3D Nucleon Imaging

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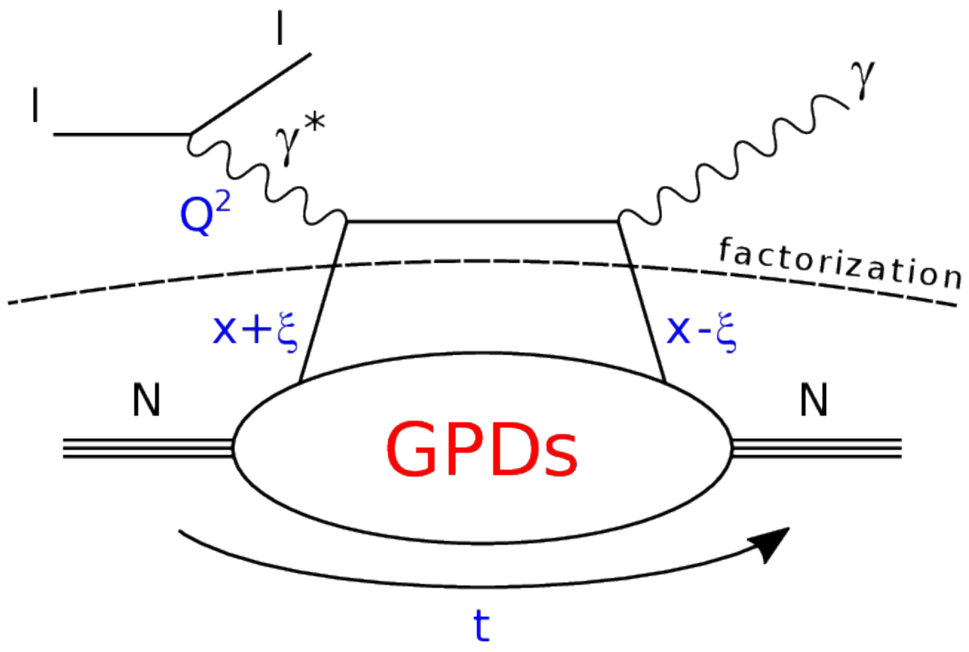
Outline

- Introduction
- Experimental campaign
- Global analysis of DVCS data - “classic” and ANN approaches
- Summary

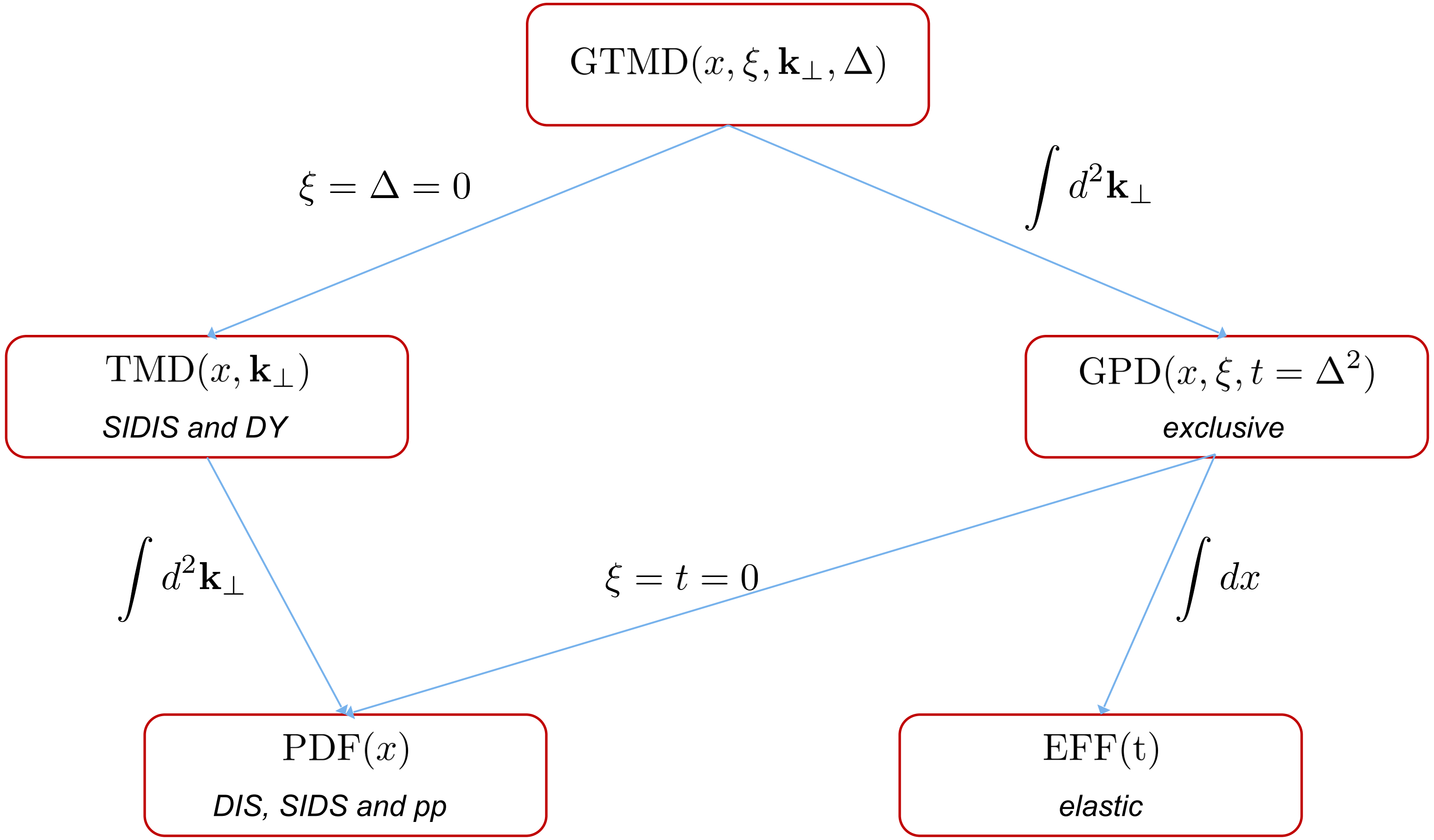
Deeply Virtual Compton Scattering (DVCS)



factorization for |t|/Q² « 1

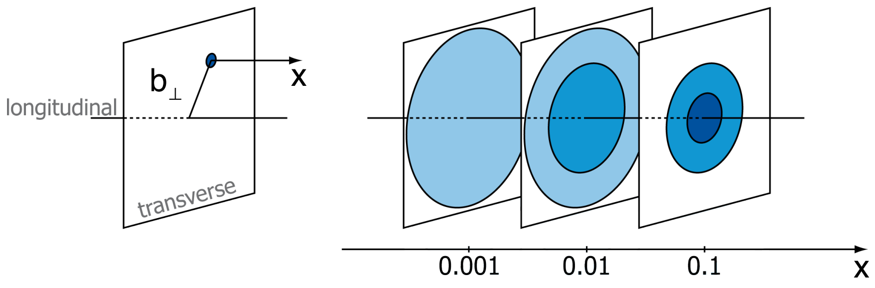
Chiral-even GPDs:
(helicity of parton conserved)

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*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*	


$\mathrm{GTMD}(x, \xi, \mathbf{k}_\perp, \Delta)$
$\xi = \Delta = 0$
$\int d^2\mathbf{k}_\perp$
$\mathrm{TMD}(x, \mathbf{k}_\perp)$
SIDIS and DY
$\mathrm{GPD}(x, \xi, t = \Delta^2)$
exclusive
$\int d^2\mathbf{k}_\perp$
$\xi = t = 0$
$\int dx$
$\mathrm{PDF}(x)$
DIS, SIDS and pp
$\mathrm{EFF}(\mathrm{t})$
elastic

