

A NEW FRAMEWORK FOR EXTRACTING GPDs

(BASED ON: C. MEZRAG, PS, J. WAGNER, HEP-PH/2608.20244)

Paweł Sznajder

National Centre for Nuclear Research, Poland



**NATIONAL
CENTRE
FOR NUCLEAR
RESEARCH
ŚWIERK**

15th International Workshop on the Physics of Excited Nucleons (NSTAR 2026)

Sevilla, September 10th, 2026

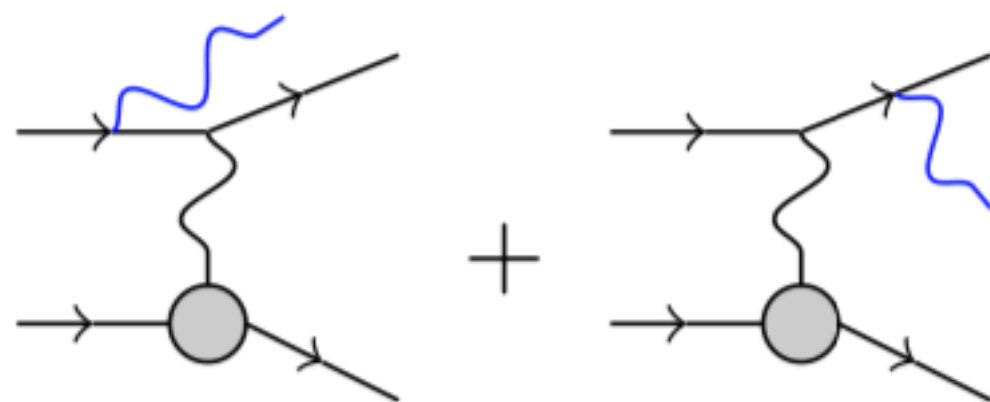
see e.g. NPB 878 (2014) 214
for more details

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

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

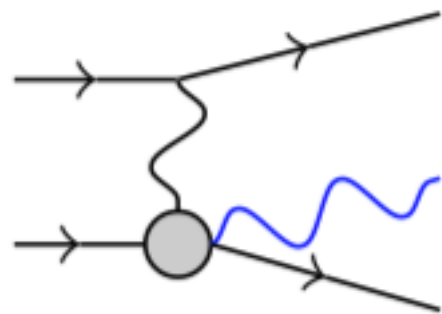


Bethe-Heitler process



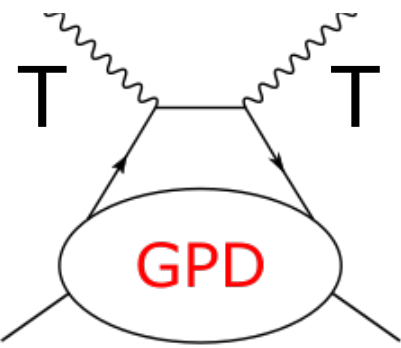
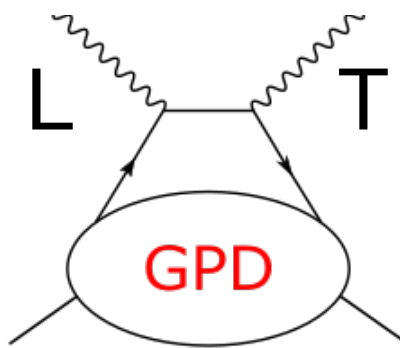
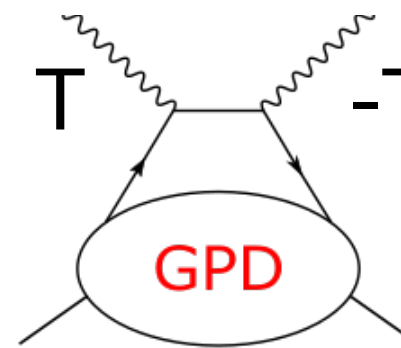
*calculable within QED
parametrised by elastic FFs*

Deeply Virtual Compton scattering



*calculable within QCD
parametrised by CFFs
(frame dependent! we use BMJ)*

List of Compton form factors:

			
related to GPDs H, H_T	$\mathcal{H}^{++}$	$\mathcal{H}^{0+}$	$\mathcal{H}^{+-}$
related to GPDs E, E_T	$\mathcal{E}^{++}$	$\mathcal{E}^{0+}$	$\mathcal{E}^{+-}$
related to GPDs $\tilde{H}, \tilde{H}_T$	$\tilde{\mathcal{H}}^{++}$	$\tilde{\mathcal{H}}^{0+}$	$\tilde{\mathcal{H}}^{+-}$
related to GPDs $\tilde{E}, \tilde{E}_T$	$\tilde{\mathcal{E}}^{++}$	$\tilde{\mathcal{E}}^{0+}$	$\tilde{\mathcal{E}}^{+-}$

considered in this study
extracted for the first time

not considered in this study

GPD information from CFF $\mathcal{H}^{++}$:

$$\text{Im}\mathcal{H}^{++}(\xi, t) \stackrel{\text{LO}}{=} \pi \sum_q e_q^2 H^{q(+)}(\xi, \xi, t)$$

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

$$\text{Re}\mathcal{H}^{++}(\xi, t) \stackrel{\text{LO}}{=} \sum_q e_q^2 \text{PV} \int_0^1 dx H^{q(+)}(x, \xi, t) \left(\frac{1}{\xi - x} - \frac{1}{\xi + x} \right)$$

$$\text{Re}\mathcal{H}^{++}(\xi, t) = \text{PV} \int_0^1 \frac{d\xi'}{\pi} \text{Im}\mathcal{H}(\xi', t) \left(\frac{1}{\xi - \xi'} - \frac{1}{\xi + \xi'} \right) + \mathcal{S}(t)$$

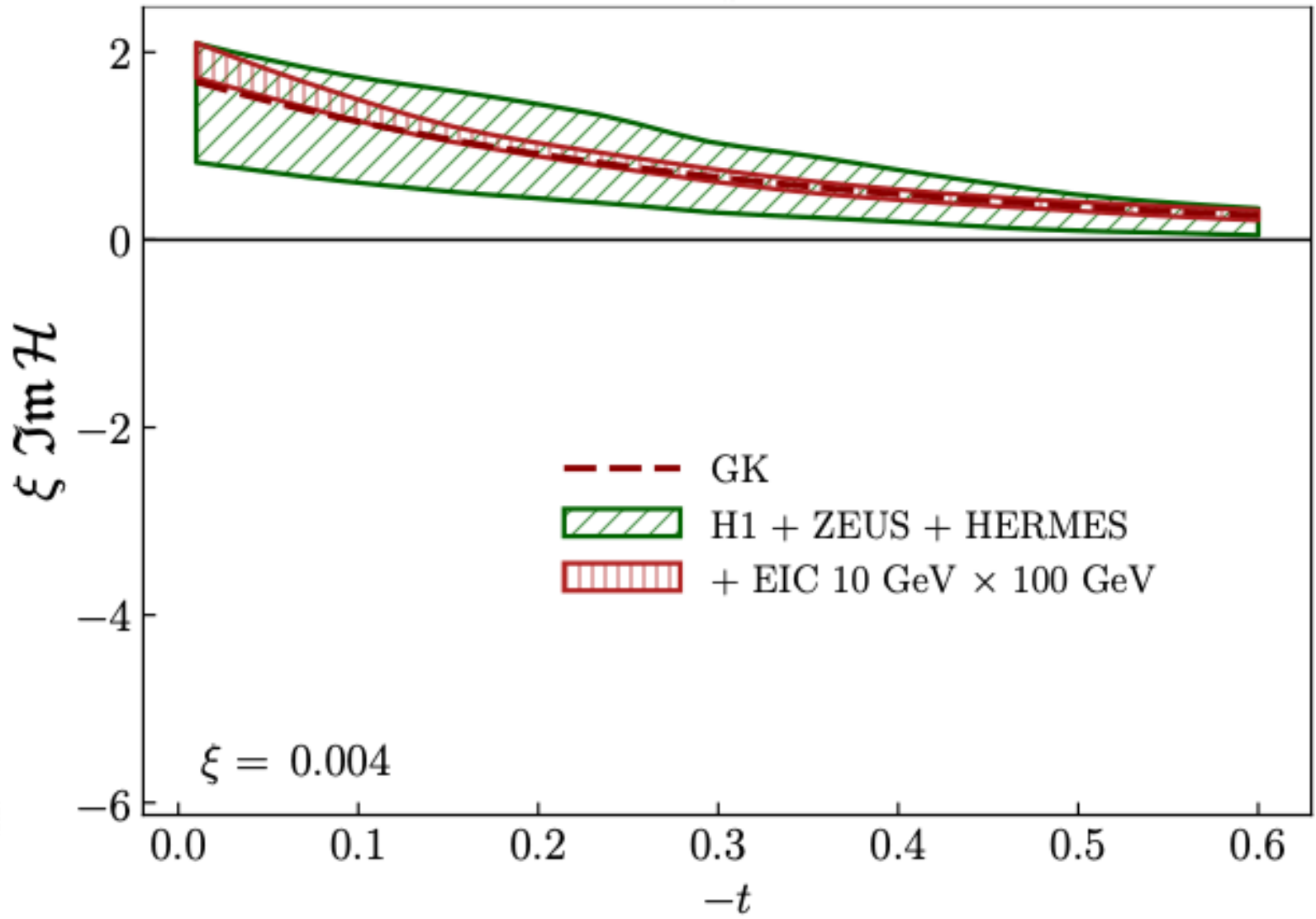
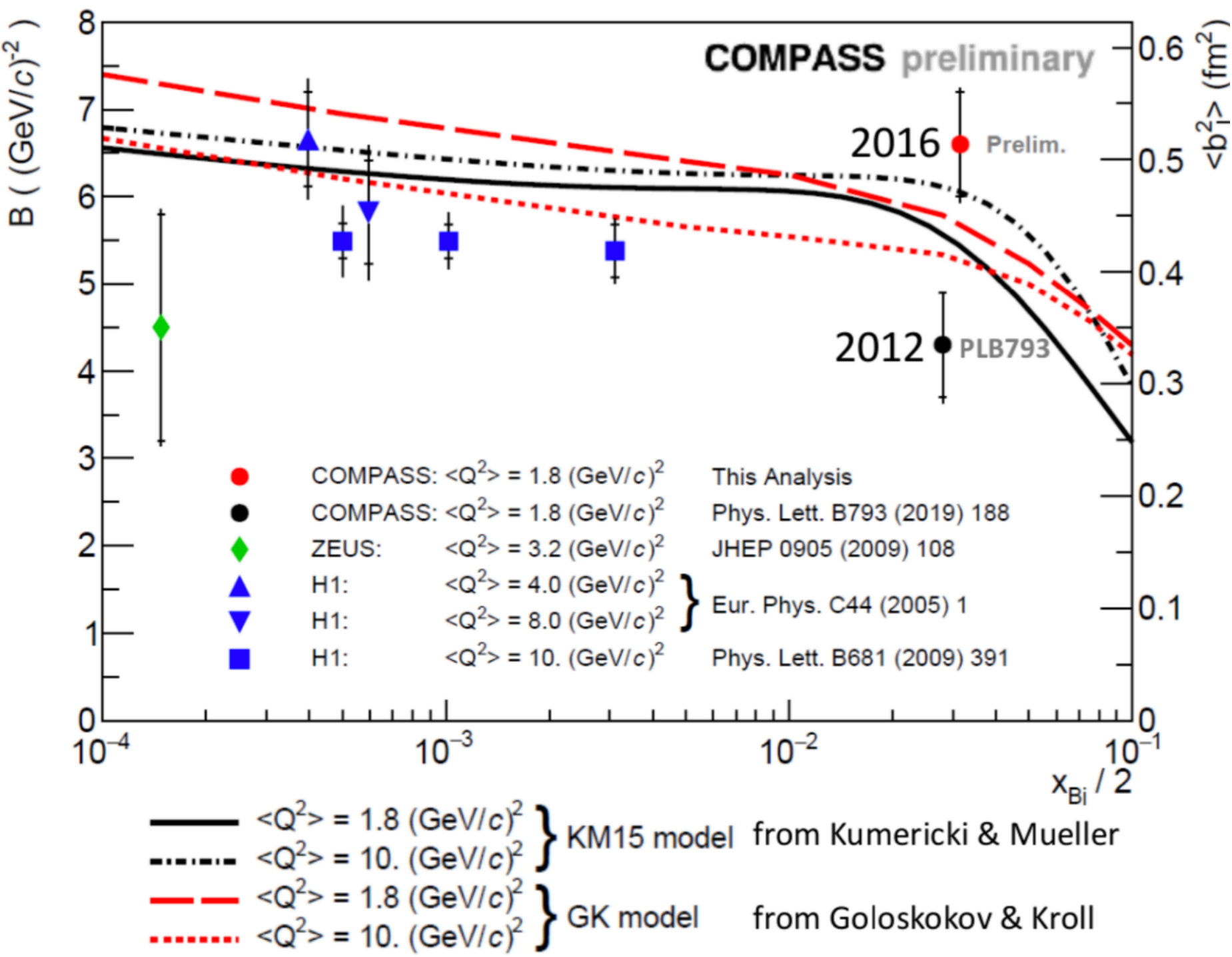
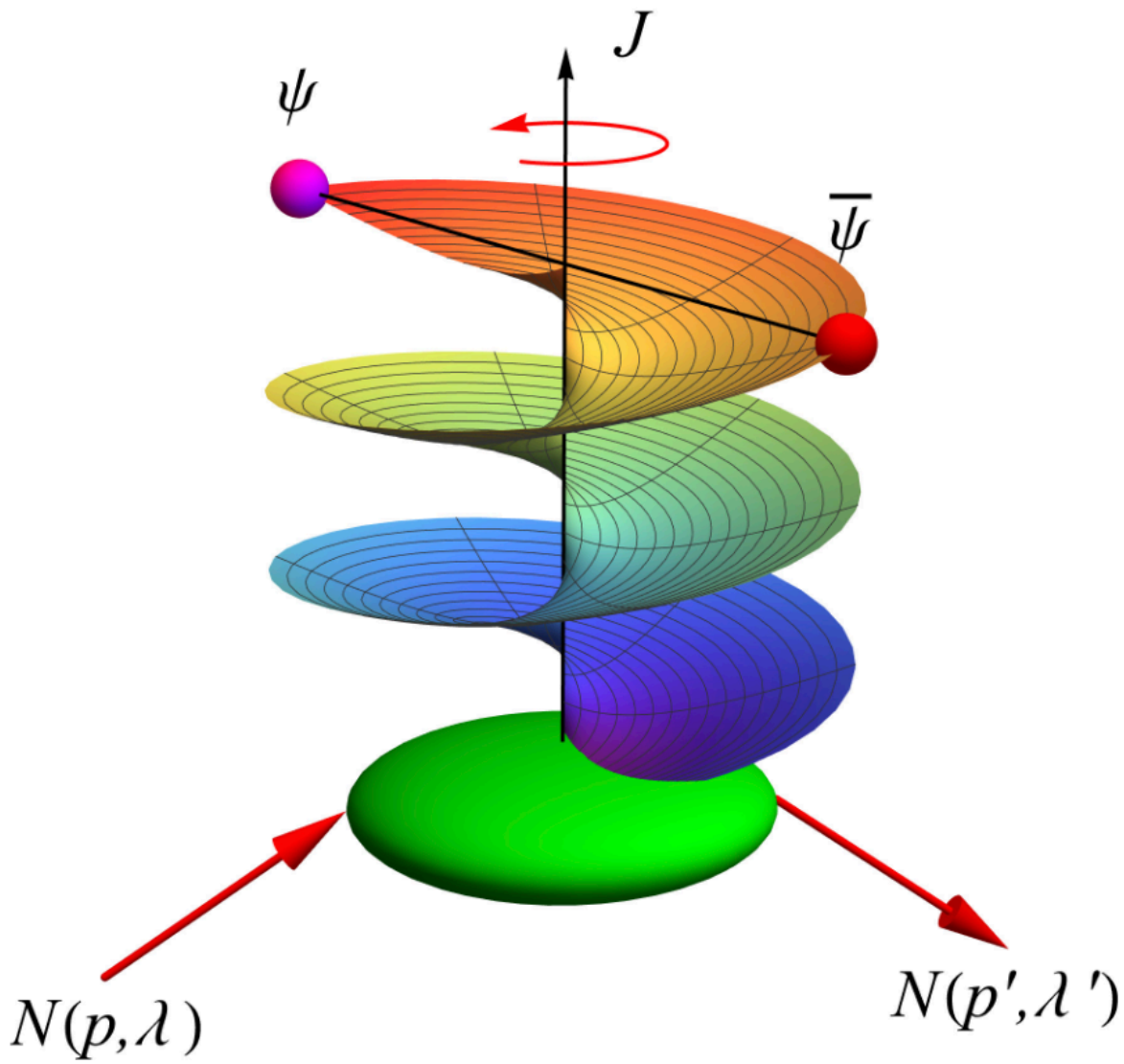
considered in this study
extracted for the first time

