Recent developments obtained with PARTONS framework

Paweł Sznajder
National Centre for Nuclear Research, Poland

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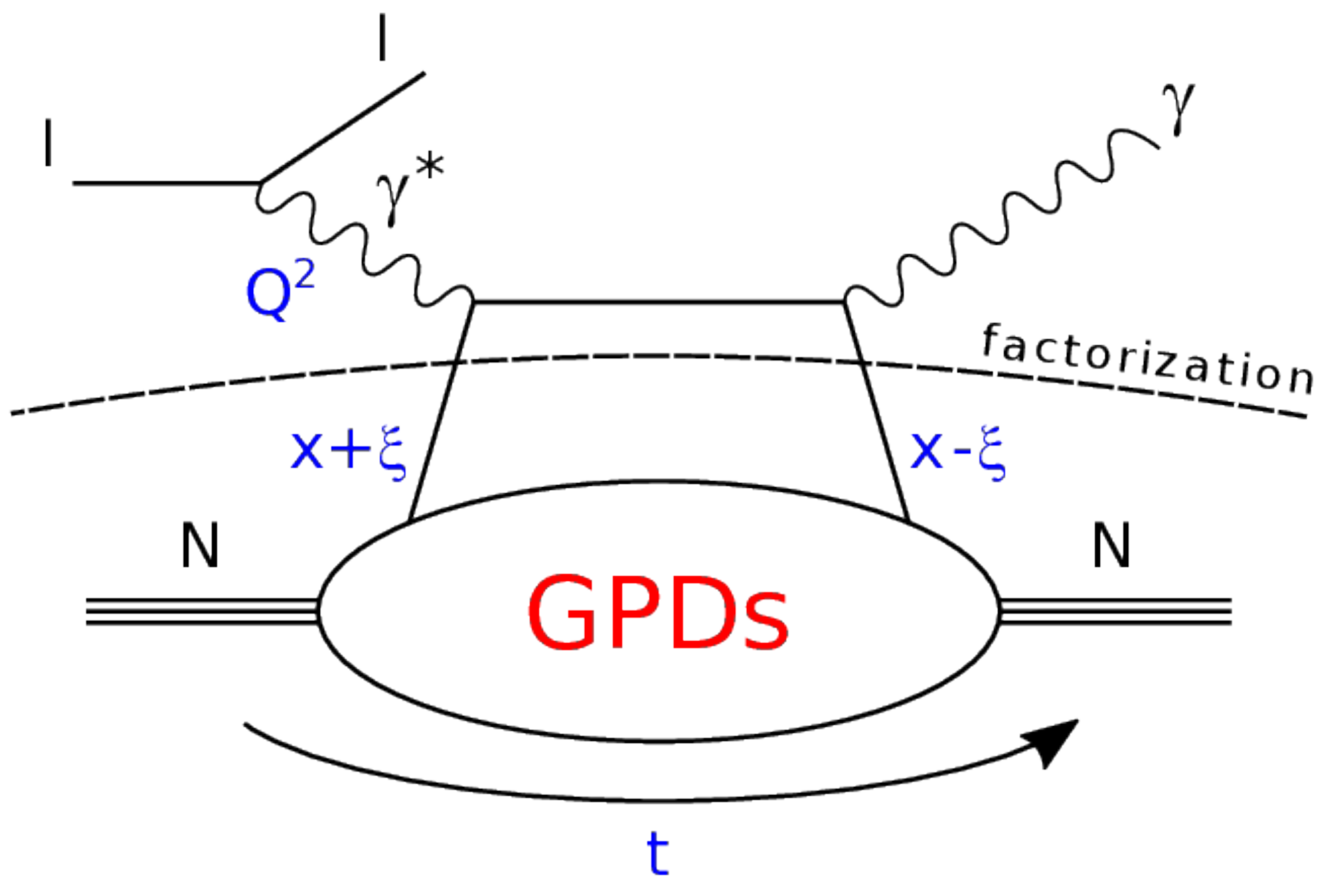
Outline

- Introduction

- Tools
- Recent developments (channel-by-channel)
- Addressing the problem of model dependency in GPD extraction

- 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*	

Reduction to PDF:

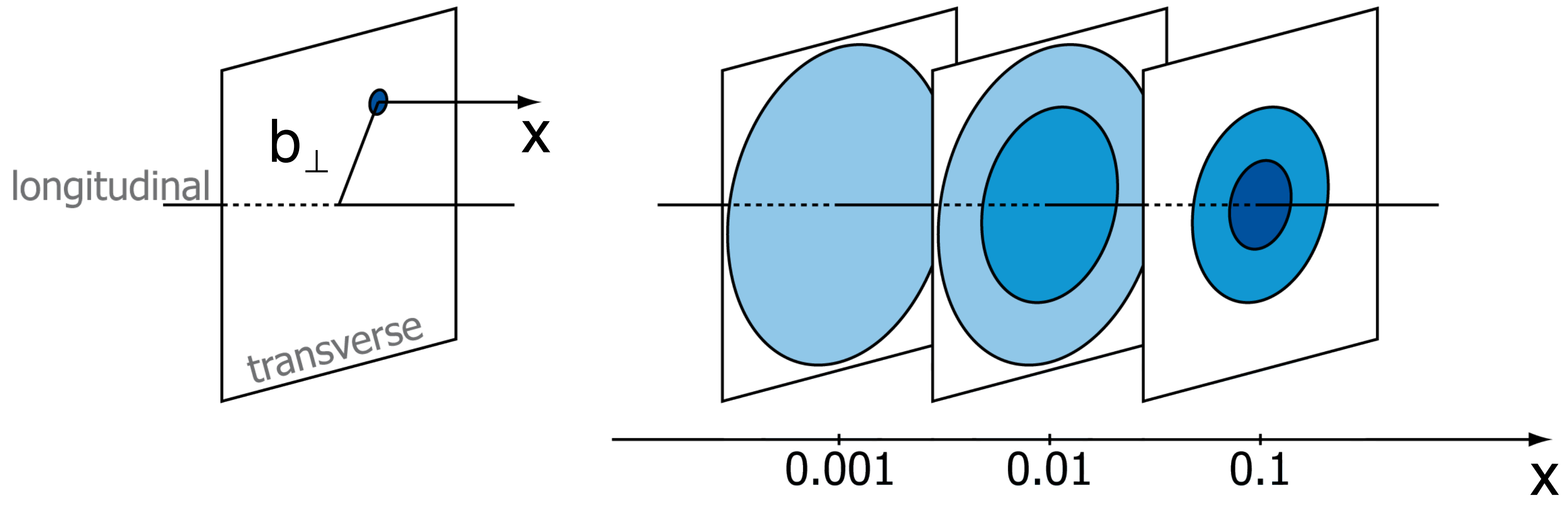
$$H(x, \xi = 0, t = 0) \equiv q(x)$$

Polynomiality - non-trivial consequence of Lorentz invariance:

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

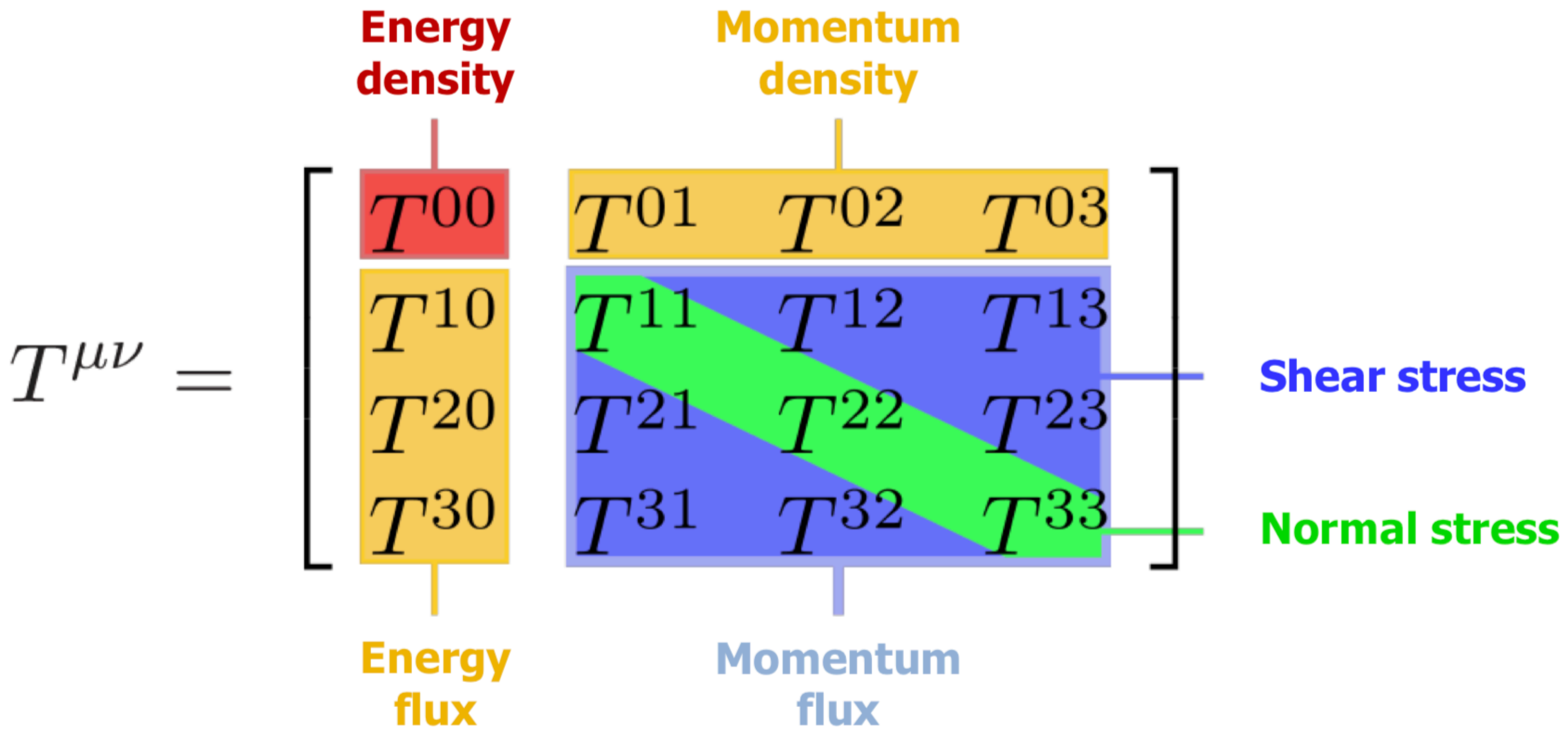
Positivity bounds - positivity of norm in Hilbert space, e.g.:

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



Nucleon tomography:

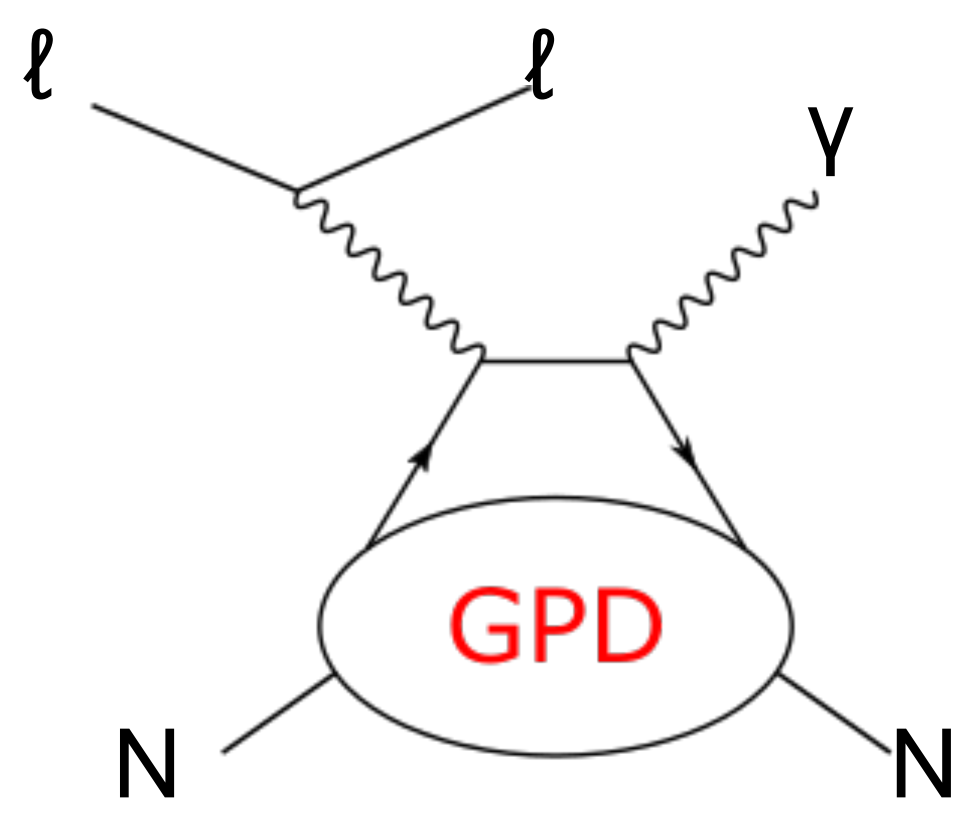
$$q(x, \mathbf{b}_\perp) = \int \frac{\mathrm{d}^2\mathbf{\Delta}}{4\pi^2} e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}} H^q(x, 0, t = -\mathbf{\Delta}^2)$$