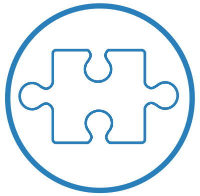
Nucleon tomography

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



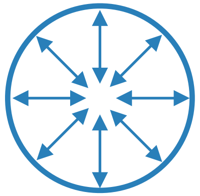
Total angular momentum

$$\underbrace{A^q(0)}_{\text{EMT form factors}} + \underbrace{B^q(0)}_{} = \underbrace{\int_{-1}^{1} x \left[H^q(x, \xi, 0) + E^q(x, \xi, 0)\right]}_{\text{Ji's sum rule}} = 2J^q$$



“Mechanical” forces acting on quarks, e.g. pressure in nucleon center

$$p(0) = \frac{1}{6\pi^2 \underbrace{M}_{\text{Nucleon mass}}} \int_{-\infty}^{0} dt \sqrt{-t}\, t \underbrace{C(t)}_{\text{EMT form factor}}$$



Experimental campaign

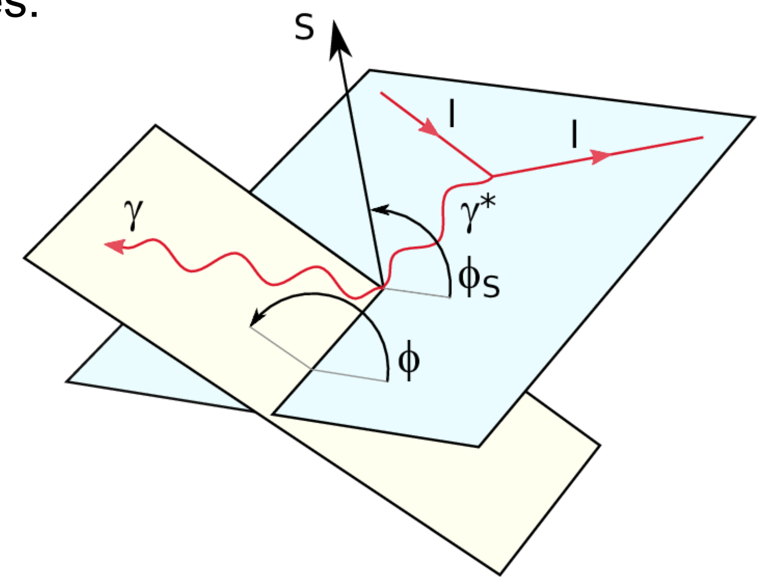
GPDs studied in various laboratories
→ need to cover a broad kinematic range

experiments

closed **active** **planned**

DVCS data

Angles:



Kinematic cuts
used in presented analyses:

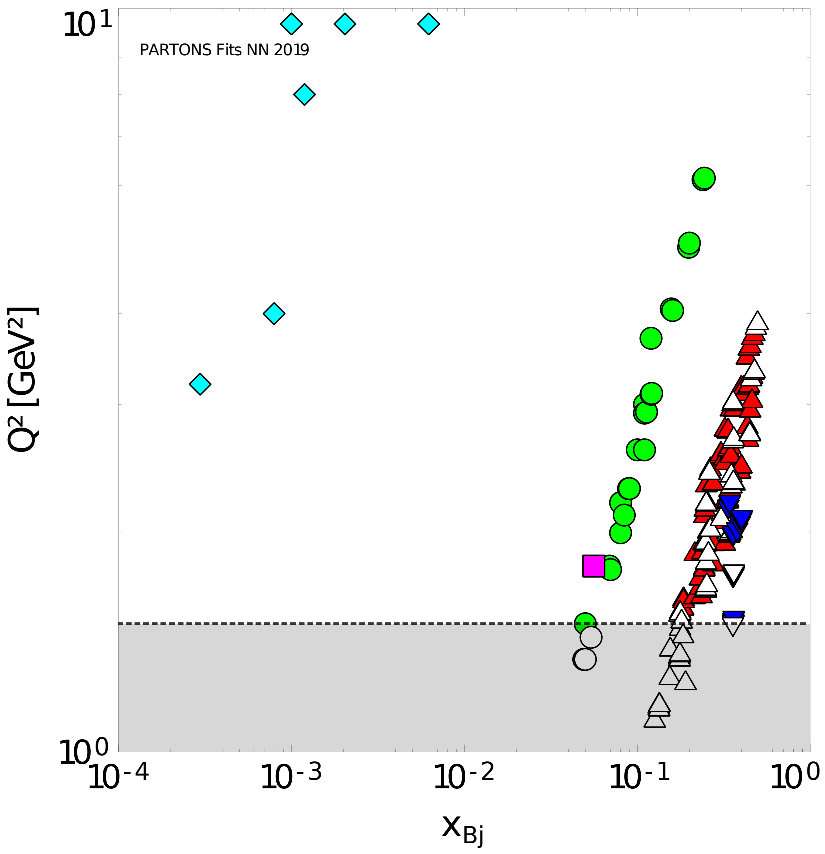
$$Q^2 > 1.5\ \mathrm{GeV}^2$$

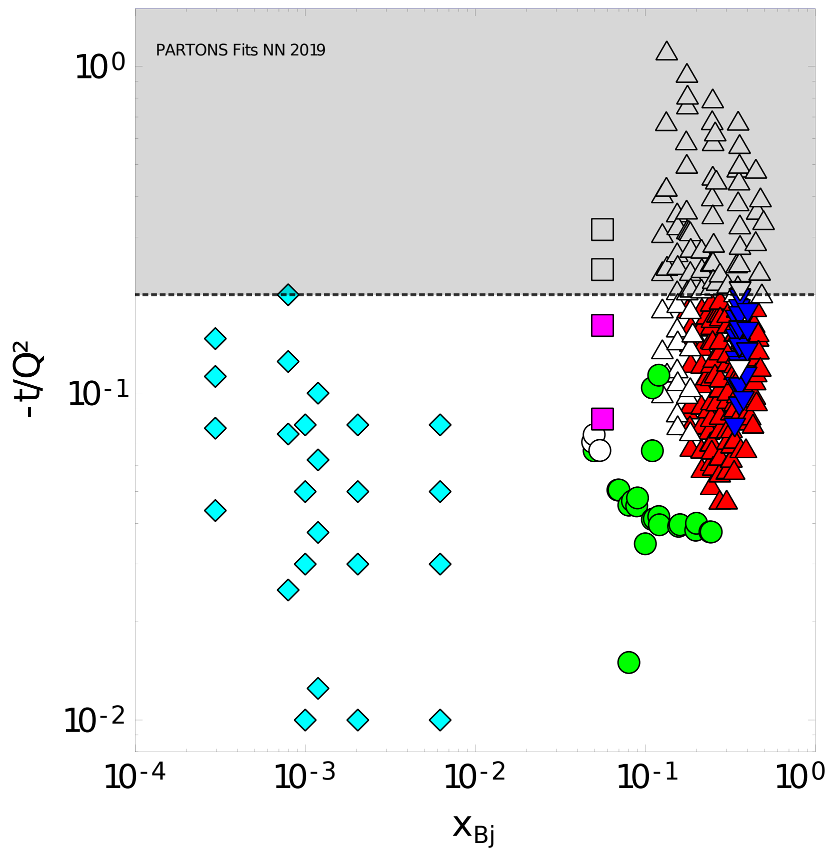
$$-t/Q^2 < 0.2$$

No.	Collab.	Year	Observable		Kinematic dependence	No. of points used / all
1	HERMES	2001	A_{LU}^{+}		ϕ	10 / 10
2		2006	$A_{C}^{\cos i\phi}$	$i=1$	t	4 / 4
3		2008	$A_{C}^{\cos i\phi}$	$i=0,1$	x_{Bj}	18 / 24
			$A_{UT,\mathrm{DVCS}}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0$		
			$A_{UT,\mathrm{I}}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0,1$		
			$A_{UT,\mathrm{I}}^{\cos(\phi-\phi_S)\sin i\phi}$	$i=1$		
4		2009	$A_{LU,\mathrm{I}}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
			$A_{LU,\mathrm{DVCS}}^{\sin i\phi}$	$i=1$		
			$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
5		2010	$A_{UL}^{+,\sin i\phi}$	$i=1,2,3$	x_{Bj}	18 / 24
			$A_{LL}^{+,\cos i\phi}$	$i=0,1,2$		
6		2011	$A_{LT,\mathrm{DVCS}}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1$	x_{Bj}	24 / 32
			$A_{LT,\mathrm{DVCS}}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1$		
			$A_{LT,\mathrm{I}}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1,2$		
			$A_{LT,\mathrm{I}}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1,2$		
7		2012	$A_{LU,\mathrm{I}}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
			$A_{LU,\mathrm{DVCS}}^{\sin i\phi}$	$i=1$		
			$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
8	CLAS	2001	$A_{LU}^{-,\sin i\phi}$	$i=1,2$	—	0 / 2
9		2006	$A_{UL}^{-,\sin i\phi}$	$i=1,2$	—	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	$d^3\sigma_{UU}^{\pm}$		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	$d^3\sigma_{UU}^{\pm}$		t	12 / 12
					SUM:	2624 / 3996