not considered in this study

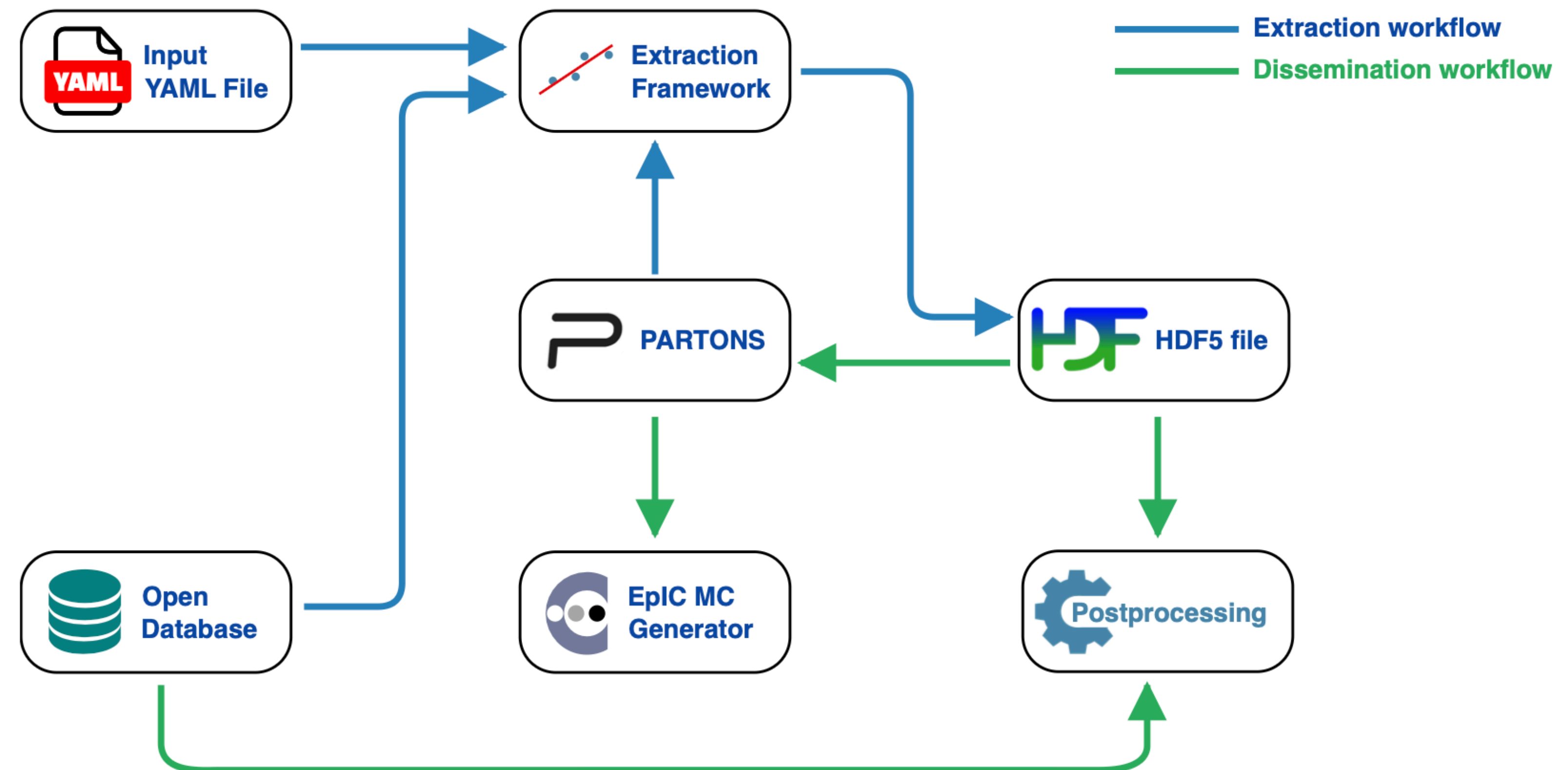
interpretation of subtraction
const. discussed by Victor
Martinez-Fernandez

Why extract CFFs?

- probing nucleon tomography at low- x_B (see: [JHEP 09 \(2013\) 093](#))
- extraction of D-term
(see: [Nature 570 \(2019\) 7759, E1](#), [EPJC 81 \(2021\) 4, 300](#))
- Froissart-Gribov projections (see: [PRD 109 \(2024\) 5, 054010](#))
- distilled version of experimental data and impact studies (see: [PRD 112 \(2025\) 3, 036010](#))
- predictions for TCS (see: [EPJC 80 \(2020\) 2](#),
- input to modern Monte Carlo generators
- comparison with lattice-QCD results
- fast analyses of GPDs



Part of a well established software environment:



PARTONS: <http://partons.cea.fr>

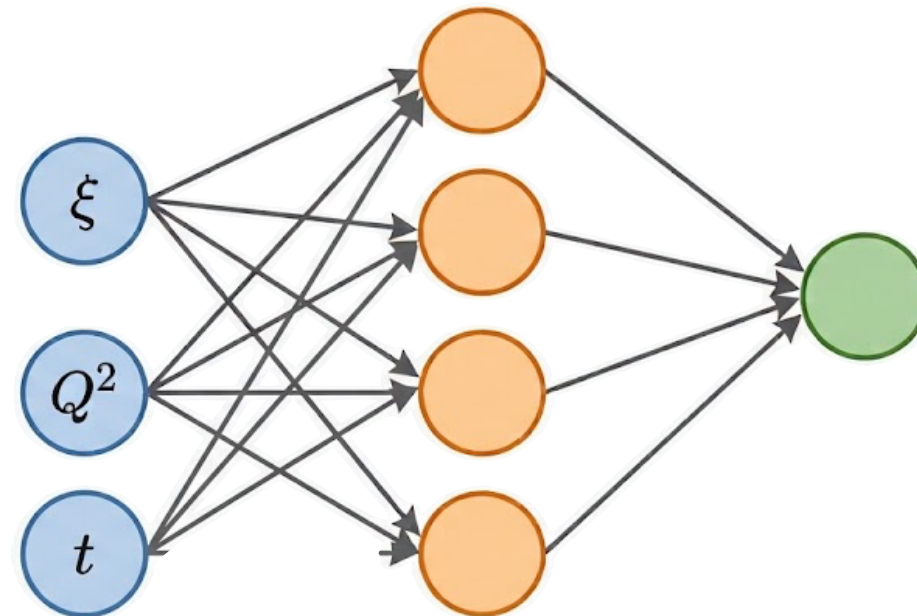
EpIC: <https://pawelsznajder.github.io/epic>

OpenDatabase: <https://opengpd.github.io/gpddatabase>

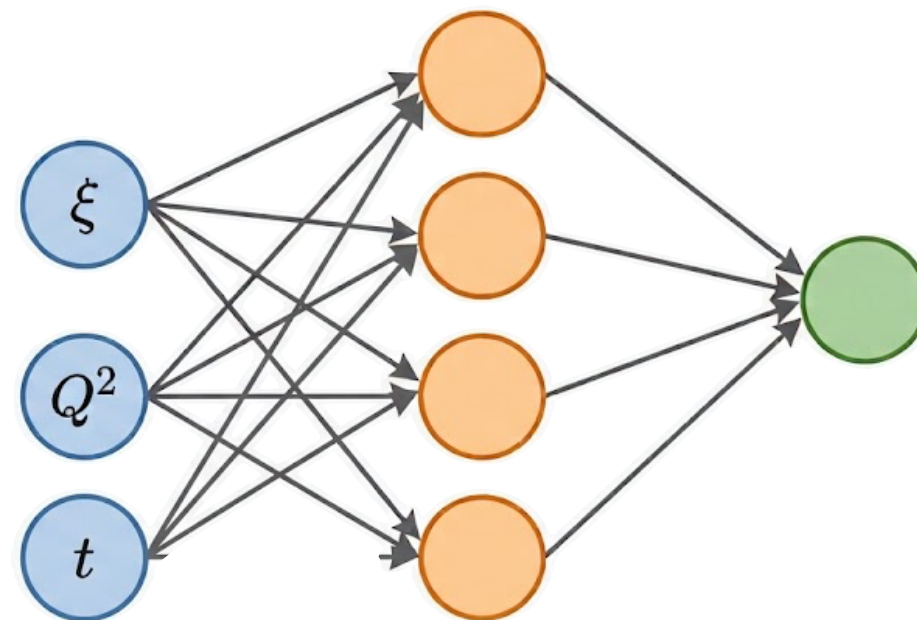
Two separate models are used, both based on machine learning techniques:

Theory-agnostic model

Re part:



Im part:

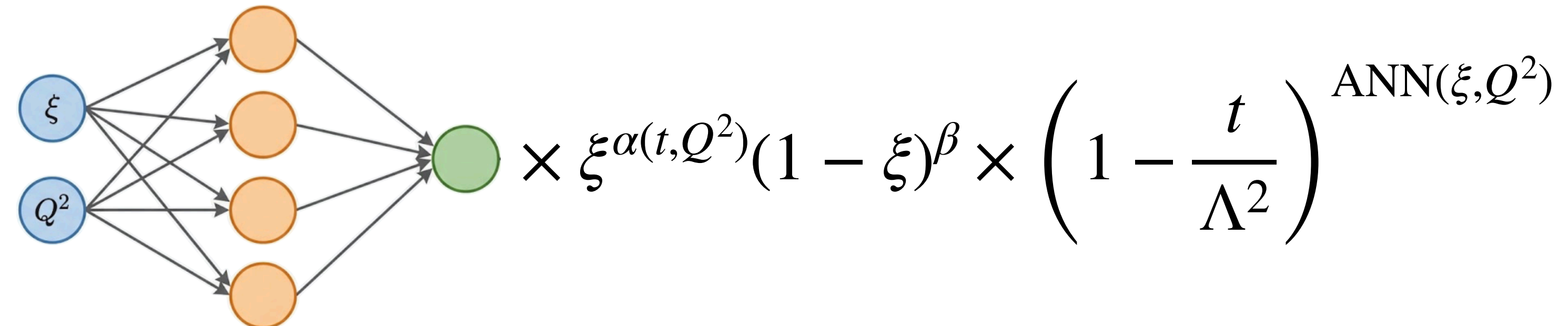


Theory-augmented model

Re part:

from dispersion relation
(involving flexible Ansatz for subtraction constant)

Im part:



Two separate models are used, both based on machine learning techniques:

Theory-agnostic model

- uses simple neural networks to separately parameterize the real and imaginary parts of each CFF
- remains free from model assumptions
- provides a baseline for further extractions
- serves as an ideal tool for impact studies

Theory-augmented model

- implements dispersion relations and power laws
- remains susceptible to model assumptions
- provides a more intuitive physical picture
- serves as an ideal tool for further GPD extractions

