Tools and practice of GPD extraction

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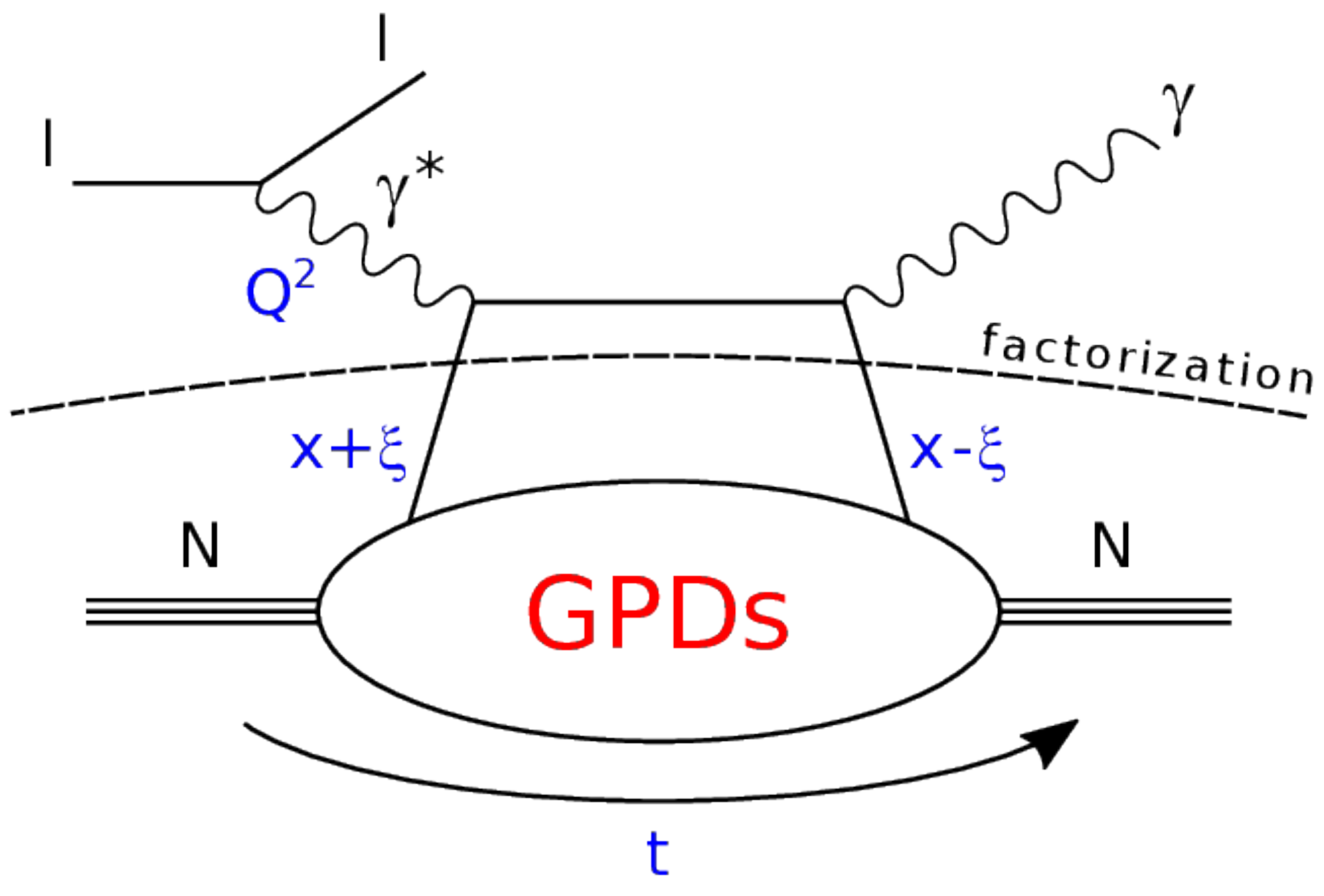
ECT*-APCTP Joint Workshop: Exploring resonance structure with transition GPDs,
Trento, Italy, August 21st, 2023

Outline

- Introduction
- Amplitud analyses
- GPDs
- New sources of GPD information
- Tools

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:

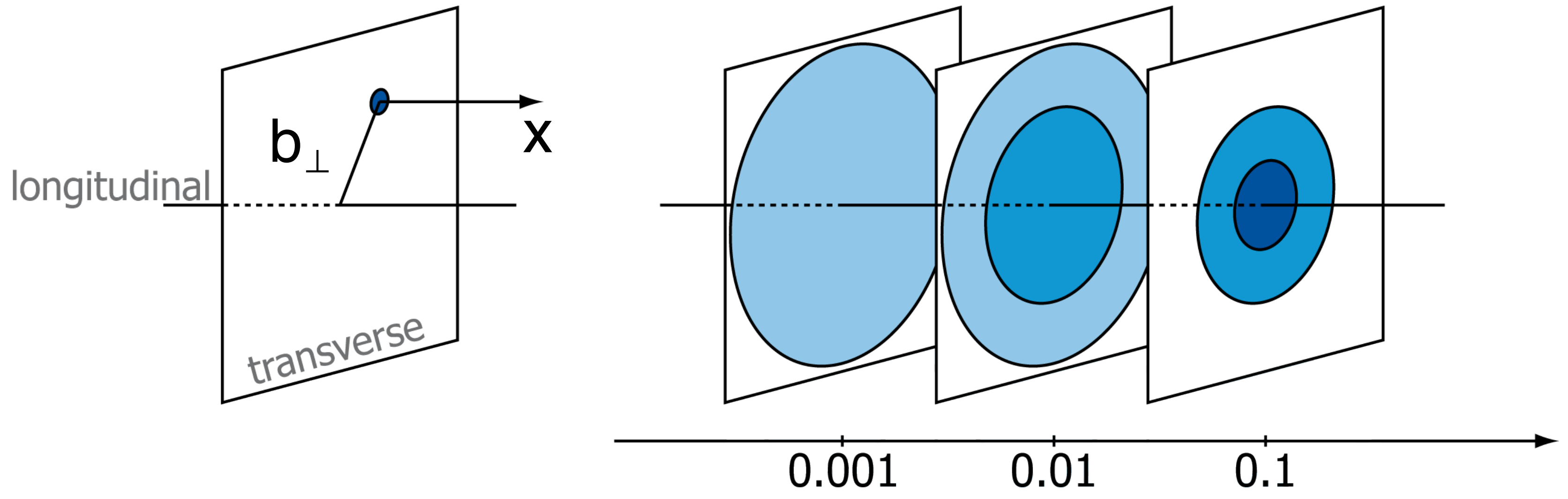
$$\mathcal{A}_n(\xi, t) = \int_{-1}^{1} \mathrm{d}x x^n H(x, \xi, t) = \sum_{\substack{j=0 \\ \mathrm{even}}}^{n} \xi^j A_{n,j}(t) + \mathrm{mod}(n, 2)\xi^{n+1} A_{n,n+1}(t)$$

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

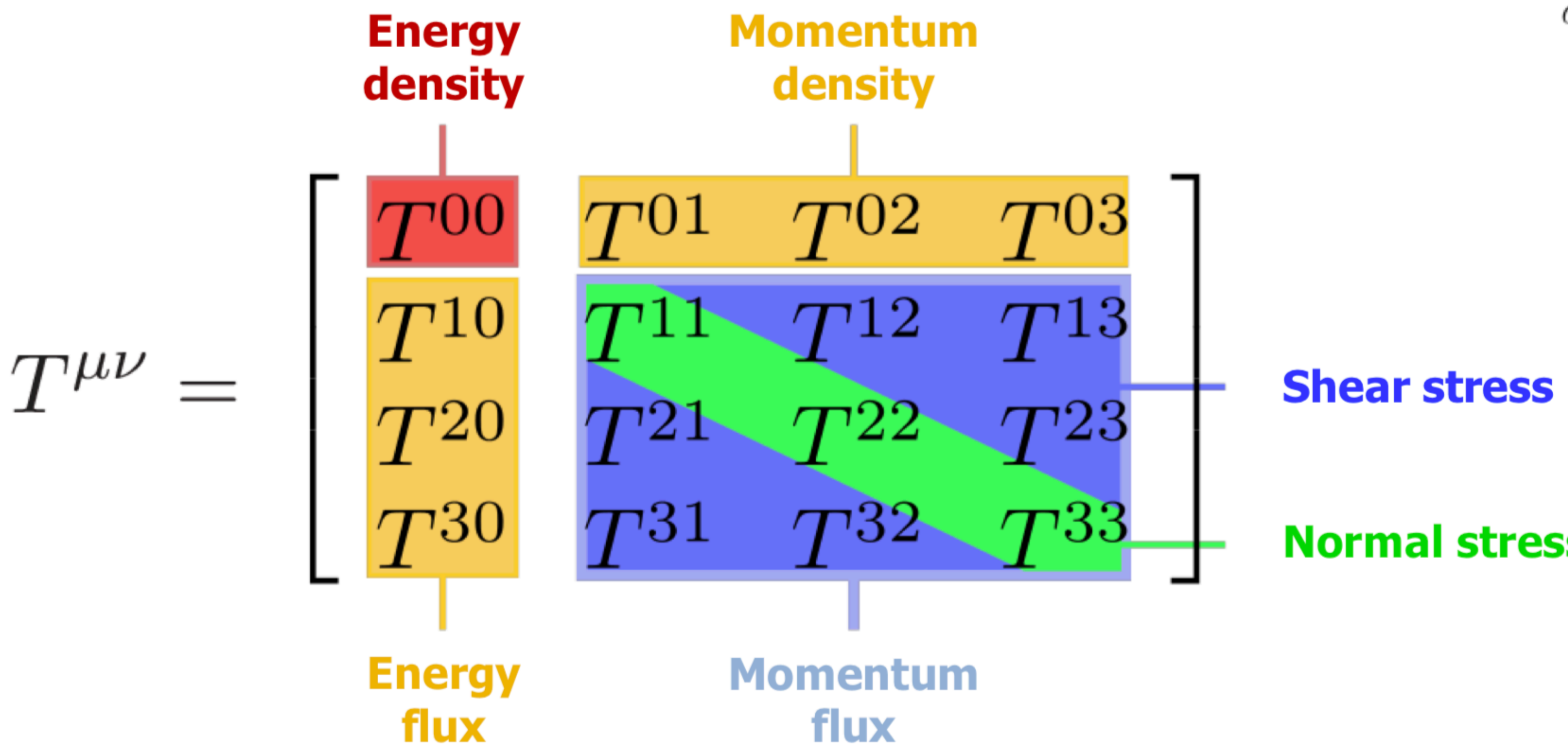
$$|H(x, \xi, t)| \leq \sqrt{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right) \frac{1}{1-\xi^2}}$$

Nucleon tomography:

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

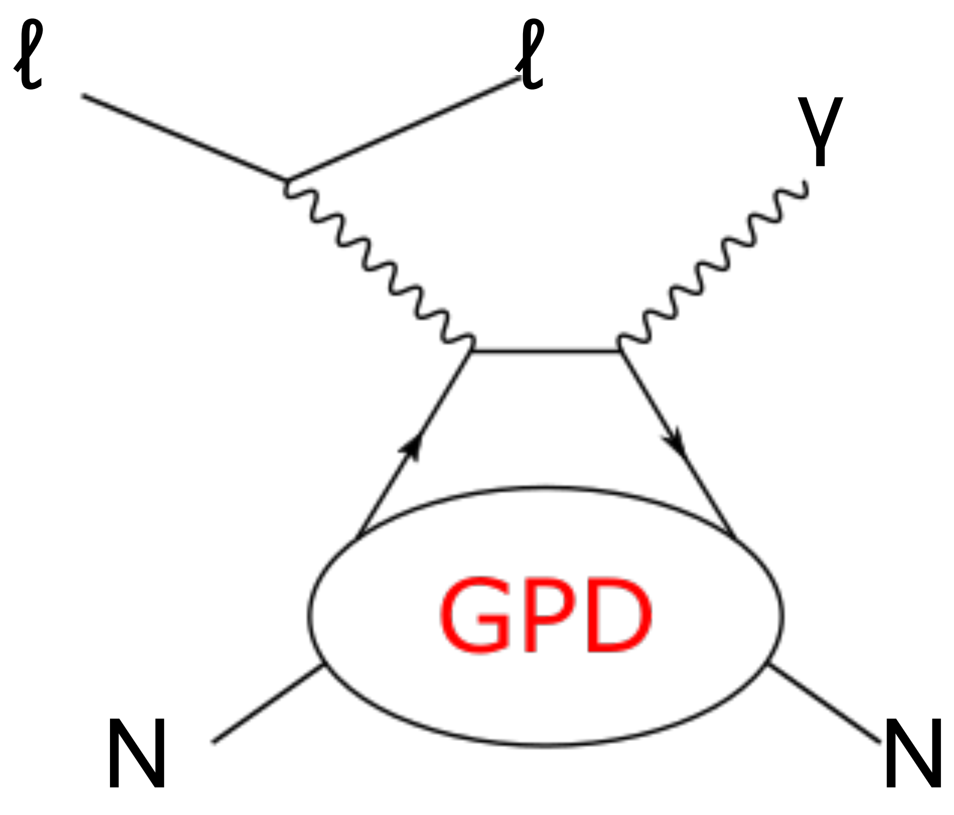


Energy momentum tensor in terms of form factors (OAM and mechanical forces):

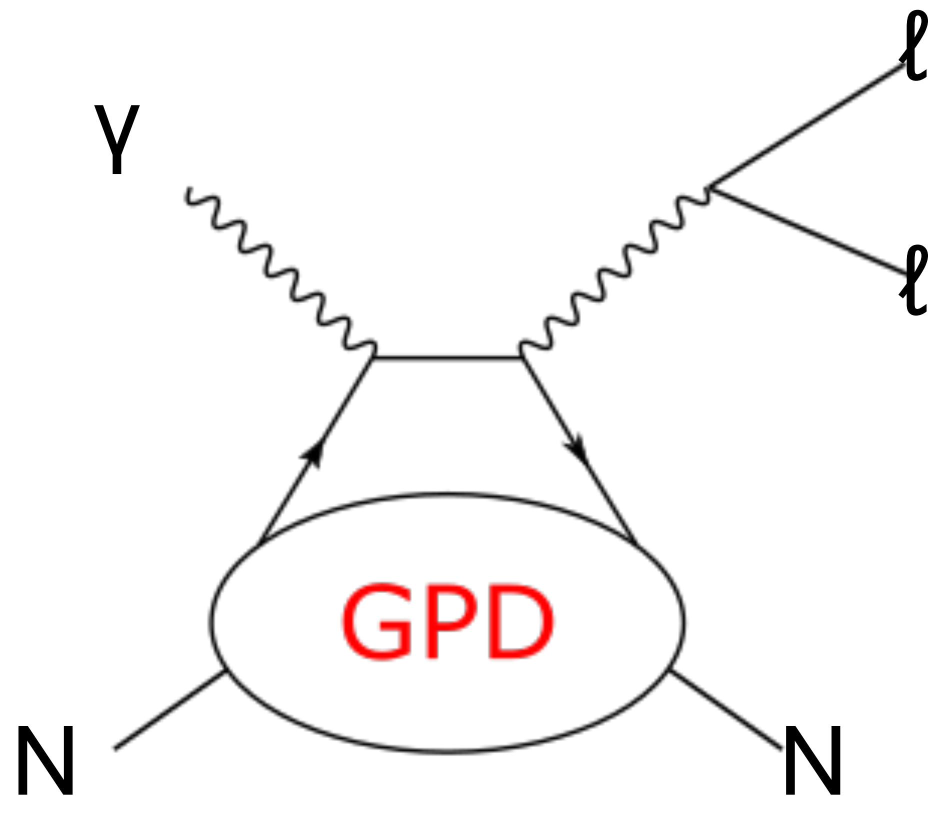


$$\langle p' | T^{\mu\nu}_{q,g} | p \rangle = \bar{u}(p')\Big[A_{q,g}(t) P^{(\mu}\gamma^{\nu)} + B_{q,g}(t)\frac{P^{(\mu} i\sigma^{\nu)\alpha}\Delta_\alpha}{2m} + C_{q,g}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{m} + \bar{C}_{q,g}(t) m g^{\mu\nu}\Big]u(p)$$

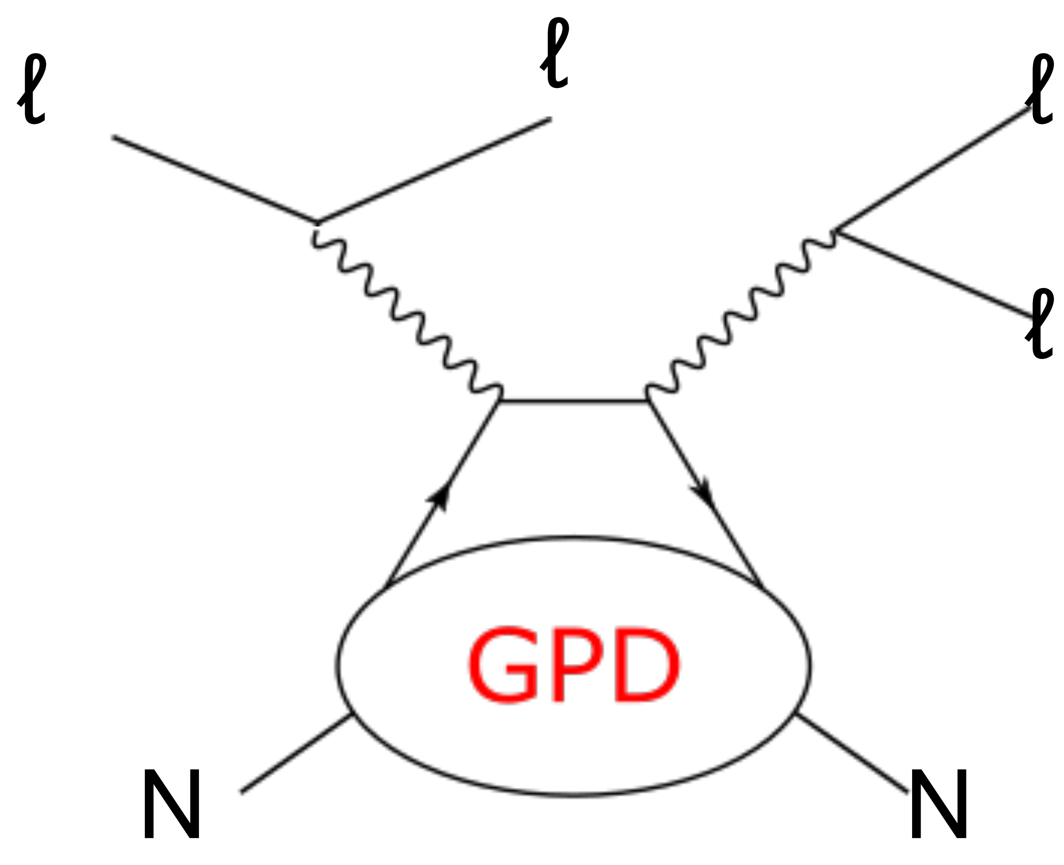
GPDs accessible in various production channels and observables
→ experimental filters



DVCS
Deeply Virtual Compton Scattering



TCS
Timelike Compton Scattering



DDVCS
Double Deeply Virtual Compton Scattering

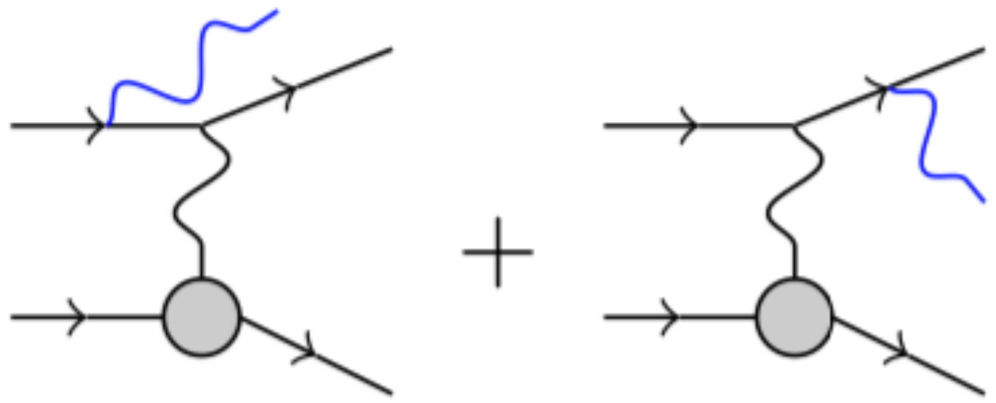
more production channels sensitive to GPDs exist!