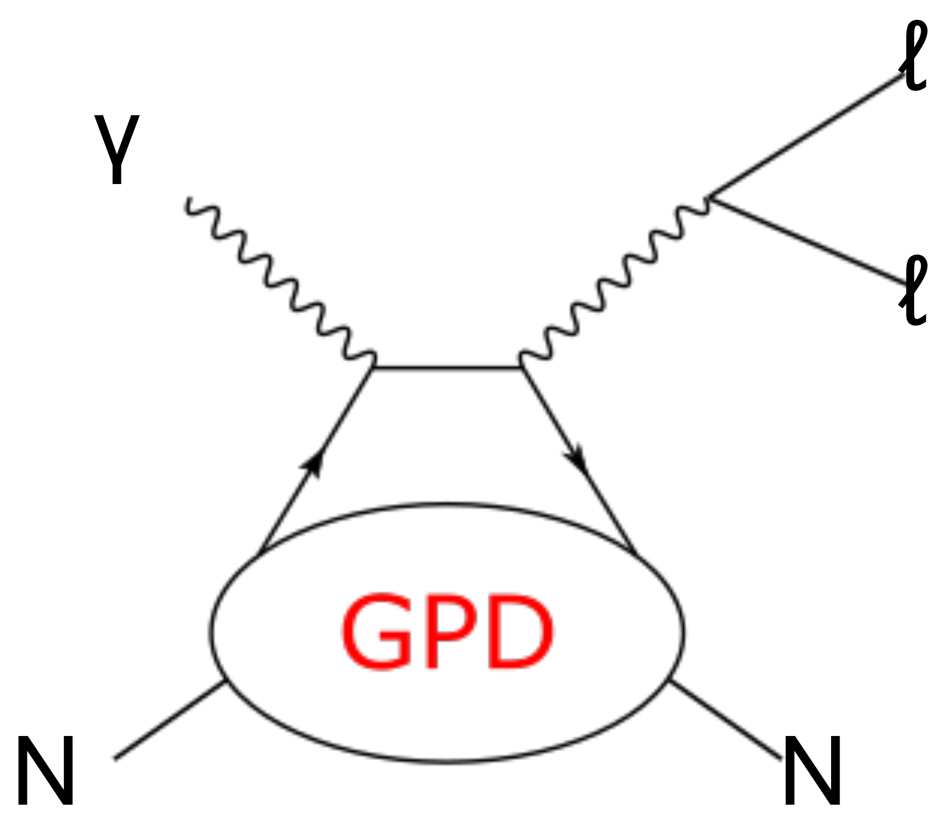
Energy momentum tensor in terms of form factors (OAM and mechanical forces):

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

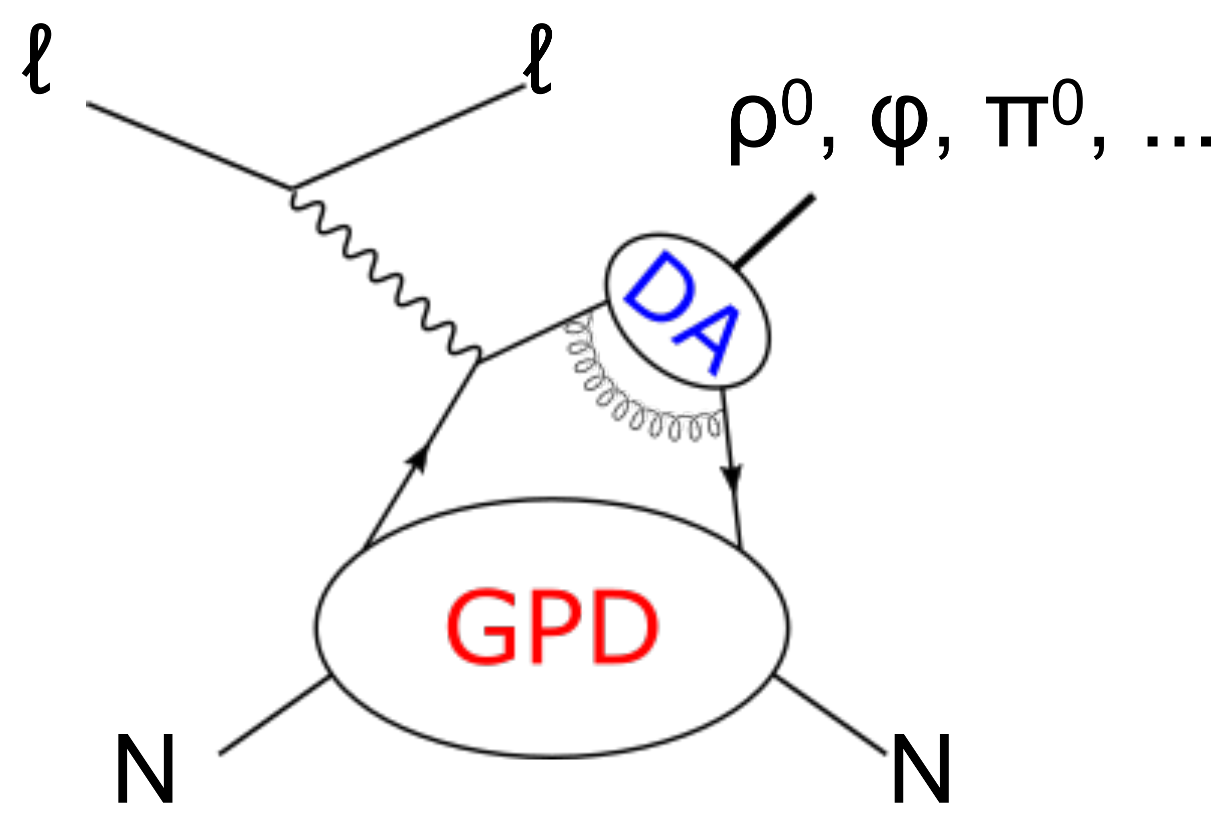
GPDs accessible in various production channels and observables
→ experimental filters



DVCS
Deeply Virtual Compton Scattering



TCS
Timelike Compton Scattering



HEMP
Hard Exclusive Meson Production

more production channels sensitive to GPDs exist!

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 (pions)
    - diphoton production and DDVCS available soon

- This is the new tool to be use in the 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

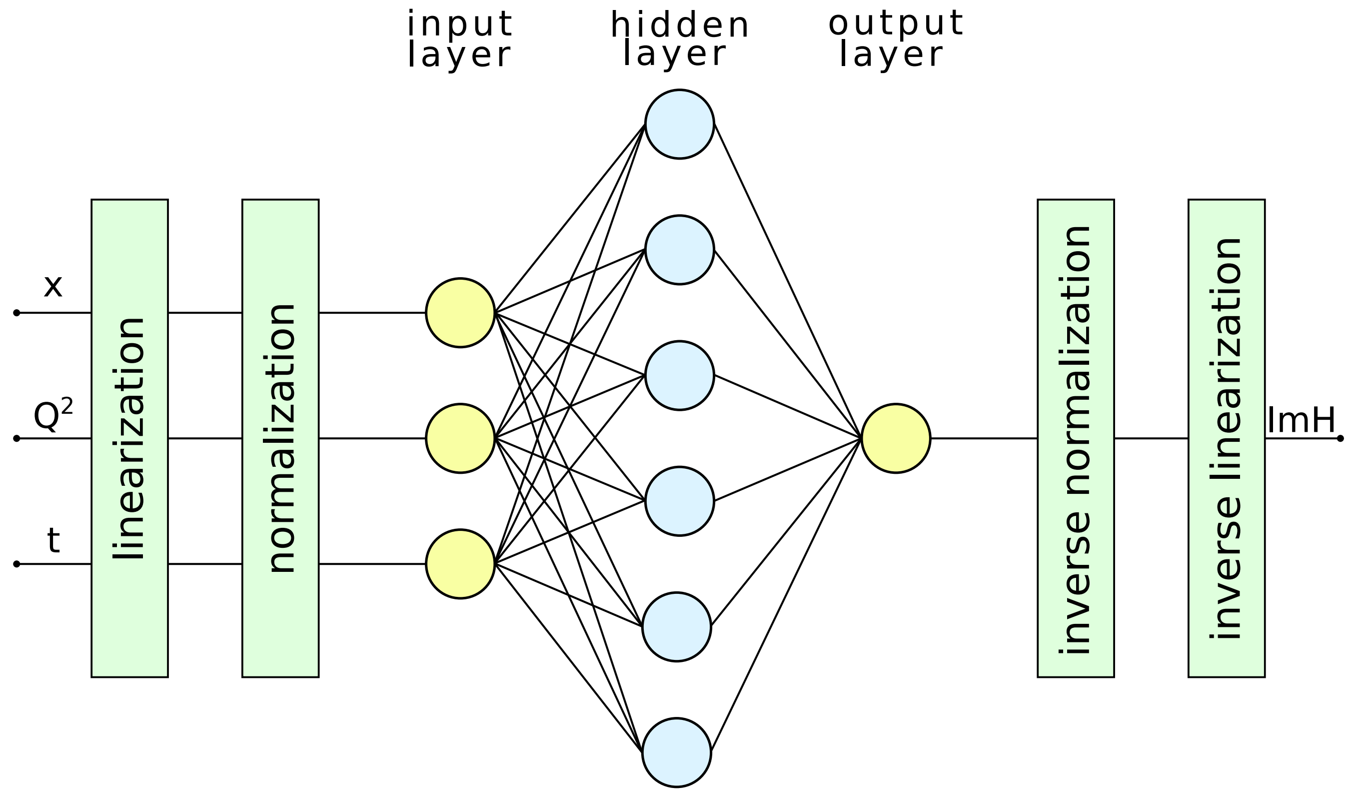
$$g^q_G(x,x,t) = \frac{a^q_G}{(1-x^2)^2}\left(1 + t(1-x)(b^q_G + c^q_G \log(1+x))\right)$$

- 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



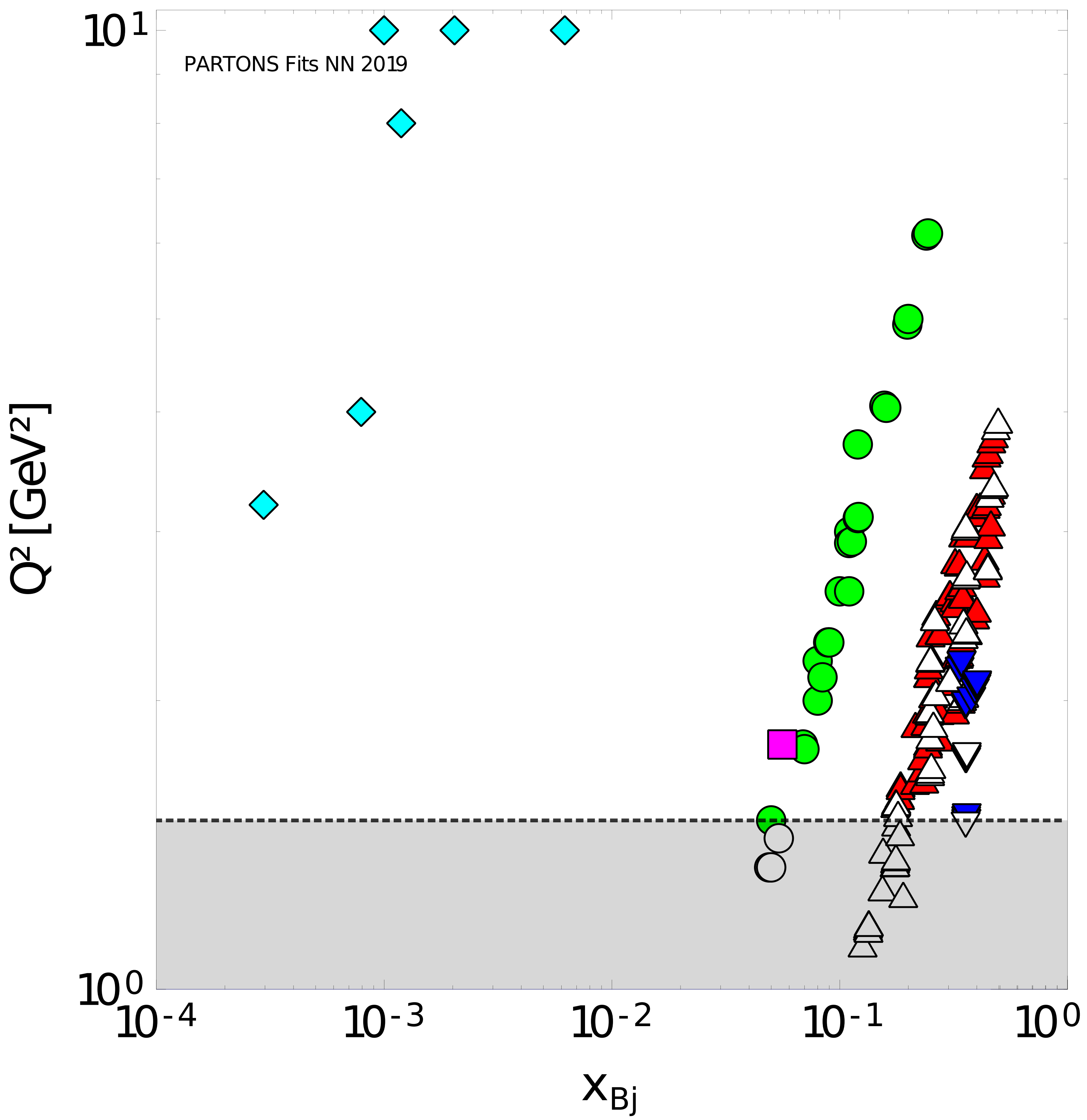
- Independent artificial neural network for each CFF and Re/Im parts
- Functions of x_B, Q^2 and t
- Network size determined using benchmark sample
- No power-behaviour pre-factors
- Trained with genetic algorithm
- Regularisation method based on early stopping criterion
- Replica method for propagation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