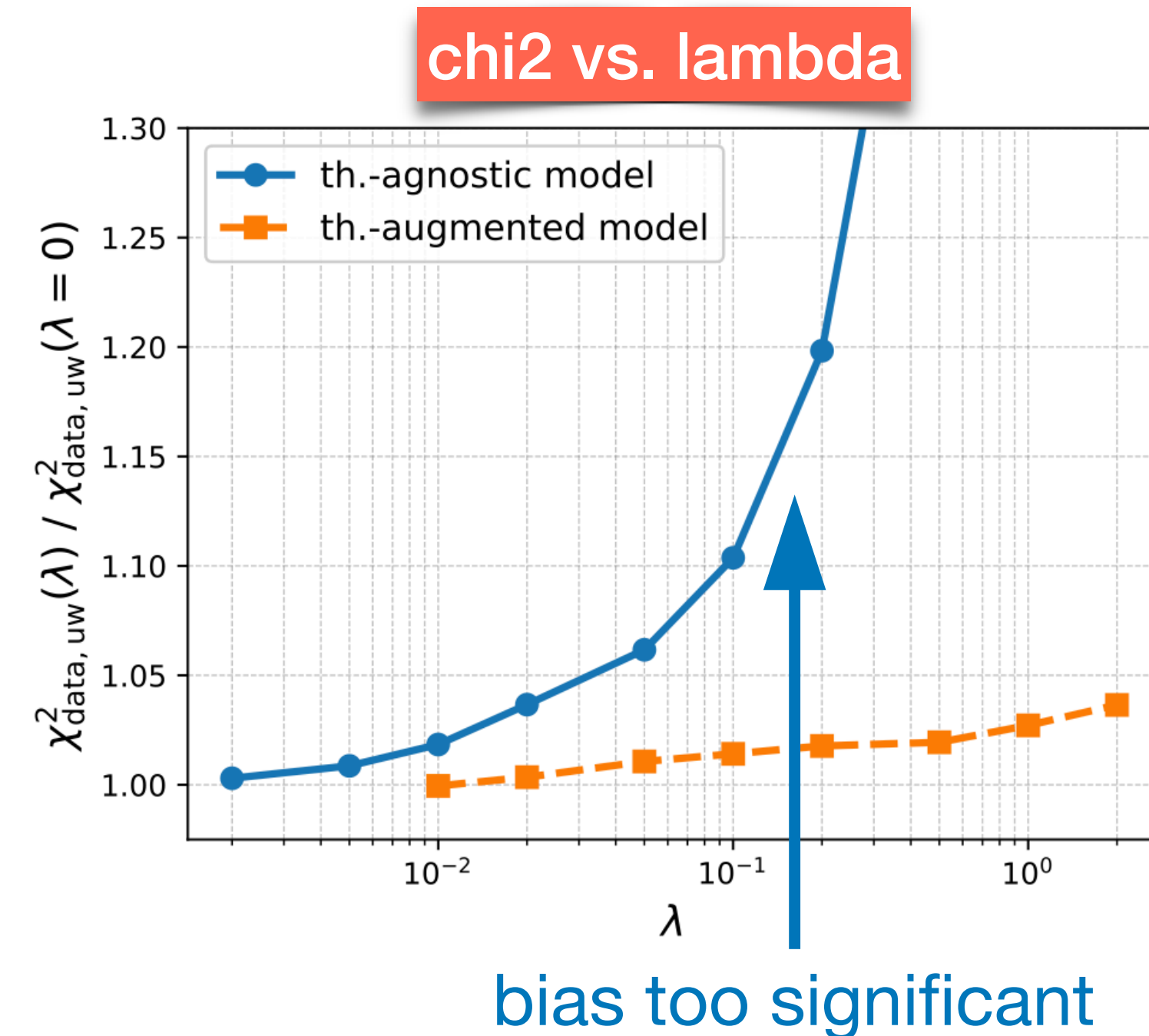
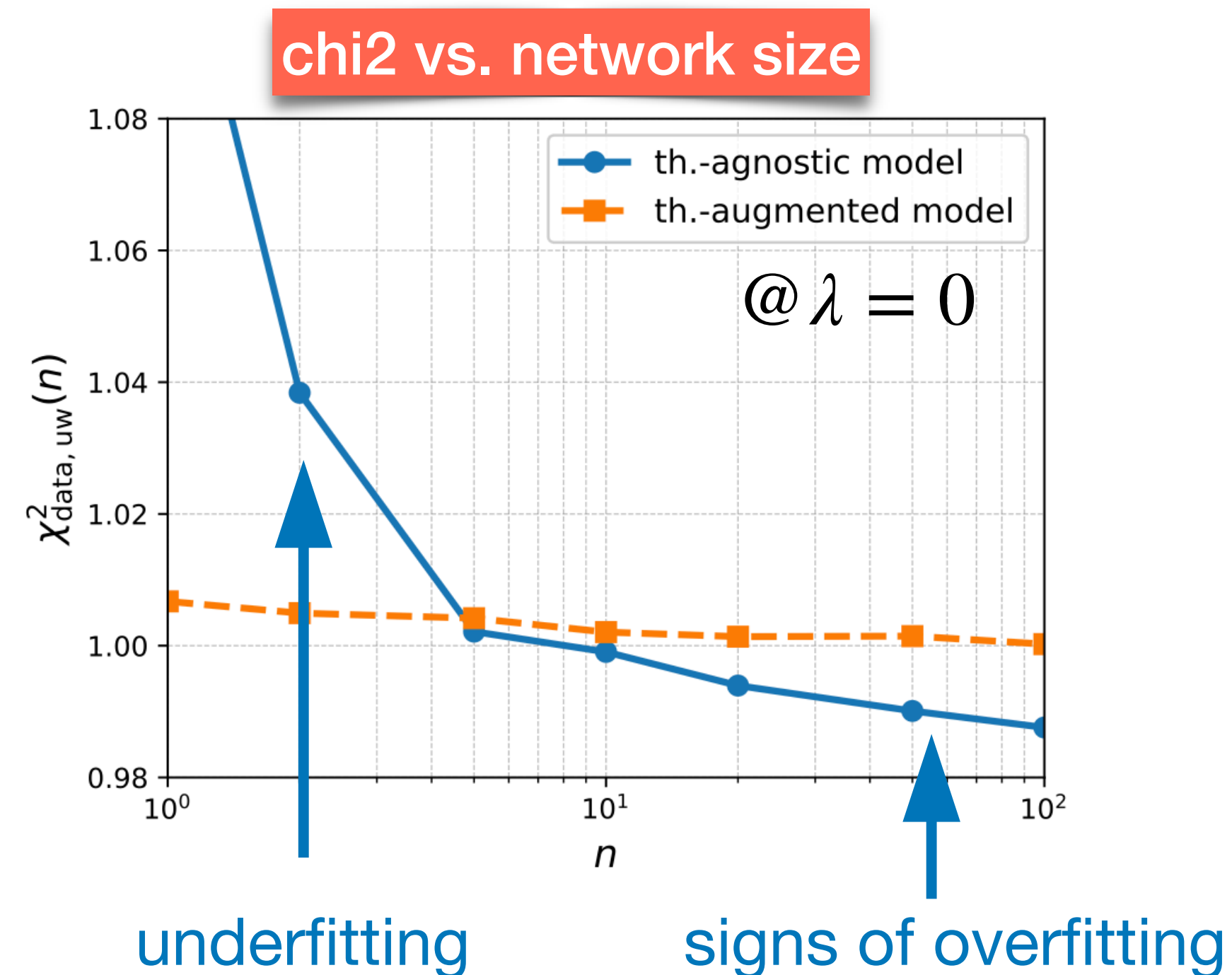
Independent extractions for proton and neutron data

- addressing bias-variance problem

$$\chi^2(\theta_i) = \chi_{\text{data}}^2(\theta_i) + \lambda \chi_{\text{anchor}}^2(\theta_i)$$

$$\chi_{\text{anchor}}^2(\theta_i) = \frac{1}{N_{\text{par}}} \sum_{j=1}^{N_{\text{par}}} \left(\theta_{i,j} - \theta_{i,j}^{(\text{prior})} \right)^2$$

- training with Adam algorithm
- warm start
- careful tuning of hyper-parameters

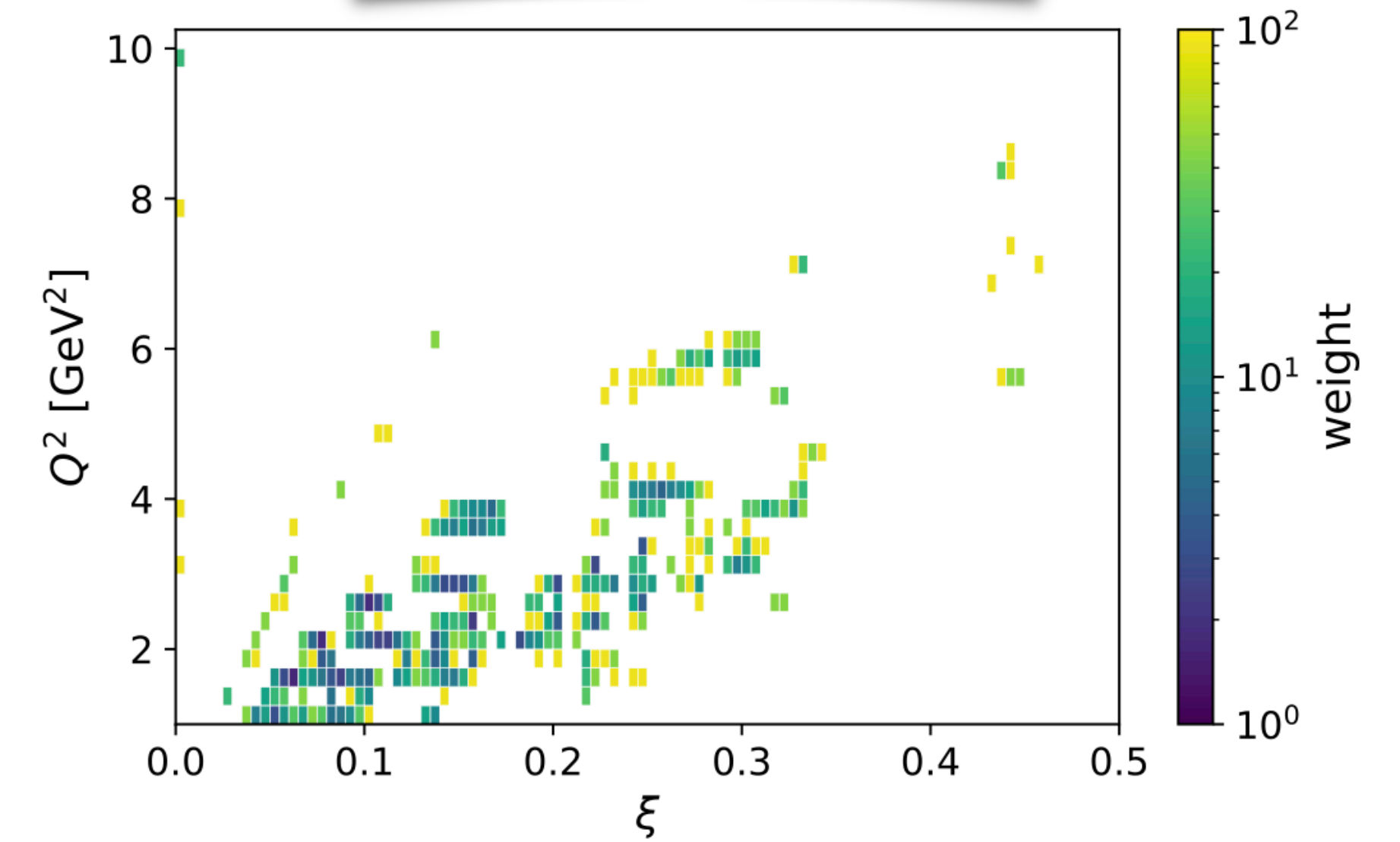


- addressing sparsity of data problem

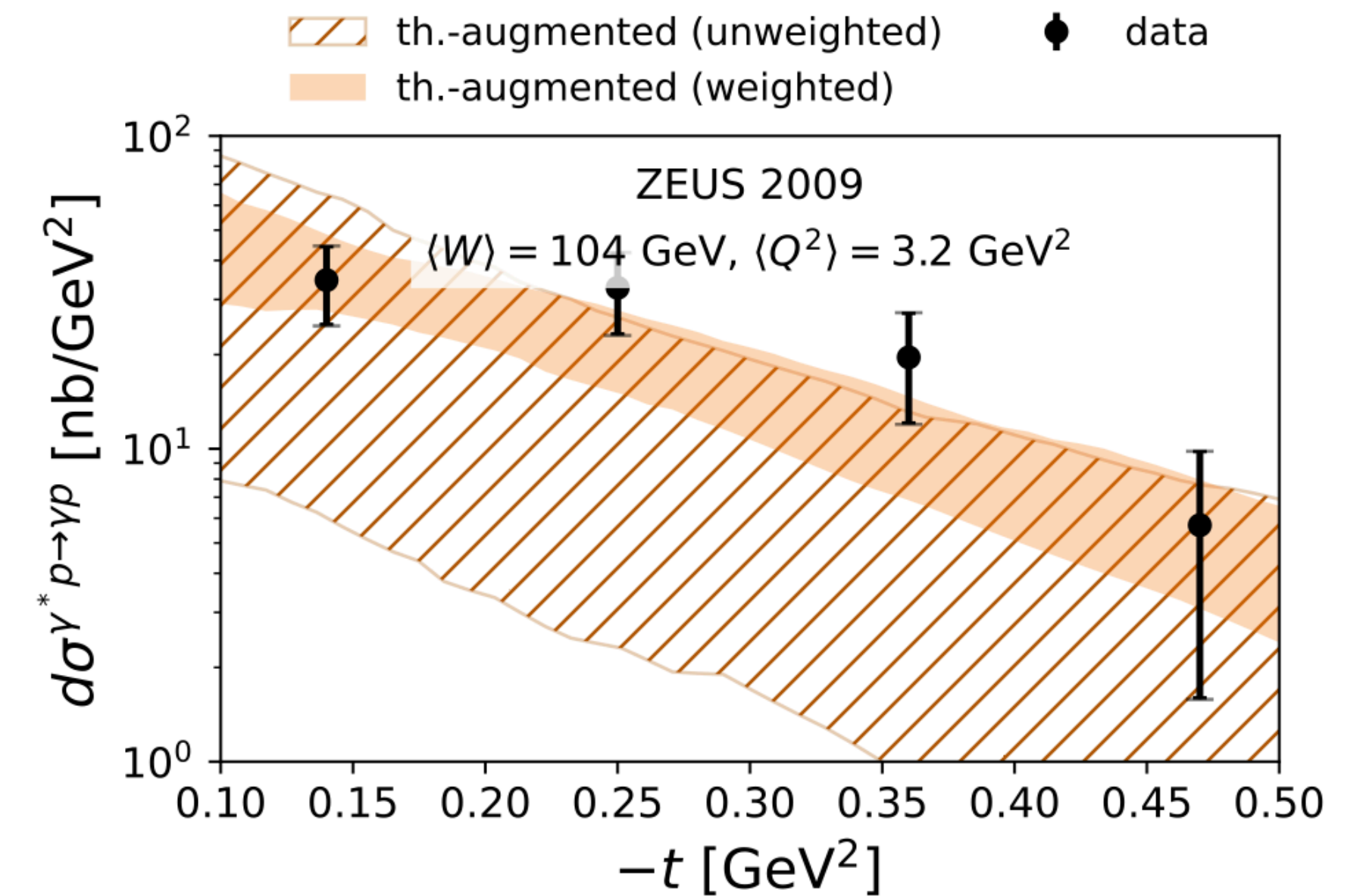
$$\chi_{\text{data}}^2(\theta_i) = \frac{1}{N_{\text{data}}} \sum_{j=1}^{N_{\text{data}}} w_j \left(\frac{v_j(\theta_i) - v_j^{(\text{exp})}}{\sigma_j^{(\text{exp})}} \right)^2$$

$$w_j = N_{\text{data}} \frac{w_{j,\text{raw}}}{\sum_k w_{k,\text{raw}}} \quad w_{j,\text{raw}} = 1/N_{\text{unique},i}$$

distribution of weights



effect of weightening



Data selection

- kinematic cuts
(significant change w.r.t. previous analyses)