DVCS Compton Form Factors

Cross-section for single photon production ($l + N \to l + N + \gamma$):

$$\sigma \propto |\mathscr{A}|^2 = |\mathscr{A}_{BH} + \mathscr{A}_{DVCS}|^2 = |\mathscr{A}_{BH}|^2 + |\mathscr{A}_{DVCS}|^2 + \mathscr{I}$$

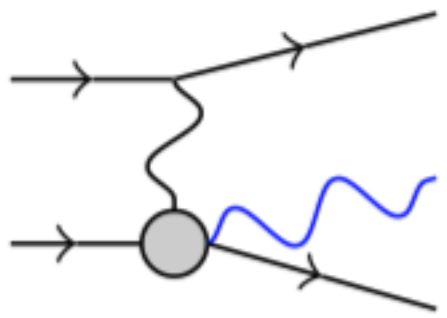
Bethe-Heitler process



calculable within QED

parametrised by elastic FFs

DVCS



calculable within QCD

parametrised by CFFs

For more details and formulae see e.g.:
A. V. Belitsky et al.
NPB 878 (2014) 214

DVCS Compton Form Factors

note: here, example for CFF $\mathcal{H}$

- imaginary part

$$\mathrm{Im}\mathscr{H}(\xi,t) \overset{\mathrm{LO}}{=} \pi H^{(+)}(\xi,\xi,t) = \pi \sum_q e_q^2 H^{q(+)}(\xi,\xi,t)$$

where

$$H^{q(+)}(x,\xi,t) = H^q(x,\xi,t) - H^q(-x,\xi,t)$$

- real part

$$\mathrm{Re}\mathscr{H}(\xi,t) \overset{\mathrm{LO}}{=} \int_0^1 \mathrm{d}x\, H^{(+)}(x,\xi,t)\left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right)$$

or using dispersion relation

$$\mathrm{Re}\mathscr{H}(\xi,t) = \frac{1}{\pi}\int_0^1 \mathrm{d}x\, \mathrm{Im}\mathscr{H}(\xi,t)\left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right) + \mathscr{C}(t)$$

$$\mathrm{Re}\mathscr{H}(\xi,t) \overset{\mathrm{LO}}{=} \int_0^1 \mathrm{d}x\, H(\xi,\xi,t)\left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right) + \mathscr{C}(t)$$

subtraction constant connected to EMT FF

DVCS Compton Form Factors

- relation between subtraction constant and D-term:

$$\mathscr{C}(t) = \mathscr{C}^g(t) + \sum_q \mathscr{C}^q(t)$$

where

$$\mathscr{C}^g(t) \overset{\text{LO}}{=} 0 \qquad \mathscr{C}^q(t) \overset{\text{LO}}{=} 2\, e_q^2 \int_{-1}^{1} \mathrm{d}z \, \frac{D^q(z,t)}{1-z} \equiv 4D^q(t) \qquad z = \frac{x}{\xi}$$

- decomposition into Gegenbauer polynomials:

$$D^q(z,t) = (1-z^2) \sum_{i=0}^{\infty} d_i^q C_{2i+1}^{3/2}(z)$$

- connection to EMT FF:

$$D^q(t) = \sum_{\substack{i=1 \\ \text{odd}}}^{\infty} d_i^q(t) \qquad d_1^q(t) \equiv 5C_q(t)$$

Parametric Ansatz of CFFs

$$G = \{H, E, \widetilde{H}, \widetilde{E}\}$$

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

$$G^q(x,0,t) = \mathrm{pdf}^q_G(x)\ \exp(f^q_G(x)t)$$

$$f^q_G(x) = A^q_G \log(1/x) + B^q_G(1-x)^2 + C^q_G(1-x)x$$

- 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

$$G^q(x,x,t) = G^q(x,0,t)\ g^q_G(x,x,t) \qquad g^q_G(x,x,t) = \frac{a^q_G}{(1-x^2)^2}\left(1+t(1-x)(b^q_G + c^q_G\log(1+x))\right)$$

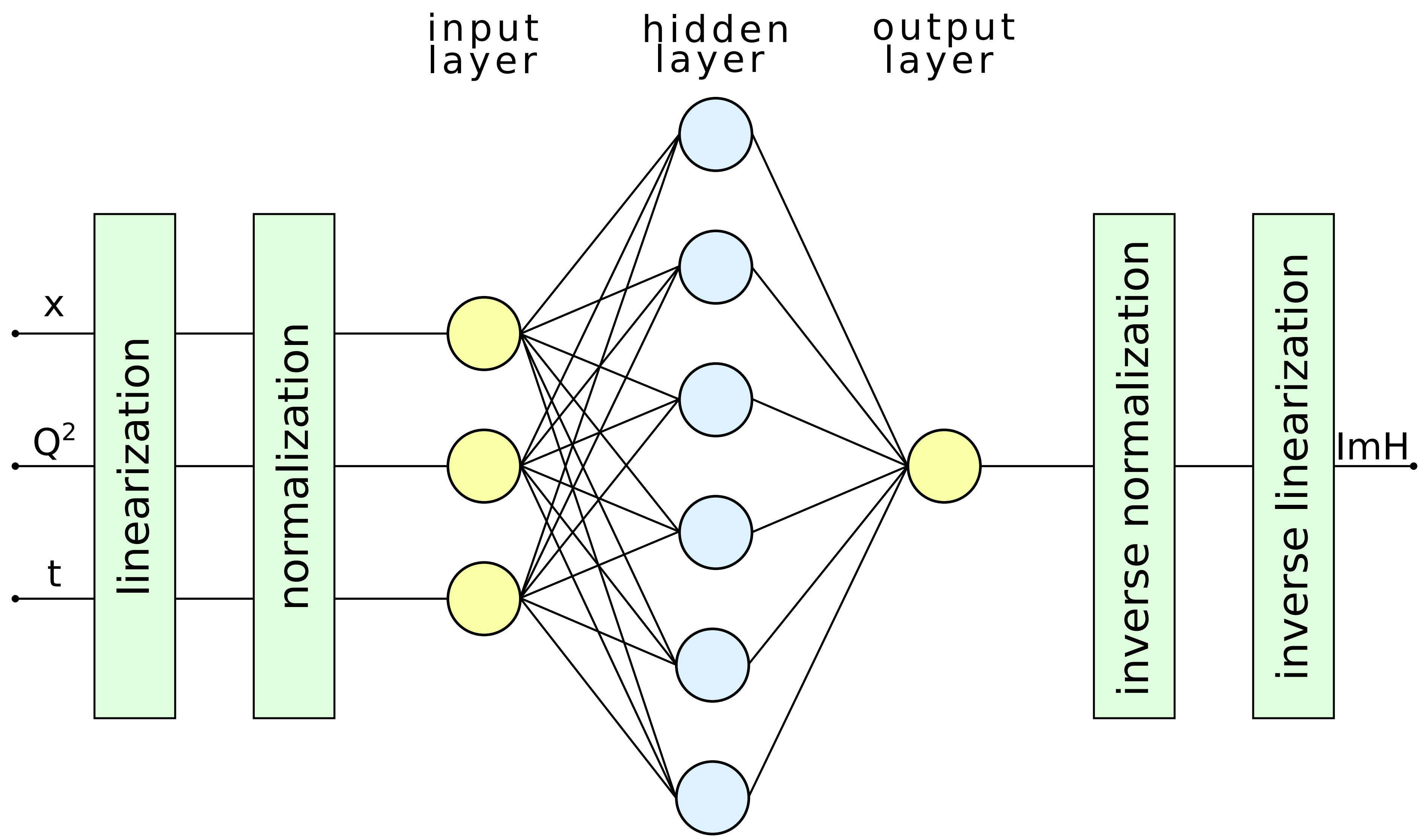
- at x → 0 constant skewness effect
- at x → 1 reproduce power behaviour predicted for GPDs in Phys. Rev. D69, 051501 (2004)
- t-dependence similar to DD-models with (1-x) to avoid any t-dep. at x = 1

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

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

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

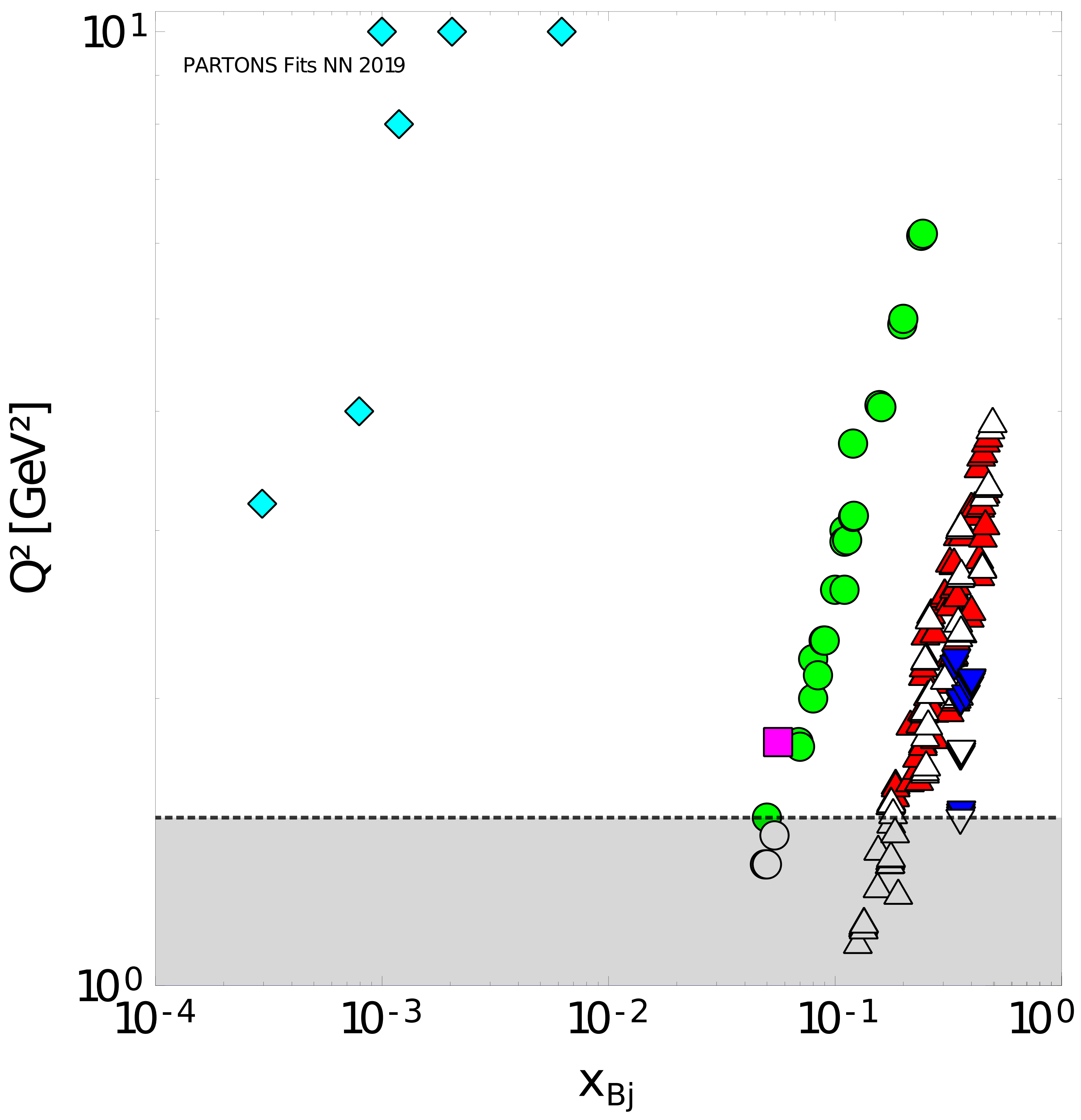
DVCS data

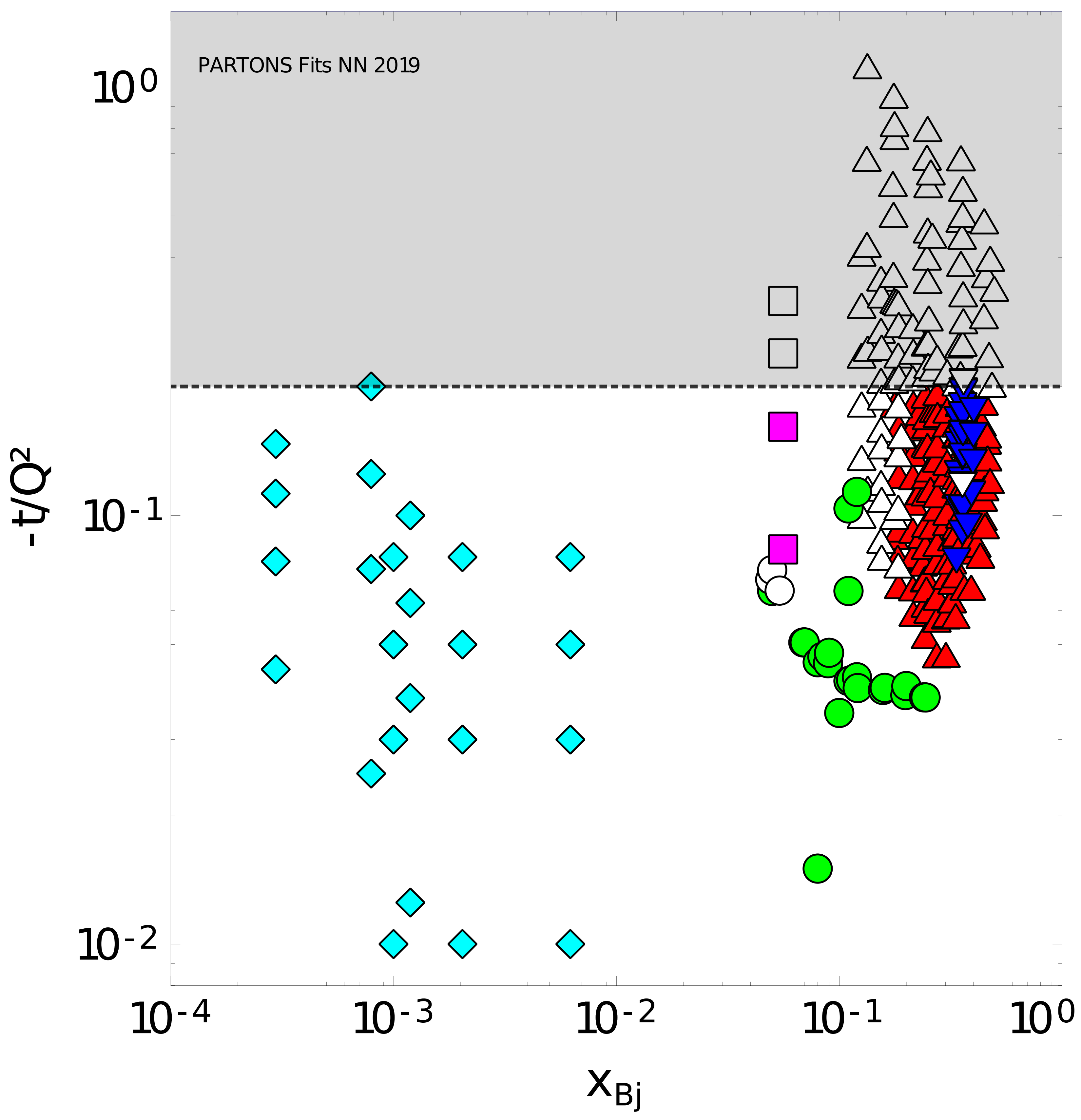
Kinematic cuts
used in our recent analyses:

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

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

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



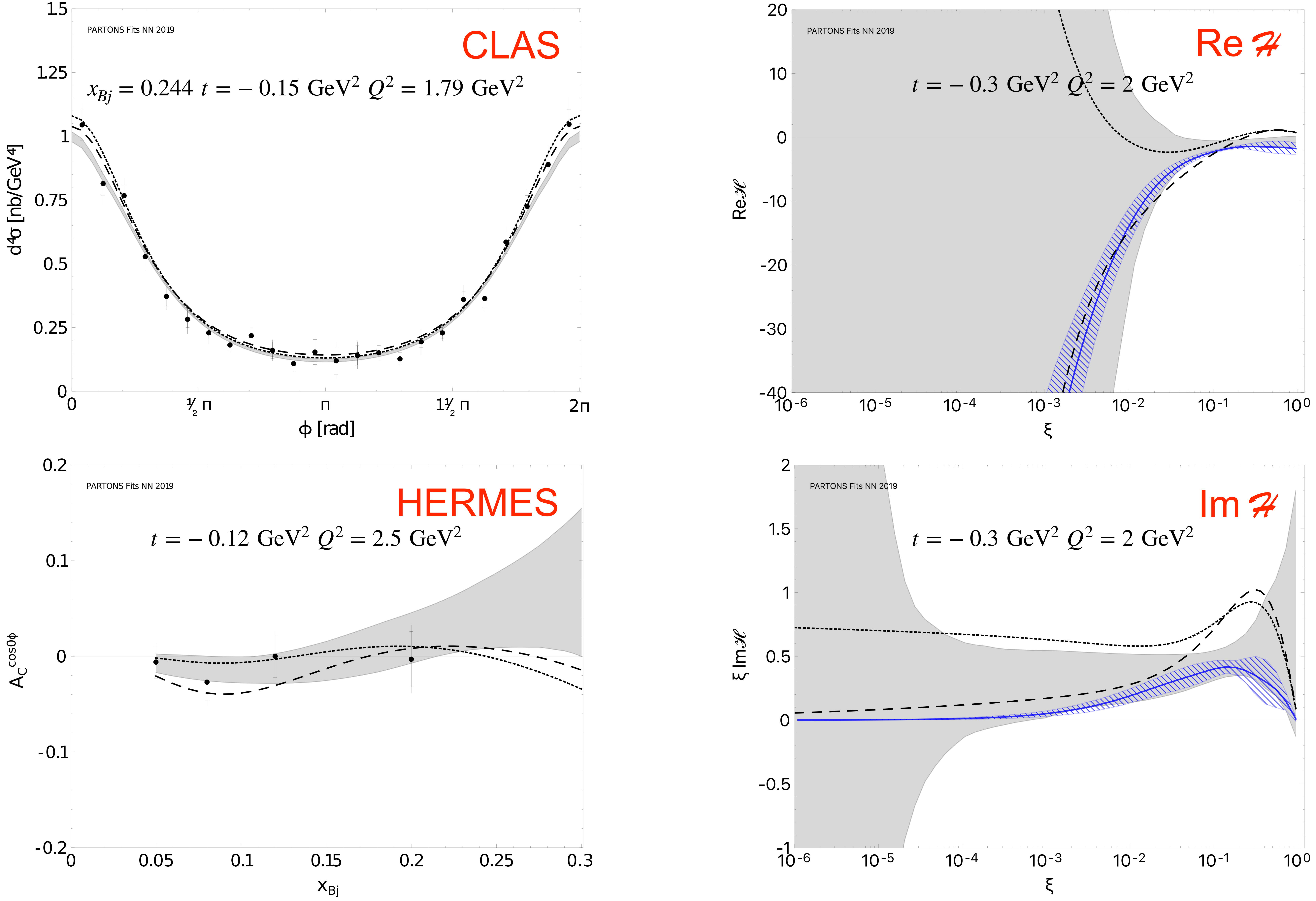


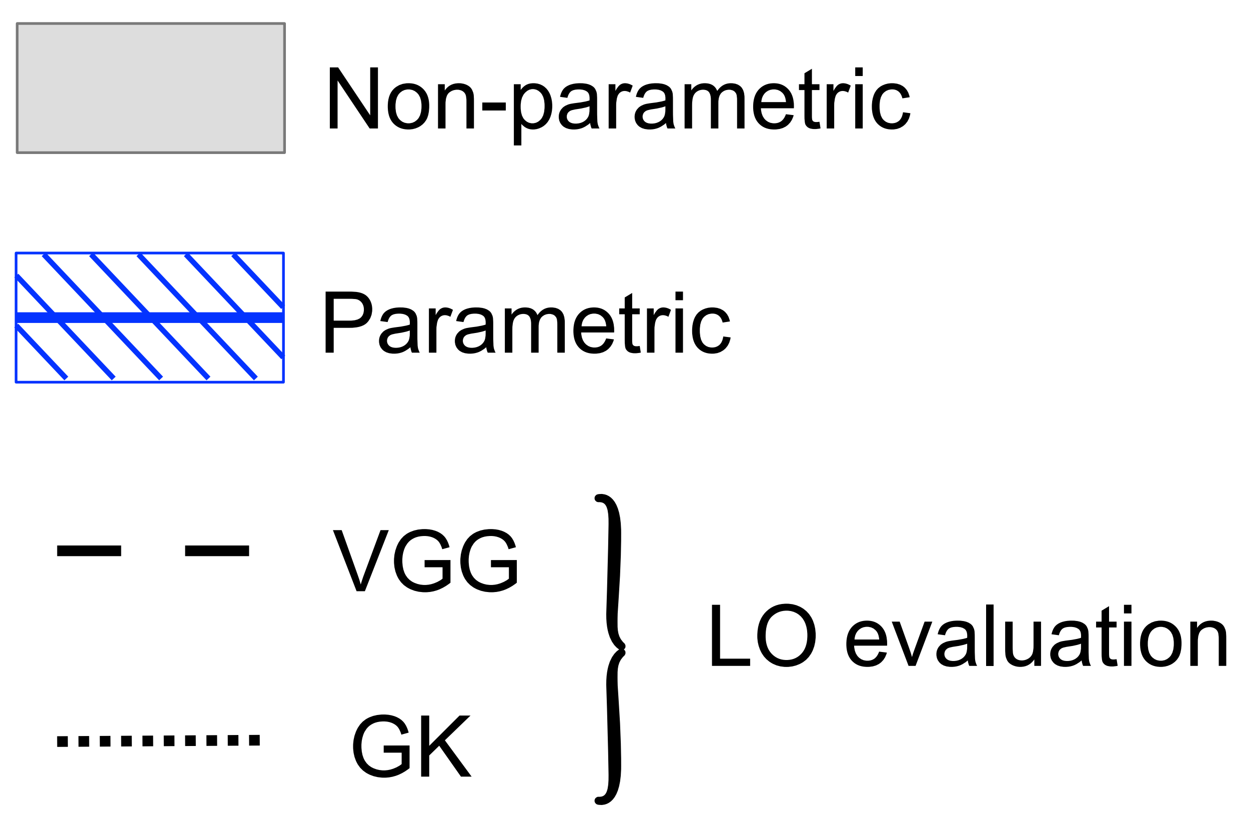
Analytic Ansatz is also fitted to elastic FF data and uses specific PDF parameterisation!!!

Results

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

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





$$\xi \approx x_{Bj}/(2 - x_{Bj})$$

Results

H. Moutarde, PS, J. Wagner,
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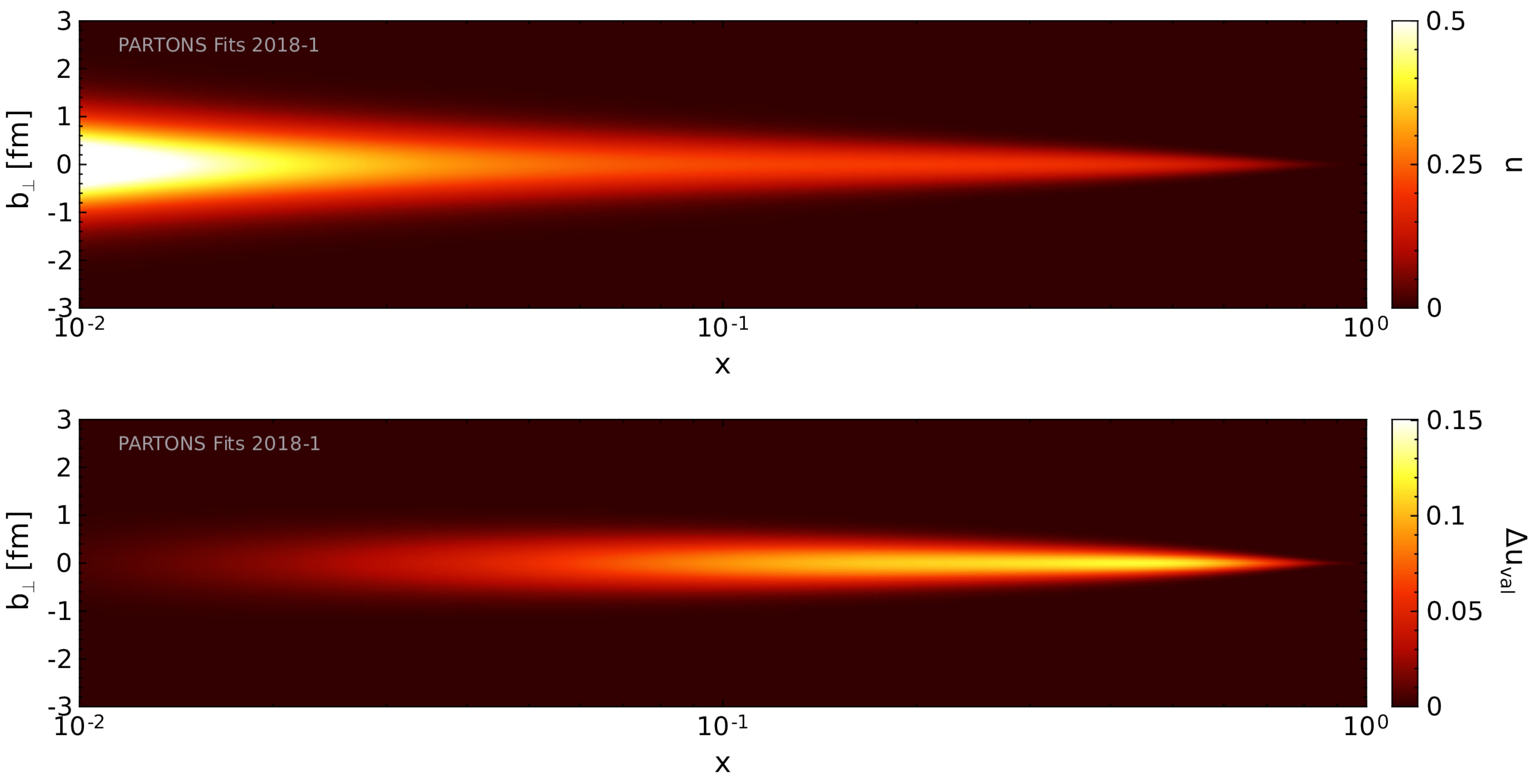
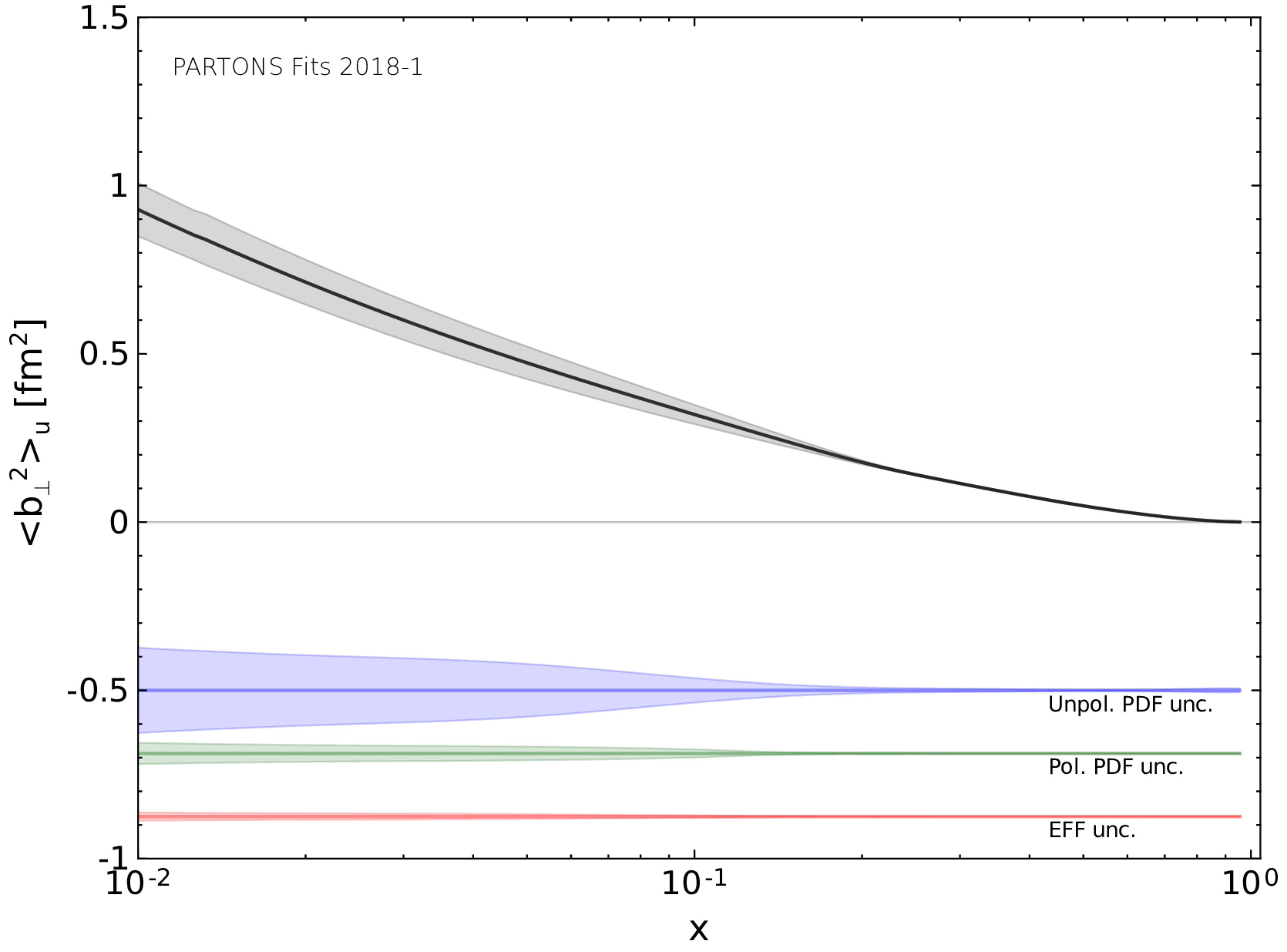
Parametric Ansatz allows us to access nucleon tomography