DVCS data

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





Kinematic cuts
used in presented analyses:

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

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

(exclusion denoted by open symbols and grey areas)

PARTONS project

PARTONS - modern platform to study GPDs

- Open source project to support effort of whole GPD community
- For theoreticians, experimentalists and phenomenologists
- Come with number of available physics developments implemented
- Addition of new developments as easy as possible

To download and for tutorials, useful information, reference documentation see:

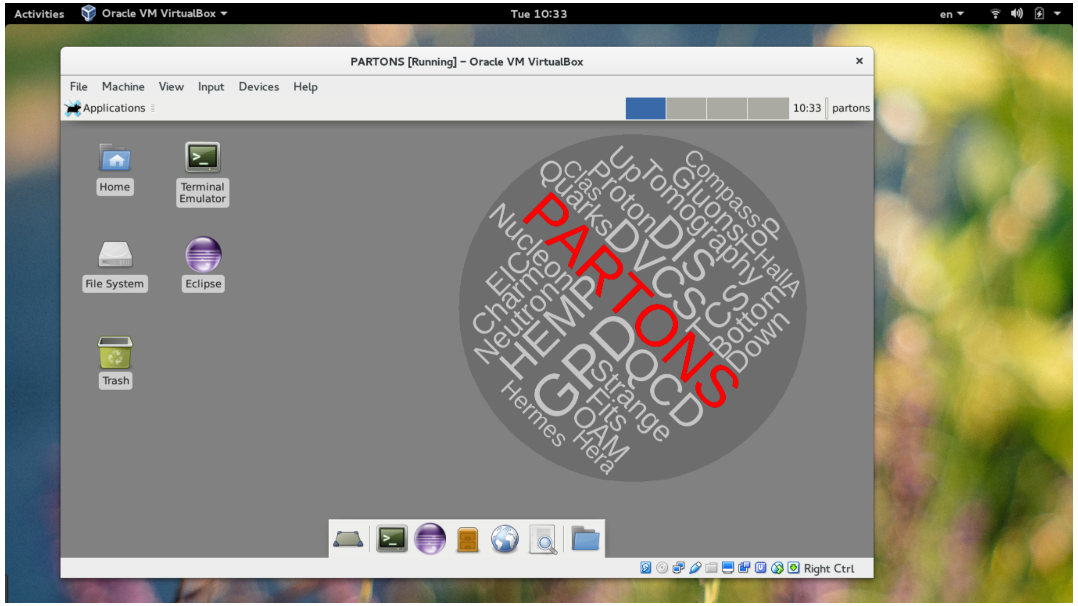
http://partons.cea.fr

For detail description of architecture see:

Eur. Phys. J. C78 (2018) 6, 478

Logo of the project:

PARTONS virtual machine (example of dissemination method):



Analysis

H. Moutarde, P. S., J. Wagner "*Border and skewness functions from a leading order fit to DVCS data*" Eur. Phys. J. C78 (2018) 11, 890

Goal: global extraction of Compton Form Factors (CFFs) from DVCS data using LO/LT formalism

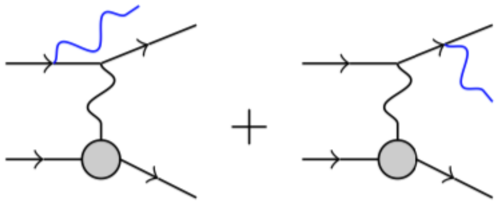
Analysis done within PARTONS project

Compton Form Factors

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

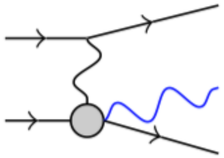
$$\sigma \propto |\mathscr{A}|^2 = |\mathscr{A}_{BH} + \mathscr{A}_{DVCS}|^2 = |\mathscr{A}_{BH}|^2 + |\mathscr{A}_{DVCS}|^2 + \mathscr{I}$$

Bethe-Heitler process



calculable within QED

DVCS



parametrised by CFFs

Compton Form Factors

- imaginary part

$$Im\mathcal{G}(\xi,t) \quad = \pi G^{(+)}(\xi,\xi,t) = \pi \sum_q e_q^2 G^{q(+)}(\xi,\xi,t)$$

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

$$G^{q(+)}(\xi,\xi,t) = G^{q_{\mathrm{val}}}(\xi,\xi,t) + 2G^{q_{\mathrm{sea}}}(\xi,\xi,t)$$

"−" for $G \in \{H, E\}$

"+" for $G \in \{\widetilde{H}, \widetilde{E}\}$

- real part

$$Re\mathcal{G}(\xi,t) = \mathrm{P.V.}\int_0^1 G^{(+)}(x,\xi,t)\left(\frac{1}{\xi - x} \mp \frac{1}{\xi + x}\right)\mathrm{d}x$$

$$Re\mathcal{G}(\xi,t) = \mathrm{P.V.}\int_0^1 G^{(+)}(x,x,t)\left(\frac{1}{\xi - x} \mp \frac{1}{\xi + x}\right)\mathrm{d}x + C_G(t)$$

$$C_H(t) = -C_E(t) \qquad C_{\widetilde{H}}(t) = C_{\widetilde{E}}(t) = 0$$

connected to EMT FF

Subtraction Constant

Relation between subtraction constant and D-term:

$$C_G^q(t) = 2\int_{-1}^{1} \frac{D^q(z,t)}{1-z}\mathrm{d}z \equiv 4D^q(t)$$

where

$$z = \frac{x}{\xi}$$

Decomposition into Gegenbauer polynomials:

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

Connection to EMT FF:

$$D^q(t) = \sum_{\substack{i=1\\ \mathrm{odd}}}^{\infty} d_i^q(t)$$

$$d_1^q(t) = 5C^q(t)$$

Ansatz

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

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

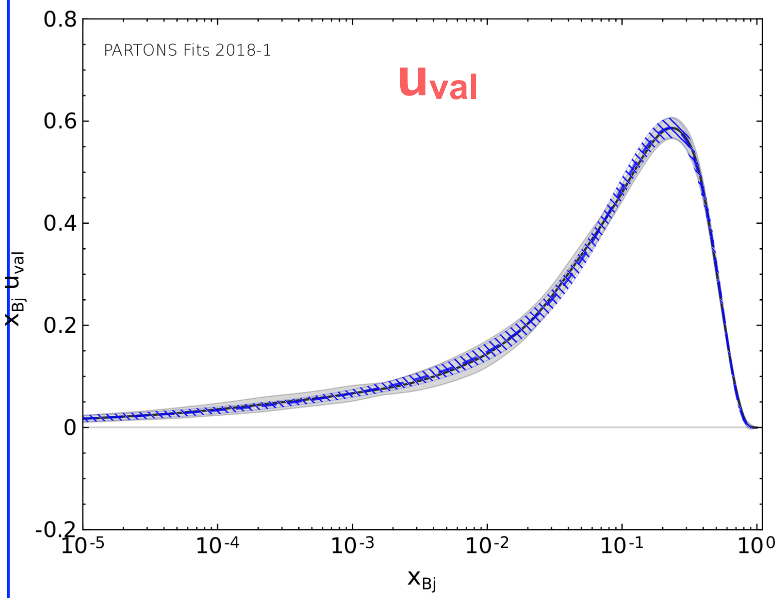
$$G^q(x,0,t) = \mathrm{pdf}_G^q(x)\ \exp(f_G^q(x)t) \qquad f_G^q(x) = A_G^q\log(1/x) + B_G^q(1-x)^2 + C_G^q(1-x)x$$