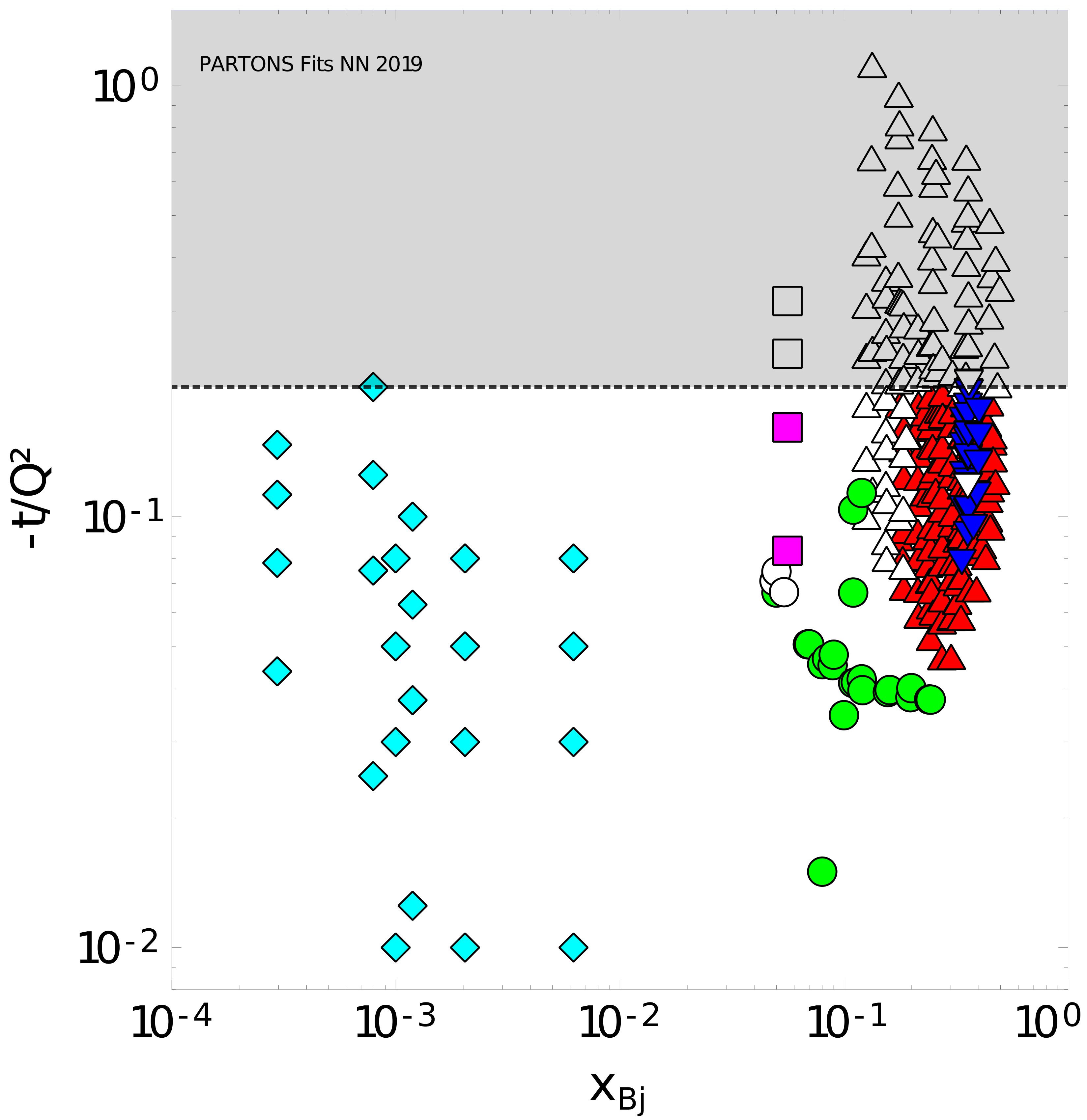
Kinematic cuts
used in our recent global
extractions of DVCS CFFs :

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

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

- HALL A
- CLAS
- HERMES
- COMPASS
- H1 and ZEUS

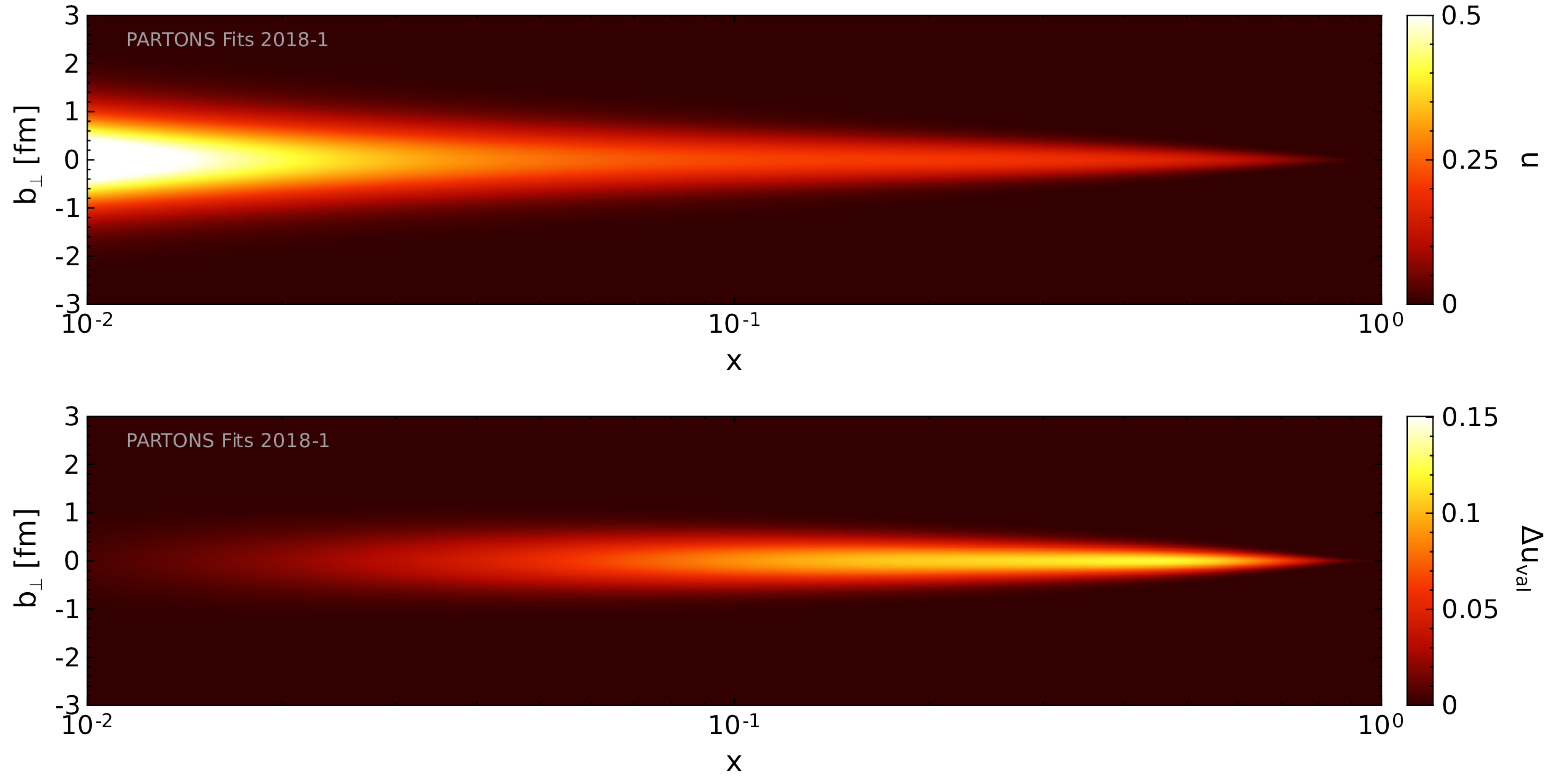




Deeply Virtual Compton scattering

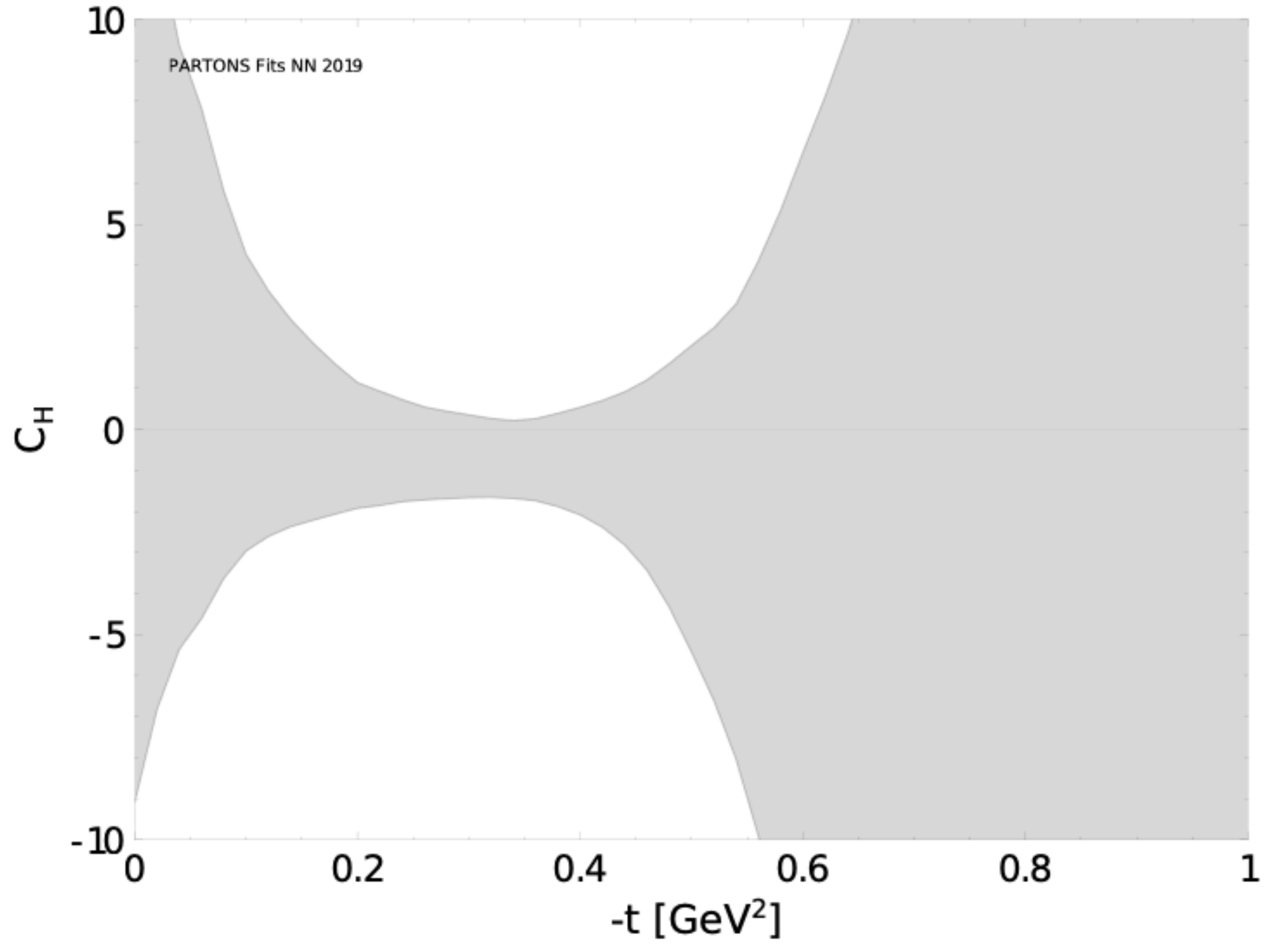
H. Moutarde, PS, J. Wagner,
Eur. Phys. J. C 78 (2018) 11, 890

Main result:
nucleon tomography



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

Main result:
unbiased extraction of subtraction constant



Relation between DVCS and TCS CFFs:

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

$$^{T}\mathcal{H} \stackrel{\mathrm{LO}}{=} {}^{S}\mathcal{H}^{*}$$

$$^{T}\widetilde{\mathcal{H}} \stackrel{\mathrm{LO}}{=} -{}^{S}\widetilde{\mathcal{H}}^{*}$$

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

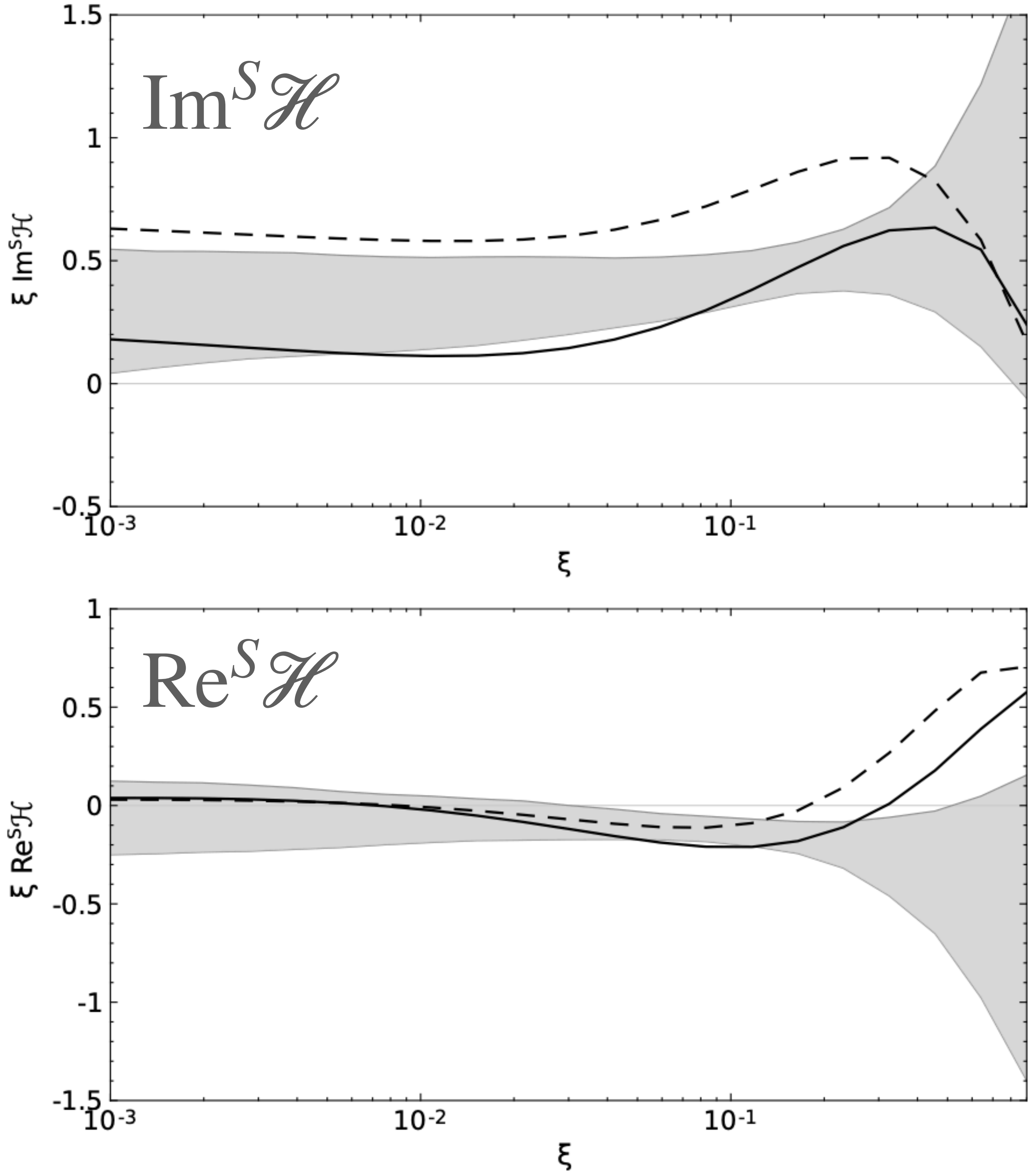
$$^{T}\widetilde{\mathcal{H}} \stackrel{\mathrm{NLO}}{=} -{}^{S}\widetilde{\mathcal{H}}^{*} + i\pi\,\mathcal{Q}^{2}\frac{\partial}{\partial\,\mathcal{Q}^{2}}\,{}^{S}\widetilde{\mathcal{H}}^{*}\,.$$