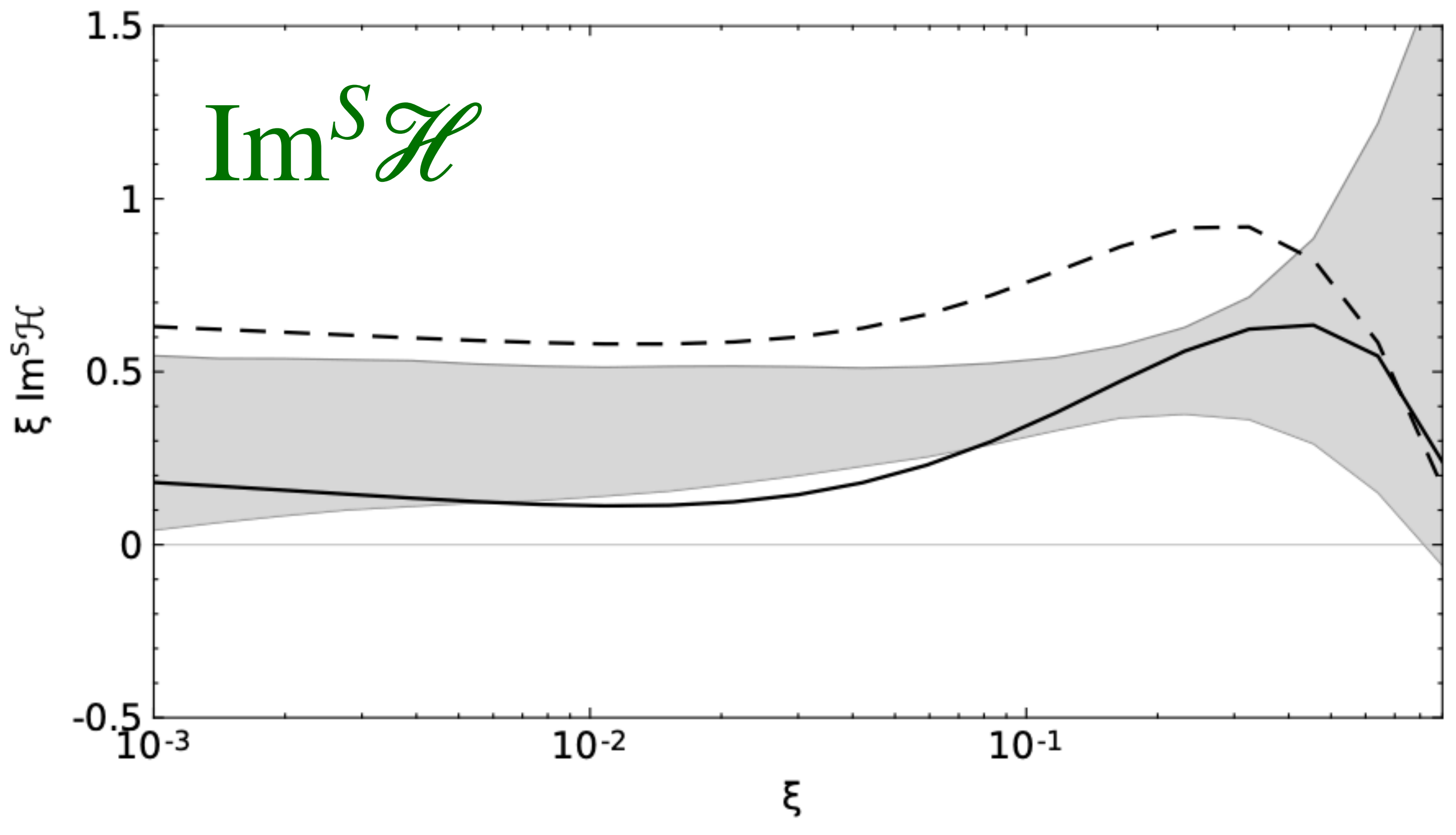


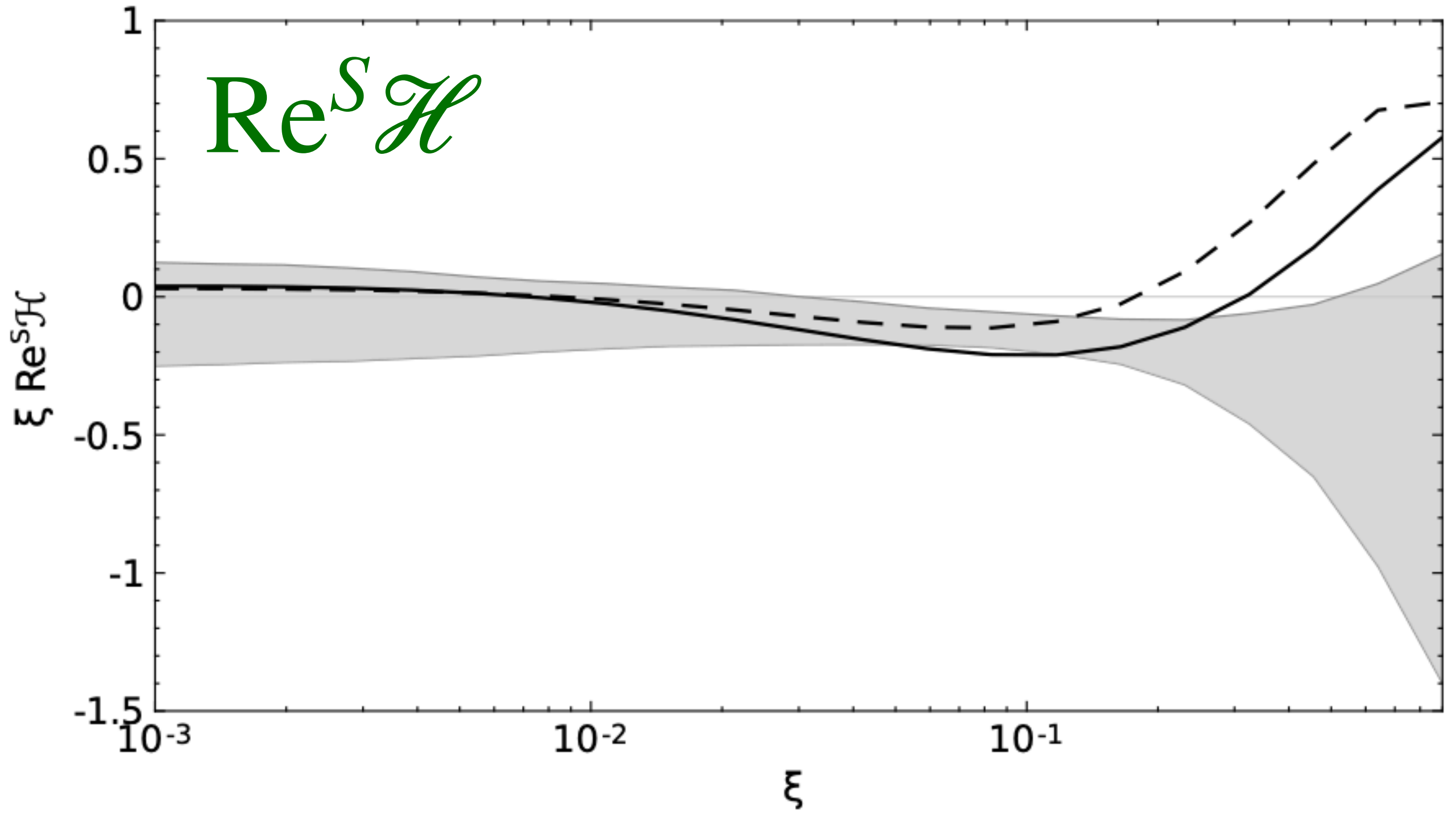


$$Q^2 = 2\ \text{GeV}^2$$

Impact of positron beam

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





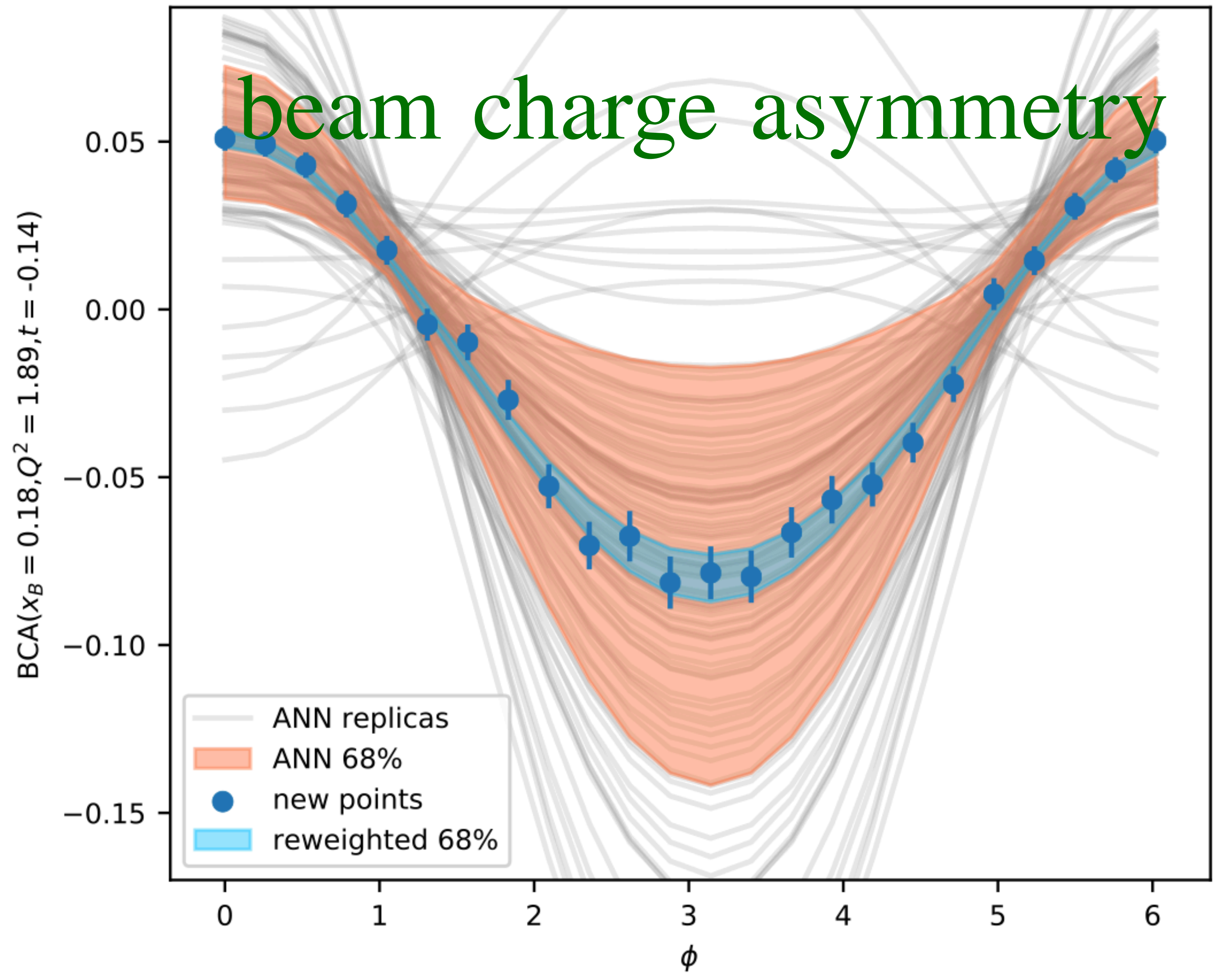
ANN analysis

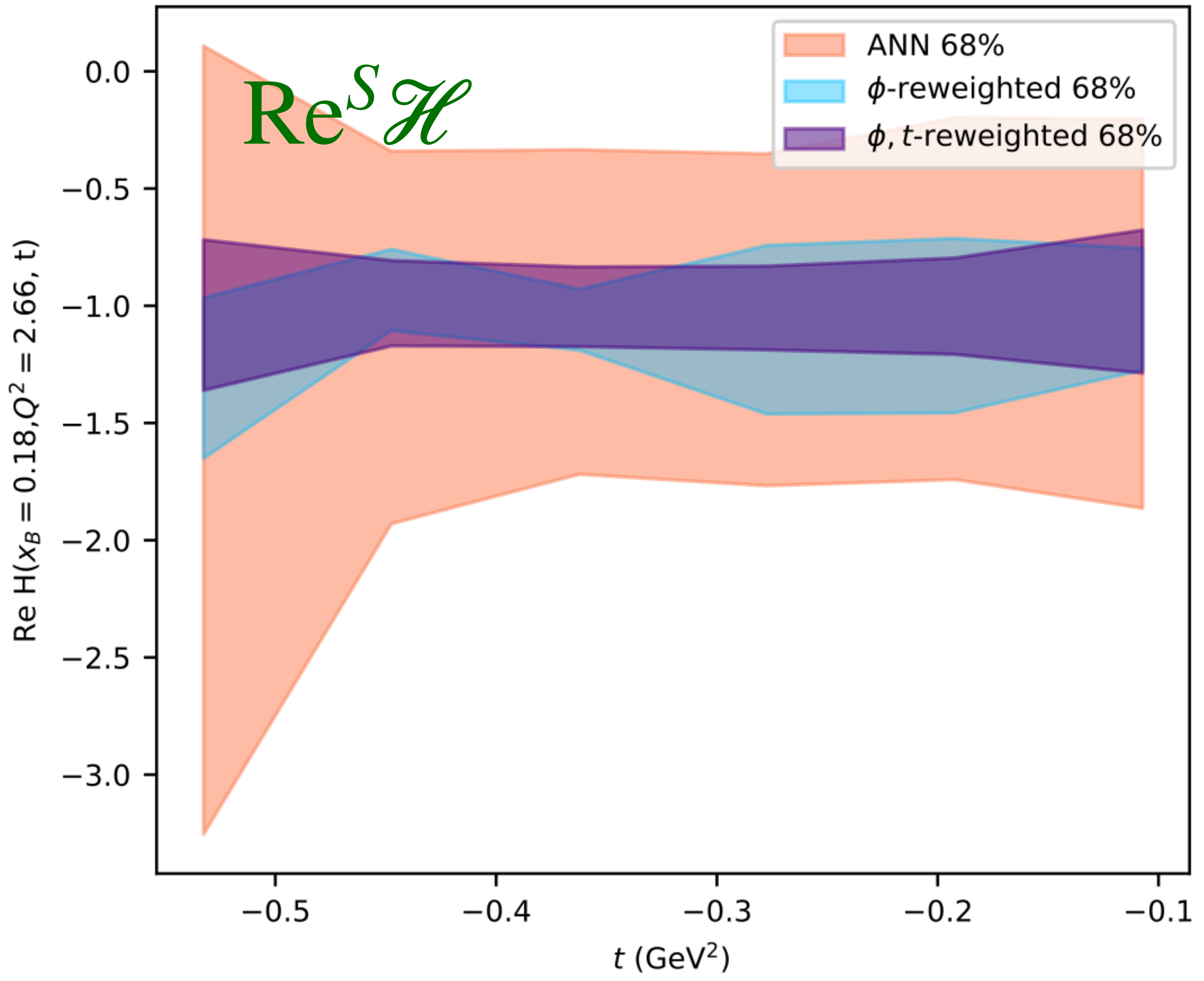
GK (LO) GK (NLO)

Re-weighting with positron pseudo-data

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

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



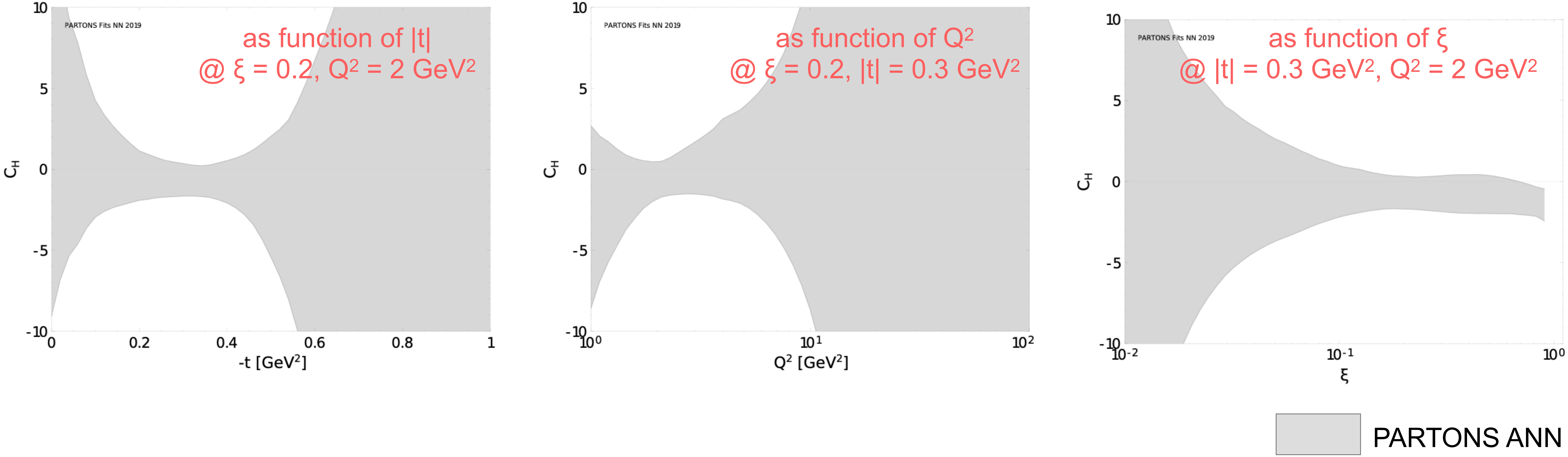


Results

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

Subtraction constant extracted using dispersion relation

$$\mathcal{C}_H(t,Q^2) = \mathrm{Re}\,\mathcal{H}(\xi,t,Q^2) - \frac{1}{\pi}\fint_0^1 \mathrm{d}\xi' \, \mathrm{Im}\,\mathcal{H}(\xi',t,Q^2)\left(\frac{1}{\xi-\xi'} - \frac{1}{\xi+\xi'}\right)$$



- not suitable for extraction of pressure anisotropy

$$s_a(r) = -\frac{4M}{r^2}\int \frac{\mathrm{d}^3\boldsymbol{\Delta}}{(2\pi)^3} e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{r}} \frac{t^{-1/2}}{M^2}\frac{\mathrm{d}^2}{\mathrm{d}t^2}\left[t^{5/2}C_a(t)\right]$$

Results

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

Master formula:

$$\mathrm{Re}\mathscr{H}(\xi,t,Q^2) - \frac{1}{\pi}\int_0^1 \mathrm{d}\xi'\,\mathrm{Im}\,\mathscr{H}(\xi,t,Q^2)\left(\frac{1}{\xi-\xi'} - \frac{1}{\xi+\xi'}\right) \overset{LO}{=} 4\sum_q e_q^2 \sum_{\mathrm{odd}\ n} d_n^q(t,\mu_F^2 \equiv Q^2)$$

Extraction of subtraction constant from DVCS data requires:

- integral over ξ (alternatively: x_{Bj} or ν) between ε and 1

$$\epsilon = 10^{-6}$$

- good knowledge of both Re and Im parts of CFF *H*

Model assumptions to extract EMT FF C from subtraction constant:

- truncation to d1

$$C_H(t,Q^2) = 4\sum_q e_q^2\, d_1^q(t,\mu_F^2 \equiv Q^2)$$

- symmetry of light quark contributions

$$d_1^u(t,\mu_F^2) = d_1^d(t,\mu_F^2) = d_1^s(t,\mu_F^2) \equiv d_1^{uds}(t,\mu_F^2)$$

- sensitivity to gluon contribution via evolution

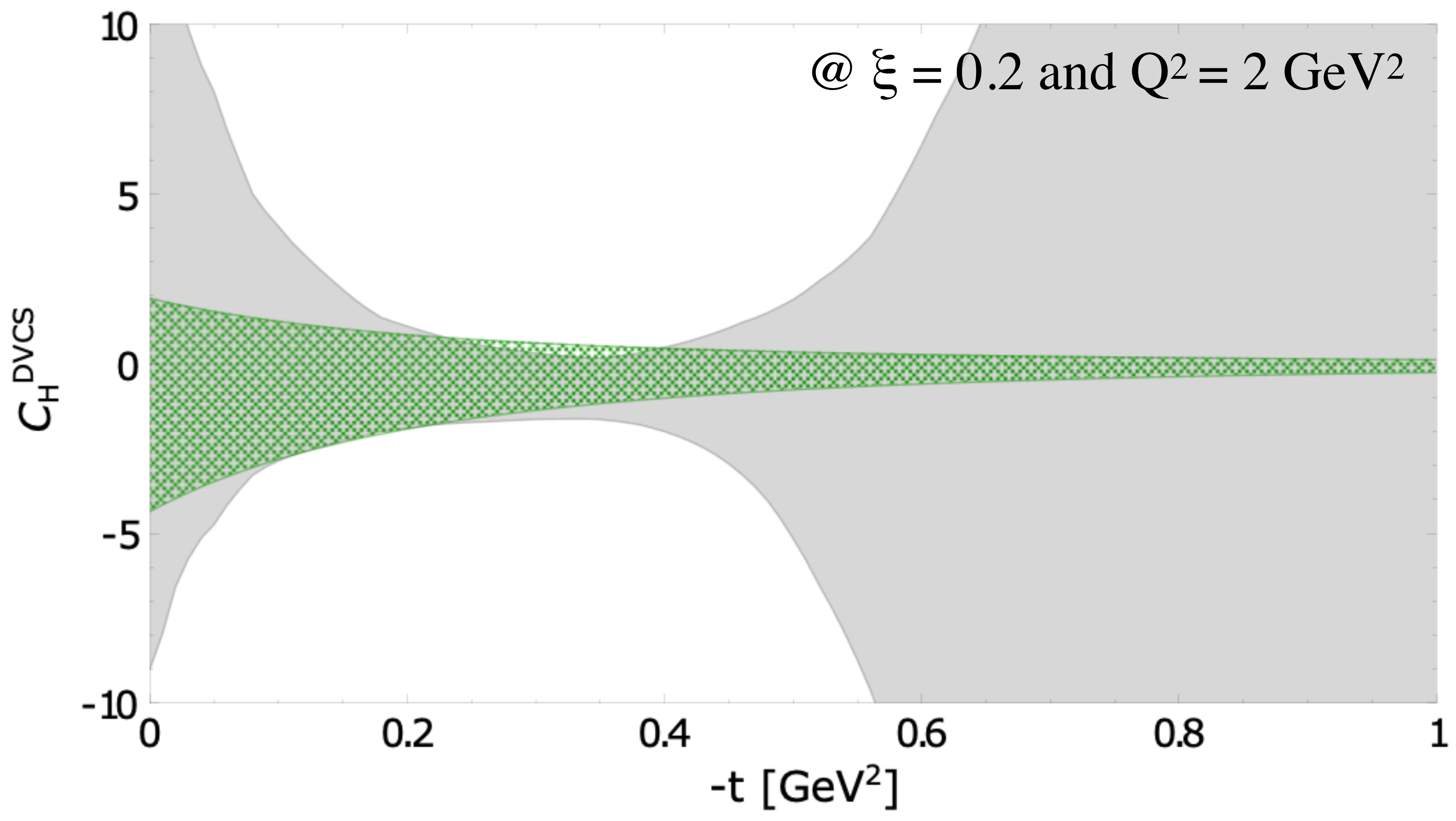
$$d_1^G(t,\mu_{F,0}^2) = 0 \qquad \mu_{F,0}^2 = 0.1\ \mathrm{GeV}^2$$