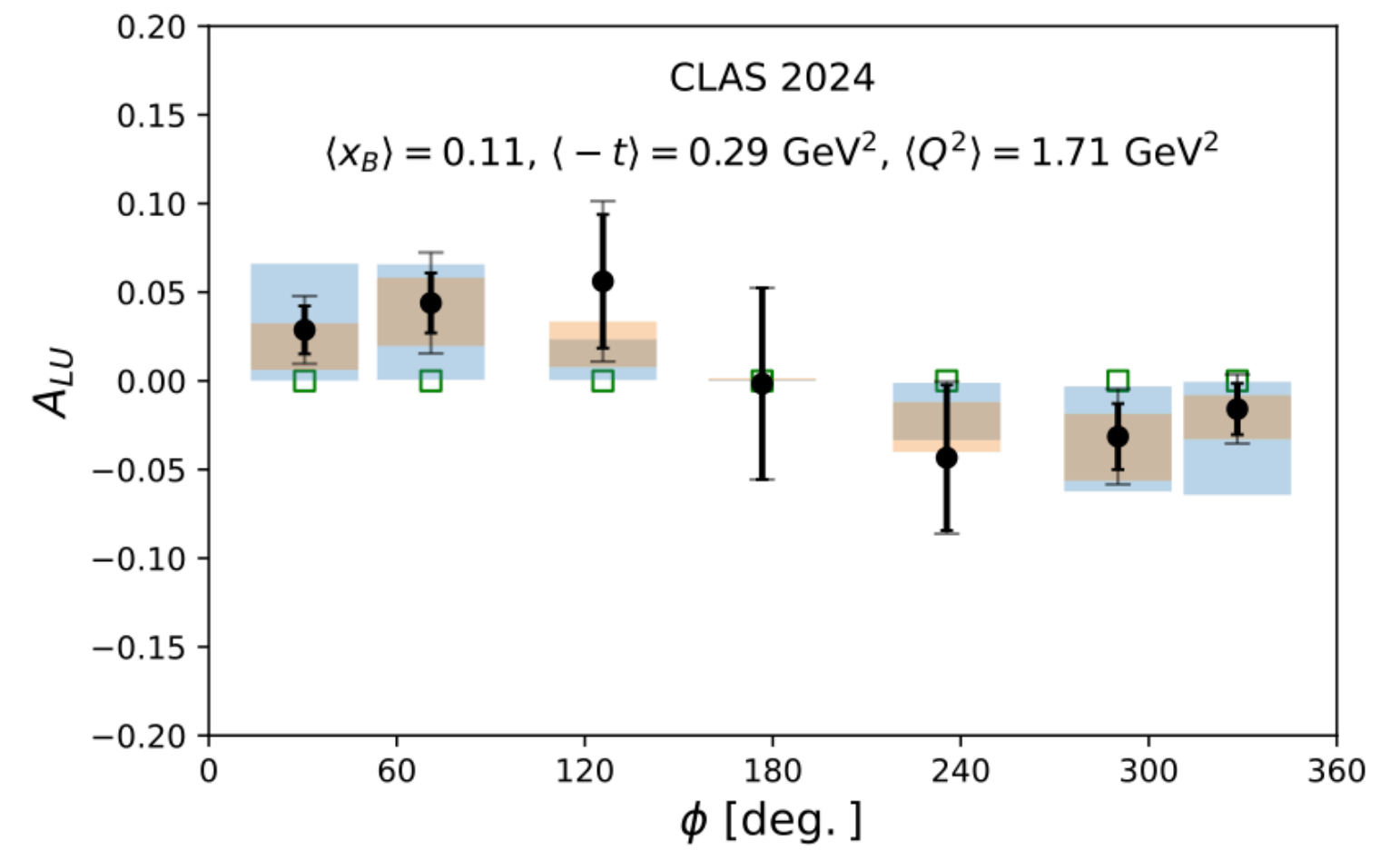
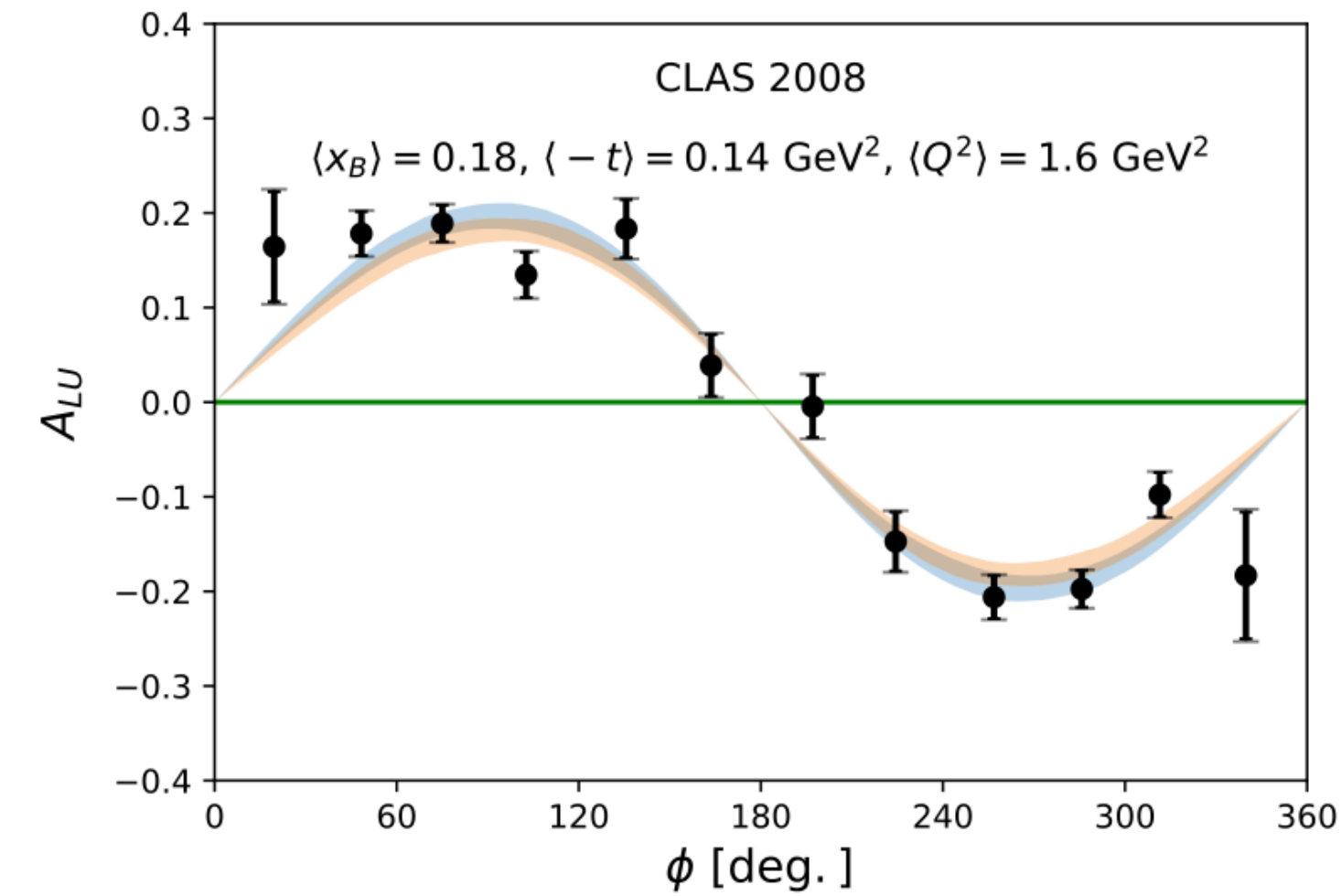
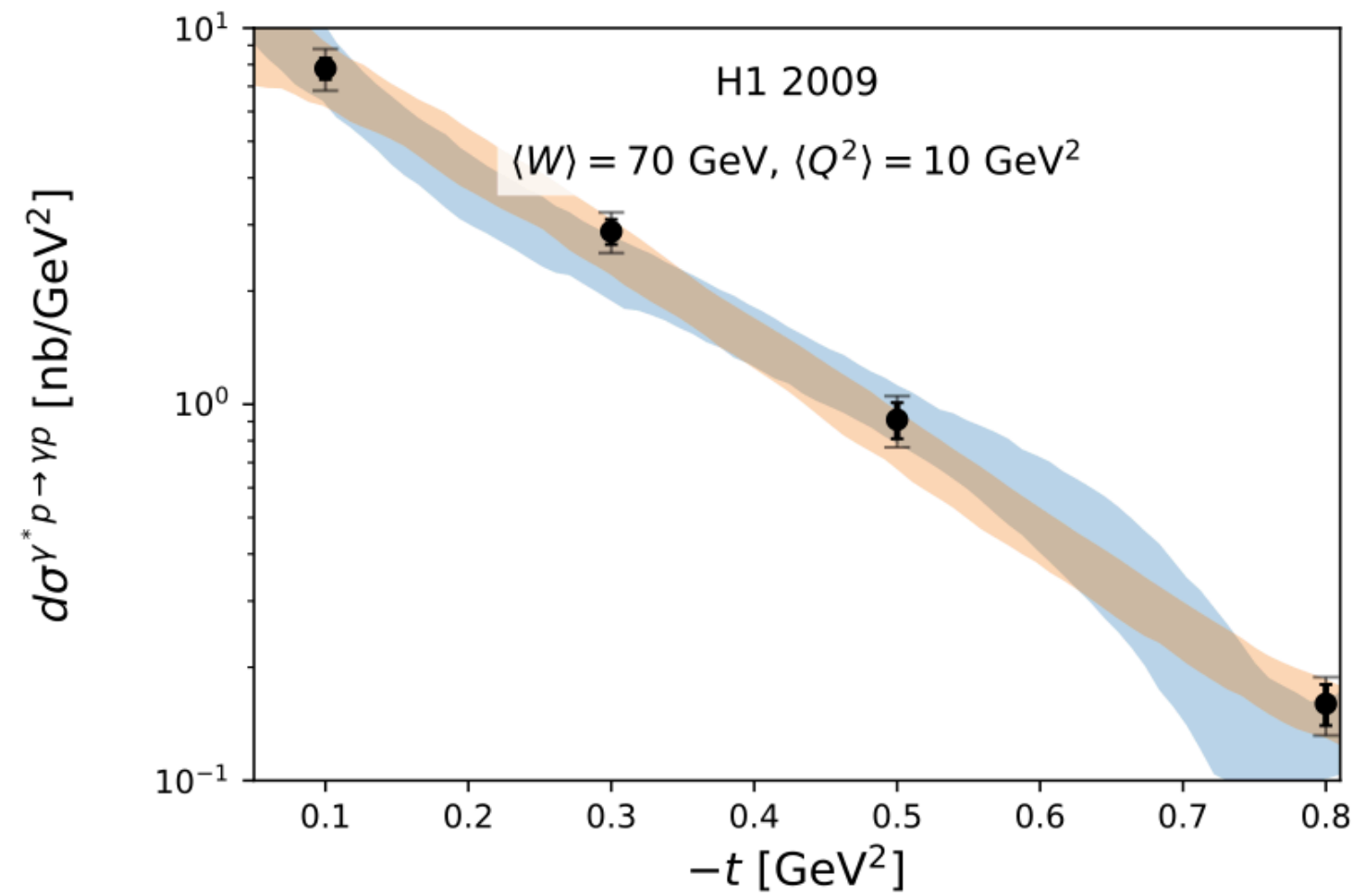
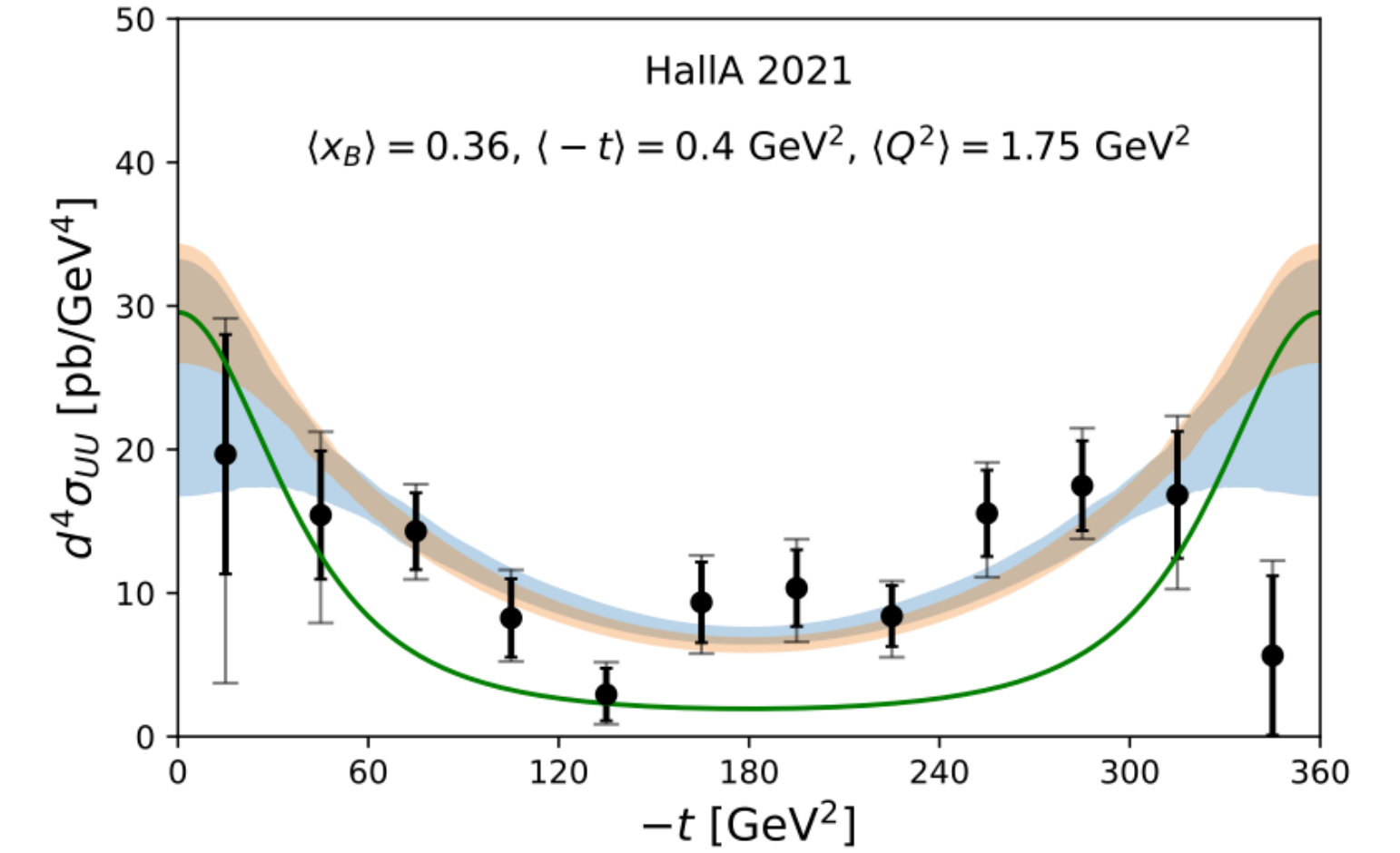
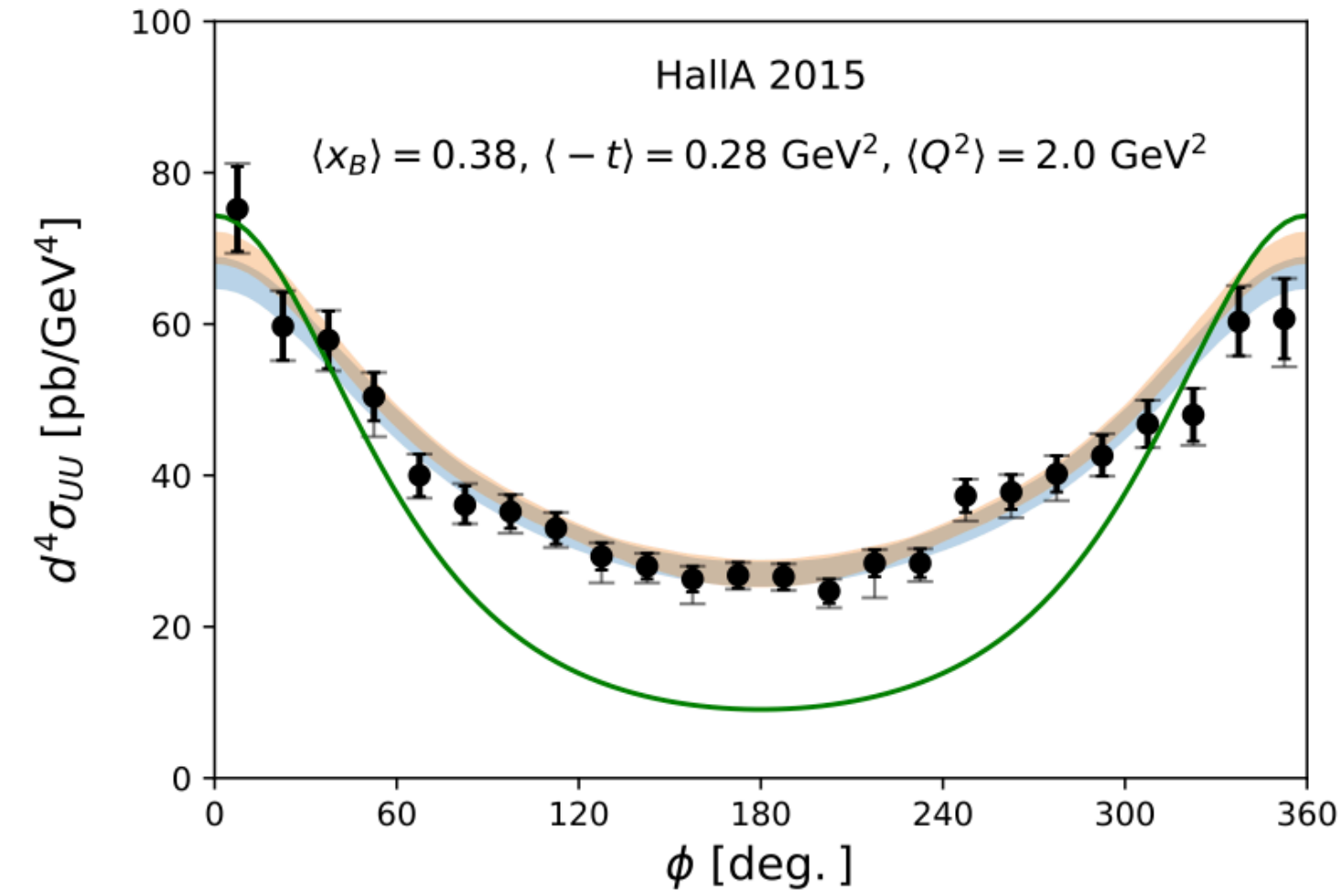
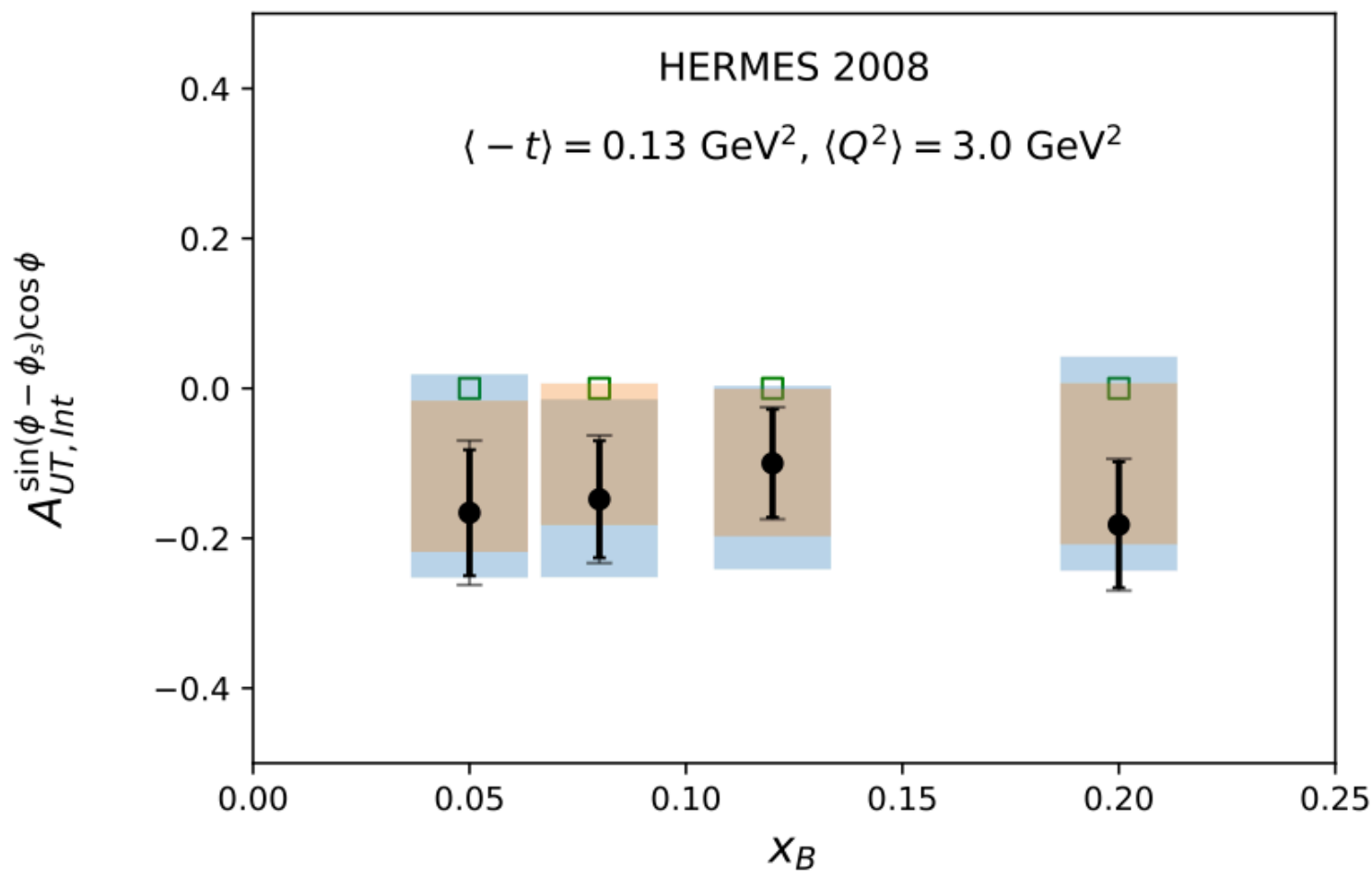
$Q^2 > 1 \text{ GeV}^2$