Combined study of DVCS and TCS:

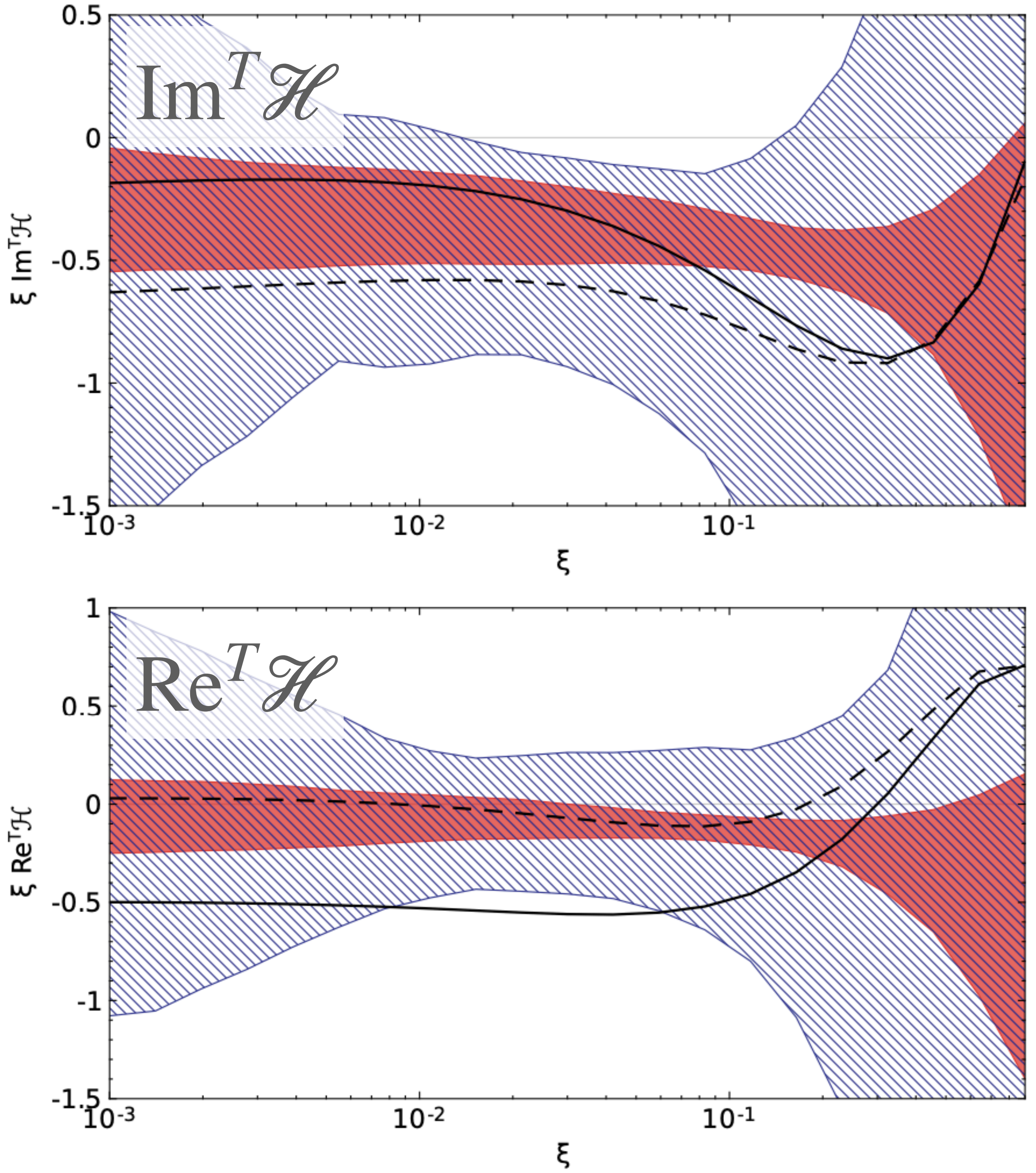
- source of GPD information
- useful to prove universality of GPDs
- impact of NLO corrections
- constrain Q2-dep. of CFFs

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

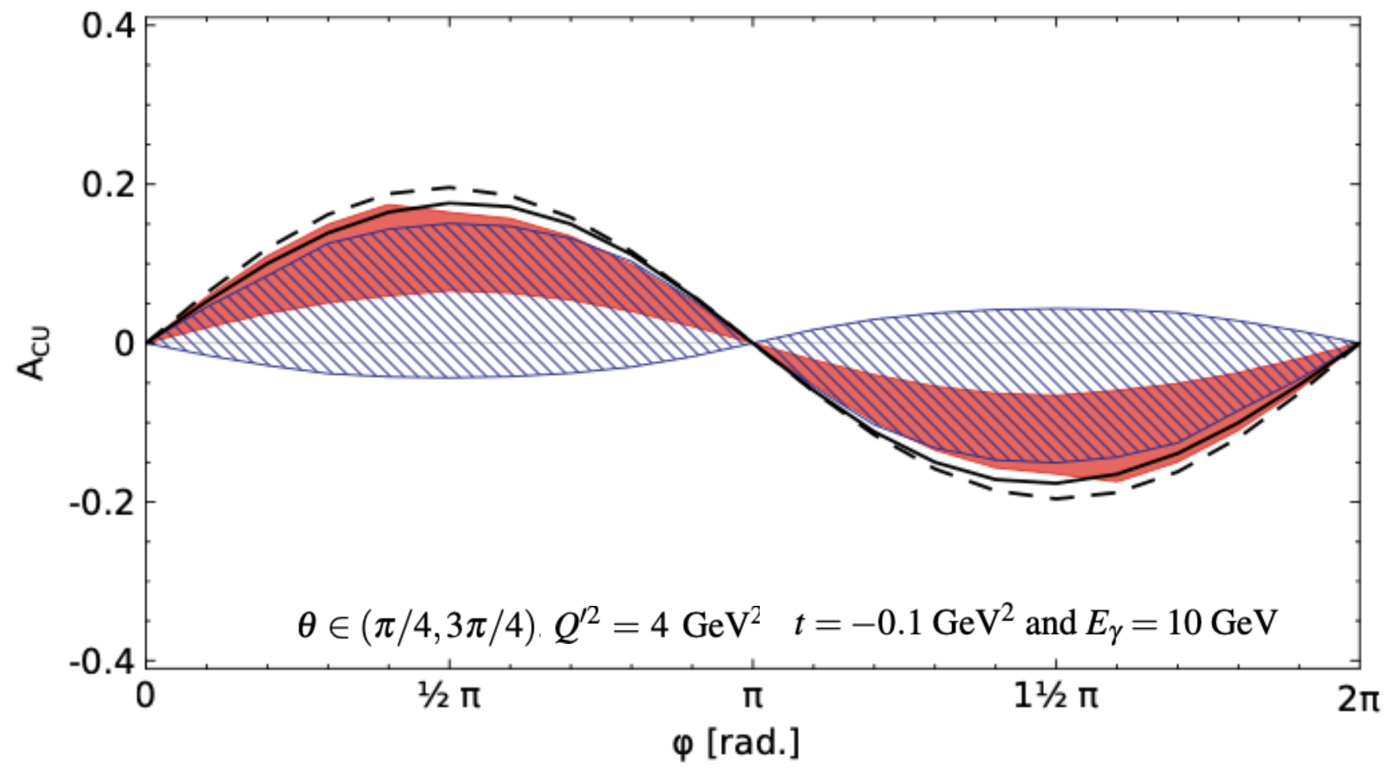
DVCS CFF (Non-parametric):



TCS CFF:



TCS circular beam asymmetry:



DVCS

TCS from DVCS (LO)

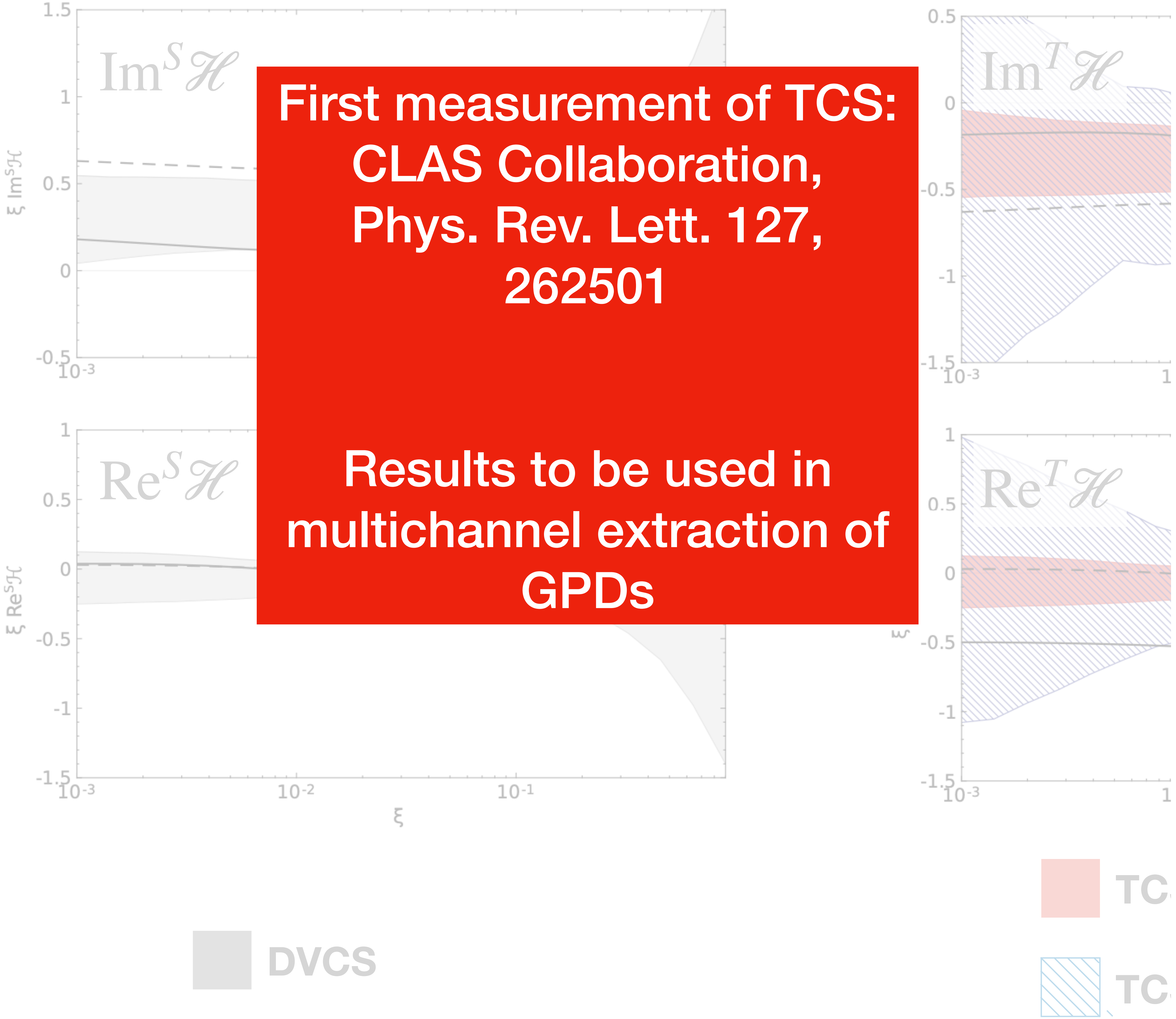
TCS from DVCS (NLO)

GK model (LO)

GK model (NLO)

Timelike Compton scattering

DVCS CFF (Non-parametric):



First measurement of TCS: CLAS Collaboration, Phys. Rev. Lett. 127, 262501

Results to be used in multichannel extraction of GPDs

PHYSICAL REVIEW LETTERS **127,** 262501 (2021)