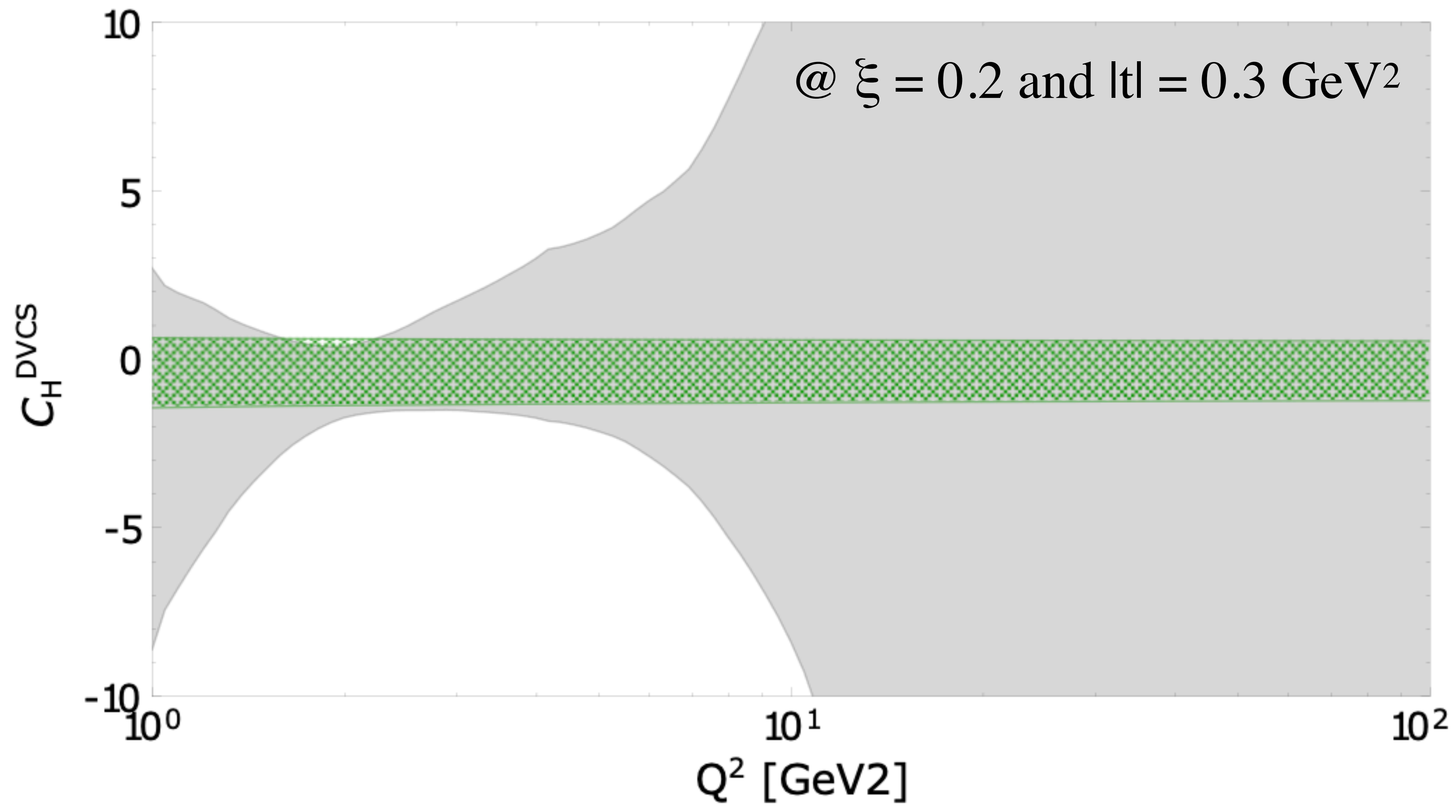
- tripole Ansatz for t-dependence

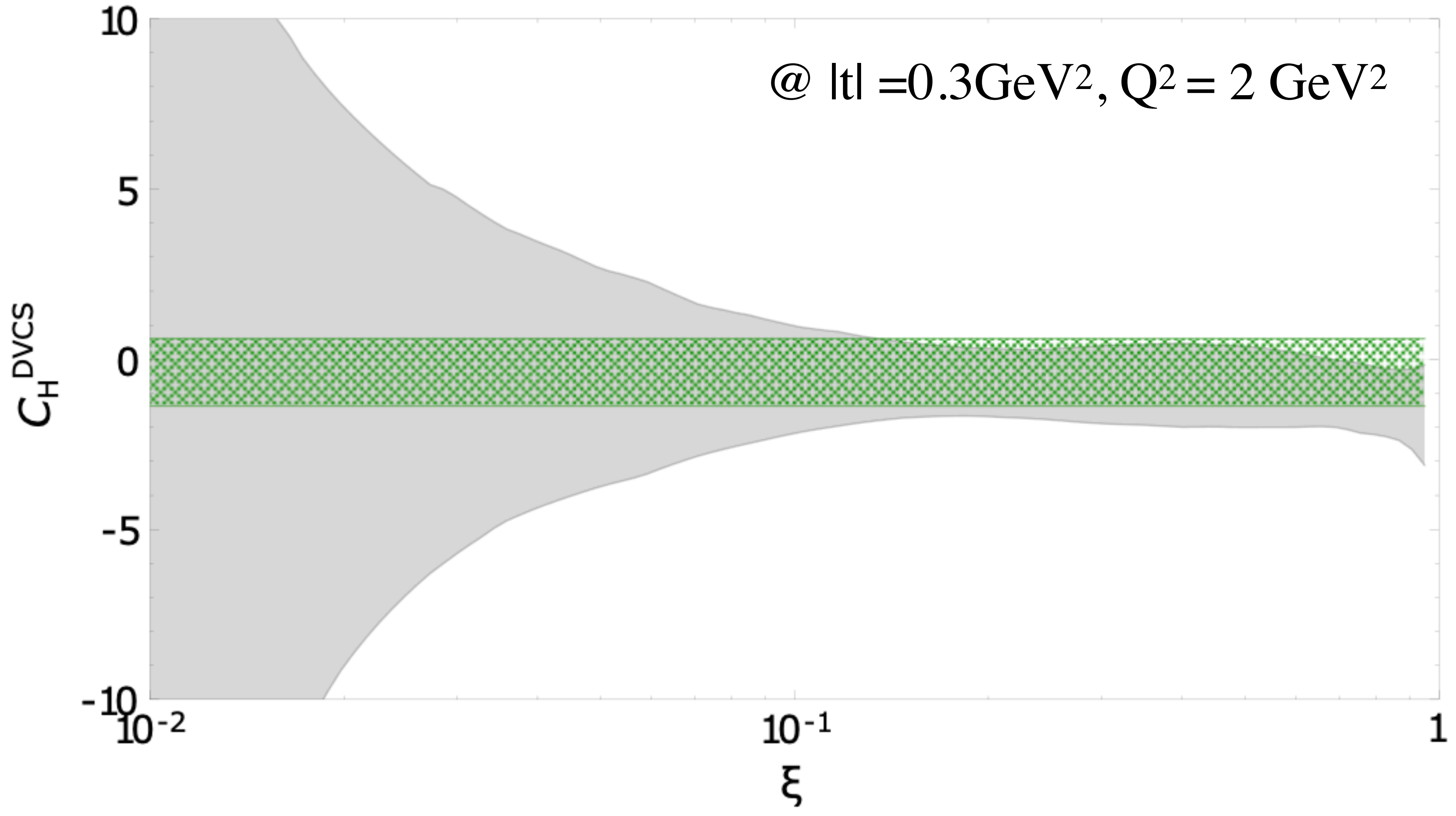
$$d_1^{uds}(t,\mu_F^2) = d_1^{uds}(\mu_F^2)\left(1 - \frac{t}{\Lambda^2}\right)^{-\alpha} \qquad \alpha = 3 \qquad \Lambda = 0.8\ \mathrm{GeV}$$

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

- Subtraction constant:
  - ANN analysis
  - Model dependent extraction







Results

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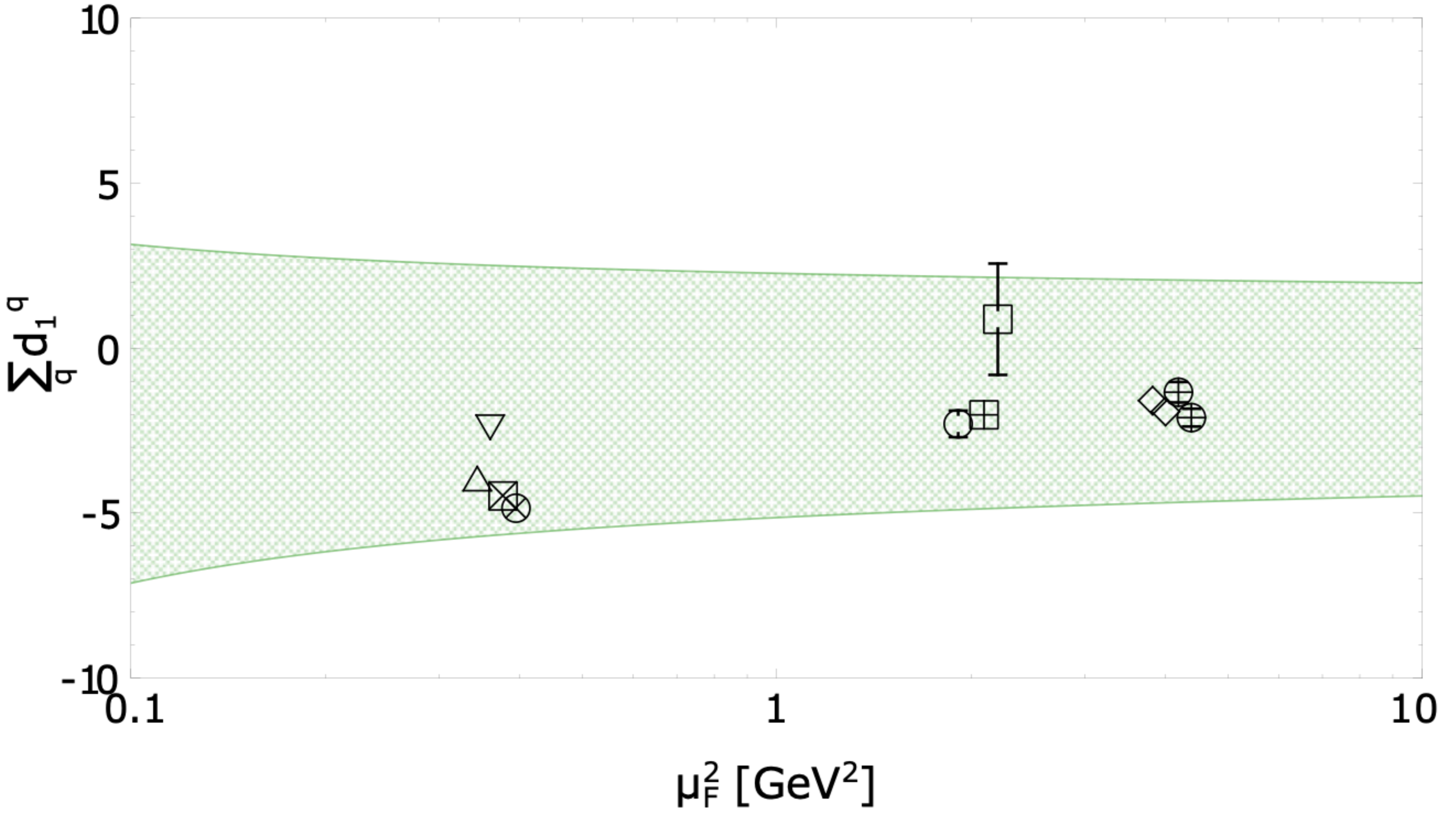
- Obtained values

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

@μ_F^2 = 2 GeV^2

- Comparison with other extractions and theory



No.	Marker	$\sum_q d_1^q(\mu_F^2)$	μ_F^2 in GeV^2	# of flavours	Type
1	○	$-2.30 \pm 0.16 \pm 0.37$	2.0	3	from experimental data
2	□	0.88 ± 1.69	2.2	2	from experimental data
3	◇	-1.59	4	2	t-channel saturated model
		-1.92	4	2	t-channel saturated model
4	△	-4	0.36	3	χQSM
5	▽	-2.35	0.36	2	χQSM
6	⊠	-4.48	0.36	2	Skyrme model
7	⊞	-2.02	2	3	LFWF model
8	⊗	-4.85	0.36	2	χQSM
9	⊕	-1.34 ± 0.31	4	2	lattice QCD ($\overline{\text{MS}}$)
		-2.11 ± 0.27	4	2	lattice QCD ($\overline{\text{MS}}$)

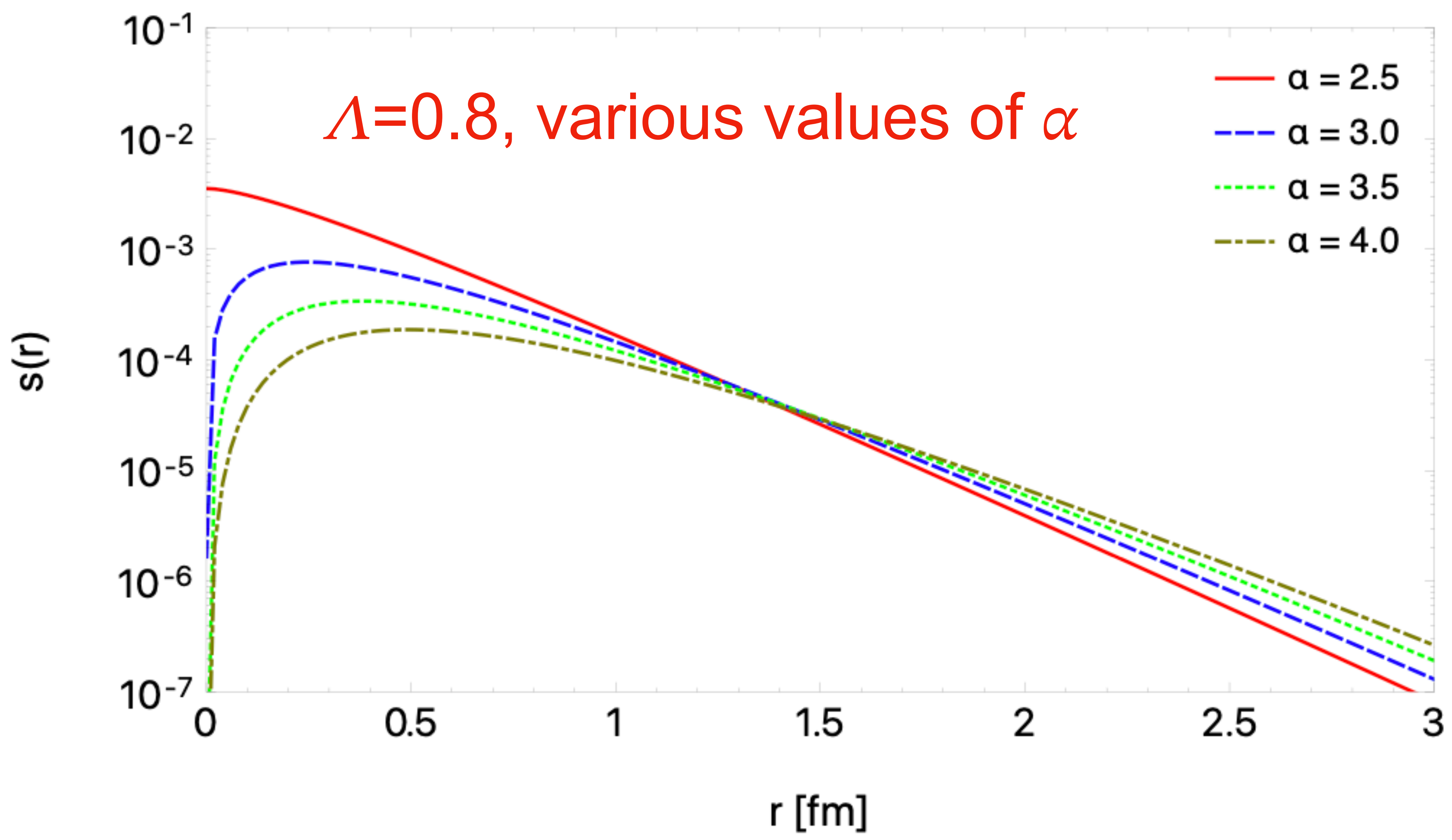
Results

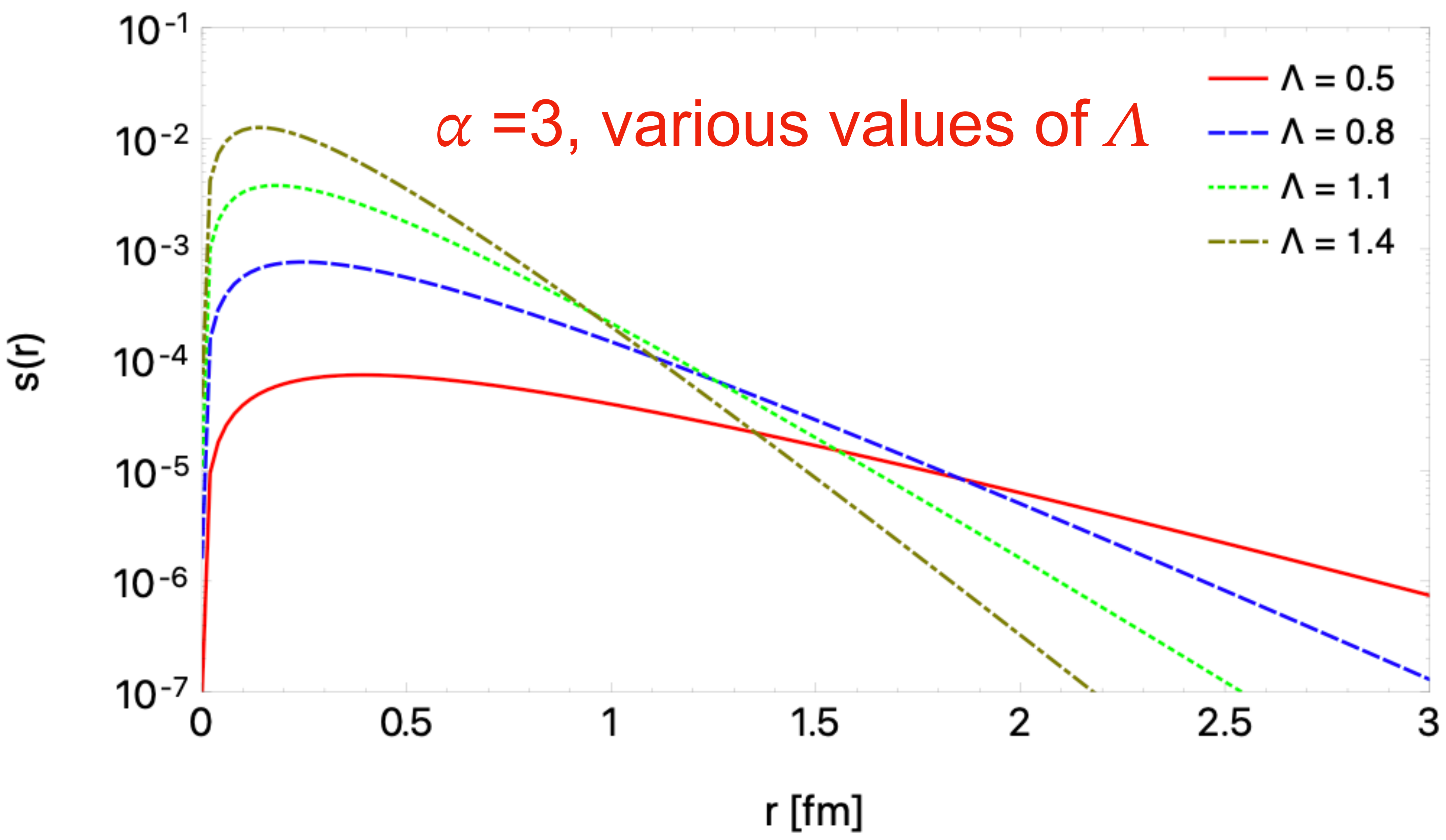
H. Dutrieux et al.,
Eur. Phys. J. C 81 (2021), 300