- 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

$$G^q(x,x,t) = G^q(x,0,t)\ g_G^q(x,x,t) \qquad g_G^q(x,x,t) = \frac{a_G^q}{(1-x^2)^2}\left(1 + t(1-x)(b_G^q + c_G^q\log(1+x))\right)$$

- 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

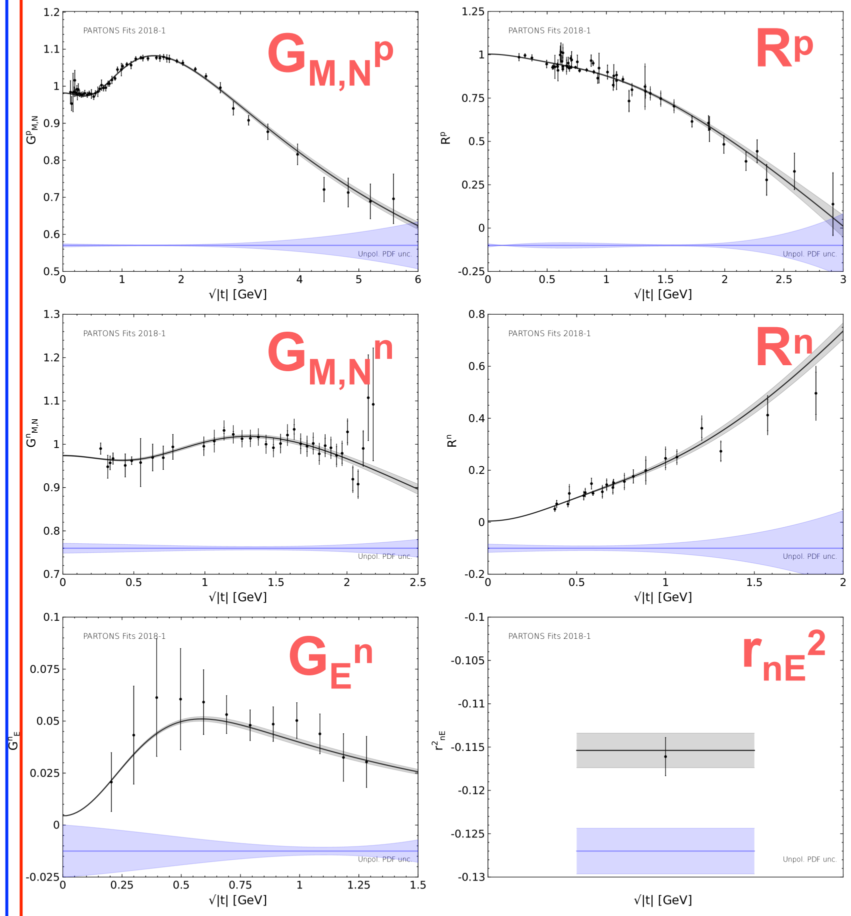
1. Analysis of PDF parameterisations



$$\mathrm{pdf}(x, Q^2) = x^{-g(\delta_p, \delta_q, Q^2)}(1-x)^{\alpha} \times \sum_{i=0}^{4} g(p_i, q_i, Q^2) x^i$$

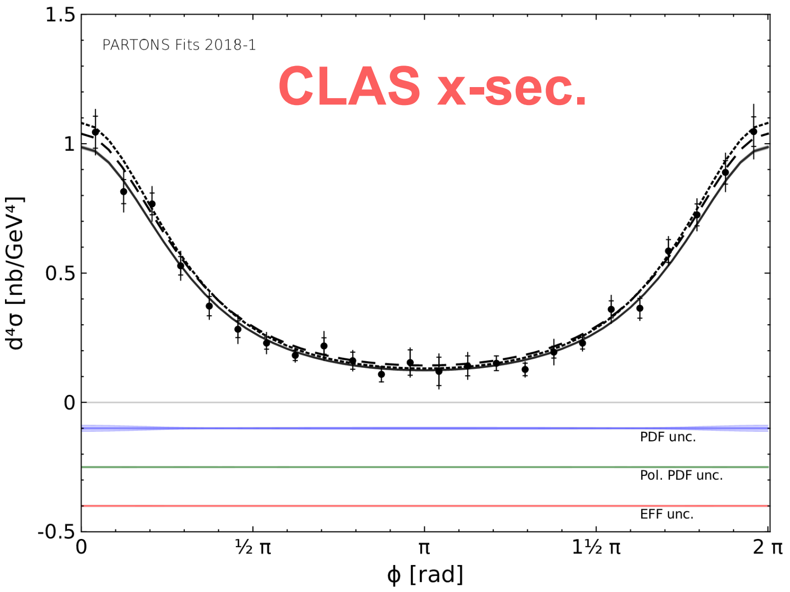
$$g(p, q, Q^2) = p + q \log \frac{Q^2}{Q_0^2}$$

2. Analysis of Elastic Form Factor data



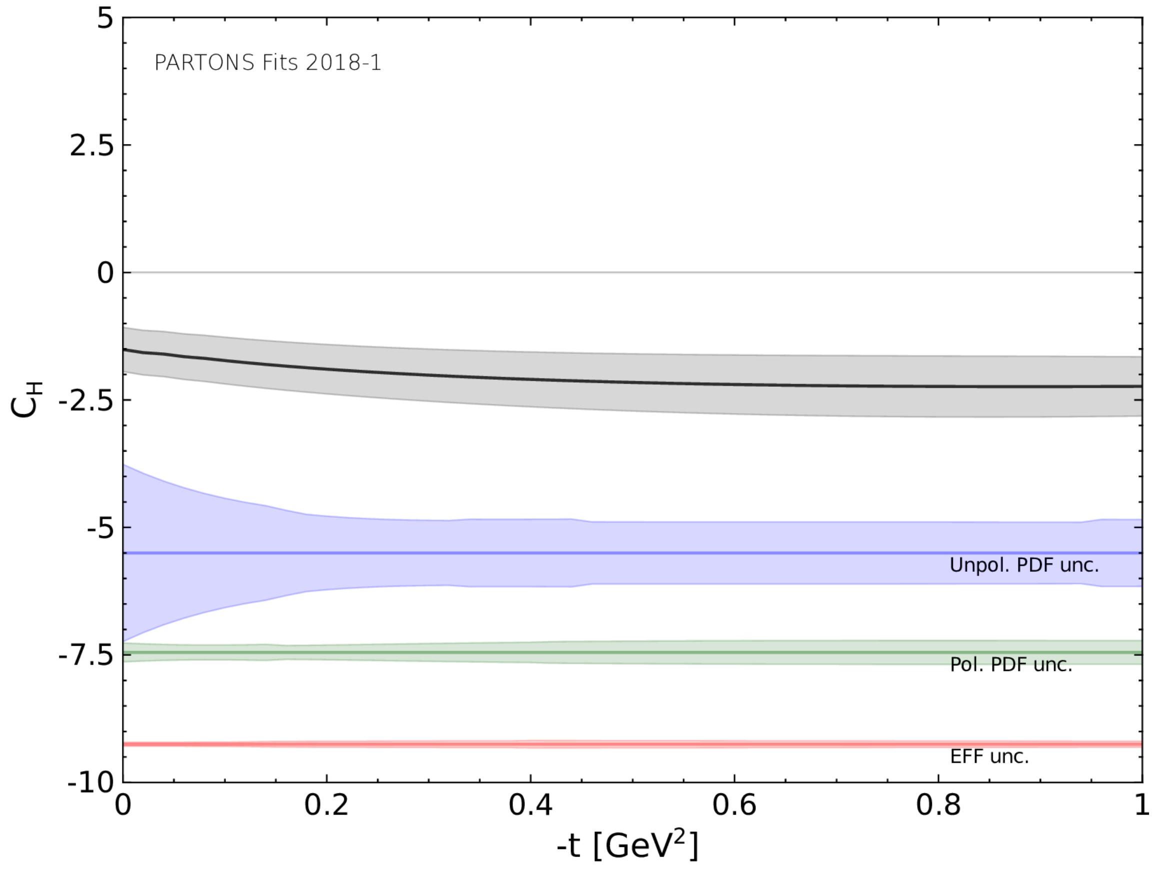
$$\chi^2/\mathrm{ndf} = 129.6/(178-9) \approx 0.77$$