$-t/Q^2 < 0.4$

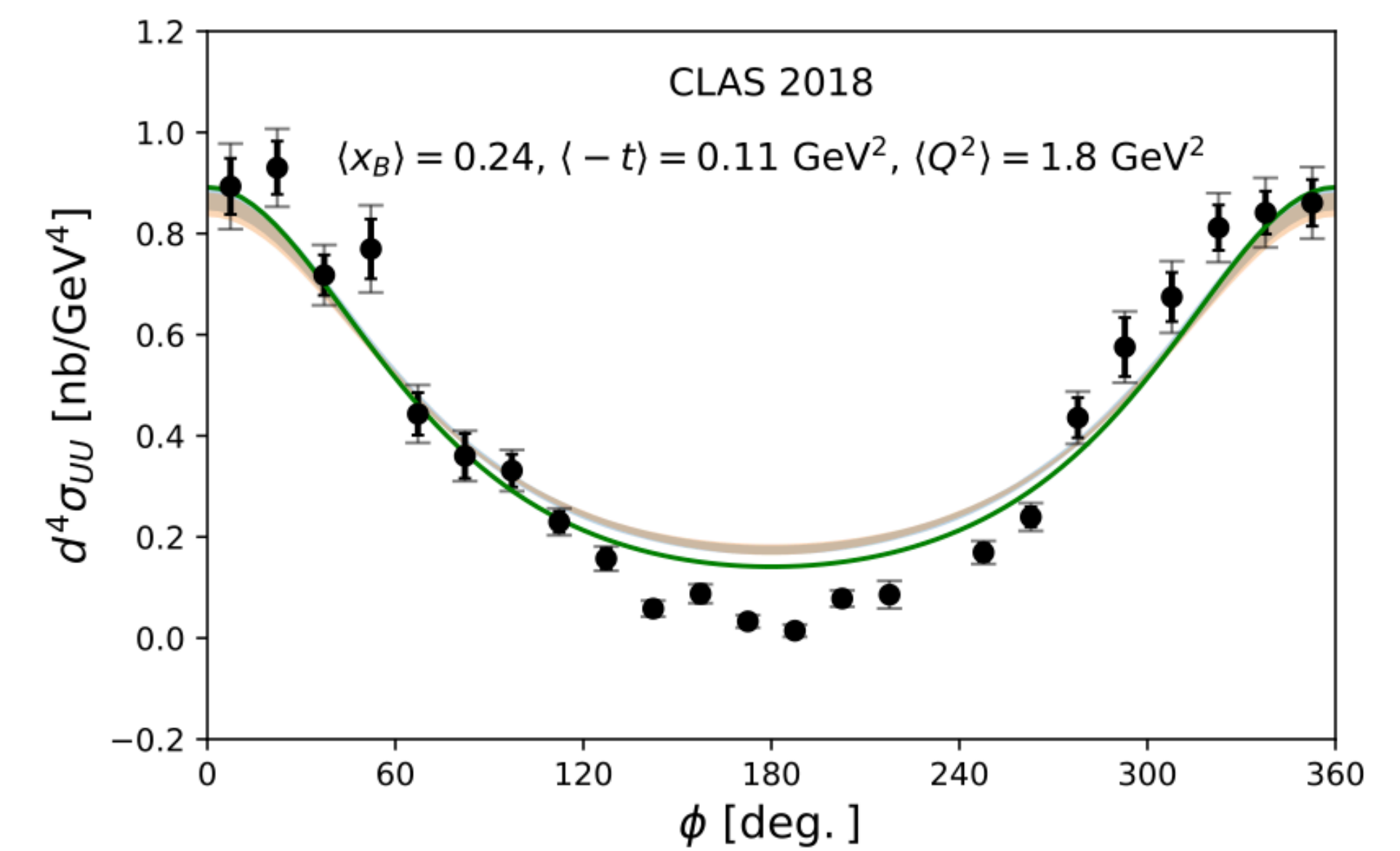
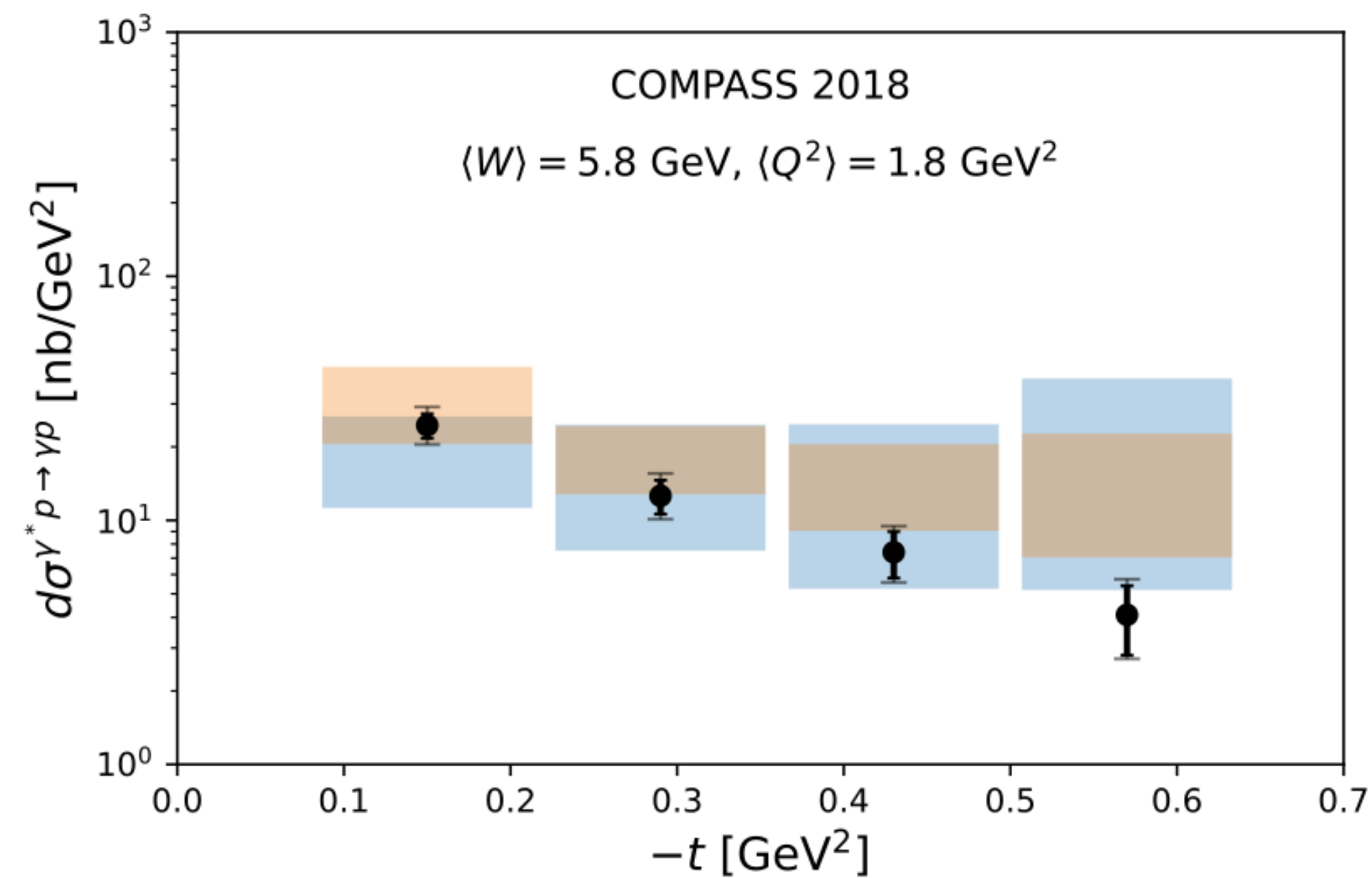
Collab.	Year	Observable	Ref.	N _{data}	$\chi^2_{\text{data,uw}}(\theta_0)$	
					th.-agnostic	th.-augmented
PROTON TARGET						
CLAS	2001	$A_{LU}^{\sin \phi}, A_{LU}^{\sin 2\phi}$	[17]	2	0.80	0.62
	2006	$A_{UL}^{\sin \phi}, A_{UL}^{\sin 2\phi}$	[18]	2	0.04	2.01
	2007	A_{LU}	[19]	546	0.88	0.84
	2008	A_{LU}	[20]	33	0.40	0.37
	2015	A_{LU}, A_{UL}, A_{LL}	[21]	389	1.24	1.47
	2015	$d\sigma_{UU}, \Delta\sigma_{LU}$	[22]	3828	0.93	0.98
	2018	$\Delta\sigma_{LU}$	[23]	2465	1.96	1.93
	2022	A_{LU}	[24]	1303	1.82	1.83
H1	2005	$d\sigma_{UU}^{\gamma^*p}$	[12]	8	1.59	0.44
	2009	$A_C, d\sigma_{UU}^{\gamma^*p}$	[14]	18	1.92	0.90
HallA	2015	$d\sigma_{UU}, \Delta\sigma_{LU}$	[34]	600	0.64	0.63
	2017	$d\sigma_{UU}, \Delta\sigma_{LU}$	[35]	806	1.15	1.60
	2022	$d\sigma_{UU}, \Delta\sigma_{LU}$	[36]	2640	1.23	1.40
HERMES	2001	A_{LU}	[26]	10	1.05	0.93
	2006	$A_C^{\cos \phi}$	[27]	4	2.81	0.94
	2008	$A_C^{\cos(n\phi)}, A_{UT}^{\sin(\phi-\phi_s)\cos(n\phi)}$	[28]	24	1.05	0.59
	2009	$A_C^{\cos(n\phi)}, A_{LU,\text{I}}^{\sin(n\phi)}, A_{LU,\text{DVCS}}^{\sin \phi}$	[29]	42	1.52	1.27
	2010	$A_{UL}^{\sin(n\phi)}, A_{LL}^{\cos(n\phi)}$	[30]	24	1.67	1.23
	2011	A_{LT}	[31]	32	0.57	0.52
	2012	$A_C^{\cos(n\phi)}, A_{LU,\text{I}}^{\sin(n\phi)}, A_{LU,\text{DVCS}}^{\sin \phi}$	[32]	42	1.00	0.85
ZEUS	2008	$d\sigma_{UU}^{\gamma^*p}$	[16]	4	0.41	1.09
Total				12822	1.29	1.36
NEUTRON TARGET						
CLAS	2024	A_{LU}	[25]	21	0.65	0.44
HallA	2020	$d\sigma_{UU}$	[37]	96	0.78	0.76
Total				117	0.76	0.70