- profile of pressure anisotropy

$$s_a(r) = -\frac{4M}{r^2}\int\frac{d^3\boldsymbol{\Delta}}{(2\pi)^3}\,e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{r}}\,\frac{t^{-1/2}}{M^2}\,\frac{d^2}{dt^2}\left[t^{5/2}\,C_a(t)\right]$$

- dependance on the choice of parameter in the multiple Ansatz





Timelike Compton scattering

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

Relation between
DVCS and TCS CFFs:

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

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

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

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

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

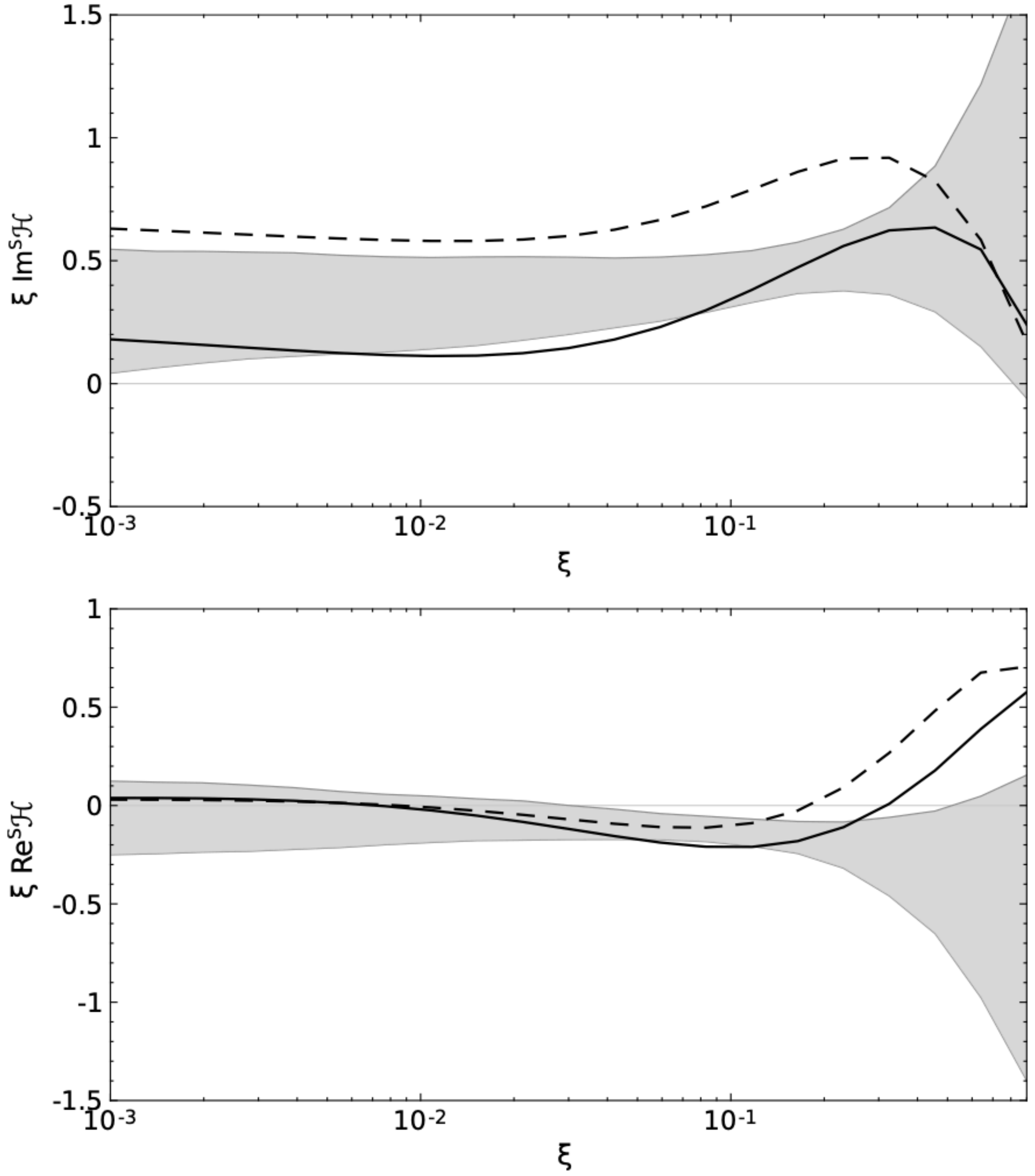
Combined study of DVCS and TCS:

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

Timelike Compton scattering

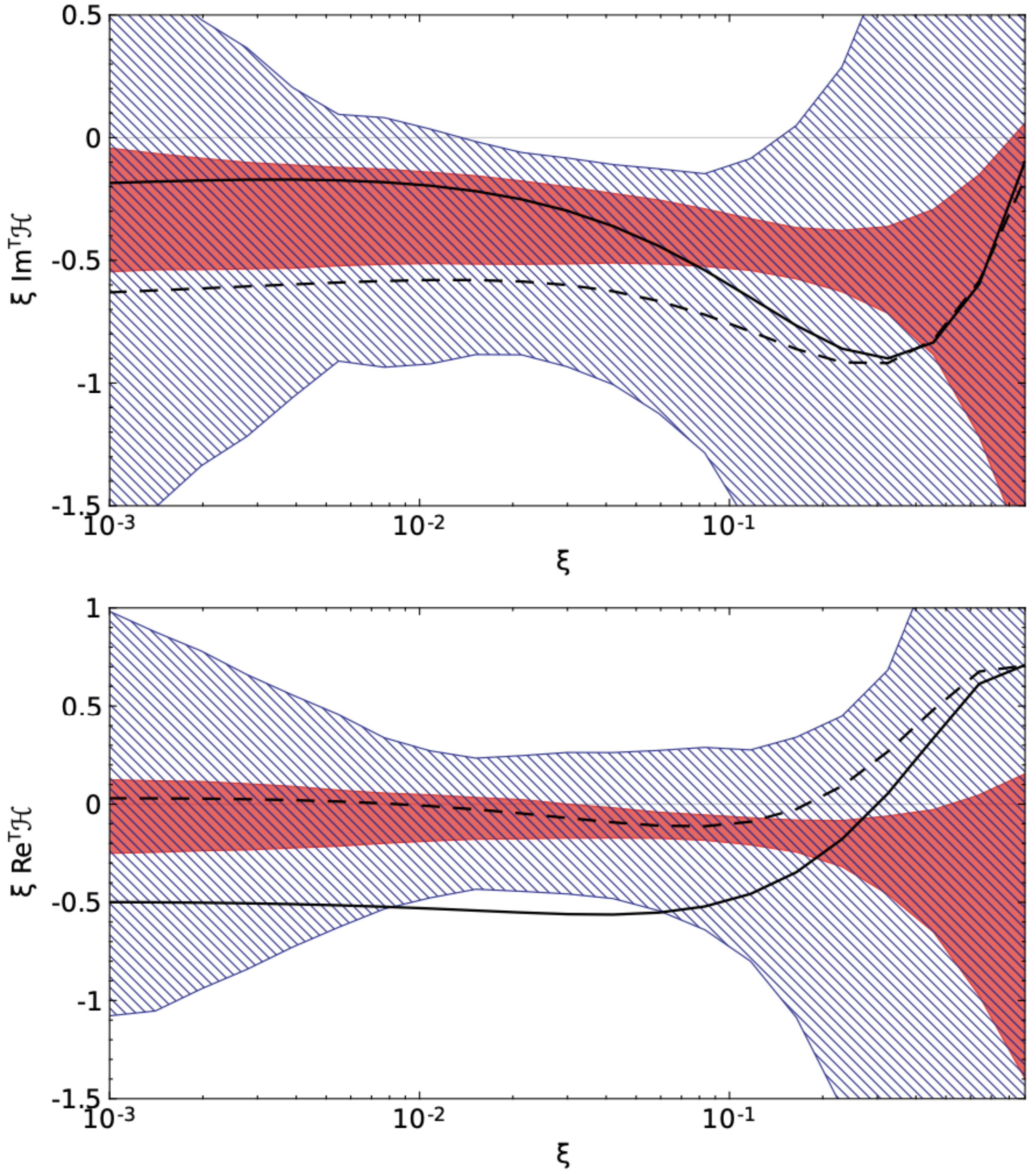
O. Grocholski et al.,
Eur. Phys. J. C 80 (2020) 2, 171

DVCS CFF (Non-parametric):



DVCS

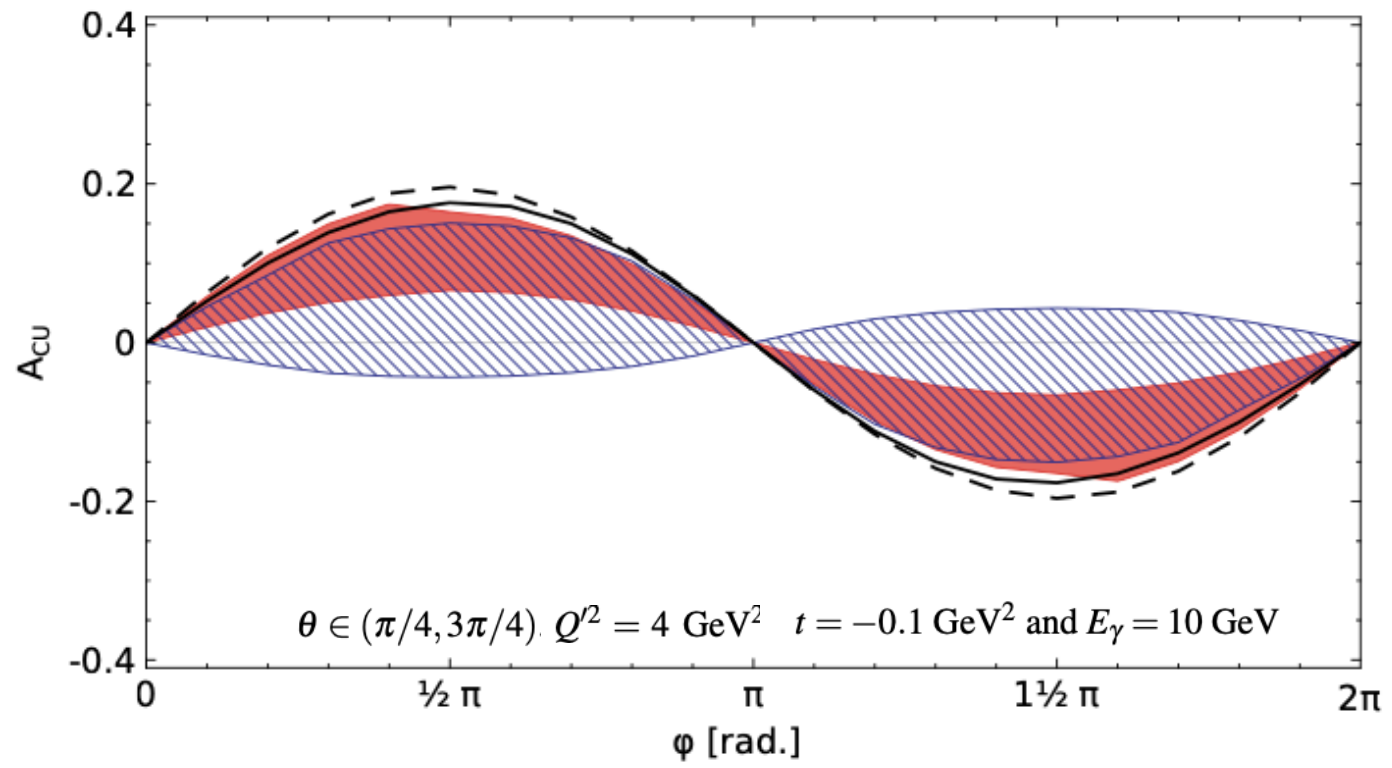
TCS CFF:



TCS from DVCS (LO)

TCS from DVCS (NLO)

TCS circular beam asymmetry:



GK model (LO)

GK model (NLO)

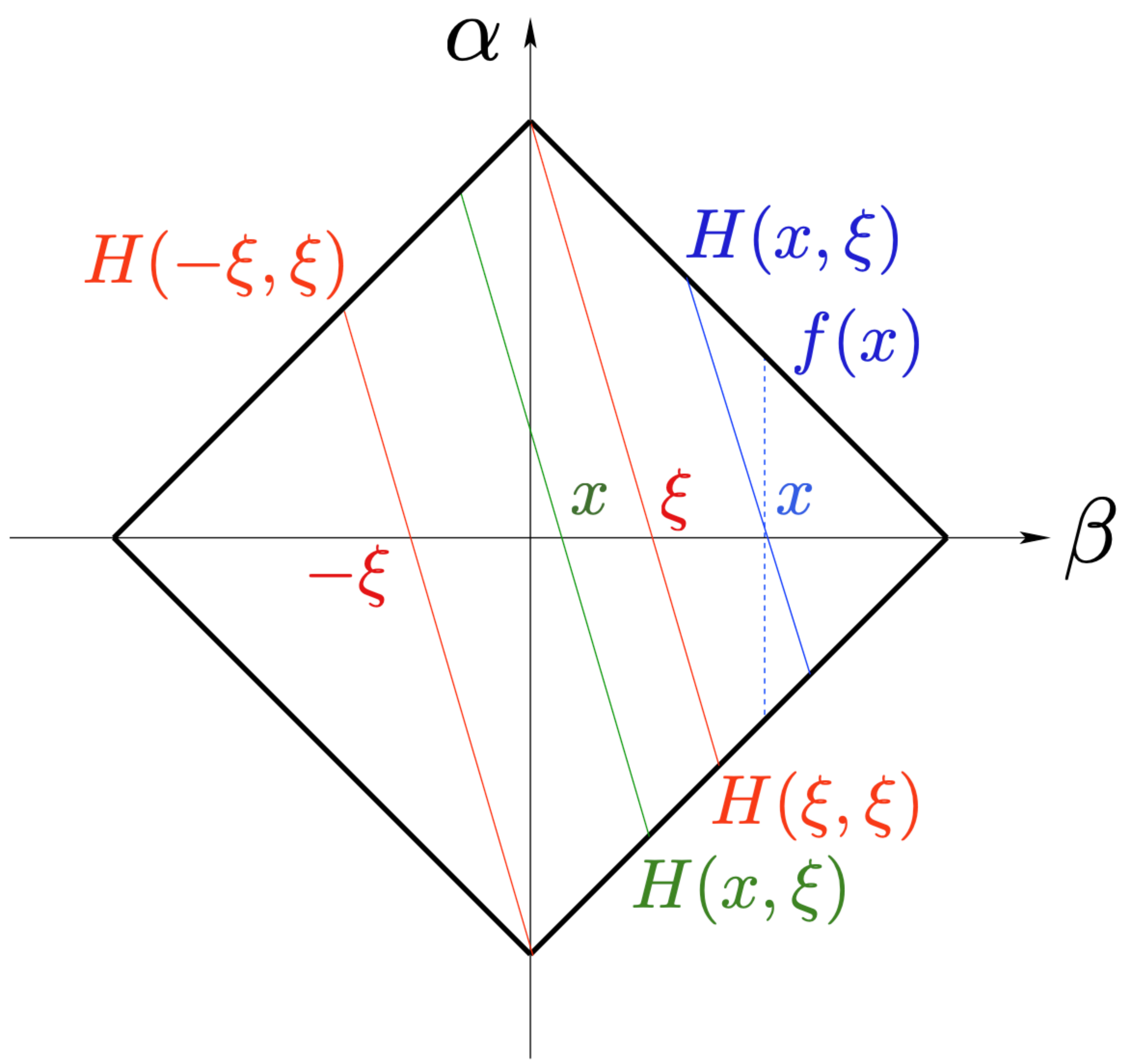
Double distribution:

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

where:

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

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



from PRD83, 076006, 2011

Principles of modelling

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

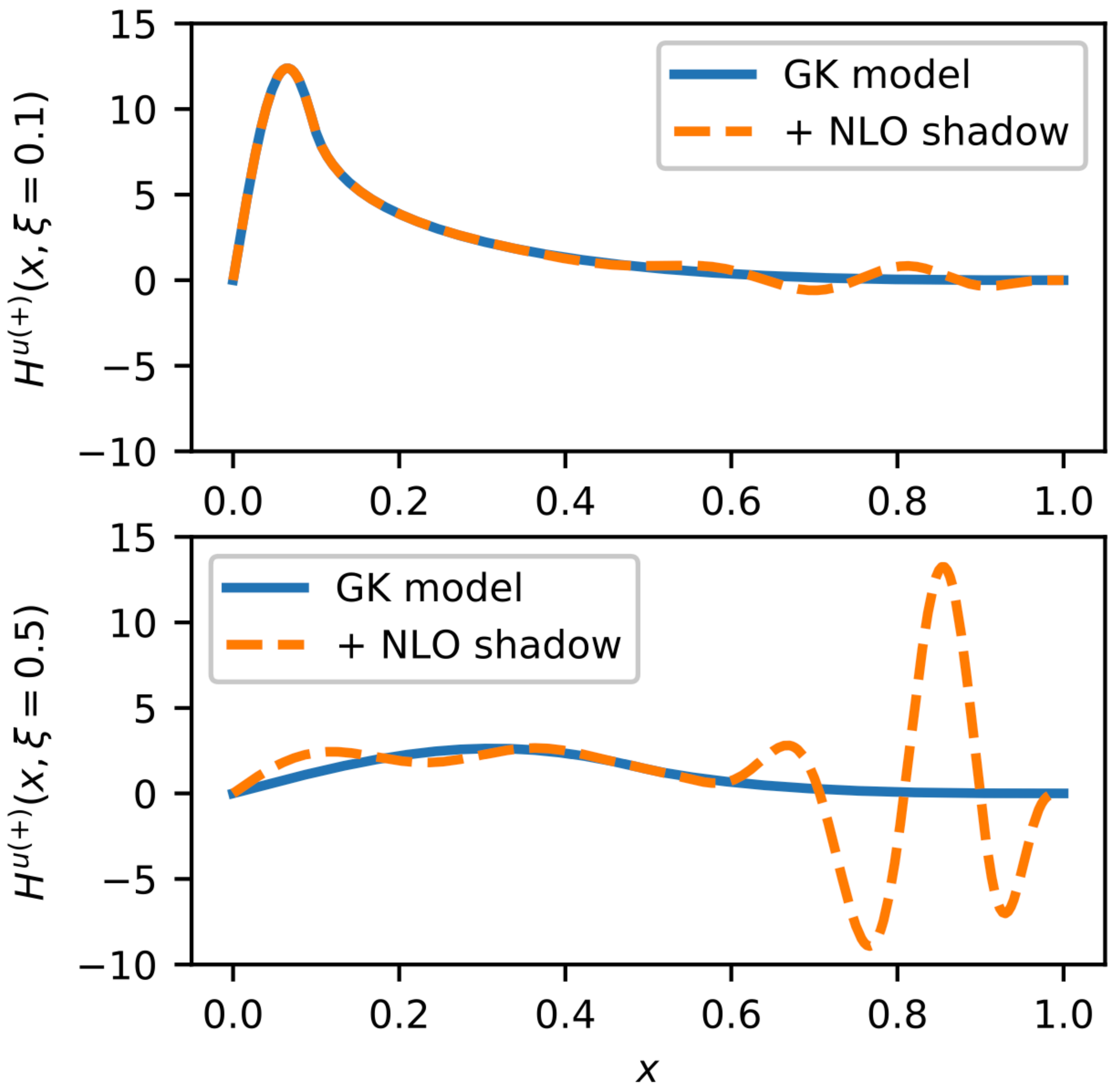
Shadow term is closely related to the so-called shadow GPDs