First Measurement of Timelike Compton Scattering

P. Chatagnon,[20,*] S. Niccolai,[20] S. Stepanyan,[36] M. J. Amaryan,[29] G. Angelini,[12] W. R. Armstrong,[1] H. Atac,[35] C. Ayerbe Gayoso,[44,†] N. A. Baltzell,[36] L. Barion,[13] M. Bashkanov,[42] M. Battaglieri,[36,15] I. Bedlinskiy,[25] F. Benmokhtar,[7] A. Bianconi,[39,19] L. Biondo,[15,18,40] A. S. Biselli,[8] M. Bondi,[15] F. Bossù,[3] S. Boiarinov,[36] W. J. Briscoe,[12] W. K. Brooks,[37,36] D. Bulumulla,[29] V. D. Burkert,[36] D. S. Carman,[36] J. C. Carvajal,[10] M. Caudron,[20] A. Celentano,[15] T. Chetry,[24,28] G. Ciullo,[13,9] L. Clark,[41] P. L. Cole,[22] M. Contalbrigo,[13] G. Costantini,[39,19] V. Crede,[11] A. D'Angelo,[16,32] N. Dashyan,[45] M. Defurne,[3] R. De Vita,[15] A. Deur,[36] S. Diehl,[30,5] C. Djalali,[28] R. Dupré,[20] H. Egiyan,[36] M. Ehrhart,[20,‡] A. El Alaoui,[37] L. El Fassi,[24] L. Elouadrhiri,[36] S. Fegan,[42] R. Fersch,[4] A. Filippi,[17] G. Gavalian,[36] Y. Ghandilyan,[45] G. P. Gilfoyle,[31] F. X. Girod,[36] D. I. Glazier,[41] A. A. Golubenko,[33] R. W. Gothe,[34] Y. Gotra,[36] K. A. Griffioen,[44] M. Guidal,[20] L. Guo,[10] H. Hakobyan,[37,45] M. Hattawy,[29] T. B. Hayward,[5,44] D. Heddle,[4,36] A. Hobart,[20] M. Holtrop,[26] C. E. Hyde,[29] Y. Ilieva,[34] D. G. Ireland,[41] E. L. Isupov,[33] H. S. Jo,[21] K. Joo,[5] M. L. Kabir,[24] D. Keller,[43] G. Khachatryan,[45] A. Khanal,[10] A. Kim,[5] W. Kim,[21] A. Kripko,[30] V. Kubarovsky,[36] S. E. Kuhn,[29] L. Lanza,[16] M. Leali,[39,19] S. Lee,[23] P. Lenisa,[13,9] K. Livingston,[41] I. J. D. MacGregor,[41] D. Marchand,[20] L. Marsicano,[15] V. Mascagna,[38,19,§] B. McKinnon,[41] C. McLauchlin,[34] S. Migliorati,[39,19] M. Mirazita,[14] V. Mokeev,[36] R. A. Montgomery,[41] C. Munoz Camacho,[20] P. Nadel-Turonski,[36] P. Naidoo,[41] K. Neupane,[34] T. R. O'Connell,[5] M. Osipenko,[15] M. Ouillon,[20] P. Pandey,[29] M. Paolone,[27,35] L. L. Pappalardo,[13,9] R. Paremuzyan,[36,26] E. Pasyuk,[36] W. Phelps,[4,12] O. Pogorelko,[25] J. Poudel,[29] J. W. Price,[2] Y. Prok,[29] B. A. Raue,[10] T. Reed,[10] M. Ripani,[15] A. Rizzo,[16,32] P. Rossi,[36] J. Rowley,[28] F. Sabatié,[3] A. Schmidt,[12] E. P. Segarra,[23] Y. G. Sharabian,[36] E. V. Shirokov,[33] U. Shrestha,[5,28] D. Sokhan,[3,41] O. Soto,[14,37] N. Sparveris,[35] I. I. Strakovsky,[12] S. Strauch,[34] N. Tyler,[34] R. Tyson,[41] M. Ungaro,[36] S. Vallarino,[13] L. Venturelli,[39,19] H. Voskanyan,[45] A. Vossen,[6,36] E. Voutier,[20] D. P. Watts,[42] K. Wei,[5] X. Wei,[36] R. Wishart,[41] B. Yale,[44] N. Zachariou,[42] J. Zhang,[43] and Z. W. Zhao[6]

(CLAS Collaboration)

[1]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*California State University, Dominguez Hills, Carson, California 90747, USA*
[3]*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[4]*Christopher Newport University, Newport News, Virginia 23606, USA*
[5]*University of Connecticut, Storrs, Connecticut 06269, USA*
[6]*Duke University, Durham, North Carolina 27708-0305, USA*
[7]*Duquesne University, 600 Forbes Avenue, Pittsburgh, Pennsylvania 15282, USA*
[8]*Fairfield University, Fairfield, Connecticut 06824, USA*
[9]*Universita' di Ferrara, 44121 Ferrara, Italy*
[10]*Florida International University, Miami, Florida 33199, USA*
[11]*Florida State University, Tallahassee, Florida 32306, USA*
[12]*The George Washington University, Washington, D.C. 20052, USA*
[13]*INFN, Sezione di Ferrara, 44100 Ferrara, Italy*
[14]*INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy*
[15]*INFN, Sezione di Genova, 16146 Genova, Italy*
[16]*INFN, Sezione di Roma Tor Vergata, 00133 Rome, Italy*
[17]*INFN, Sezione di Torino, 10125 Torino, Italy*
[18]*INFN, Sezione di Catania, 95123 Catania, Italy*
[19]*INFN, Sezione di Pavia, 27100 Pavia, Italy*
[20]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[21]*Kyungpook National University, Daegu 41566, Republic of Korea*
[22]*Lamar University, 4400 M. L. King, Jr. Boulevard, P.O. Box 10046, Beaumont, Texas 77710, USA*
[23]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA*
[24]*Mississippi State University, Mississippi State, Mississippi 39762-5167, USA*
[25]*National Research Centre Kurchatov Institute—ITEP, Moscow, 117259, Russia*
[26]*University of New Hampshire, Durham, New Hampshire 03824-3568, USA*
[27]*New Mexico State University, P.O. Box 30001, Las Cruces, New Mexico 88003, USA*
[28]*Ohio University, Athens, Ohio 45701, USA*
[29]*Old Dominion University, Norfolk, Virginia 23529, USA*
[30]*II Physikalisches Institut der Universitaet Giessen, 35392 Giessen, Germany*

0031-9007/21/127(26)/262501(7) 262501-1 Published by the American Physical Society

et al., 2020) 2, 171

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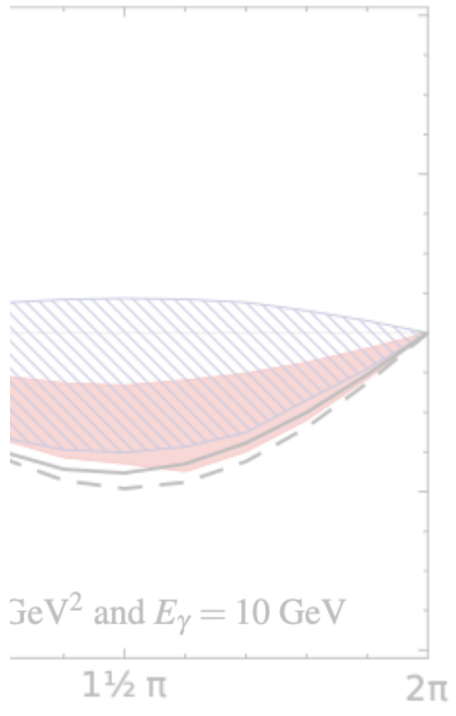

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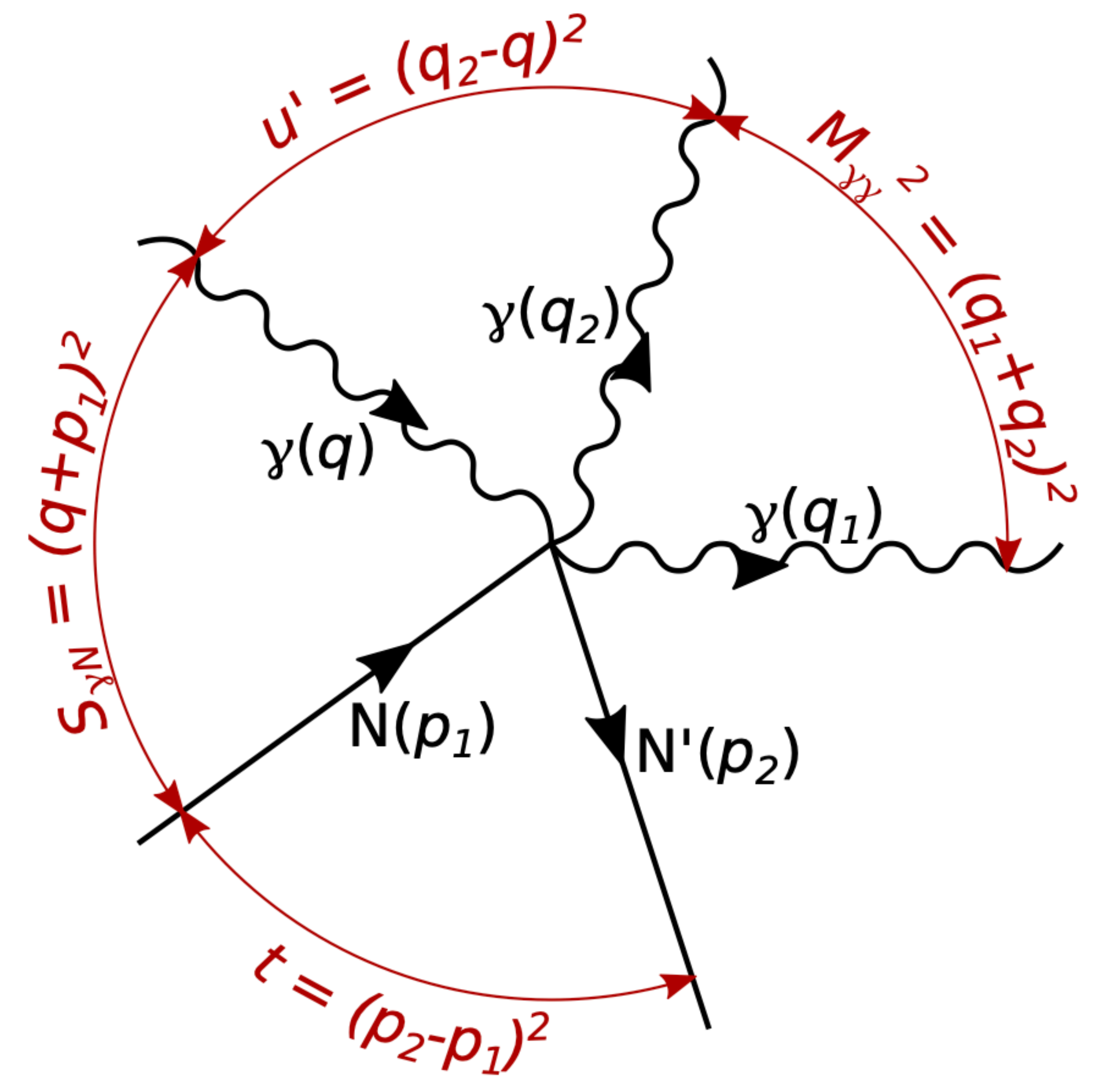
Exclusive diphoton photoproduction

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

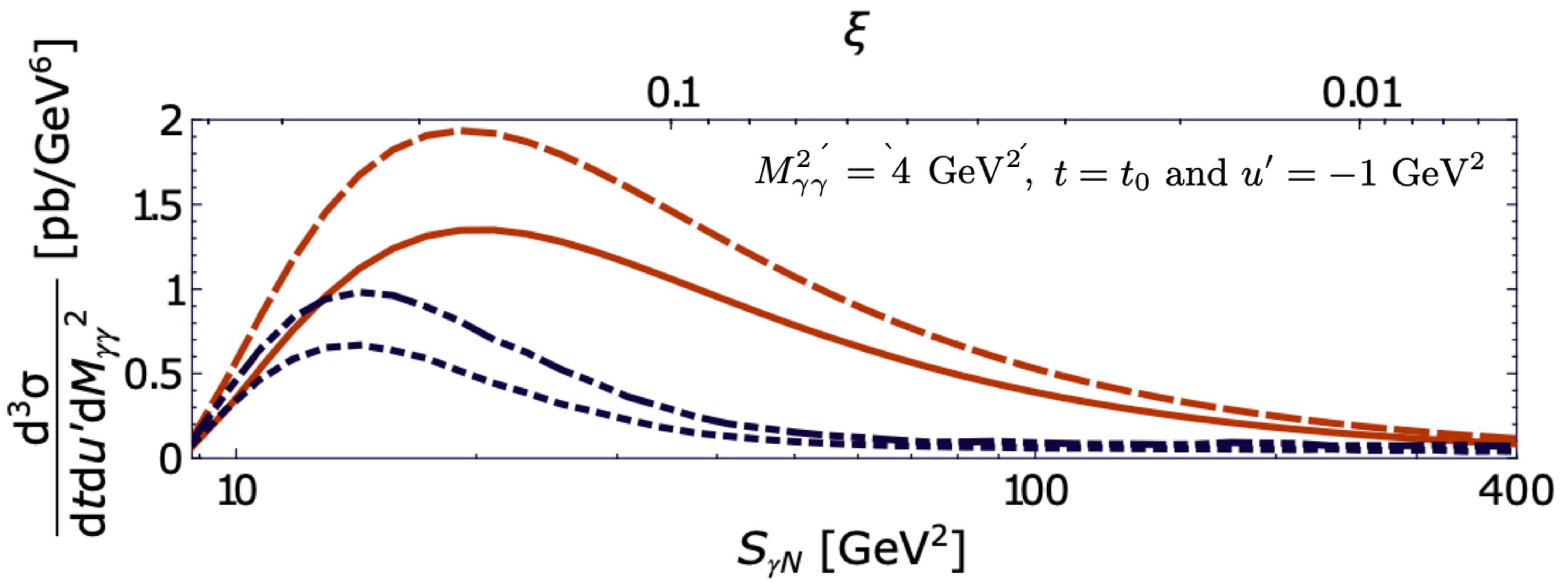


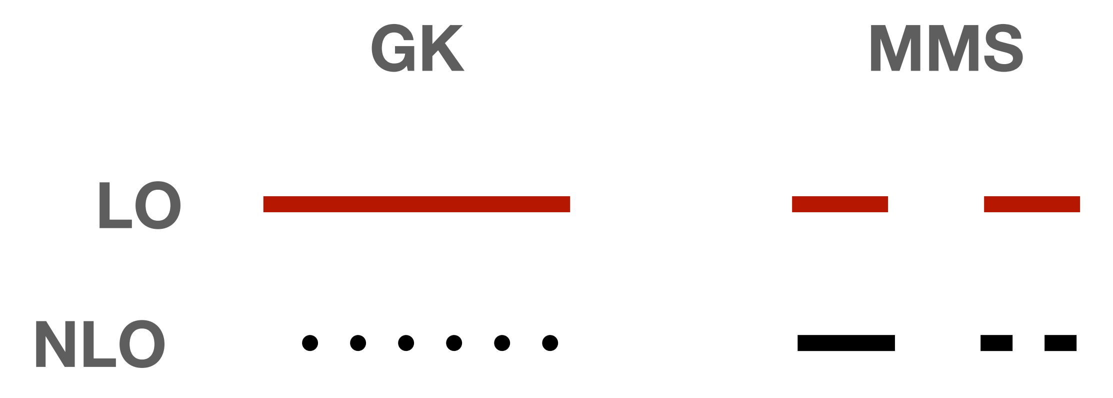
- Process probes C-odd GPDs
- No contribution of D-term
- No non-perturbative ingredients other than GPDs
- Gluons do not contribute also at NLO