proton

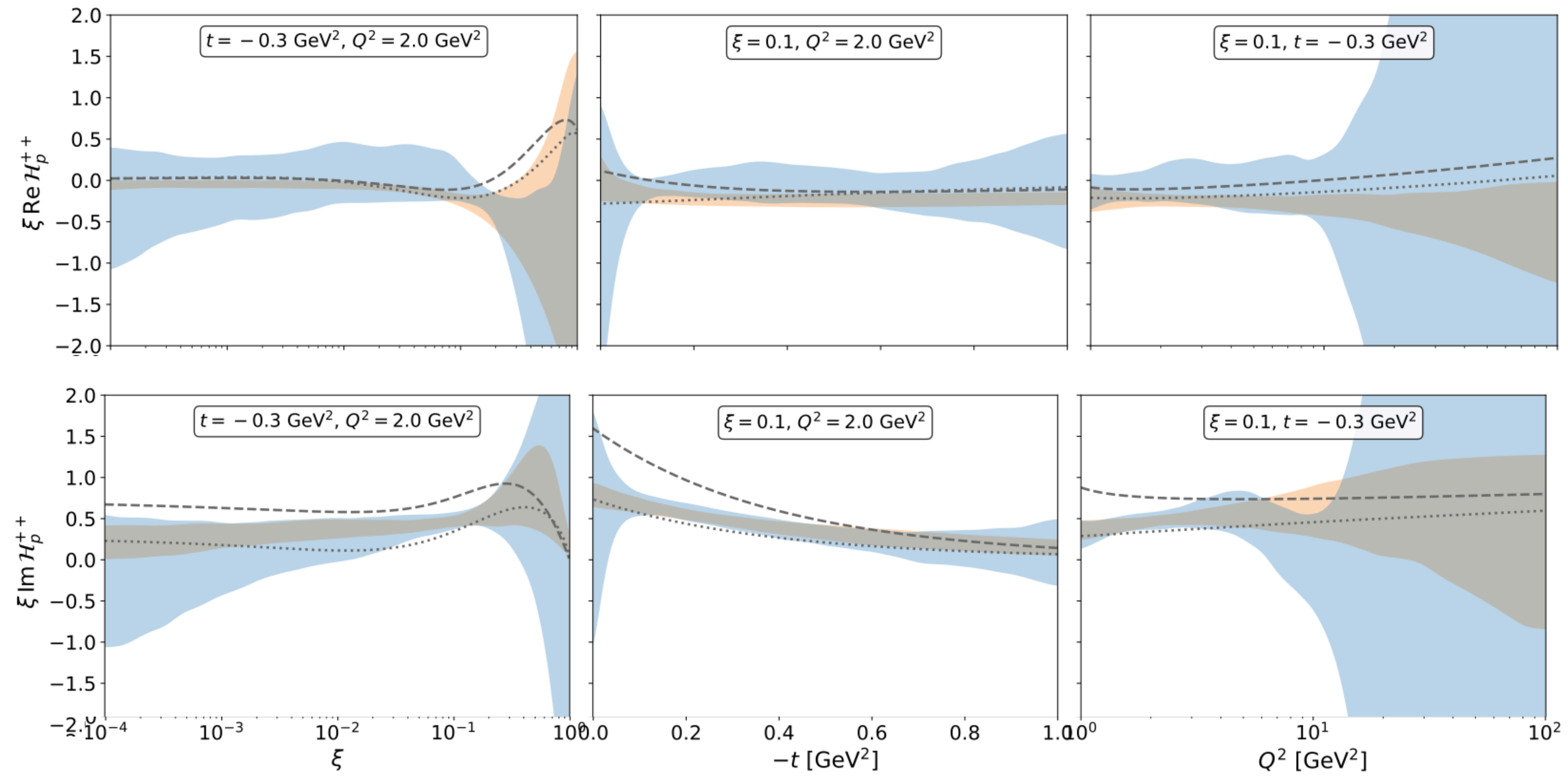
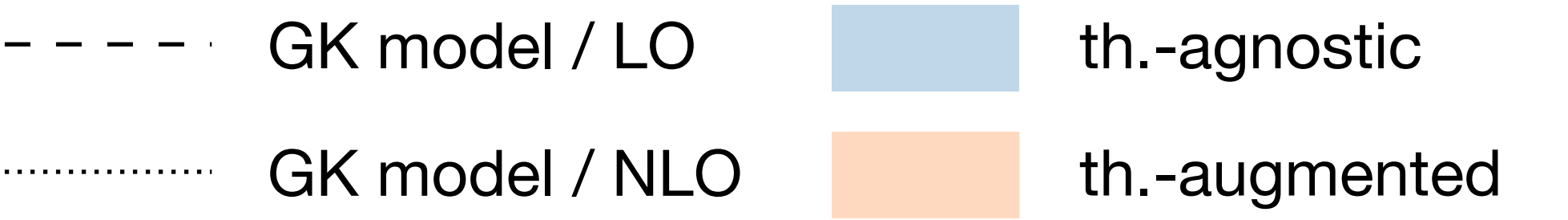
neutron



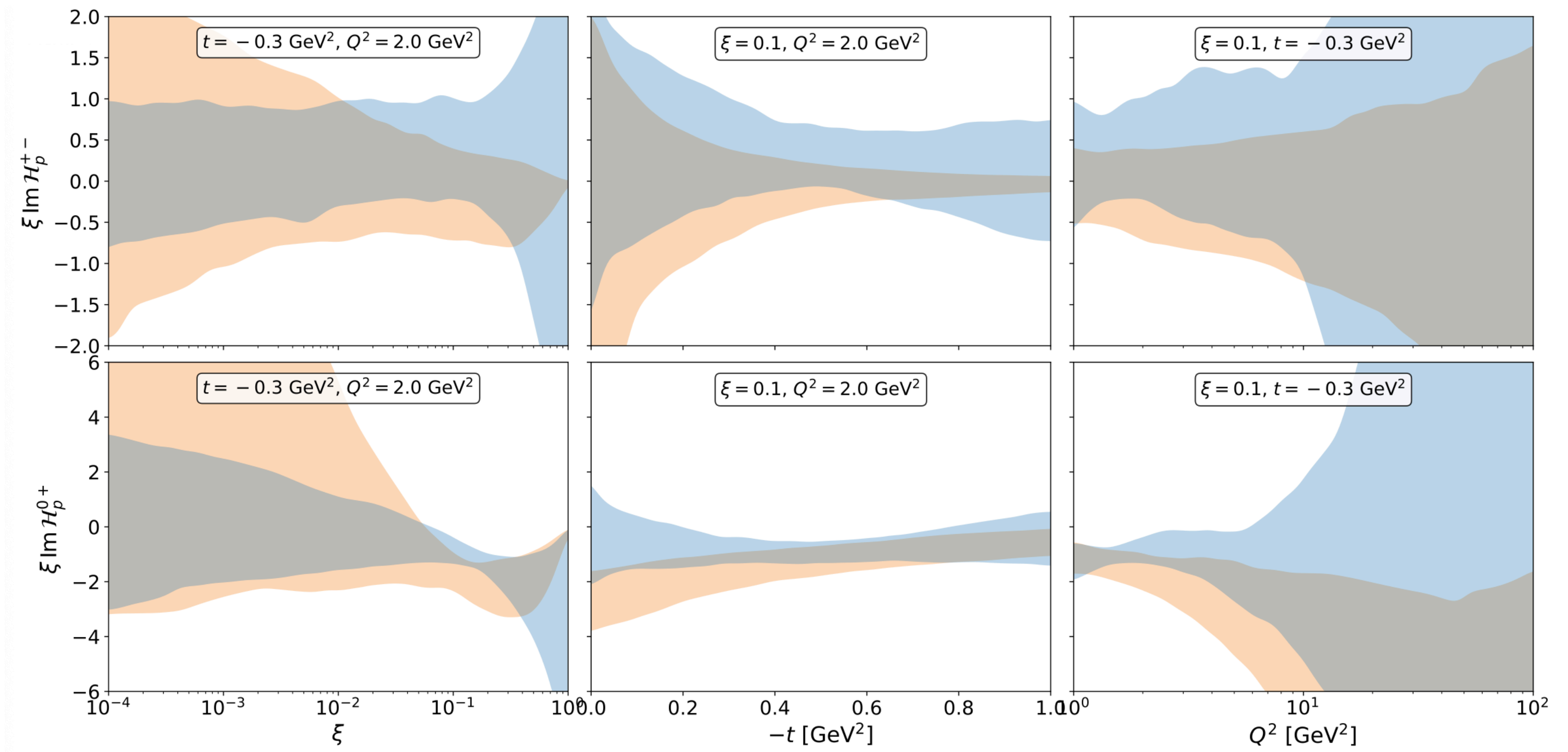
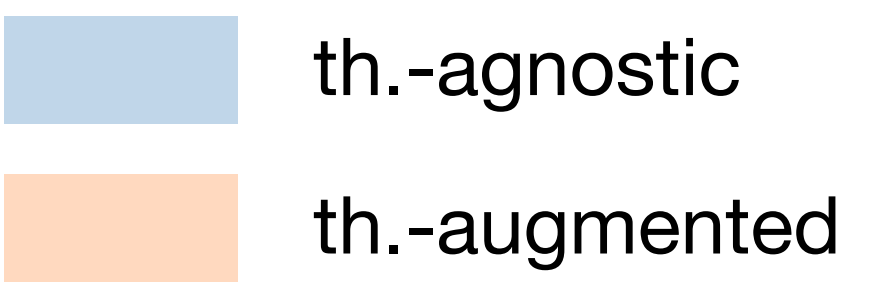
- COMPASS data excluded due to computationally expensive multidimensional integration
- cross-section data measured by CLAS excluded from the fit due to a tension with other results