3. Analysis of DVCS data

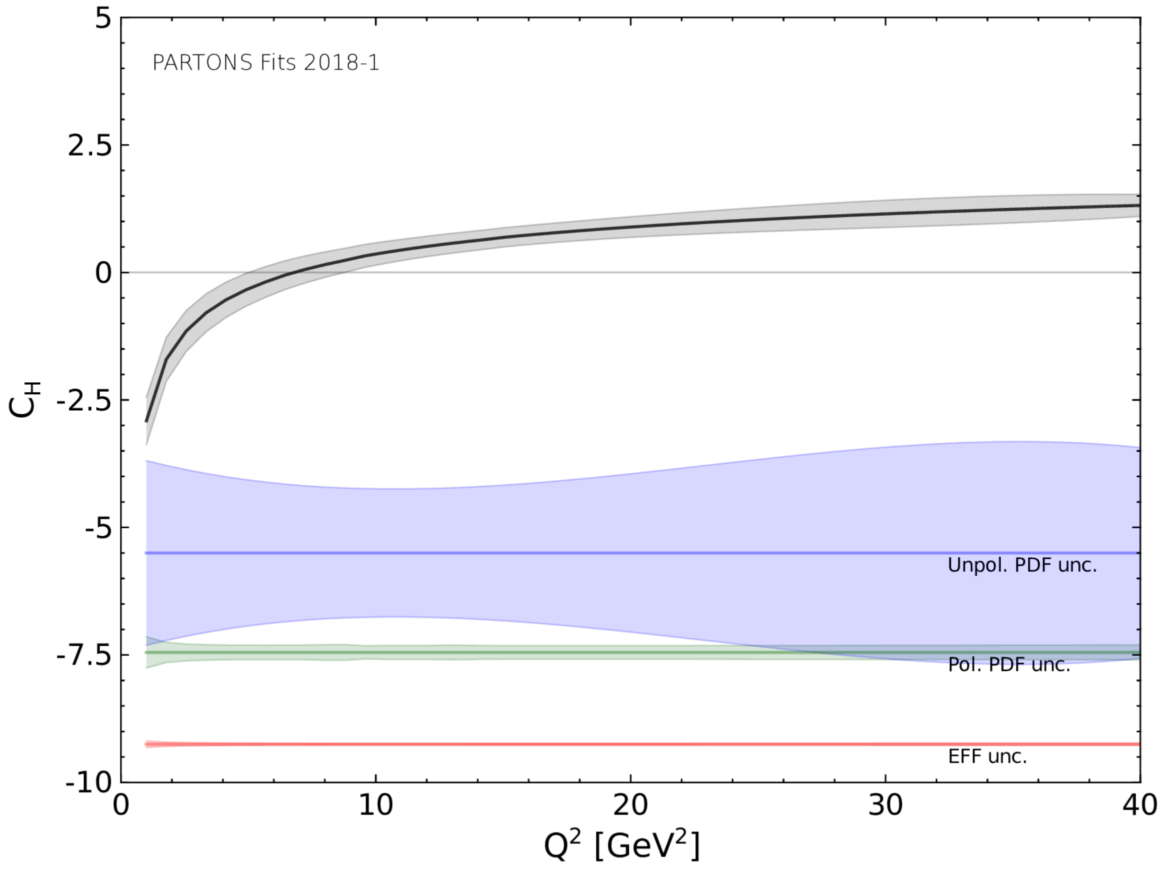


$$\chi^2/\mathrm{ndf} = 2346.3/(2600-13) \approx 0.91$$

Subtraction constant:

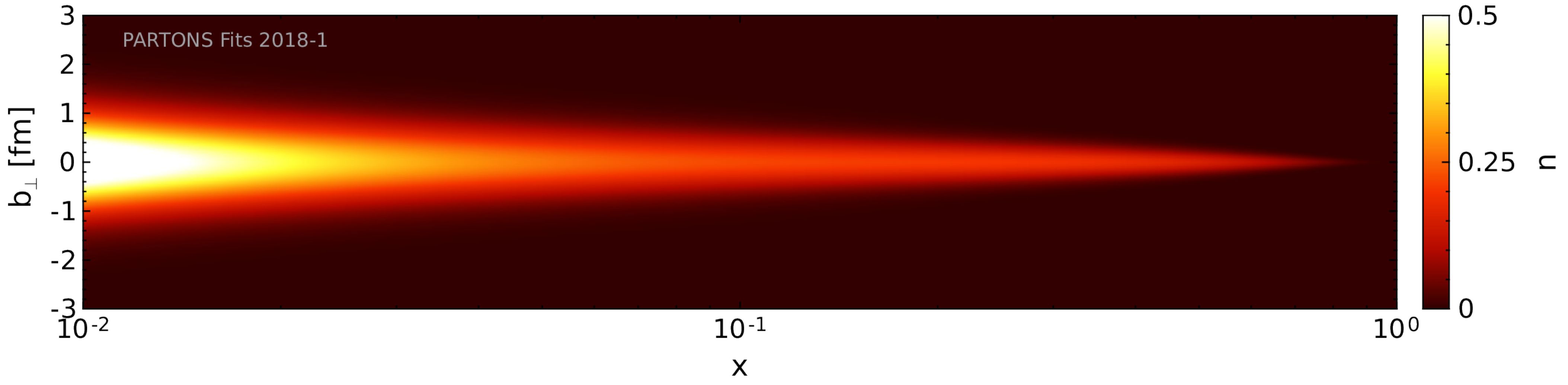


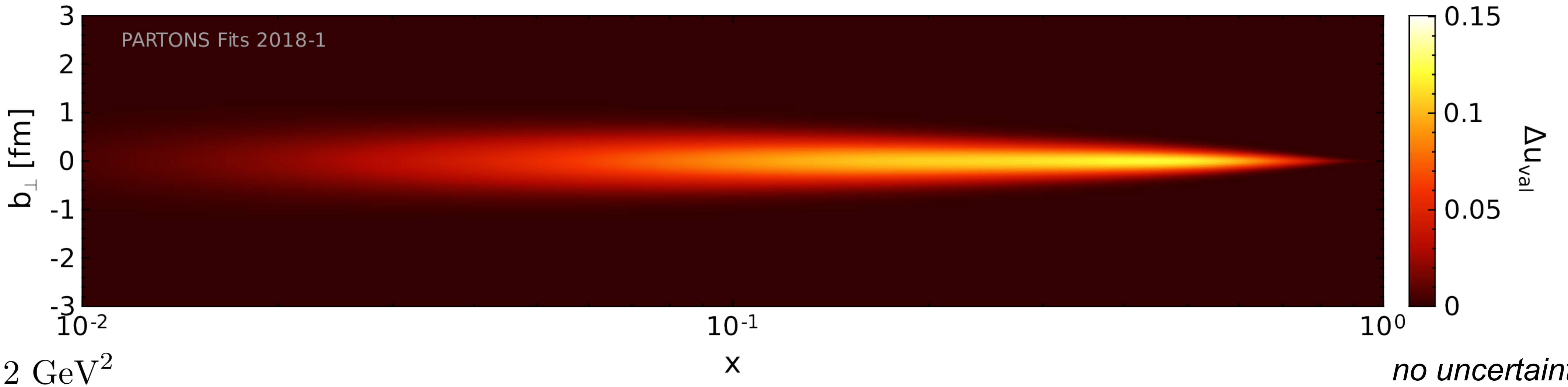
$Q^2 = 2\ \mathrm{GeV}^2$



$t = 0$

Nucleon tomography:





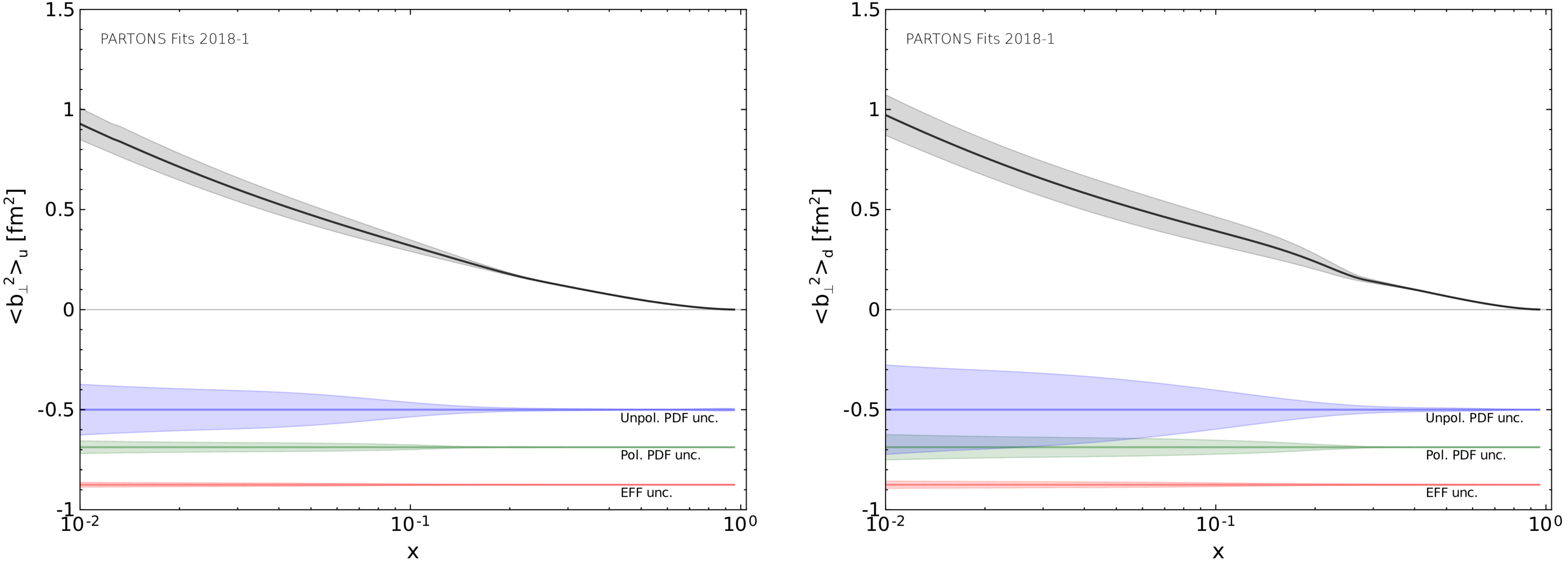
$Q^2 = 2\ \mathrm{GeV}^2$

no uncertainties!

Results

Nucleon tomography:

$$\langle b_\perp^2 \rangle_q (x) = \frac{\int d^2\mathbf{b}_\perp \; \mathbf{b}_\perp^2 q(x, \mathbf{b}_\perp)}{\int d^2\mathbf{b}_\perp \; q(x, \mathbf{b}_\perp)}$$



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

H. Moutarde, P. S., J. Wagner "*Unbiased determination of Compton Form Factors*"
accepted by Eur. Phys. J. C, preprint: arXiv: hep-ph/1905.02089

Goal: global extraction of Compton Form Factors (CFFs) from DVCS data using ANN technique

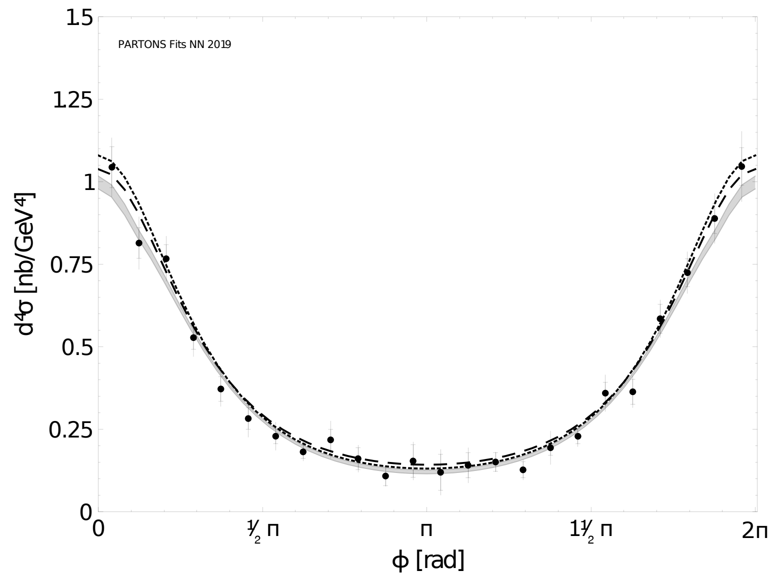
Analysis done within PARTONS project

Input data

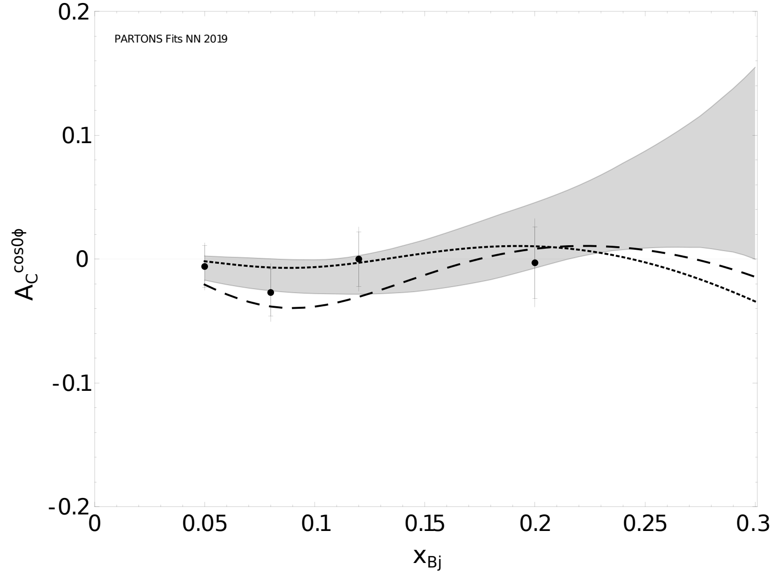
Performance:

$$\chi^2/\text{nPoints} = 2243.5/2624 \approx 0.85$$

No.	Collab.	Year	Ref.	χ^2	n	χ^2/n
1	HERMES	2001	[17]	10.7	10	1.07
2		2006	[18]	5.5	4	1.38
3		2008	[19]	18.5	18	1.03
4		2009	[20]	34.7	35	0.99
5		2010	[21]	40.7	18	2.26
6		2011	[22]	16.7	24	0.70
7		2012	[23]	22.4	35	0.64
8	CLAS	2001	[24]	—	0	—
9		2006	[25]	1.0	2	0.52
10		2008	[26]	376.4	283	1.33
11		2009	[27]	28.3	22	1.29
12		2015	[28]	306.6	311	0.99
13		2015	[29]	884.7	1333	0.66
14	Hall A	2015	[15]	231.8	228	1.02
15		2017	[16]	211.4	276	0.77
16	COMPASS	2018	[30]	3.0	2	1.50
17	ZEUS	2009	[31]	5.49	4	1.38
18	H1	2005	[32]	22.2	7	3.17
19		2009	[33]	23.4	12	1.95