- Both LO and NLO description available

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

Cross-section



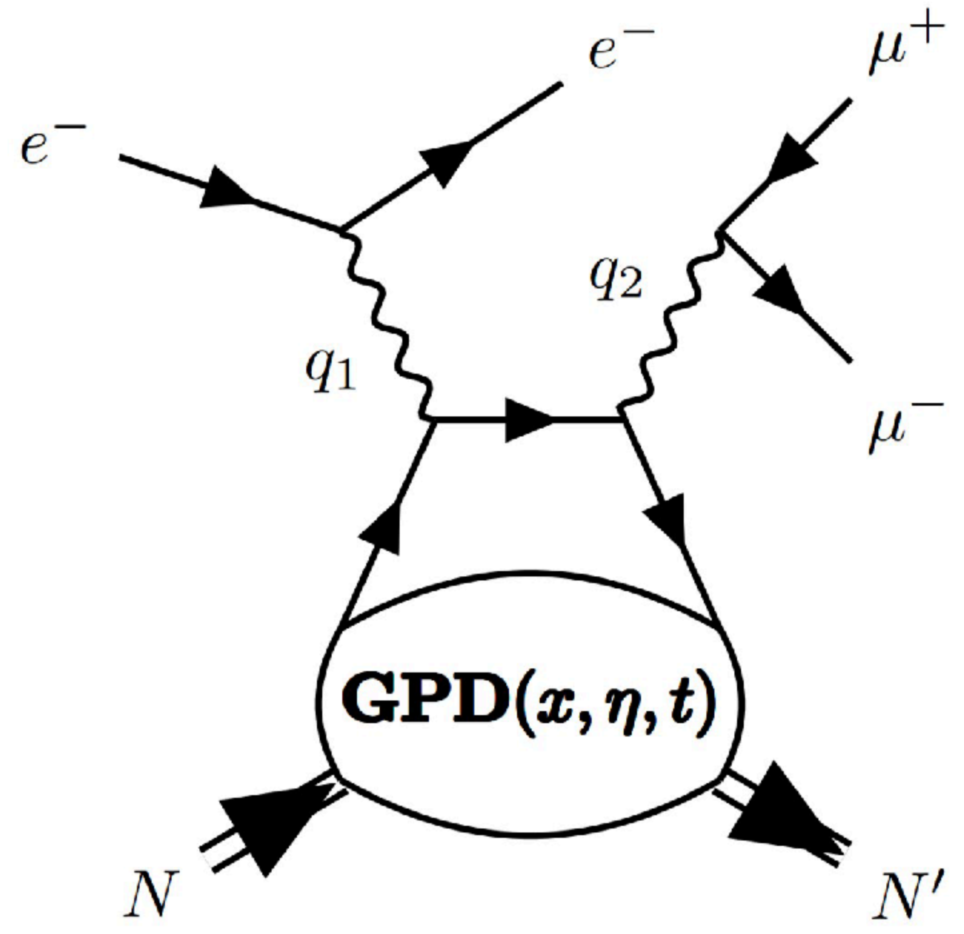


Double DVCS

PRELIMINARY !!!

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

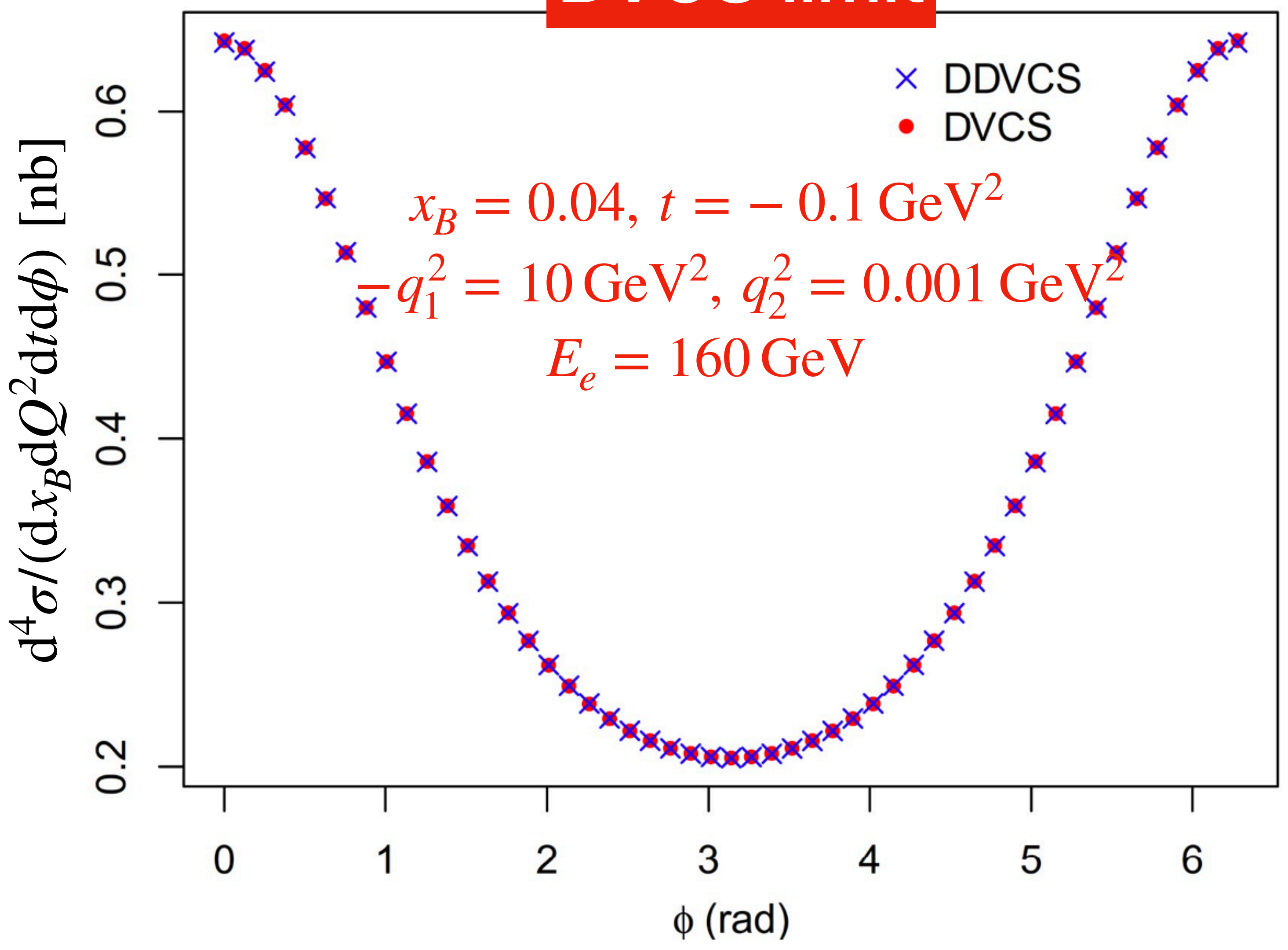
$$\mathcal{A}_{\mathrm{DDVCS}} \overset{LO}{\sim} \int_{-1}^{1} dx \, \frac{1}{x - \xi + i0} \mathrm{GPD}(x, \eta, t)$$



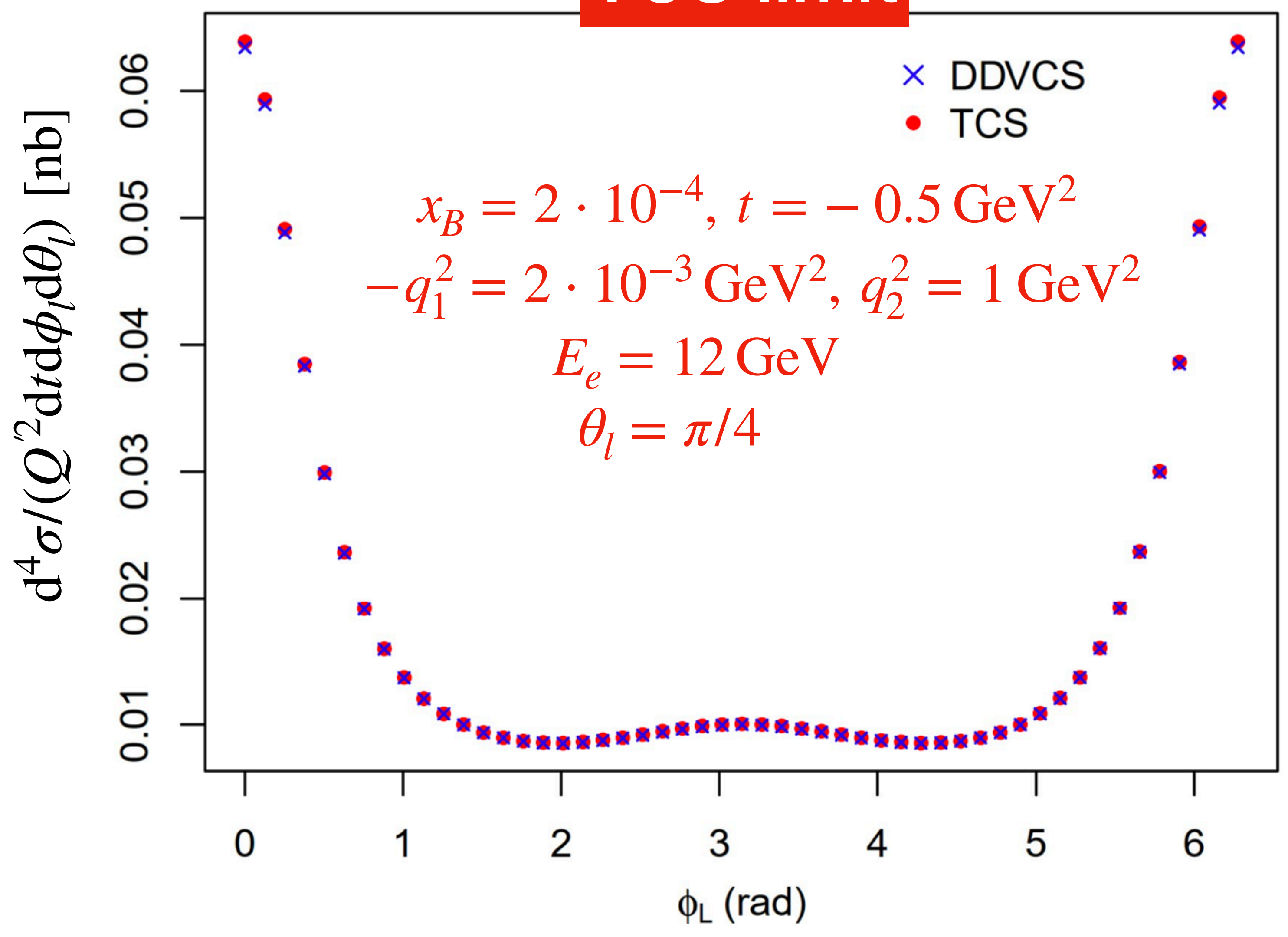
- We are revisiting DDVCS for phenomenological studies
- We plan to release obtained formulae in PARTONS and EpIC MC generator

