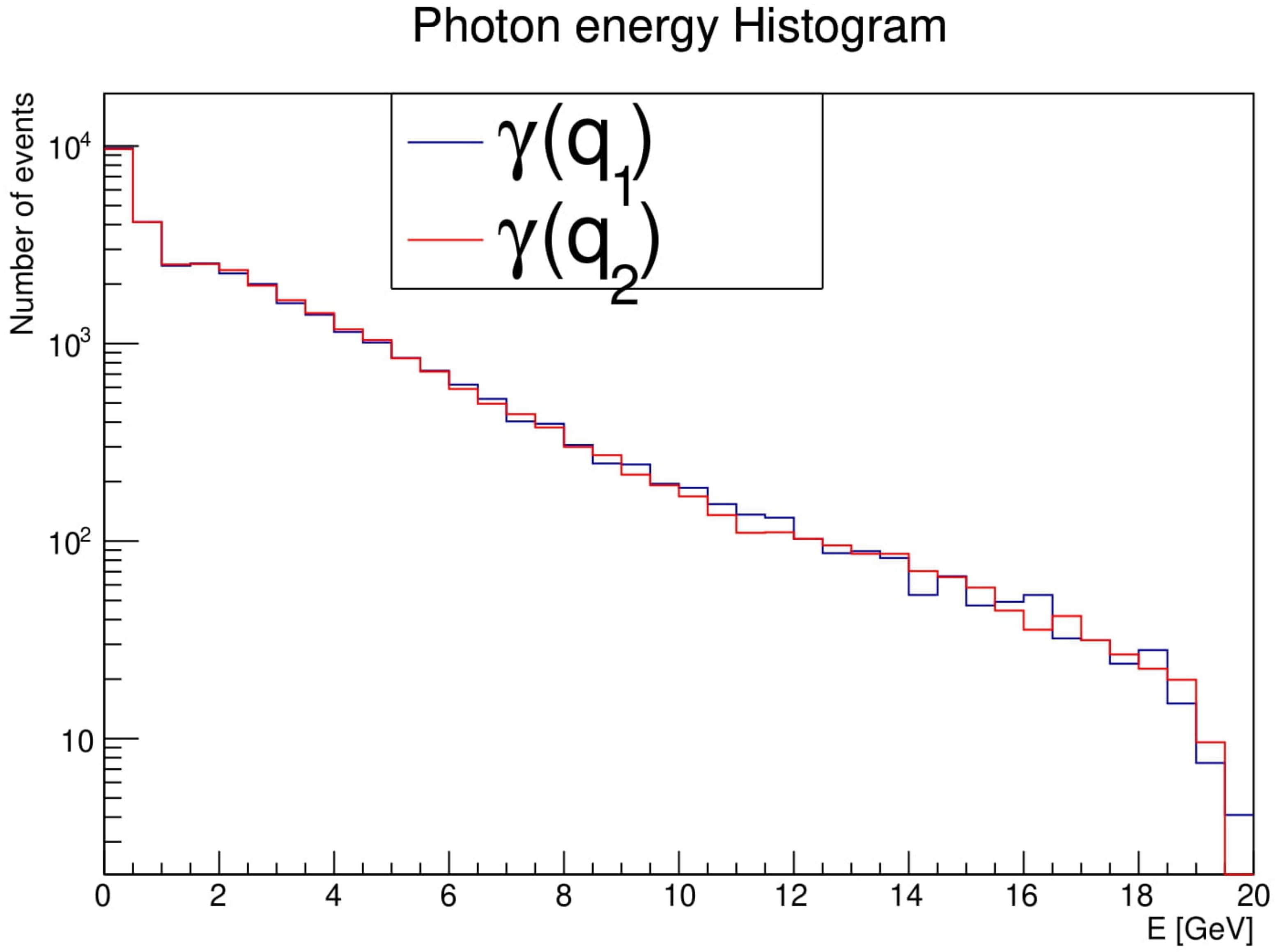
Cross-section



Exclusive diphoton photoproduction

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





- The process implemented in EpIC MC generator with equivalent-photon approximation

$$\frac{d^6\sigma}{dQ^2\,dy\,dt\,du'\,dM^2_{\gamma\gamma}d\phi} = \Gamma(y, Q^2)\times\frac{d^4\sigma_{2\gamma}}{dt\,du'\,dM^2_{\gamma\gamma}d\phi}$$

- 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}

Summary

- Progress in:
  - delivering open-source tools for the community
    → to suport both experimentalists and theoreticians
  - phenomenology
    → fits and development of methodology for interpretation of experimental data
    → convenient tools for impact studies
  - description of exclusive processes
    → new sources of GPD information
  - understanding of fundamental problems, like deconvolution of CFFs
    → important for extraction of GPDs
  - modelling of GPD, fulfilling all theory-driven constraints (including positivity)
    → subject not touched enough in the current literature
    → developed in mind for easy inclusion of latticeQCD data
    → tool for addressing the long-standing problem of model dependency of GPDs

H. Dutrieux et al.,
Eur. Phys. J. C 82 (2022) 3, 252

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

Important for the precision era of GPD extraction allowed by the new generation of experiments