CLAS

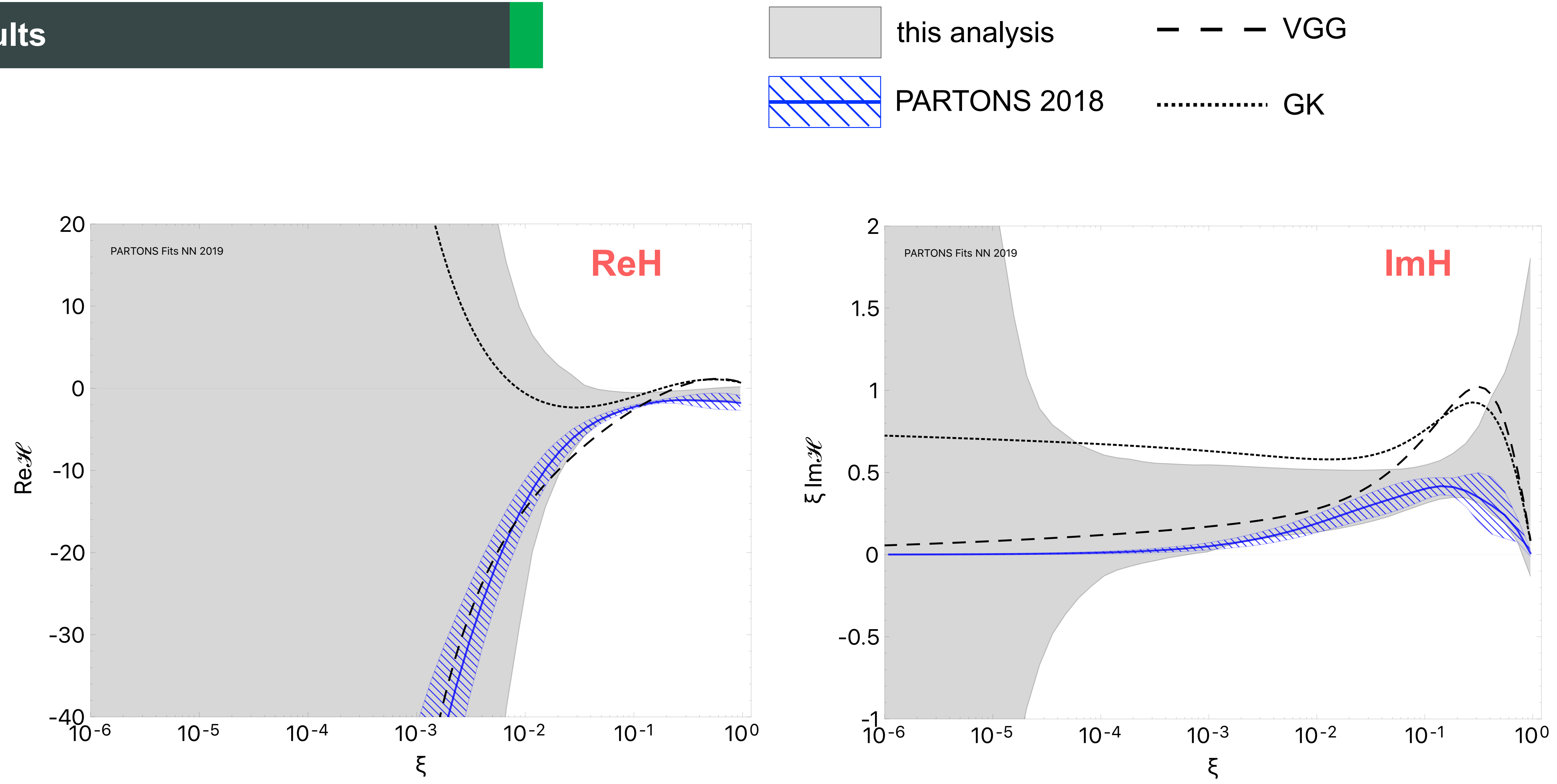


HERMES

Replication of experimental data to propagate corresponding uncertainties:

$$v_i \pm \Delta_i^{\text{tot}} \xrightarrow{\text{replica } j} \left(\text{rnd}_j(v_i, \Delta_i^{\text{tot}}) \pm \Delta_i^{\text{tot}}\right) \times \text{rnd}_j(1, \Delta_i^{\text{norm}}) \qquad \Delta_i^{\text{tot}} = \sqrt{(\Delta_i^{\text{stat}})^2 + (\Delta_i^{\text{sys}})^2}$$