Preliminary results:
BH cross-section in DVCS and TCS limits

DVCS limit



TCS limit



Motivation

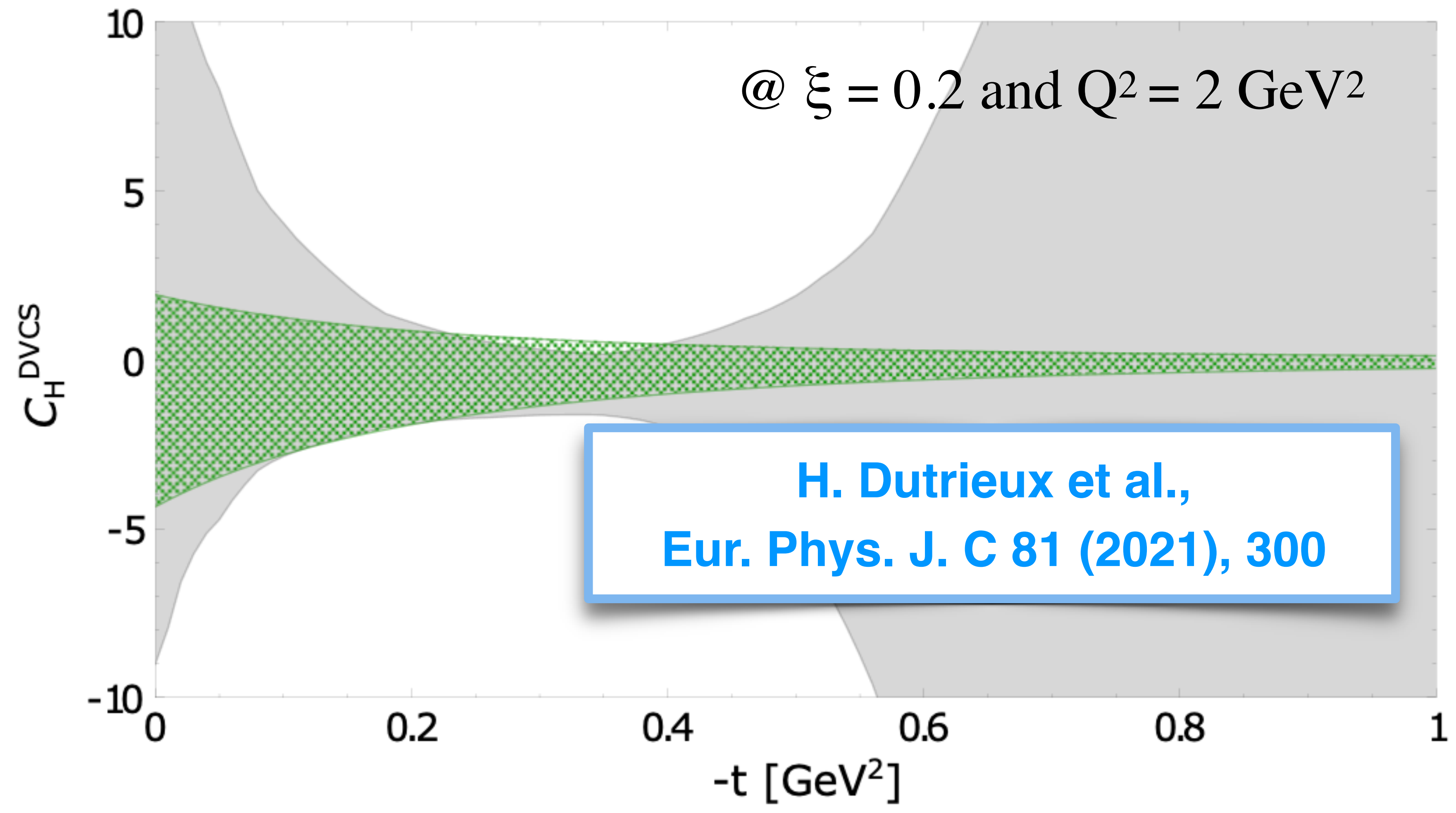
- Despite a substantial progress in both measurement and description of exclusive processes, and in lattice-QCD the problem of the model dependency of GPDs is still poorly addressed.

- Exceptions:
  - probing nucleon tomography at low-xB (see: *N. d'Hose's talk*)
  - extraction of D-term (see: *Nature 570 (2019) 7759, E1*, *EPJC 81 (2021) 4, 300 and below*)

ANN analysis

Model dependent extraction

$$d_1^{uds}(t, \mu_F^2) = d_1^{uds}(\mu_F^2)\left(1 - \frac{t}{\Lambda^2}\right)^{-\alpha} \qquad \alpha = 3 \qquad \Lambda = 0.8 \text{ GeV}$$



- No GPD models that could be considered non-parametric → no tools to study model dependency of the extraction of GPDs, nucleon tomography and orbital angular momentum (see: *EPJC 82 (2022) 3, 252 and next slides*)

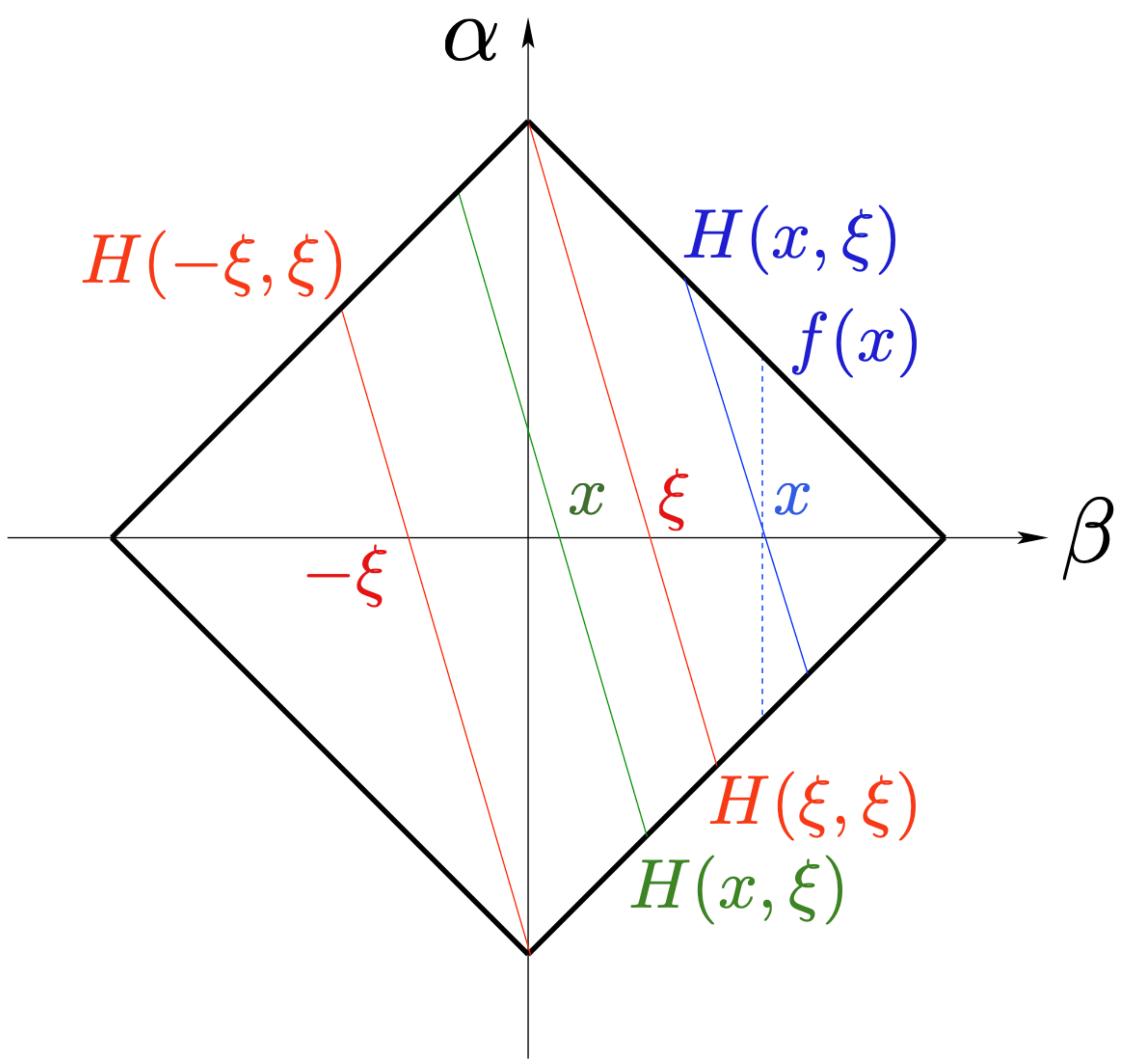
Double distribution:

$$H(x, \xi, t) = \int \mathrm{d}\Omega \, F(\beta, \alpha, t)$$

where:

$$\mathrm{d}\Omega = \mathrm{d}\beta \, \mathrm{d}\alpha \, \delta(x - \beta - \alpha\xi)$$

$$|\alpha| + |\beta| \leq 1$$



from PRD83, 076006, 2011

Modelling in (β, α)-space

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

Double distribution: $(1-x^2)F_C(\beta,\alpha) + (x^2-\xi^2)F_S(\beta,\alpha) + \xi F_D(\beta,\alpha)$

Classical term:

$$F_C(\beta,\alpha) = f(\beta)h_C(\beta,\alpha)\frac{1}{1-\beta^2}$$

$$f(\beta) = \mathrm{sgn}(\beta)q(|\beta|)$$

$$h_C(\beta,\alpha) = \frac{\mathrm{ANN}_C(|\beta|,\alpha)}{\int_{-1+|\beta|}^{1-|\beta|} \mathrm{d}\alpha \mathrm{ANN}_C(|\beta|,\alpha)}$$

Shadow term:

$$F_S(\beta,\alpha) = f(\beta)h_S(\beta,\alpha)$$

$$f(\beta) = \mathrm{sgn}(\beta)q(|\beta|)$$

$$h_S(\beta,\alpha)/N_S = \frac{\mathrm{ANN}_S(|\beta|,\alpha)}{\int_{-1+|\beta|}^{1-|\beta|} \mathrm{d}\alpha \mathrm{ANN}_S(|\beta|,\alpha)} - \frac{\mathrm{ANN}_{S'}(|\beta|,\alpha)}{\int_{-1+|\beta|}^{1-|\beta|} \mathrm{d}\alpha \mathrm{ANN}_{S'}(|\beta|,\alpha)}.$$

$$\mathrm{ANN}_{S'}(|\beta|,\alpha) \equiv \mathrm{ANN}_C(|\beta|,\alpha)$$

D-term:

$$F_D(\beta,\alpha) = \delta(\beta)D(\alpha)$$

$$D(\alpha) = (1-\alpha^2)\sum_{\substack{i=1\\ \mathrm{odd}}} d_i C_i^{3/2}(\alpha)$$

Modelling in (β, α)-space

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

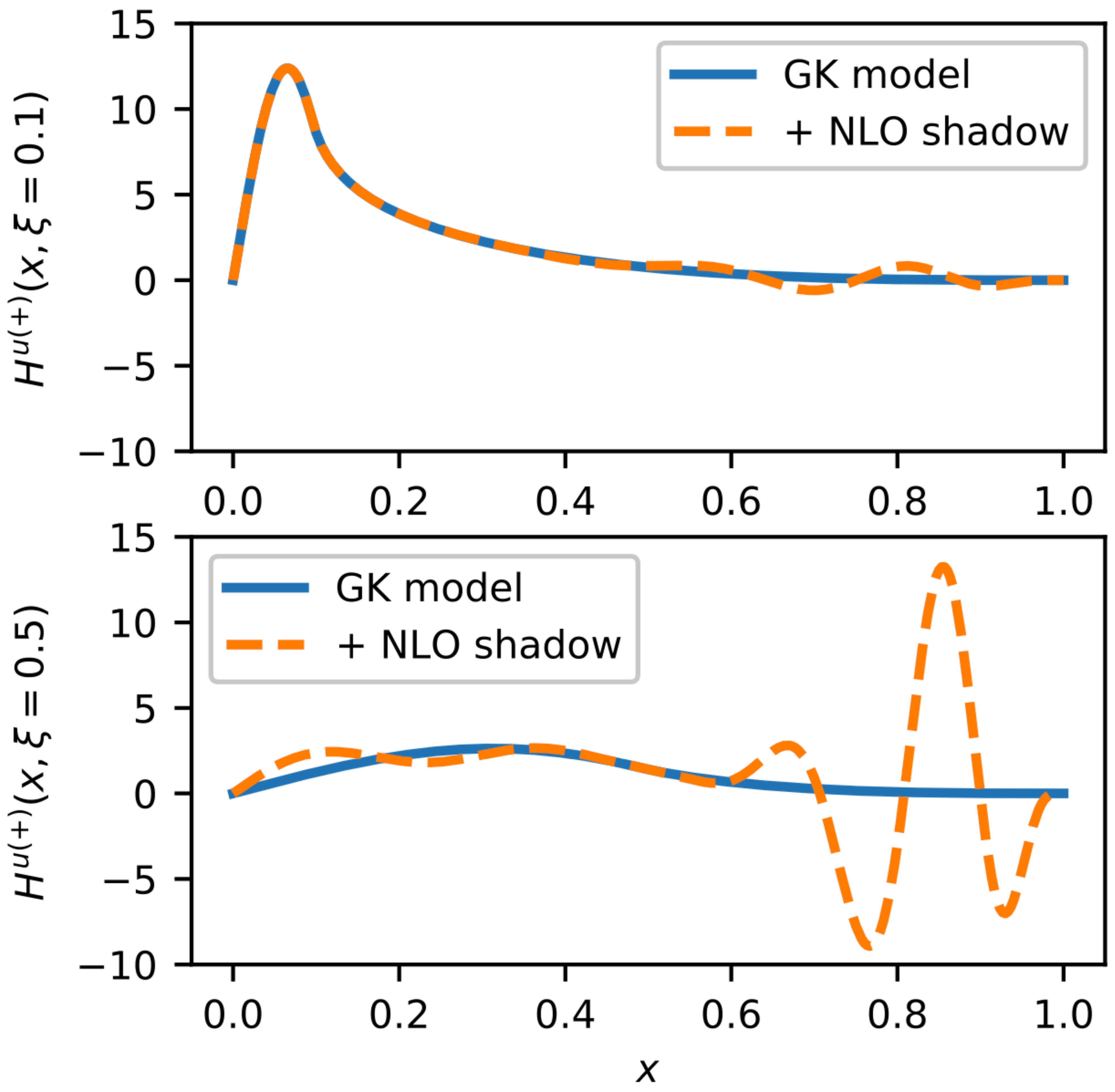
Shadow term is closely related to the so-called shadow GPDs