Shadow GPDs have considerable size and:

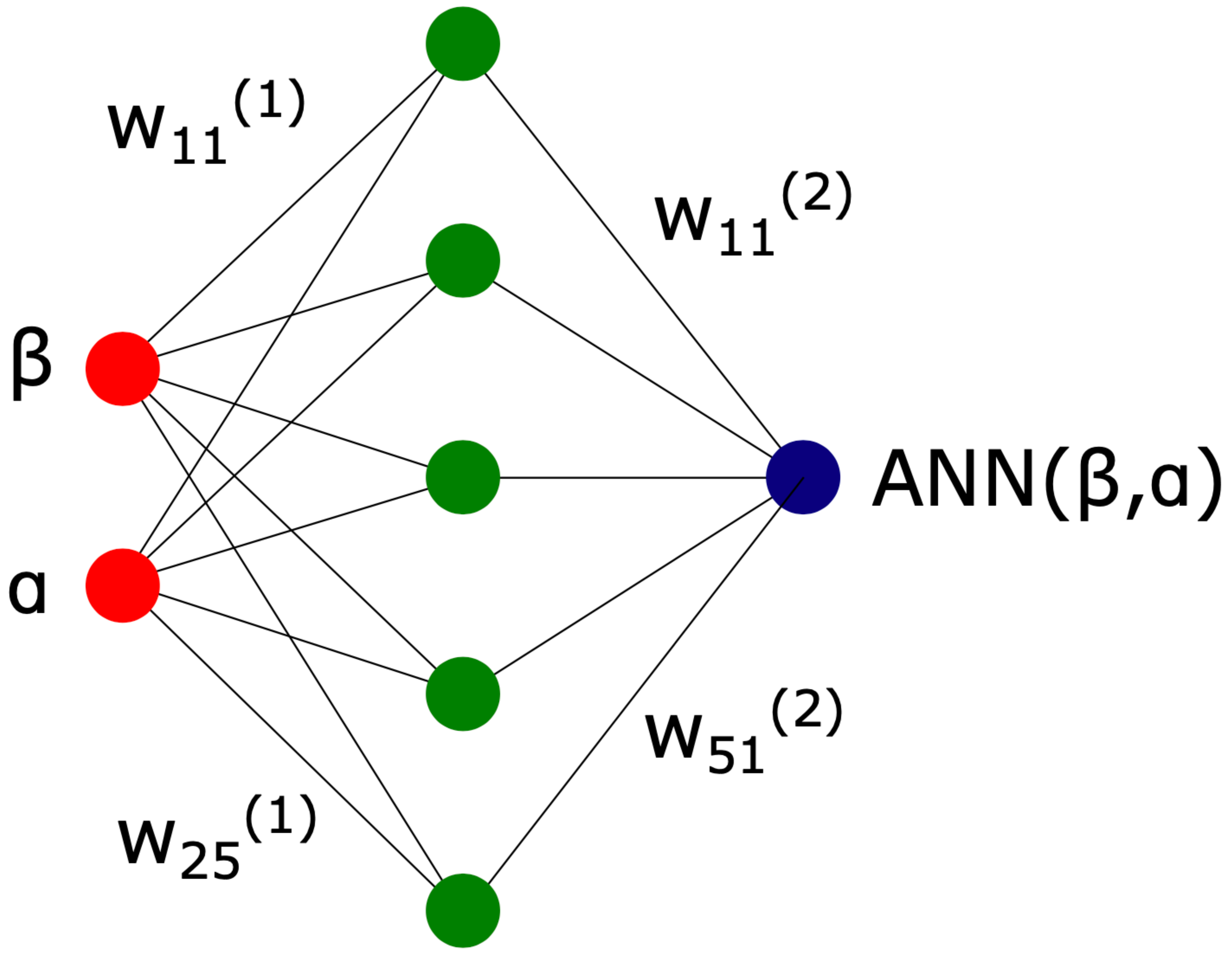
- at the initial scale do not contribute to both PDFs and CFFs
- at some other scale they contribute negligibly

making the deconvolution of CFFs ill-posed

We found such GPDs for both LO and NLO



Our ANNs:



Requirements:

symmetric w.r.t. α

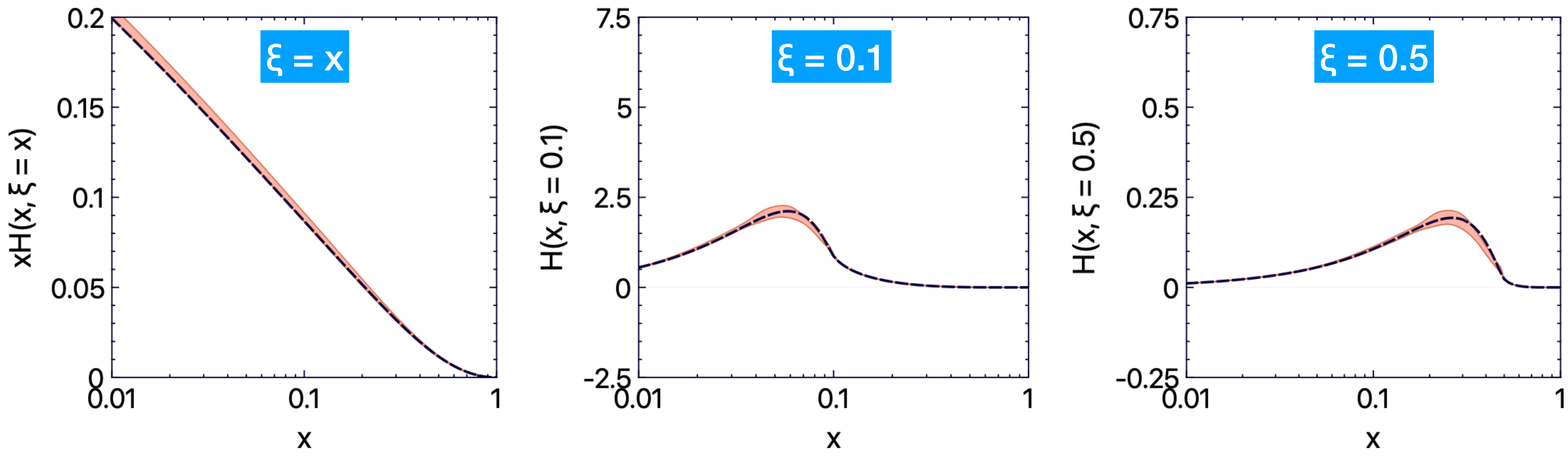
symmetric w.r.t. β

vanishes at $|\alpha| + |\beta| = 1$

Activation function:

$$\left(\varphi_i\left(w_i^\beta|\beta| + w_i^\alpha\alpha/(1-|\beta|) + b_i\right) - \varphi_i\left(w_i^\beta|\beta| + w_i^\alpha + b_i\right)\right) + (w^\alpha \to -w^\alpha)$$

Demonstration of results



Conditions:

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

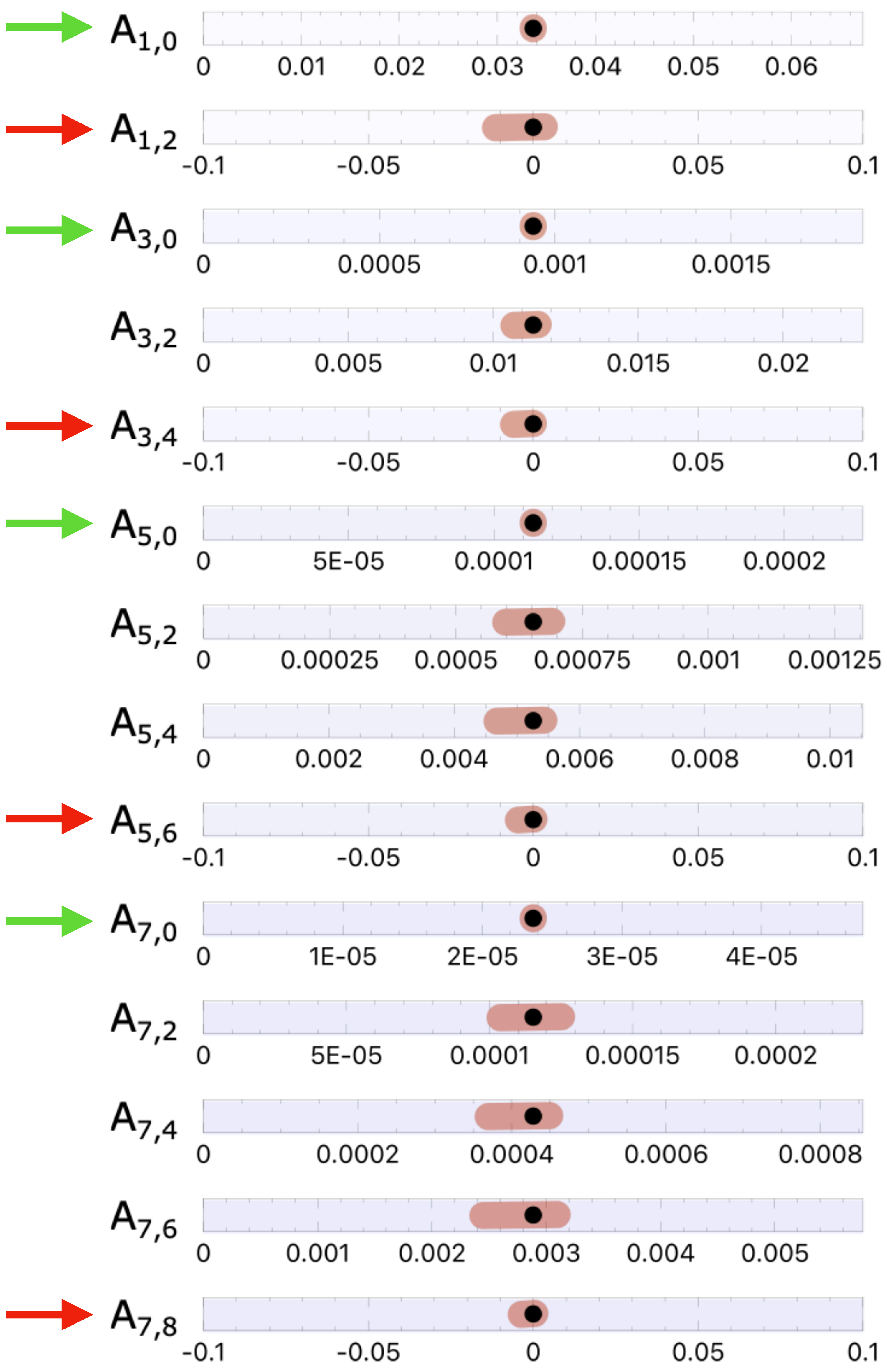
Technical detail of the analysis:

- 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



● **GK**

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

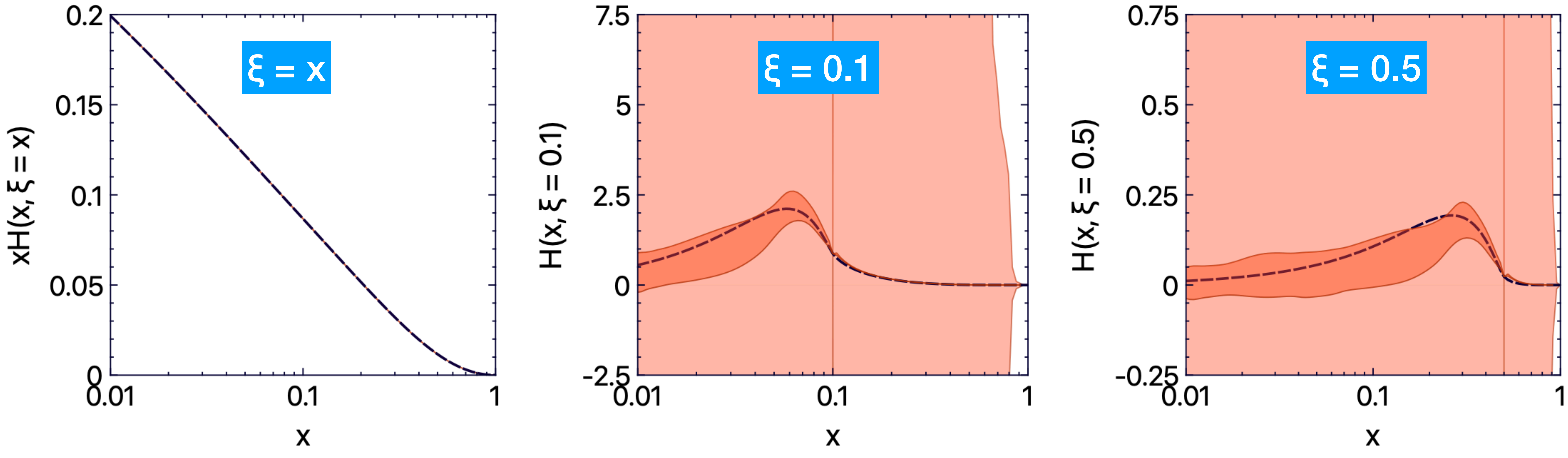
Mellin mom. coefficients:

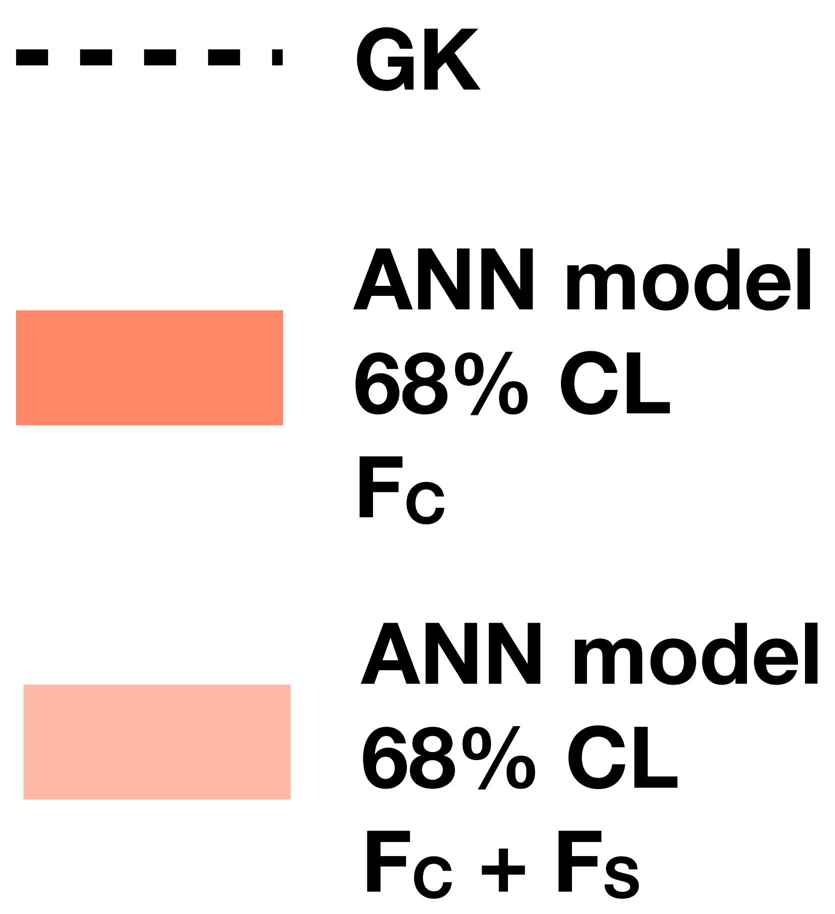
→ related to PDF

→ related to D-term

Conditions:

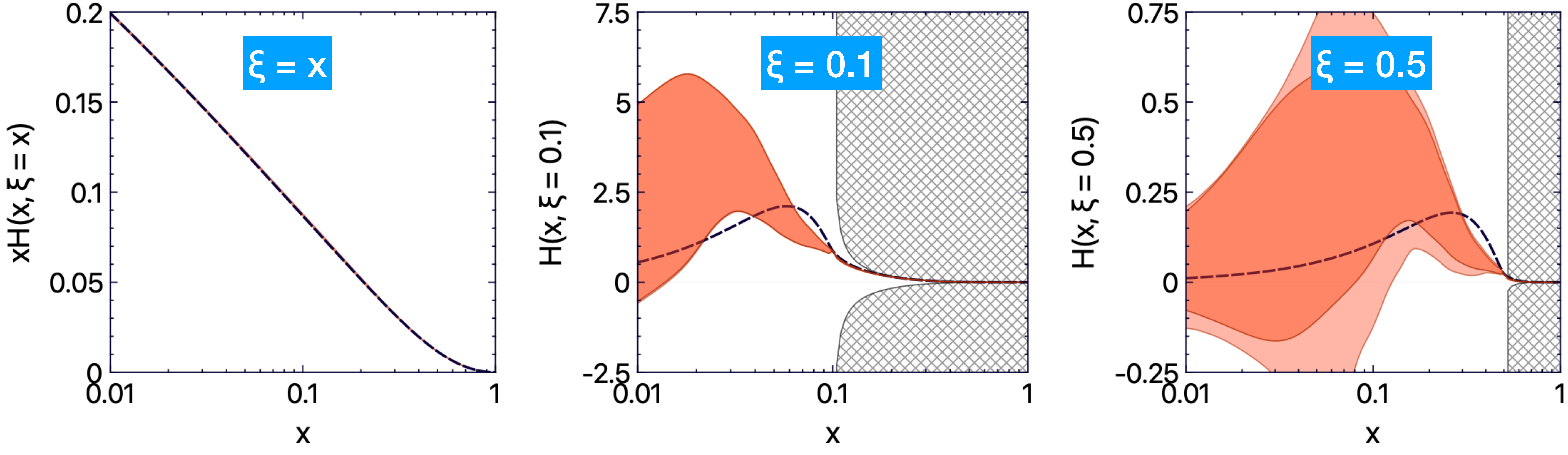
- Input: 400 x ≠ ξ points generated with GK model
- Positivity not forced