- CFF H^{++} for proton

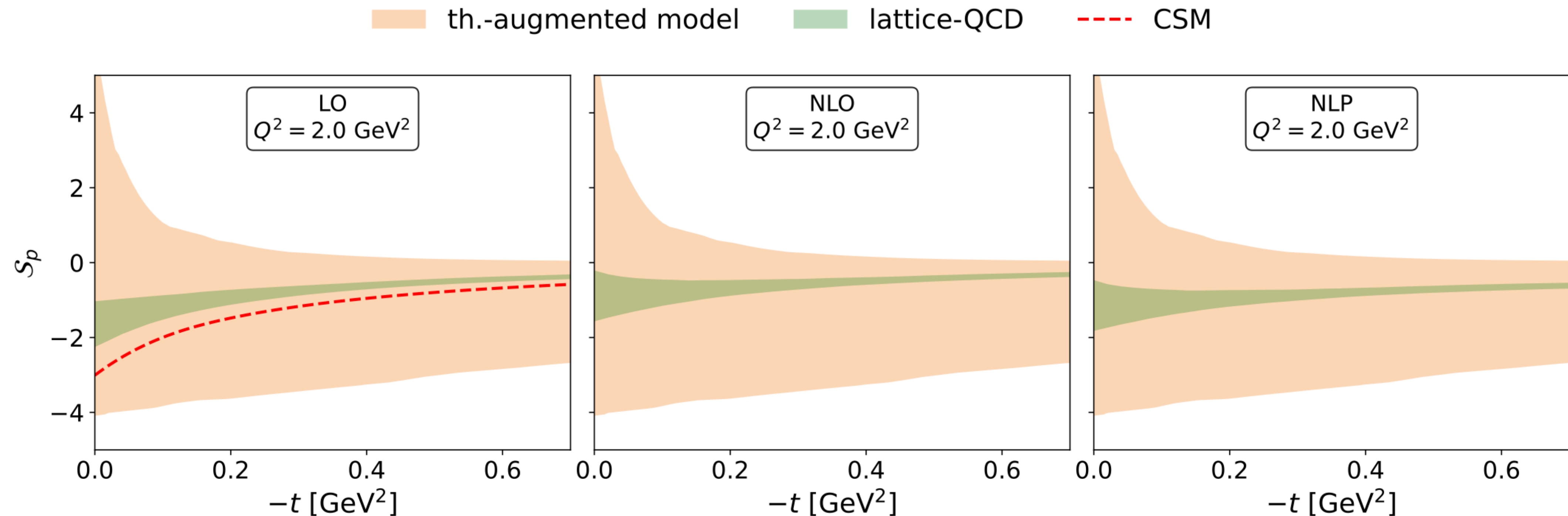


- helicity-flip CFFs for proton



possible signal of CFF H^{0+}

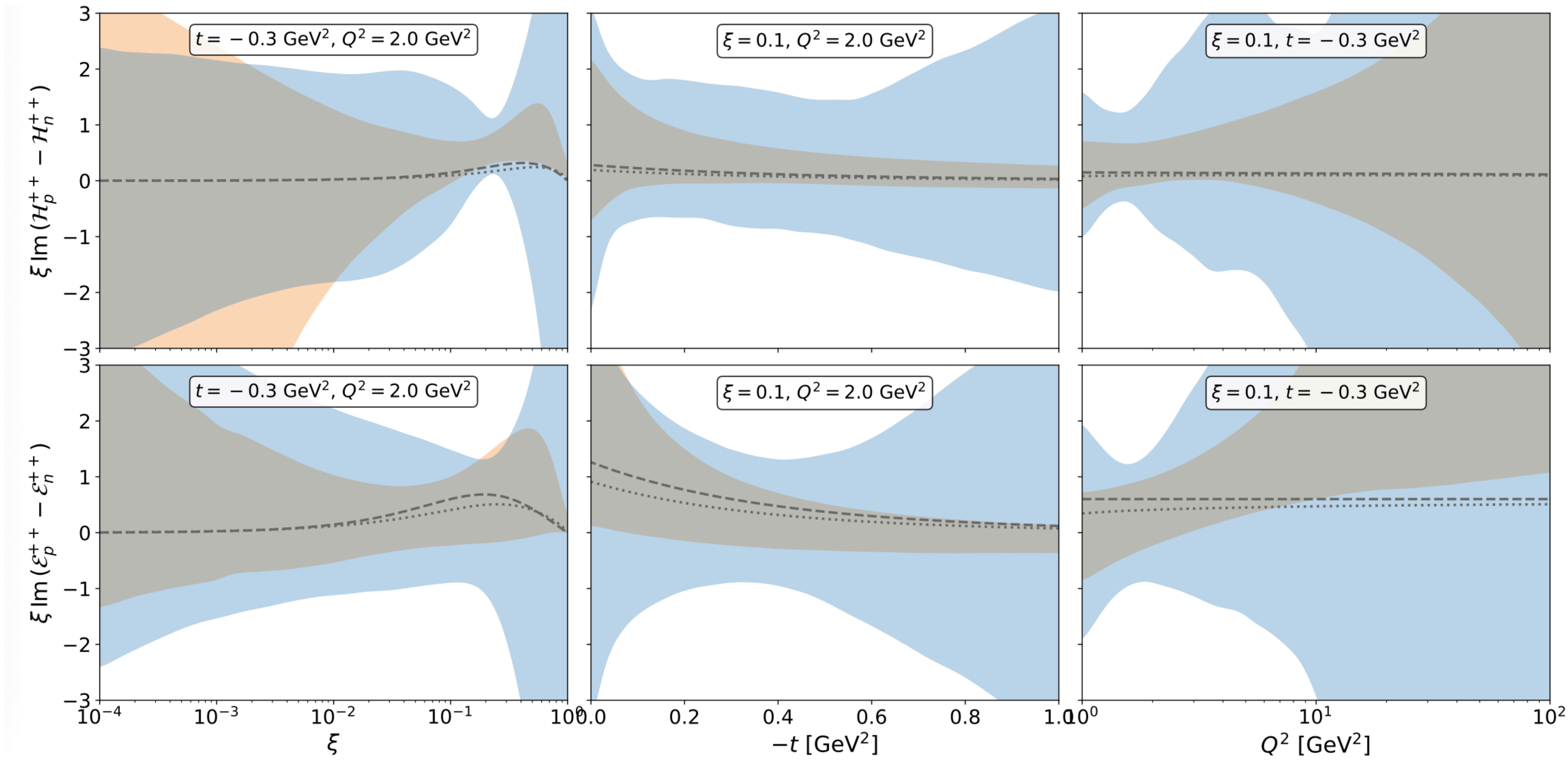
- Subtraction constant vs. lattice-QCD and Continuum Schwinger Method predictions



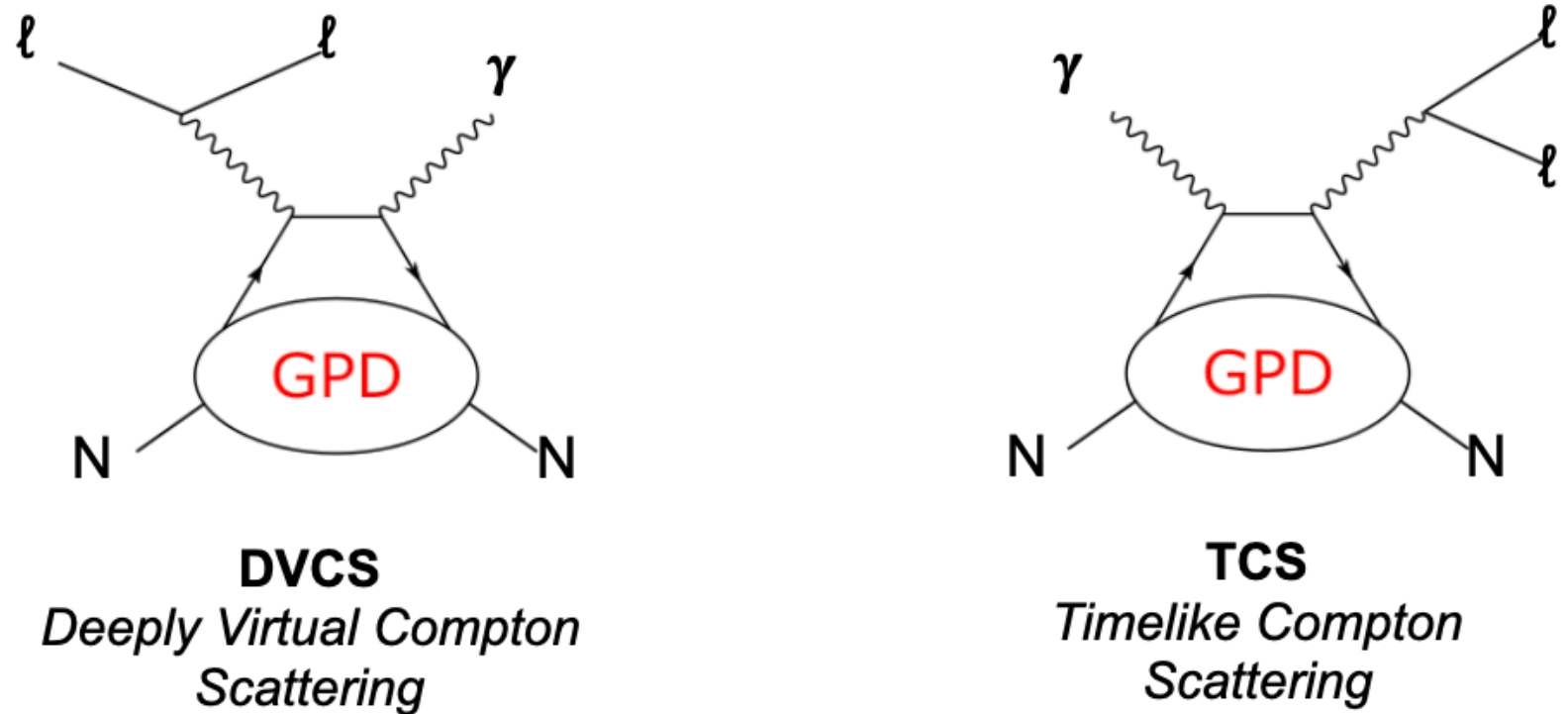
Subtraction constant at $t = 0$: $\Delta_0 = -0.69^{+6.92}_{-3.13}$ at $Q^2 = 2$ GeV²

See the article for neutron data extraction → surprising sensitivity found!

- Isovector CFFs

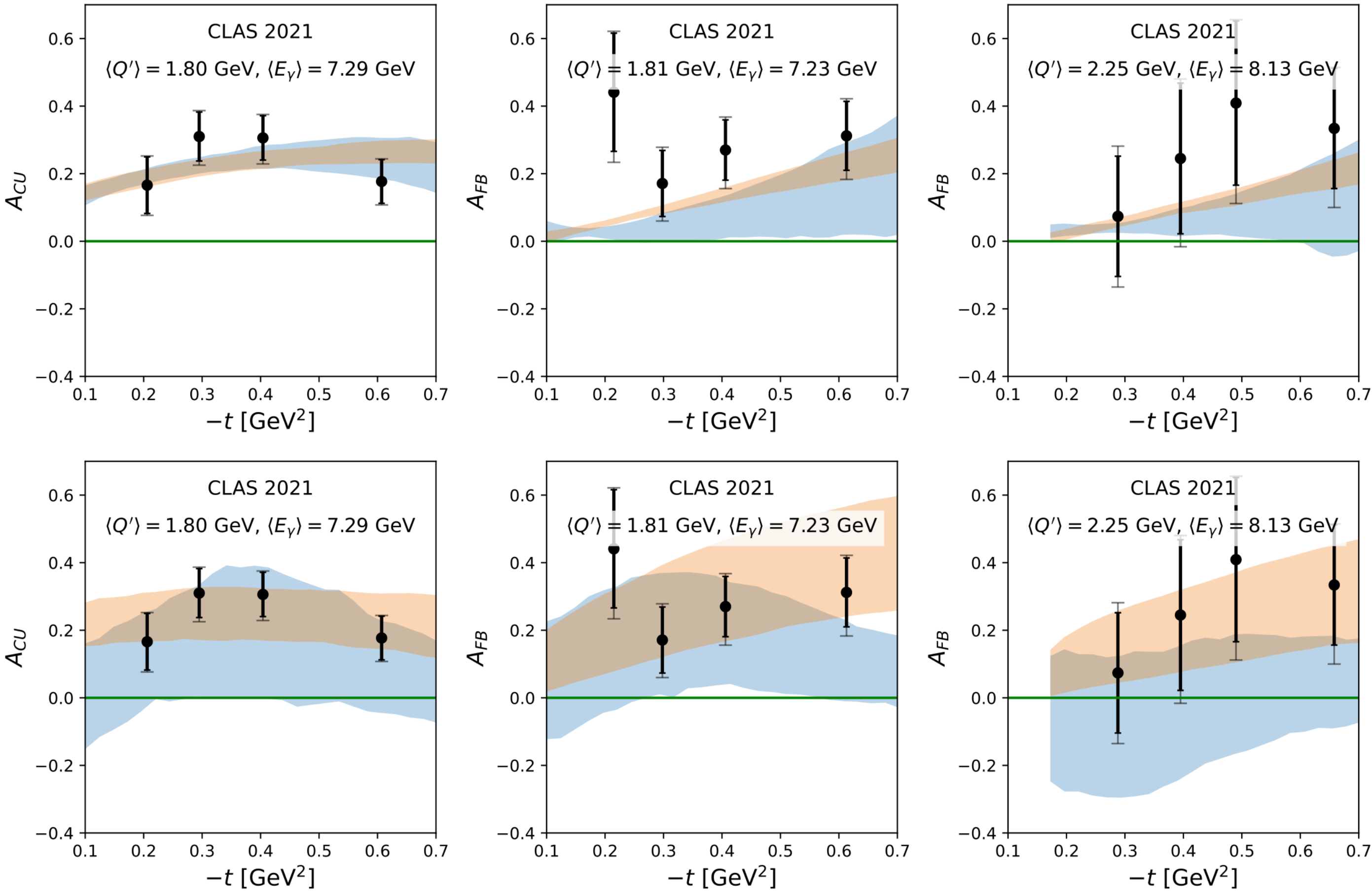


- Comparison with TCS data



LO relation between amplitudes

$$T\mathcal{H}^{++} \stackrel{\text{LO}}{=} \text{conj} ({}^S\mathcal{H}^{++})$$



NLO relation between amplitudes

$$T\mathcal{H}^{++} \stackrel{\text{NLO}}{=} \text{conj} ({}^S\mathcal{H}^{++}) - i\pi Q^2 \frac{\partial}{\partial Q^2} \text{conj} ({}^S\mathcal{H}^{++})$$

- Standardizing GPD research

transitioning the community from isolated tools to a unified, open-source framework ([see backup slides](#))

- PARTONS

core modular framework for robust GPD modeling and evaluation

- EpIC

universal, long-term event generator for next-generation facilities (EIC, JLab)