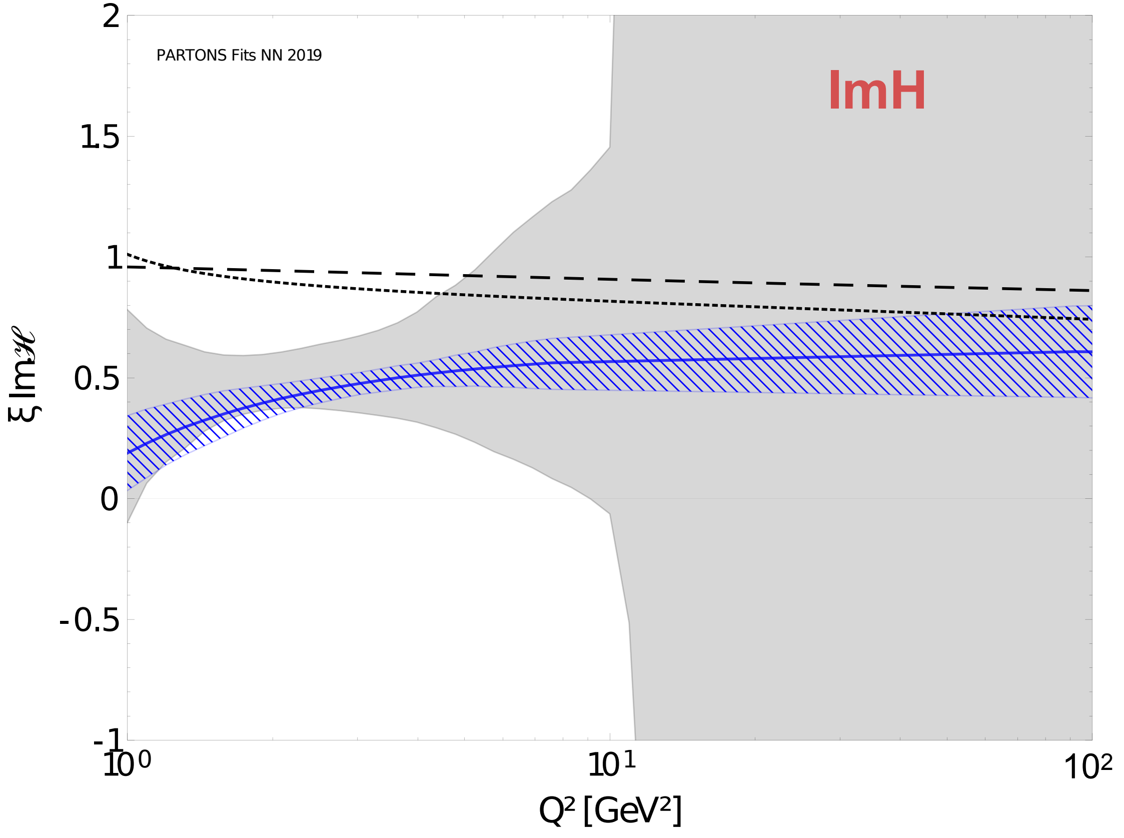
Results

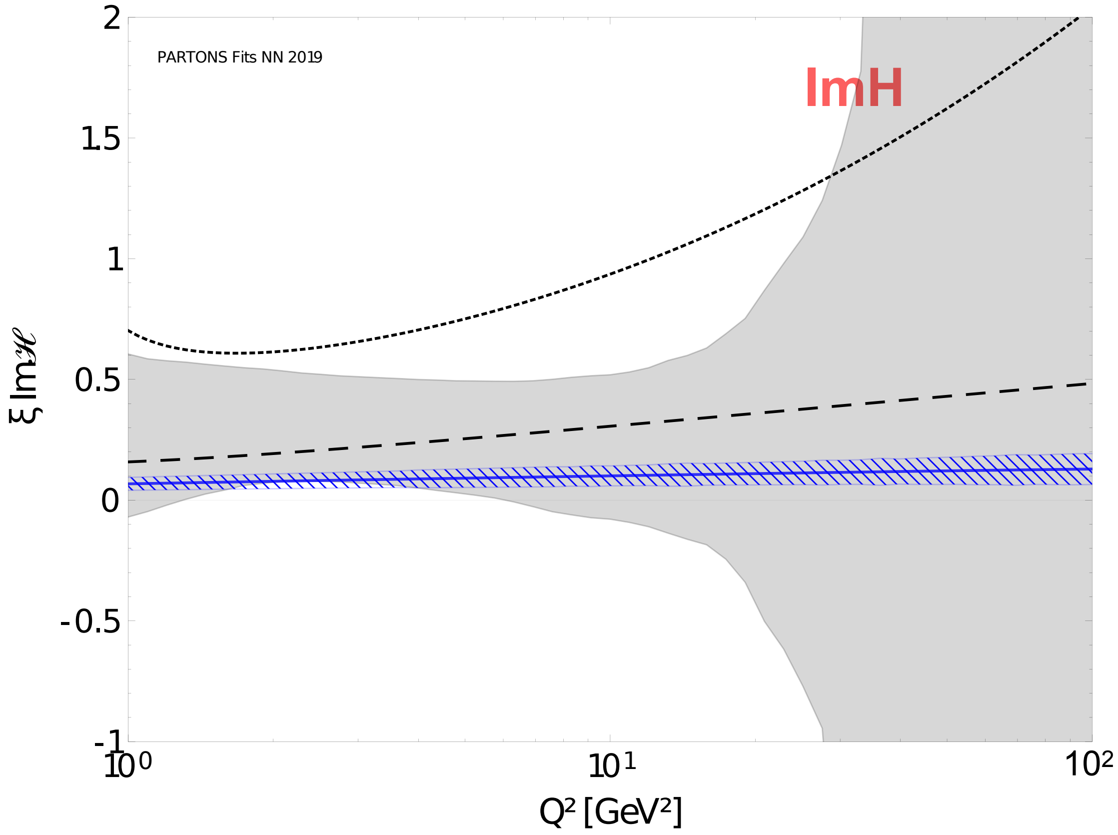


@ t = -0.3 GeV², Q² = 2 GeV²

$$\xi \approx \frac{x_B}{2 - x_B}$$

Results



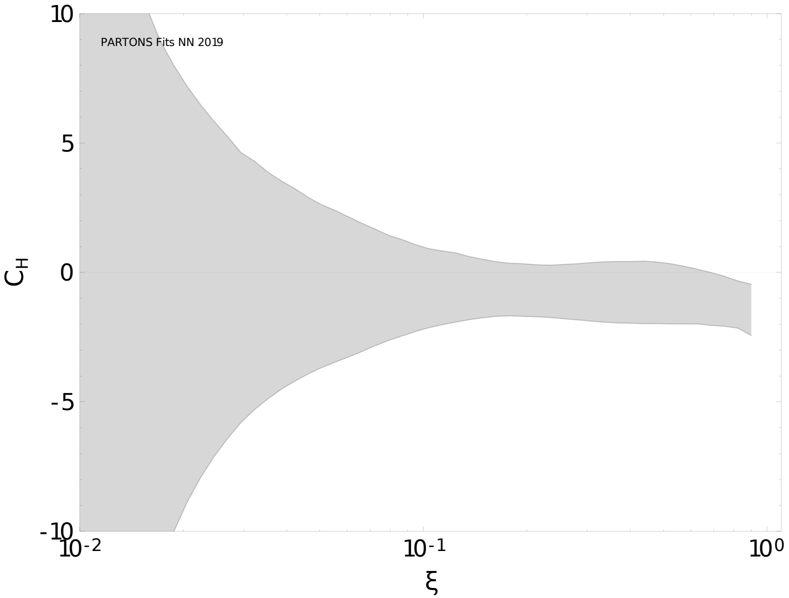


@ $\xi = 0.2$, $t = -0.3$ GeV^2

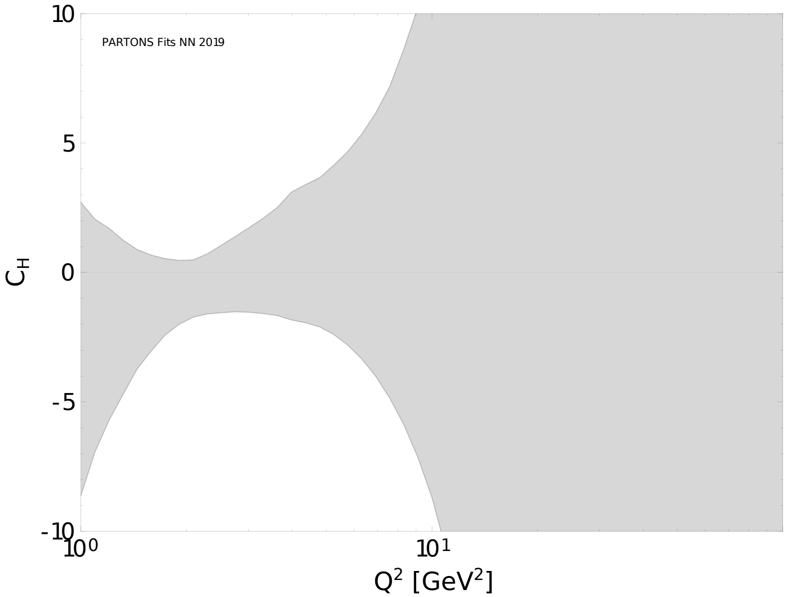
@ $\xi = 0.002$, $t = -0.3$ GeV^2

Subtraction constant

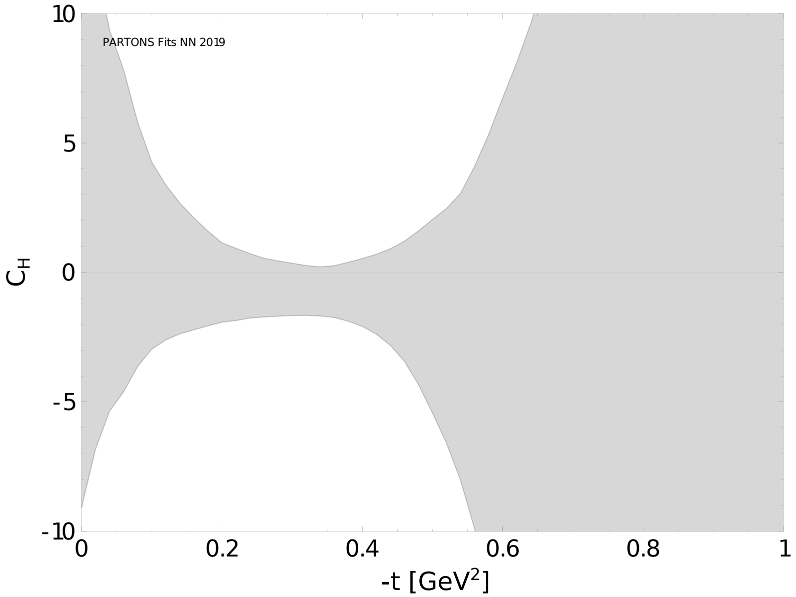
as function of ξ
@ $|t|$ = 0.3 GeV², Q^2 = 2 GeV²



as function of Q^2
@ ξ = 0.2, $|t|$ = 0.3 GeV²



as function of $|t|$
@ ξ = 0.2, Q^2 = 2 GeV²



- Direct extraction of subtraction constant → encouraging precision
- As expected, no ξ behaviour observed
- Strong, model independent constraints on modeling of this quantity

SUMMARY

Generalised Parton Distributions

- novel way to describe partonic structure of nucleon
- allows to study (highlights):
  - → nucleon tomography
  - → total angular momentum of partons
  - → “mechanical” properties of parton distributions

Global analysis of DVCS data

- complementary approaches → classic Ansatz and ANN
- done with PARTONS framework -
- allows to access (highlights):
  - → nucleon tomography
  - → “mechanical” properties of parton distributions

Clear need to have EIC!