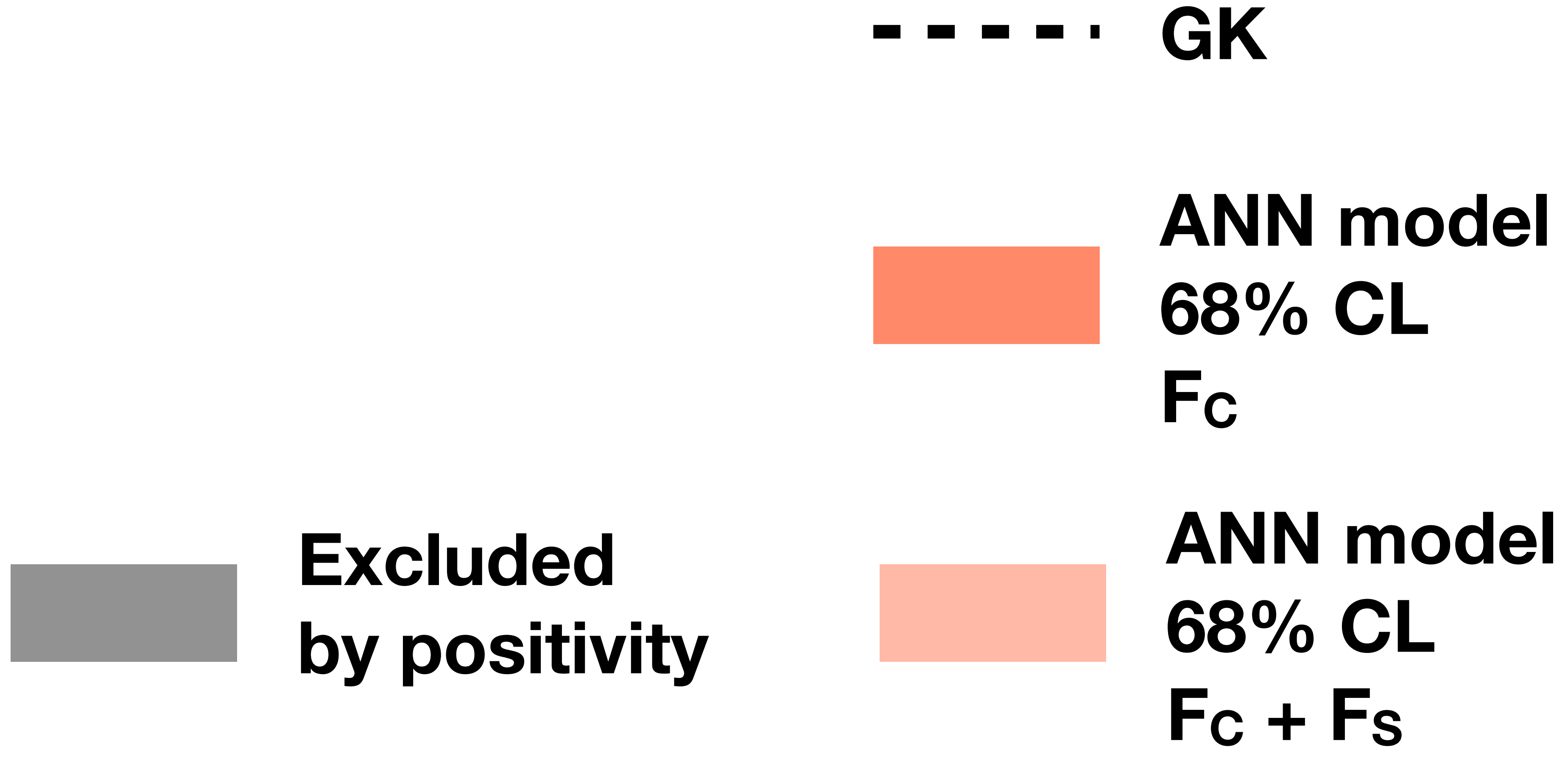




Conditions:

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





Conditions:

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

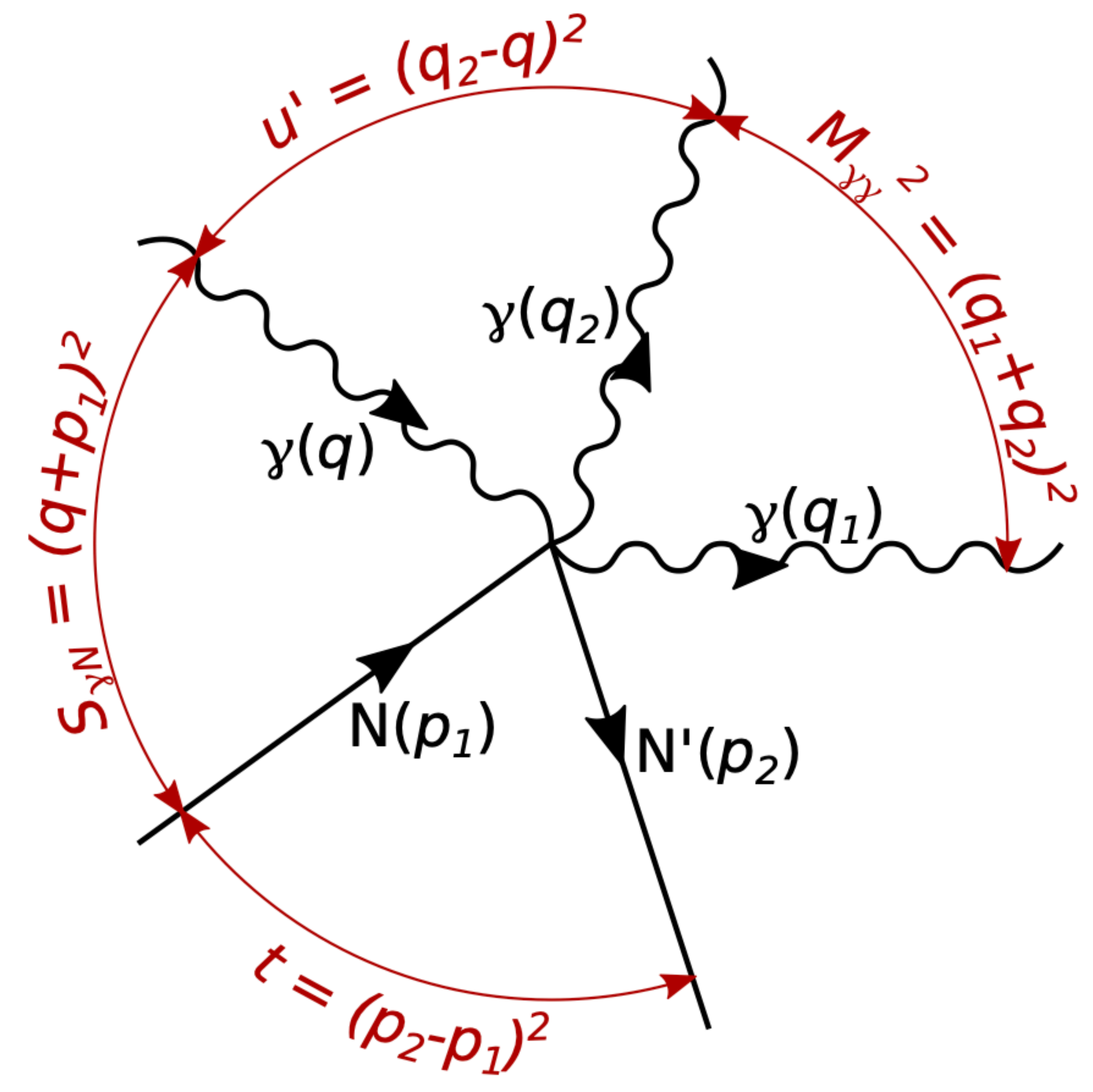
Exclusive diphoton photoproduction

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

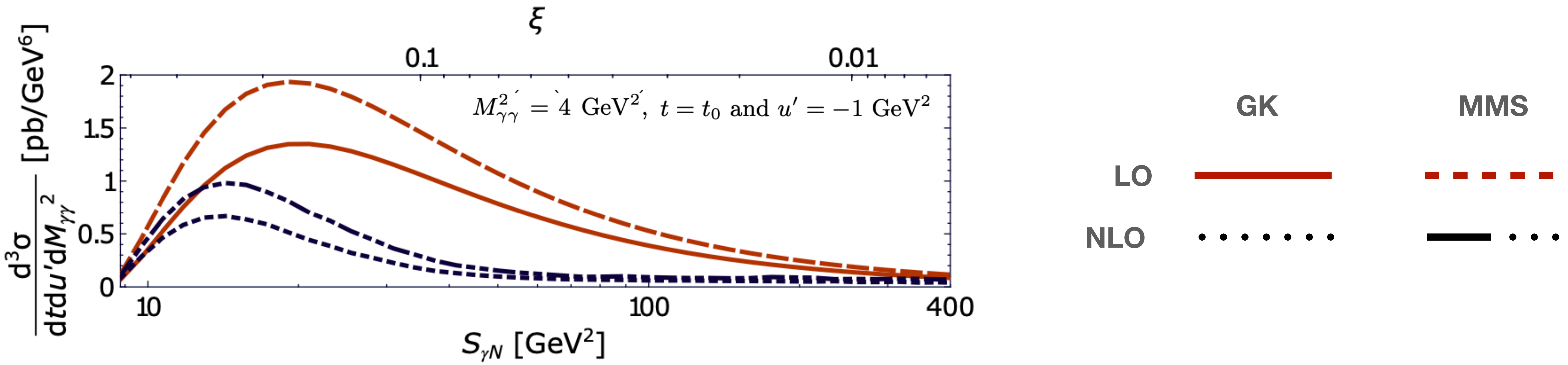
- Process probes C-odd GPDs
- No contribution of D-term
- No non-perturbative ingredients other than GPDs
- Gluons do not contribute also at NLO

- Both LO and NLO description available

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



Cross-section



Double DVCS

K. Deja, V. Martínez-Fernández, B. Pire, PS, J. Wagner
Phys. Rev. D 107 (2023) 9, 094035

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

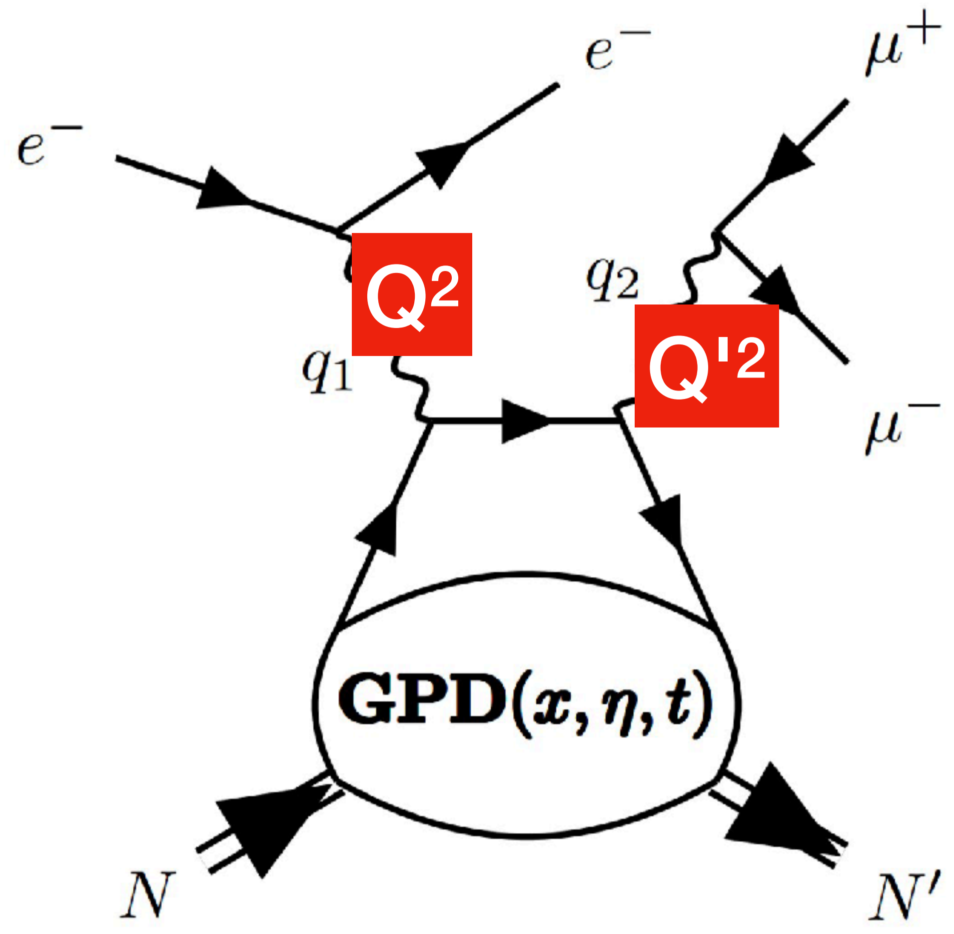
$$(\mathcal{H},\mathcal{E})(\rho,\xi,t) = \sum_{f=\{u,d,s\}} \int_{-1}^{1} dx\; C_f^{(-)}(x,\rho)(H_f,E_f)(x,\xi,t)$$

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

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

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

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

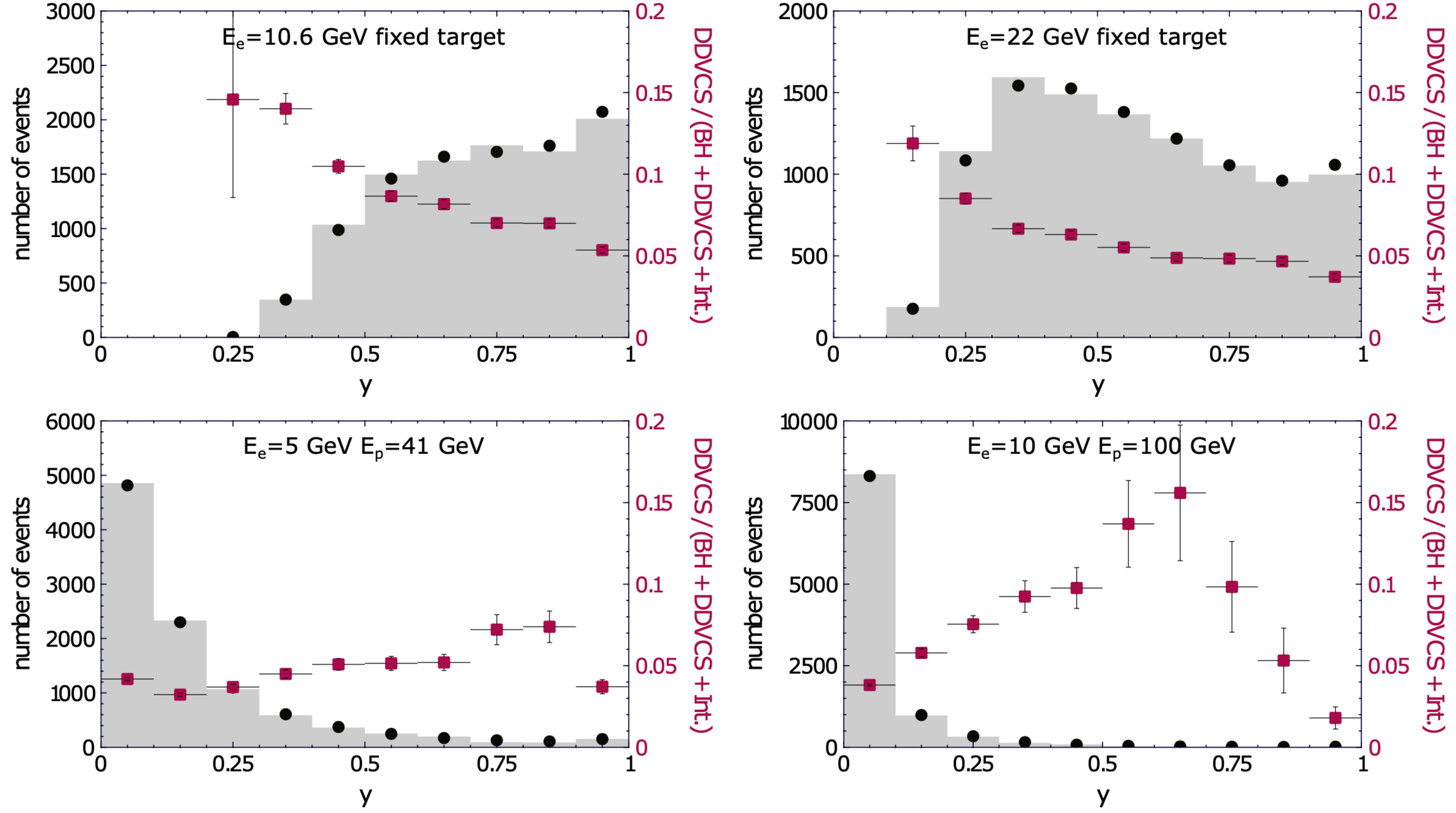


- We revisit DDVCS phenomenology in view of new experiments, including reevaluation of DDVCS and BH cross-sections with Kleiss-Stirling spinor techniques

- Obtained results are available in PARTONS and EpIC MC generator

Double DVCS

K. Deja, V. Martínez-Fernández, B. Pire, PS, J. Wagner
Phys. Rev. D 107 (2023) 9, 094035



EpIC MC
● integrated cross-section
■ pure DDVCS contribution

Kinematic cuts:

- 0.15 GeV^2 < Q^2 < 5 GeV^2
- 2.25 GeV^2 < Q'^2 < 9 GeV^2
- 0.1 GeV^2 < t < 0.8 GeV^2 (JLab)
- 0.05 GeV^2 < t < 1 GeV^2 (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

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
- v4 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)

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

- v1.1.0 version of EpIC is now available!

Summary

- Analyses of amplitudes prove to be very useful, e.g. for:
  - study of "mechanical" forces
  - impact studies
- Crucial role of dispersion relations
- Joint DVCS-TCS analysis possible
- Prominent role of machine learning techniques in estimation of model uncertainties, now also available for GPDs
- Open-source tools and development of phenomenology methods crucial for the community
- Exploratory study to include lattice-QCD results!

M. J. Riberdy, H. Dutrieux, C. Mezrag, PS, hep-ph/2306.01647

Reduction of GPD model uncertainties due to inclusion of pseudo-latticeQCD results