- Open Database

flexible, YAML-based data storage seamlessly bridging theory and experiment

- New results on the extraction of DVCS CFFs from world data

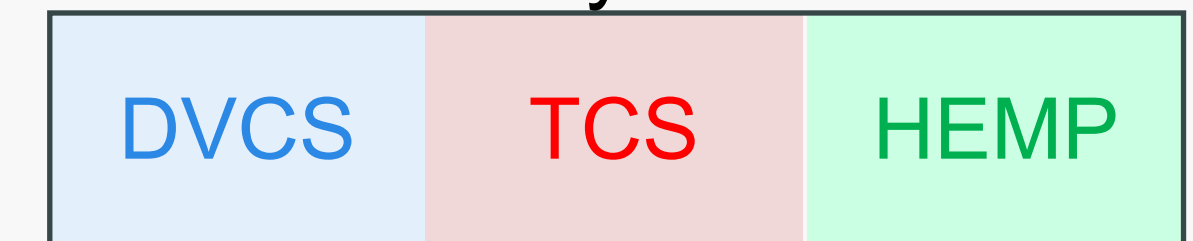
PARTONS FRAMEWORK



PARTONS - a platform to study GPDs

- includes a variety of utility tools and built-in physics developments
- written in C++ to ensure high performance (requires some technical expertise)
- functions either as a library within custom programs or as a standalone executable using XML input files
- groups evaluations into computational layers
- features a highly modular structure, making it easy to integrate new developments
- integrates with external physics-oriented libraries:
 - Apfel++ for GPD evolution
 - LHAPDF for PDFs
- note another project of this type
GeParD: <https://gepard.phy.hr/>

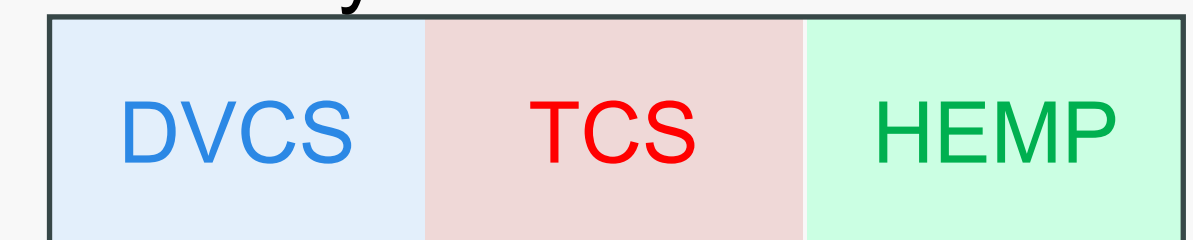
Observable Layer



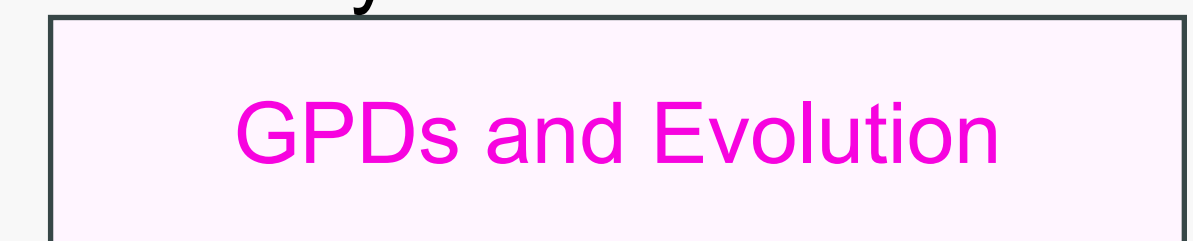
Process Layer



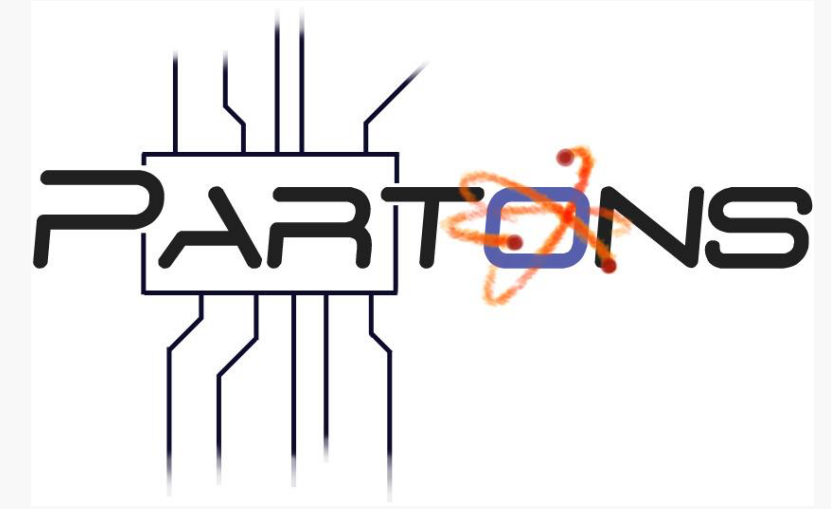
CCF Layer



GPD Layer



PARTONS FRAMEWORK



- Licensing:
distributed as an open-source project, with specific licenses varying by subproject
- Main Website & Source Code:
<http://partons.cea.fr>
<https://github.com/3d-partons> (note: source code repository recently relocated)
- Available as a Docker image:
<https://hub.docker.com/repository/docker/partons/partons>
- Reference publication:
Eur. Phys. J. C 78 (2018) 6, 478
- Version 5 available
optimized to be “lighter”
- Processes included:
DVCS, TCS, DDVCS, DVMP, and GAM2

PARTONS: PARtonic Tomography Of Nucleon Software

A computing framework for the phenomenology of Generalized Parton Distributions

B. Berthou¹, D. Binosi², N. Chouika¹, L. Colaneri^{3,4}, M. Guidal³, C. Mezrag⁵, H. Moutarde^{1,a}, J. Rodríguez-Quintero^{7,8}, F. Sabatié¹, P. Sznajder^{3,6}, J. Wagner⁶

¹ IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

² ECT*/Fondazione Bruno Kessler, Villa Tambosi, Strada delle Tabarelle 286, 38123 Villazzano, TN, Italy

³ Institut de Physique Nucléaire d'Orsay, CNRS-IN2P3, Université Paris-Sud, Université Paris-Saclay, 91406 Orsay, France

⁴ University of Connecticut, Storrs, CT 06269, USA

⁵ Istituto Nazionale di Fisica Nucleare, Sezione di Roma, P. le A. Moro 2, 00185 Roma, Italy

⁶ National Centre for Nuclear Research (NCBJ), 00-681 Warsaw, Poland

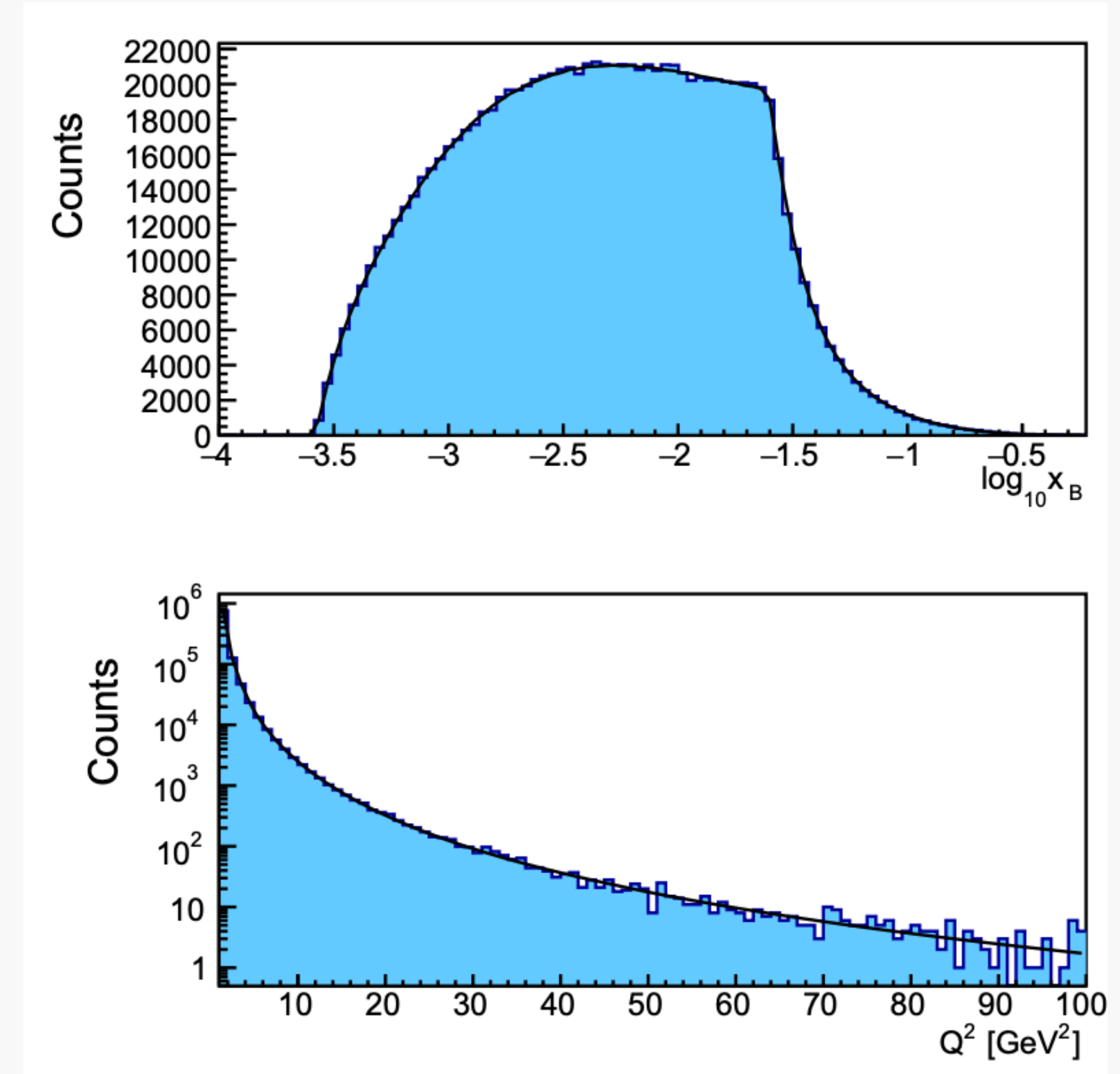
⁷ Dpto. Ciencias Integradas, Centro de Estudios Avanzados en Fis., Mat. y Comp., Fac. Ciencias Experimentales, Universidad de Huelva, 21071 Huelva, Spain

⁸ CAFPE, Universidad de Granada, 18071 Granada, Spain

Received: 3 April 2018 / Accepted: 29 May 2018 / Published online: 11 June 2018

© The Author(s) 2018

- universal (generic):
standardized for CERN, JLab, and the EIC, ...
replaces "home-made" generators
- multichannel:
brings all processes (DVCS, TCS, DVMP, etc.) implemented in PARTONS
- modular:
built for maximum flexibility and simplicity.
- uses rigorous coding practices and modern C++ paradigms
- highly maintainable
engineered for a 20+ year lifespan with comprehensive documentation





- Licensing:
distributed as an open-source project
- Main Website & Source Code:
<https://pawelsznajder.github.io/epic>
<https://github.com/pawelsznajder/epic>
- Available as a Docker image:
<https://hub.docker.com/repository/docker/partons/epic>
- Reference publication:
Eur. Phys. J. C 82 (2022) 9, 819
- Version 1.1.8 available
a few bugs corrected, some minor improvements
- Processes included:
DVCS, TCS, DDVCS, DVMP, and GAM2

EpIC: novel Monte Carlo generator for exclusive processes

E. C. Aschenauer^{1,a}, V. Batozskaya^{2,b}, S. Fazio^{3,c}, K. Gates^{4,d}, H. Moutarde^{5,e}, D. Sokhan^{4,5,f}, H. Spiesberger^{6,g},
P. Sznajder^{2,h} , K. Tezgin^{1,i} 

¹ Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA

² National Centre for Nuclear Research (NCBJ), Pasteura 7, 02-093 Warsaw, Poland

³ University of Calabria and INFN-Cosenza, 87036 Rende (CS), Italy

⁴ University of Glasgow, Glasgow G12 8QQ, UK

⁵ IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

⁶ PRISMA+ Cluster of Excellence, Institut für Physik, Johannes Gutenberg-Universität, 55099 Mainz, Germany

Received: 13 June 2022 / Accepted: 27 July 2022 / Published online: 15 September 2022
© The Author(s) 2022

OPEN DATABASE

- comprehensive data storage:
 - accommodates experimental, lattice QCD, and theoretical data
 - a clear distinction between actual and pseudo-data
- tailored YAML format:
 - uses human-readable YAML with predefined types for units and observables,
 - optimized specifically for GPD physics
- dual-language interfaces:
 - features native Python and C++ interfaces
- GitHub-backed ecosystem:
 - leverages GitHub for version control, CI/CD pipelines, user communication, and team management
- scalable architecture:
 - built to allow seamless future transfer to external databases (e.g., MySQL) to bypass hosting storage limits.

OPEN DATABASE

- Licensing:
distributed as an open-source project
- Main Website & Source Code:
<https://github.com/opengpd/gpddatabase>
<https://opengpd.github.io/gpddatabase>
- Available as a Python module:
<https://pypi.org/project/gpddatabase>
- Reference publication:
Eur. Phys. J. C 85 (2025) 8, 838
- Version 1.1.3 available
a few bugs corrected, some minor improvements
- Data included:
all DVCS data on proton
some DVCS EIC pseudo-data
some lattice-QCD data

Open database for GPD analyses

V. D. Burkert¹, **A. Camsonne¹**, **P. Chatagnon^{1,2}**, **K. Cichy³**, **M. Constantinou⁴**, **H. Dutrieux⁵**,
I. M. Higuera-Angulo^{1,a}, **C. Mezrag²**, **D. Richards¹**, **P. Sznajder⁶**

¹ Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, 23606 Newport News, VA, USA

² Irfu, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

³ Faculty of Physics and Astronomy, Adam Mickiewicz University, ul. Uniwersytetu Poznańskiego 2, 61-614 Poznań, Poland

⁴ Department of Physics, Temple University, Philadelphia 19122-1801, USA

⁵ Physics Department, William & Mary, Williamsburg 23187, USA

⁶ National Centre for Nuclear Research, 02-093 Warsaw, Poland

Received: 11 April 2025 / Accepted: 9 July 2025

© The Author(s) 2025