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

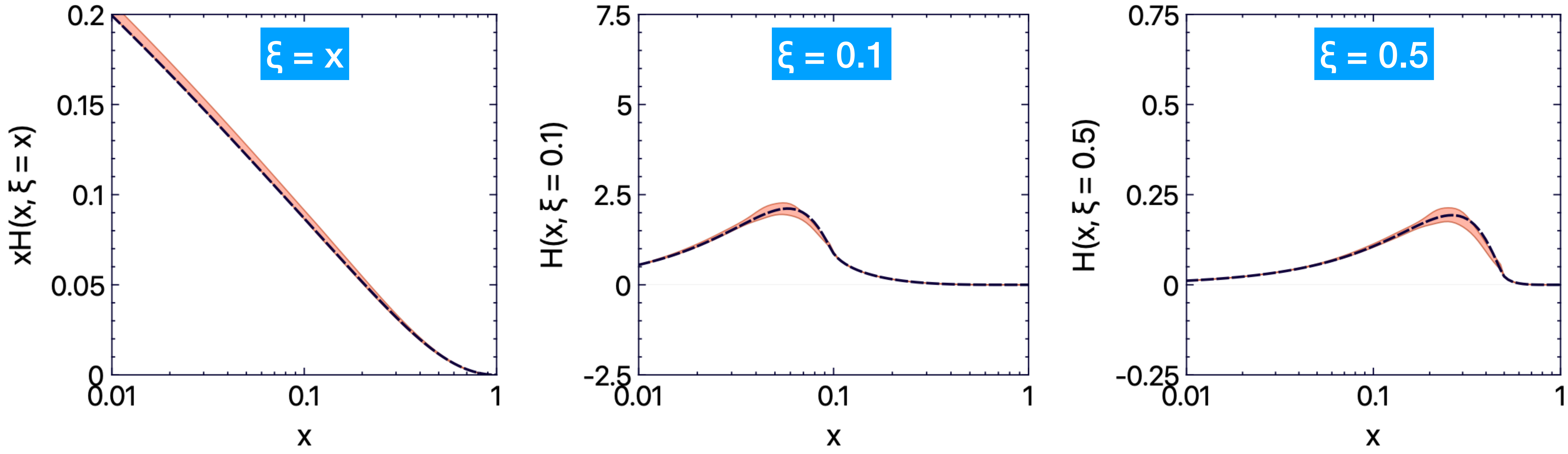
making the deconvolution of CFFs ill-posed

We found such GPDs for both LO and NLO



Demonstration of results

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



Conditions:

- Input: 400 x ≠ ξ points generated with GK model
- Positivity not forced

Technical detail of the analysis:

- Minimisation with genetic algorithm
- Replication for estimation of model uncertainties
- “Local” detection of outliers
- Dropout algorithm for regularisation

GK

ANN model 68% CL $F_C + F_S + F_D$

Demonstration of results

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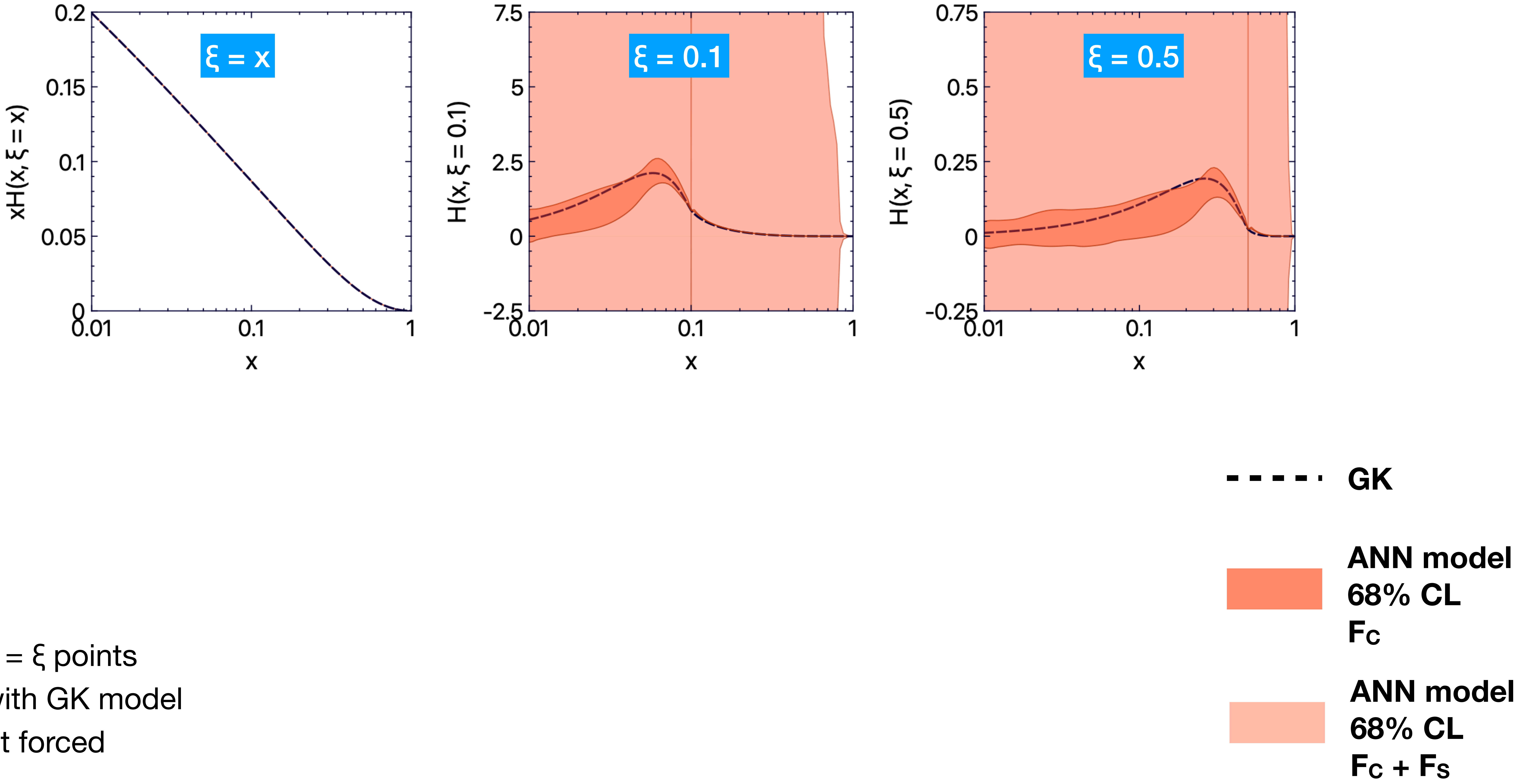

Conditions:

- Input: 200 x = ξ points generated with GK model
- Positivity not forced

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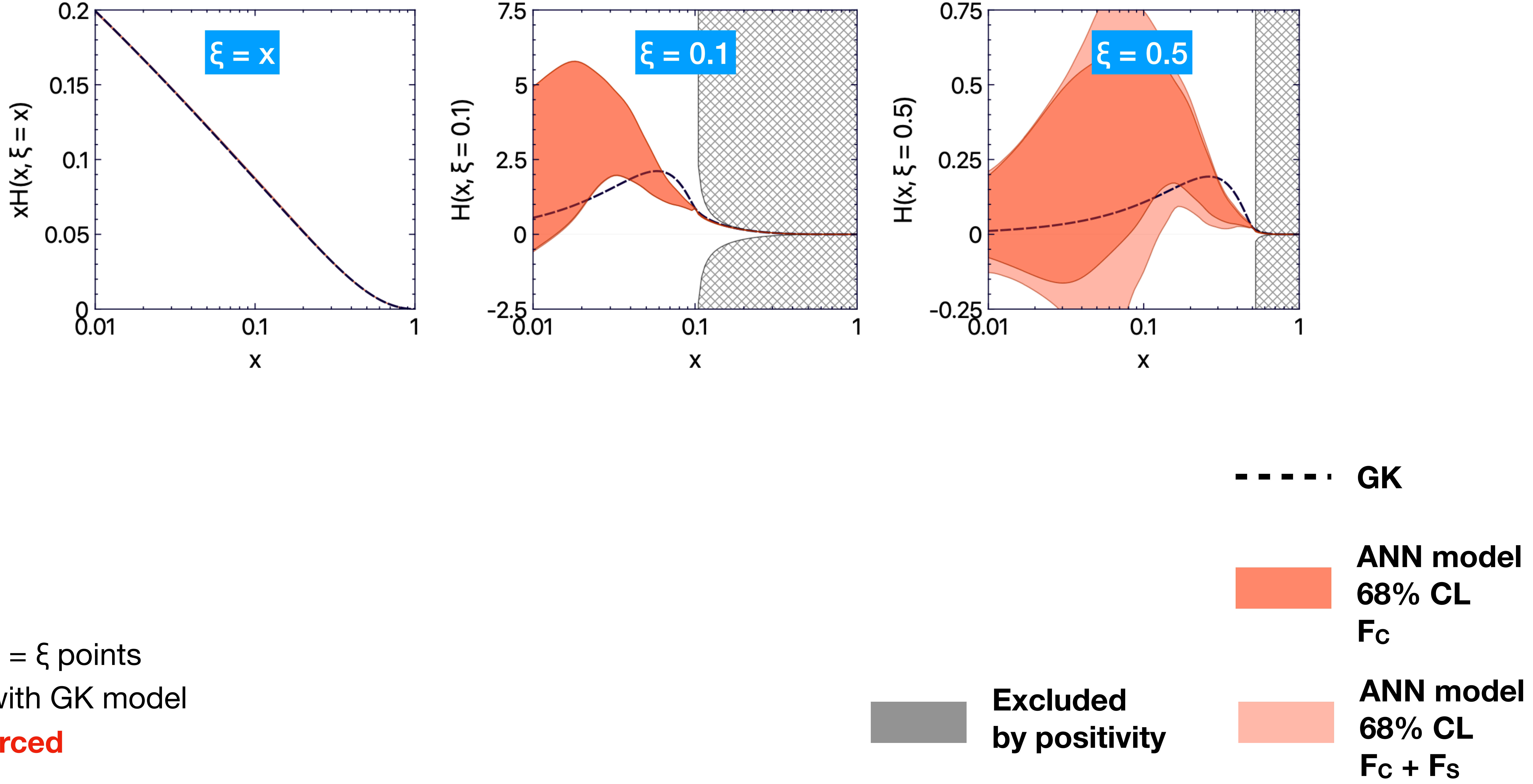
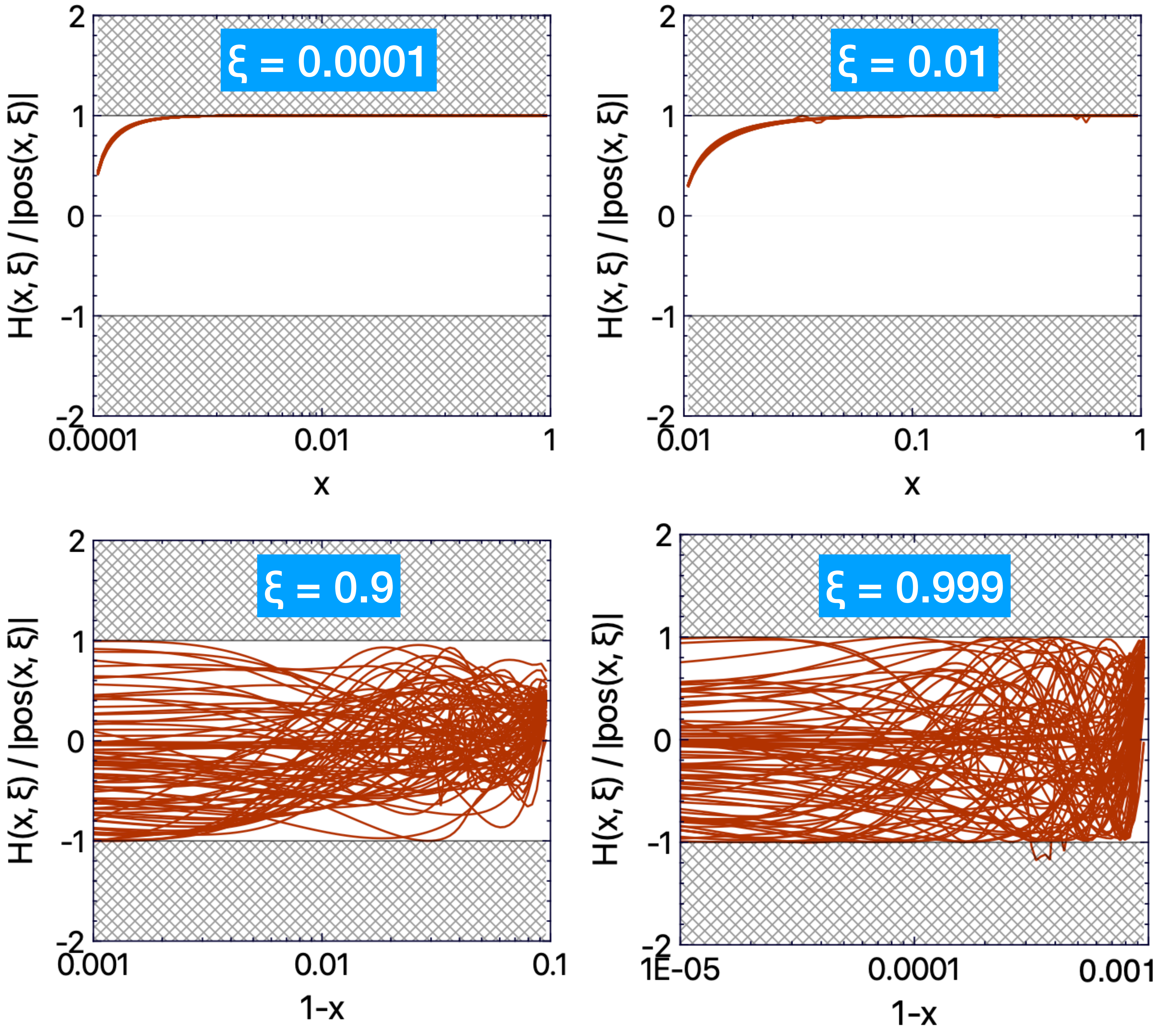


Conditions:

- Input: 200 x = ξ points generated with GK model
- Positivity **forced**

Demonstration of results



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GK

single replica

Excluded by positivity

Conditions:

- Input: 200 x = ξ points generated with GK model
- Positivity **forced**

Summary

- Review of recent results given
- Substantial progress in:
  - understanding fundamental problems, like deconvolution of CFFs, and analysis methods
    → important for extraction of GPDs
  - description of exclusive processes
    → new sources of GPD information
  - 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
  - addressing the long-standing problem of model dependency of GPDs
    → nontrivial and timely analysis
  - delivering open-source tools for the community
    → to suport both experimentalists and theoreticians

This progress is important for the current GPD programme and for the era of the new generation of experiments